Understanding the implications of industrial decarbonisation

A multidisciplinary approach towards the transition of the basic materials industry and its impact on our energy systems

Timo Gerres

Supervisors:

Dr. José Pablo Chaves Ávila

Prof. Dr. Tomás Gómez San Román

ICAI School of Engineering

Comillas Pontifical University

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Daß ich erkenne, was die Welt
Im Innersten zusammenhält, …[1]

"Faust. Der Tragödie erster Teil" von Johann Wolfgang von Goethe

[1] That I may detect the inmost force
which binds the world, and guides its course, …

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Timo Gerres

Madrid, December 2021

Words of gratitude…

The last 4.5 years have been full of twists and turns. Unexpected changes can be positive and negative. Positive changes were almost always closely linked to colleagues, family and friends who encouraged me to push forward and coping with negative changes wouldn't have been possible without their unselfish support.

First, I would like to thank my first supervisor José Pablo Chaves Ávila. Without your encouragement, curious mind, and guidance, my thesis wouldn´t have evolved into a work that seemed to be further away from your field of research with each new day. Together with Tomás Gómez San Román, my second supervisor, you two granted me the liberty to depart from studying the electricity market and explore the bigger picture of industrial transition while always asking the right questions at the right time.

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Abstract

The industrial processes we have used for producing basic materials over the last centuries are unsuitable for an economy with a net-zero carbon footprint. Basic materials like steel, cement, aluminium and (petro)chemicals are the building blocks of our industrialised societies, but today their production is highly energy and emission-intensive. There is no other alternative. These industries need to decarbonise over the next decades for keeping global warming below 2°C. However, the implications of this transition for the industry, our energy systems and society are little understood.

This thesis asks how this transition can take place by exploring the technical, economic, and regulatory dimensions of decarbonising the energy-intensive basic material sector. By following a multidisciplinary approach, the thesis looks upon these different dimensions separately, identifying propositions that characterise the industrial transition and help us understand its implications for our energy systems.

The first part of the thesis studies technology options for climate-friendly basic material production in different industries and evaluates their cross-sectorial significance. Findings highlight the challenge of reducing emissions linked to the high thermal energy demand required to produce most basic materials and process emissions originating from the chemical transformation of naturally occurring resources to basic materials. Decarbonisation across all industries requires breakthrough technologies that are not available on a commercial scale.

Today´s conventional production technologies are highly standardised. They rely primarily on fossil fuels, obtaining basic materials in high quantities while keeping energy costs low. However, climate-friendly breakthrough technologies mark a shift from fossil fuels to low-emission alternatives. Therefore, the second part of this thesis studies the functioning of future electricity markets and explores the implication of decarbonising energy systems for industrial consumers. Future energy markets should be designed to ensure the emission avoidance, affordability, and adequacy of energy for industrial consumers.

Higher costs for low-emission energy sources or potentially higher energy demand to avoid emissions make climate-friendly basic material production more expensive than conventional processes. Breakthrough technologies require a regulatory framework to support the transition. The third part of this thesis demonstrates how different policies are needed to kick-start the transition, create markets for climate-friendly materials and ensure long-term climate neutrality.

Finally, the last part of this thesis reflects upon the propositions that characterise the transition´s technological, economic, and regulatory dimensions and argues that models to study the transition need to incorporate the three dimensions sufficiently. Since energy-system models and bottom-up approaches are insufficient, a new sector-specific modelling approach is necessary. The thesis introduces the conceptual model TRANSid (**Trans**ition towards **I**ndustrial **D**ecarbonisation) to address this modelling gap. It uses a simplified case study to demonstrate how the conceptual model could be translated into a mathematical formulation.

The thesis concludes with various recommendations about the future research needs to study industrial decarbonisation across the technological, economic and policy dimensions.

Resumen

Los procesos industriales que se han utilizado para fabricar materias primas, pero durante los últimos siglos esto procesos no están adecuados a contribuir a una economía con una huella de carbono neta de cero. Las materias primas como el acero, el cemento, el aluminio y los productos (petro)químicos forman la base de nuestras sociedades industrializadas, pero hoy en día su producción es intensiva en energía y emisiones. Actualmente, es necesaria la descarbonización de estas industrias para mantener el calentamiento global por debajo de los 2°C durante las próximas décadas. Sin embargo, las implicaciones de esta transición para la industria, los sistemas energéticos y la sociedad son poco conocidas.

En esta tesis se pregunta cómo se puede realizar esta transición, explorando las dimensiones técnicas, económicas y regulatorias de la descarbonización del sector de materias primas intensivas en el uso energía. Se analizan estas diferentes dimensiones con un enfoque multidisciplinario, identificando propuestas que caracterizan la transición industrial y ayudan a entender sus implicaciones para los sistemas energéticos.

En la primera parte de la tesis se estudian las opciones tecnológicas para la producción sostenible de materias primas en diferentes industrias y se evalúa su importancia intersectorial. Los resultados destacan el desafío de reducir las emisiones vinculadas a la alta demanda de energía térmica necesaria para producir la mayoría de los materiales básicos y las emisiones de procesos que se originan en la transformación química de recursos naturales. La descarbonización en todas las industrias requiere tecnologías innovadoras que no están disponibles a escala comercial.

Las tecnologías de producción convencionales están altamente estandarizadas y se basan principalmente en el uso de combustibles fósiles, manteniendo bajos costes de energía y obteniendo materias primas en grandes cantidades. Sin embargo, las innovadoras tecnologías sostenibles marcan un cambio de los combustibles fósiles a alternativas de bajas emisiones. Por tanto, en la segunda parte de esta tesis se estudia el funcionamiento de los futuros mercados eléctricos y se exploran las implicaciones de la descarbonización de los sistemas energéticos para los consumidores industriales. Se concluye que deben diseñar los mercados de la energía en tal manera que garantizan la reducción de emisiones, su asequibilidad y la disponibilidad de la energía para los consumidores industriales.

Los altos costes para fuentes de energía de bajas emisiones o un consumo energético más elevado para evitar las emisiones hacen que la producción sostenible de materias primas sea más costosa que los procesos convencionales. Las tecnologías innovadoras requieren un marco regulatorio que guía la transición. En la tercera parte de esta tesis se demuestra cómo diferentes medidas regulatorias serán necesarias para impulsar la transición, crear mercados para materias primas de producción sostenible y garantizar la neutralidad climática a largo plazo.

En la última parte de la tesis se presenta una reflexión sobre las propuestas que caracterizan las dimensiones tecnológica, económica y regulatoria de la transición y se sostiene que los modelos para estudiar la transición necesitan incorporar estas tres dimensiones. Dado que los modelos de sistemas energéticos y los modelos "bottom-up" son insuficientes, se necesita un nuevo enfoque de modelado. Para abordar esta brecha de modelado, se presenta el moldeo conceptual TRANSid (**Transi**ción hacía una **i**ndustria **d**escarbonizada). Además, se presenta un caso de estudio simplificado para demostrar cómo el modelo conceptual se traduce en una formulación matemática y obtener conclusiones cuantitativas sobre las implicaciones de la transición de la descarbonización en un sector determinado.

La tesis concluye con recomendaciones de cómo avanzar en el estudio de la descarbonización de la industria en las distintas áreas estudiadas.

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Abbreviations

BAT	Best Available Technology
BF-BOF	Blast Furnace - Blast Oxygen Furnace
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CC	Climate Contribution
CCGT	Combined Cycle Gas Turbine
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CE	Conformité Européenne (European conformity)
CfD	Contract for Differences
CFMP	Climate Friendly Materials Platform
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide and equivalent
COVID-19	Coronavirus Disease 2019
CSP	Concentrated solar power
DAC	Direct Air Capture
Dii	Desertec initiative
DRI	Direct Reduced Induction
DSO	Distribution System Operator
EAF	Electric Arc Furnace
EC	European Commission
EMAS	Eco-Management and Audit Scheme
ESM	European social model
ETS	Emission Trading System
EU	European Union
EUROSTAT	European Statistical Office
FLEGT VPA	Forest Law Enforcement, Governance and Trade Voluntary Partnership Agreement
FOB	Free On Board
GATT	General Agreement on Tariffs and Trade
GPP	Green public Procurement
HCC	Hard Coking Coal
HTHP	high-temperature heat pumps
HVC	high-value chemicals
HVDC	High Voltage Direct Current
IDAE	Instituto para la Diversificación y Ahorro de la Energía
IEA	International Energy Agency
IIT	Instituto de Investigación Tecnológica
IPCC	Intergovernmental Panel on Climate Change (United Nations)
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardisation
JRC	Joint Research Centre of the European Commission
LCOE	Levelised Cost Of electricity
LCOH	Levelised Cost Of Hydrogen
LCONG	Levelised supply Cost Of Natural Gas
LNG	Liquified Natural Gas
LP	Linear Programming
MEA	Monoethanolamine
MITECO	Ministerio para la Transición Ecológica y el Reto Demográfico
NECP	National Energy and Climate Plan
NEM	National Electricity Market (Australia)
NIMBY	Not In My Backyard
NPV	Net Present Value
O&M	Operations and Maintenance
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
OPEX	Operating Expenses
PV	Photovoltaic
REE	Red Eléctrica de España (TSO of Spain)
RES	Renewable Energy Sources
SCM	Subsidies and Countervailing Measures agreement
SMR	Steam Methane Reforming
TBT	Technical Barriers to Trade
TRANSid	TRANSition towards industrial decarbonisation
TSO	Transmission System Operator
TTF	Title Transfer Facility (virtual natural gas trading point in the Netherlands)
VEPL	Variable Weights Energy Price Levels
WLTP	World Harmonised Vehicle Test Procedure
WTO	World Trade Organisation

Chapter 1

Introduction

1.1. Foreword

This thesis manuscript is a guide to the various facets of my work on industrial decarbonisation at the Instituto de Investigación Tecnológica (IIT) over the last 4.5 years. What began as a research project focusing on the future role of heavy industry on electricity markets became a truly multidisciplinary journey to grasp the magnitude of the transition faced by the energy and emission-intensive basic material sector over the next decades. Seeking an answer for one question may not lead to a satisfactory response but instead opens up more questions.

A PhD thesis is the result of a process, and the following 200 pages allow the reader to follow my personal journey towards understanding the implications of industrial decarbonisation. After departing from a predominantly technical view on conventional production methods and potential alternatives to produce the likes of steel, cement, or plastics, it turned out to be an even greater challenge to create a business case for climate-friendly basic materials and design policies to support the transition.

Addressing these challenges is a monumental task that goes far beyond the scope of this thesis. Academia, industry, governments, and society need to face it together to achieve the common goal of net-zero emissions in the European Union. However, for myself, this thesis is a first step, and I am curious and looking forward to taking the next ones, contributing at least a little bit to the biggest challenge our generation faces over the next decades.

1.2. Research objectives

The general motivation of the thesis is to explore how future industrial energy demand might develop when facing stringed decarbonisation policies over the upcoming decades. What started as a question about how to model industrial energy consumption became a scientific journey to understand the drivers that define the evolution of the basic material sector towards climate-friendly production processes. The main research objective and specific sub-objectives for this thesis are as follows.

1.2.1. Main objective

Identify the implications of decarbonising the energy-intensive basic material sector and frame its role in future energy systems under consideration of technical, economic, and regulatory aspects.

1.2.2. Sub-objectives

Each of the first three sub-objectives addresses one of the multidisciplinary dimensions stated in the main objective to understand technical, economic and regulatory aspects of the transition. The fourth sub-objective combines these different dimensions to provide an answer for the main objective.

I. *Evaluate the principal emission abatement options for the basic material sector, their cross-sector applicability and decarbonisation potential for the European industrial sector.*

II. *Analyse the interplay of the energy system evolution and industrial transformation, emphasising the role of the electricity markets and a potential hydrogen economy.*

III. *Contrast long-term policy options that can foster desirable transitions of the industrial park to reach decarbonisation targets without jeopardising the economic viability of all stakeholders.*

IV. *Explore how the energy demand and characteristics of the basic material sector can evolve by introducing new process innovations under various premises concerning available technologies, market scenarios and policies.*

1.3. Structure

Each chapter in this thesis is structured to explore the different dimensions stated in the main research question.

Chapter 2 sets the stage for energy-intensive industries. The background information provided in this chapter motivates the focus on the basic materials sector and the multidisciplinary approach chosen to study the basic materials sector.

Chapter 3 to 4 focus on the technical, (energy) economic, and policy dimensions of the transition and sub-objectives I to III. Each chapter concludes with a list of propositions that will define the transition of the basic material sector.

Chapter 6 identifies the modelling gap that needs to be addressed for meeting sub-objective IV based on the propositions formulated in Chapter 3 to 5. It then introduces the conceptual design for the TRANSid model, which aims to address this modelling gap.

Chapter 7 revisits the main objective, reflects on the results presented in this thesis and evaluates to what extent the main and sub-objectives have been met. I conclude by identifying future research needs that arise from the analysis presented in this thesis.

Figure 1-1 summarises the building blocks of this thesis and reflects on how the different chapters and sub-objectives are interlinked.

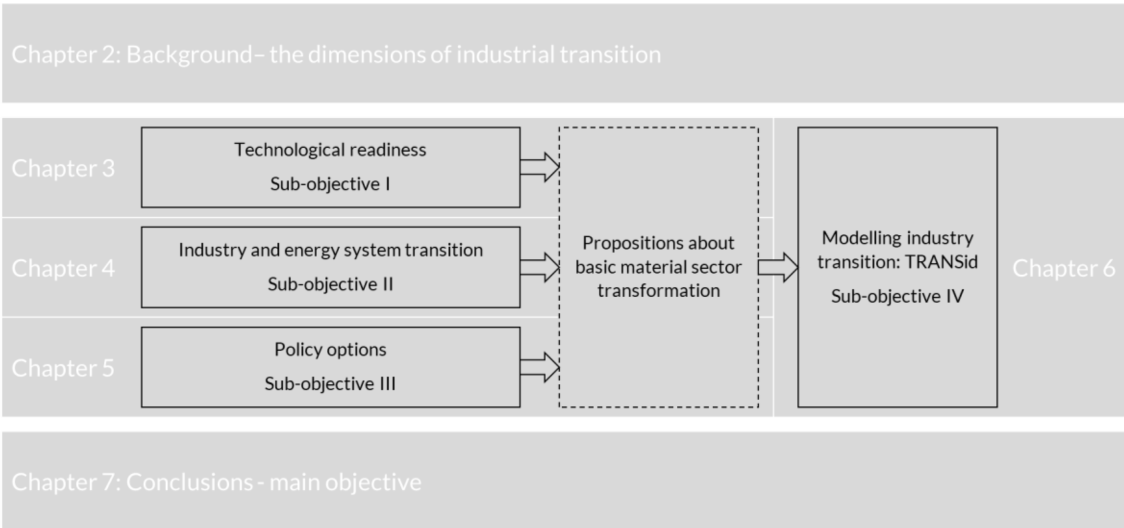

Figure 1-1: Thesis structure

Chapter 2

Background: basic materials, industry, energy, emissions

“Man has too long forgotten that the earth was given to him for usufruct alone, not for consumption, still less for profligate waste. [ ] … [nature] has left it within the power of man irreparably to derange the combinations of inorganic matter and of organic life, which through the night of æons she had been proportioning and balancing, ... [ ].“. George P. Marsh (1864) wrote these lines about the destructiveness of man more than 150 years ago. Nevertheless, they still accurately describe how we use materials made from natural resources in our day-to-day life. Starting with the laptop used to write this chapter and the printer bringing it onto paper, all manufactured goods or artefacts surrounding us are made from processed organic or inorganic matter. One day when used, broken, or not needed anymore, they will be returned to nature as profligate waste.

The role of basic materials used to manufacture any physical good in our daily life is often overlooked when referring to our society´s impact on nature, particularly the challenges related to global warming and climate change. Its emission and energy-intensive processing and production often take place in industrial plants, which are out of sight during our daily life, and might even be situated on the other side of the globe. Other than the smoke from the neighbour´s chimney, the smell of diesel exhaust gases from the passing truck or the contrails above our heads, we do not take notice of the cement plant situated far beyond the city borders, the steel mill on the other side of the country or the chemical plant supplying textile factories with polyester feet in East Asia.

The following chapter frames the industrial decarbonisation challenge. It aims at highlighting the interlinkage between basic material production, energy supply and policymaking. Commencing from a global view on direct and indirect emissions linked to the industrial sector and basic material production, I explain the origins of basic material emissions in section 2.1. Section 2.2 takes a deep dive into the current energy consumption of different industrial sectors in Europe. By contrasting energy consumption patterns with technological and economic aspects, I show what the industrial transition might mean for our energy systems and highlight the importance of electricity supply for decarbonising basic materials. In section 2.3, I then compare electricity and basic materials, which allows me to frame the decarbonisation challenge as multidisciplinary in section 2.4, considering technical, economic and policy aspects.

2.1. Basic materials: an overlooked emission reduction challenge

In the following, I first explore industrial sector emissions and their impact on our global carbon footprint (section 2.1.1). I then show why basic material production is the primary source for these industrial emissions by reflecting on the mass balances of basic material production processes and their energy intensities (section 2.1.2). The resulting overview shows why the transition of the basic material sector is without alternative for reaching carbon neutrality (section 2.1.3).

2.1.1. Industrial emissions

Estimations about the global emission intensity caused by human activity vary. Difficulties in ensuring the validity of global emission inventories have long been identified (Olivier, 2002). However, emission reporting can provide valuable insights for tracing the origins of emissions and associating them with different economic activities. The sum of all emissions is here the sum of all direct emissions from all point sources on the entire planet, and these direct emissions are commonly referred to as Scope 1 emissions (Box 2-1). The International Energy Agency (IEA) estimates that the total annual sum of these direct emissions increased from 32.2 Gt/year in 2015 to 33.3 Gt/year in 2019 (IEA, 2020a). For 2018, about 18.5% of direct emissions were linked to the industry, while electricity and heat generation was the main contributor (41.9%) (IEA, 2020b). In the case of the European Union, the share of direct industrial emissions is similar, accounting for 19.0 % in 2017 (EEA, 2019).

Box 2-1: Defining direct and indirect emission scopes

Internationally the most common and widely accepted approach to differentiate between direct emission and indirect emissions was defined by the GHG Protocol, a private sector initiative, and divides emissions caused by an entity in three different groups. The following wording is used by the IPCC and has been adopted for this work (Allwood et al., 2014):

Scope 1: direct greenhouse gas (GHG) emissions that are from sources owned or controlled by the reporting entity.

Scope 2: indirect GHG emissions associated with the production of electricity, heat, or steam purchased by the reporting entity.

Scope 3: all other indirect emissions, i.e., emissions associated with the extraction and production of purchased materials, fuels, and services, including transport in vehicles not owned or controlled by the reporting entity, outsourced activities, waste disposal, etc.

Not every mentioning of the term “emissions” in this work is followed by a clear definition of its scope. If not explicitly specified otherwise, “emissions” refers to direct Scope 1 emissions and “indirect emissions” refers to both Scope 2 and Scope 3 emissions.

Direct emission reporting hides the interrelations between different activities responsible for our global carbon footprint. Indirect emission reporting, which can be further differentiated between scope 2 and scope 3 emissions (Box 2-1), considers the direct emissions of all activities linked to the existence of each point source of emissions. Bearing in mind that indirect emissions are not accumulative, the detailed carbon footprint analysis of the five IPCC[2] sectors (energy, transport, industry, buildings and agriculture) by Hertwich and Wood (2018) demonstrate the critical role of industry in causing indirect emission by other end-uses in both relative and absolute terms (Figure 2-1). Based on their detailed analysis for the global industrial sector, the authors show that these indirect industrial emissions were mainly caused by energy provision (18.6%) and emissions from other industrial activities (63.0%). Additionally, direct industrial emissions are the primary source of indirect emissions in other sectors and account, for example, for 67.1% of indirect emissions in the building sector.

[2] IPCC: Intergovernmental Panel on Climate Change of the United Nations

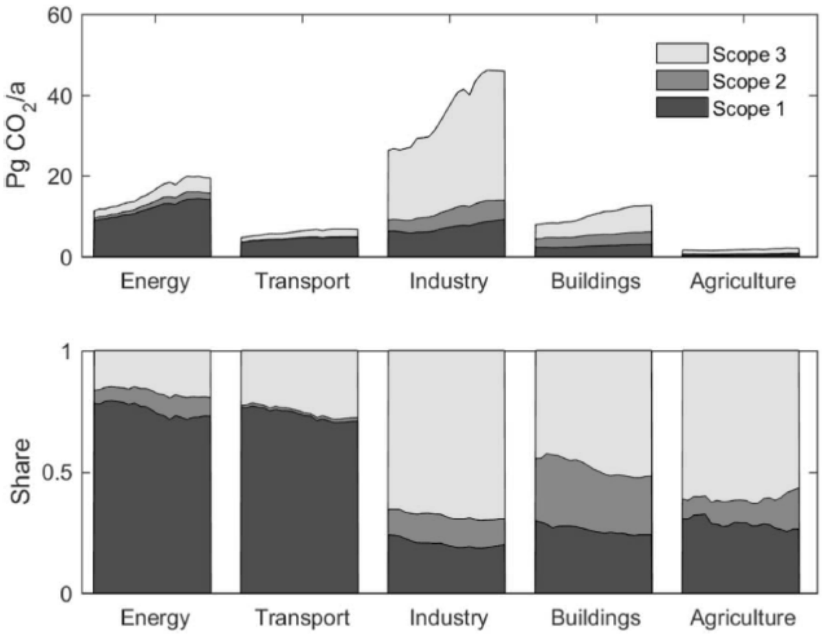

Figure 2-1: Global emissions of the five IPCC sectors from 1995 to 2015 (Hertwich and Wood, 2018)

Very few highly emission-intensive processes cause most direct industrial emissions. Namely, the production of basic materials such as cement, iron & steel, chemicals, aluminium, and paper was responsible for 71% of European direct industrial emissions in 2018 (Figure 2-2). Manufacturing causes minor direct emissions compared to the production of basic materials. Nevertheless, reducing the indirect carbon footprint of manufacturing requires the decline of direct emission linked to the basic material production, resulting in the 63.0% share of indirect industrial emissions related to other industrial activities stated by Hertwich and Wood (2018). Consequently, manufacturing a car with a zero-carbon footprint, as announced by carmaker Volkswagen (electrive, 2019), primarily requires the decarbonisation of basic material production, given that no carbon offsetting[3] or direct air capture (DAC) of carbon dioxide-equivalent emissions[4] are available.

Those emissions linked to the end-of-life of industrial products are accounted for in the indirect (Scope 3) emissions balance of all IPCCC sectors. The choice for one final product over another is primarily based on the characteristics of manufactured goods and the service they provide. In other words, nobody installs an air conditioning system in their apartment due to the material characteristics of its components, but because of its cooling and heating functionalities. End-of-life emissions caused by the recycling or disposal of these manufactured goods, then again, primarily depend on choices made by the manufacturer about the material type and use during the manufacturing process. End-of-life emissions of basic materials, therefore, define the end-of-life emissions of all manufactured goods. For plastics made from hydrocarbons, emissions from production sum about 4 tCO_2 per ton of final product, whereas incineration can cause another 0.5 tCO_2 (Zheng and Suh, 2019). The demolition of structures containing steel, other metals, composite and construction materials is energy and emission-intensive (Sandin et al., 2014). In contrast, cement possesses carbonation qualities that bind atmospheric CO_2 during the product life cycle and even after demolition (García-Segura et al., 2014).[5]

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[3] *See*, section 5.4.3 for the discussion of carbon offsets in context of deep decarbonisation.
[4] Carbon dioxide-equivalent emissions is used to refer to CO_2 and any other greenhouse gas with a global-warming potential.
[5] Carbonation during over the life cycle can only partially capture the emissions caused during the production processes, so that the role foreseen by sector organizations for re-(carbonation) needs to be looked over carefully (OFICEMEN, 2020).

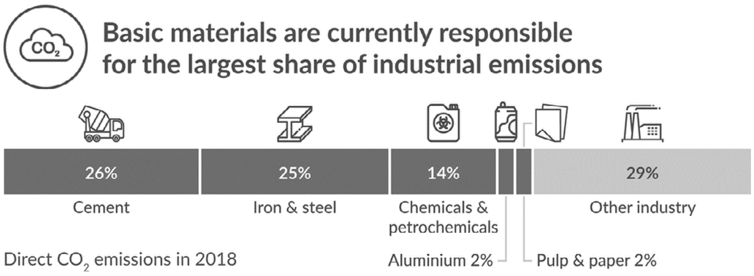

Figure 2-2: Share of basic material production in the direct emission balance of EU industry[6]

Over the last century, the production, use and consumption of industrial goods have been the backbone of industrialised societies. Global climate goals such as the 2015 Paris Agreement and national and regional strategies like the European Green Deal[7] for the long-term decarbonisation of our society by 2050 require us to rethink how our industry works and operates. While the carbon dioxide-equivalent emissions of industrial production might only account for a fifth of direct emissions, almost all human activity relies on the direct emissions reductions of basic material production to significantly reduce its indirect carbon footprint. Since direct industrial emissions are primarily caused by basic material production, it is vital to understand why the cement, iron & steel, chemicals, aluminium, and paper industries are emission-intensive.

2.1.2. The origins of basic material emissions

All industrially produced goods are made from naturally occurring raw material that has been transformed, enhanced, and shaped. As such, industrial emissions can be associated with all the steps needed to create a final product out of this raw material. In the following, I explore the origins of the emissions caused by basic material production, starting from the chemical reaction within each production process, the required energy needed to transform raw materials, and the efficiency of industrial processes in place.

Mass balance

Basic materials are obtained by processing raw materials, which involves their molecular transformation.[8] As such, simplified mass balances[9] can describe the chemical reactions for the different basic material production routes.

Steel is produced from naturally occurring iron ore, naturally occurring as iron oxides (Fe_xO_y)[10]. A reduction agent is required to obtain elemental iron (Fe) by binding the non-ferrous components of iron ore. For primary industrial steel production, carbon (C), either in the form of coal or natural gas, is used, first forming the greenhouse gas carbon monoxide (CO) and subsequently carbon dioxide (CO_2).

$$Fe_2O_3 + 3\,C \quad \rightarrow \quad 2\,Fe + 3\,CO$$

Aluminium production relies on a reaction that is similar to the one for steel making. Alumina (AL_2O_3), obtained from refining Bauxite, is reduced with a carbon-based reduction. Other than primary steel production with high-temperature furnaces, aluminium is produced using graphite (C) anodes, consumed during electrolysis.

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[6] Calculated based on data published by (EEA, 2019; Material Economics, 2018).
[7] *See*, Commission (EU), 'A European Green Deal' (Communication) COM(2019) 640 final, 11 December 2019 (EU Green Deal).
[8] The only exception is the production of paper from cellulose fibres.
[9] Mass balances presented in this section are highly simplified to highlight the role of carbon in the reduction process and do not reflect the multi-stage reactions taking place within the different basic materials processes.
[10] Small letters are used to indicate that more than one specific molecular structure is referenced to by this chemical notation.

$Al_2O_3 + 3\ C \rightarrow 2\ Al + 3\ CO$

Cement and any fossil-based hydrocarbons have in common that their raw material consists of degraded fossil carbon. Limestone ($CaCO_3$) is fossil calcium bonded with fossil carbon and oxygen, whereas crude oil contains fossil carbon and hydrogen (C_xH_y). The strength of cement originates from the properties of calcium oxide (CaO), which are obtained by the thermal reaction of limestone at high temperatures. CO_2 is a by-product of this reaction.

$CaCO_3 \rightarrow CaO + CO_2$

Crude oil molecules (C_xH_y) are refined into other hydrocarbons with a variant number of carbon and hydrogen molecules (C_aH_b). Lighter fuels such as kerosene are composed of fewer molecules than heavy fuels such as marine diesel oil. For the production of petrochemicals, such as ethylene, methanol or any plastic containing polymer chains, the fossil carbon and hydrogen molecules are refined further. Since these processes are not ideal, secondary reactions with oxygen and other atmospheric gases result in greenhouse gases such as CO_2 or NO_x.

$C_xH_y \rightarrow C_aH_b$

Other non-metallic basic materials are different in such that a single mass balance cannot describe their production process. Ceramics and glass production processes have in common that quartz (SiO_2) is a key raw material. Fused quartz glass consists of up to 100% SiO_2, while some types are based on silicon carbide (SiC) obtained from processing quartz.

$SiO_2 + 3\ C \rightarrow SiC + 2\ CO$

Paper is different from the aforementioned basic materials since it is made from bio-based cellulose fibre. It is not produced by a molecular transformation but by extracting and rearranging fibres. Since raw materials for paper production are plant-based, no fossil carbon is required for the process reaction.

Energy consumption

Process reactions to transform raw materials into basic materials do not occur spontaneously and require external energy sources. Except for electricity-based Aluminium production, process heat triggers these process reactions and separates cellulose fibres in the case of papermaking. Though energy demand varies for each process, basic material production processes are the industrial activities with the highest energy intensities.

Steel plants with modern blast furnaces (BF-BOF) require about 16.7 GJ/t for the entire process, from iron ore, coal, and other raw materials to crude steel. About 95% is thermal energy needed to reach process temperatures beyond 1500 ⁰C. Electricity consumption is mainly linked to secondary and auxiliary processes (Chan and Kantamaneni, 2015). Direct reduced induction for primary steelmaking (DRI-EAF) is equally energy-intensive, requiring about 13.0 GJ/t of crude steel (DEEDS, 2020).

For aluminium, the electrochemical reaction inside best-available-technology (BAT) electrolysers consumes about 46.5 GJ/t of electricity. Additionally, 19.0 GJ/t of thermal energy is needed. The thermal energy used for the production of graphite anodes needs to be added to the energy balance (14.0 GJ/t) so that the total energy consumption is about 79.5 GJ/t (IEA ESTAP, 2012; Saevarsdottir et al., 2020).

Cement production with the latest multi-stage kiln technology has a total energy intensity of 2.7 GJ/t of cement, with about 90% thermal and 10% electric energy (Voldsund et al., 2019). The process reaction takes place at about 1450 ⁰C.

Petrochemicals are the results of a wide range of distillation processes with varying temperature ranges. Best available technology (BAT) for naphtha steam cracking to produce ethylene, the most energy-intensive production step for most high-value chemicals (HVC), operates at temperatures between 750-950°C and requires 13.4 GJ/t of thermal energy. About 1.4 GJ/t of this energy can be recovered as process steam and subsequently used in other processes (IEA, 2018a). Ammonia and methanol are produced by catalytic steam reforming, using natural gas to produce hydrogen and process it further into the different basic chemicals. Net BAT energy consumption to facilitate process reactions at 400-450 ºC is 9.0 GJ/t, given that about one-third of the thermal energy can be recovered as steam and reused for other production steps (IEA, 2018a).

Energy consumption of glass and ceramic production covers a wide range of different product types, making these sectors more heterogenic than the production of other basic materials. BAT for flat glass production is estimated to consume about 6.5 GJ/t and container glass about 3.6 GJ/t of thermal energy. About 0.6 GJ of electricity is needed per ton of melted glass. Thermal energy is required to heat the raw materials to temperatures between 1450-1650°C, though consumption of individual installations can go up to 13 to 14 GJ/t (Dorn et al., 2017; Scalet et al., 2013). Due to the number of different product groups of ceramics, process temperatures range from as low as 450°C for some technical ceramics to processes exceeding 2000°C. Specific thermal energy consumption for the two most common products ranges from 2.31 GJ/t for bricks and roof tiles to 5.60 GJ/t for wall and floor tiles (JRC, 2007).[11]

The primary energy needed on average for producing one ton of paper is about 11.5 GJ, resulting in an energy intensity similar to that for primary steel production. The wide range of paper products, different recycling rates and the availability of two highly different processes for pulping, chemical and mechanical, means that just for the producing of packaging paper, thermal energy consumption can range from 7.3 GJ/t to 35.2 GJ/t. Additionally, 1.3-4.4 GJ/t of electric energy are required (Mora and Pavel, 2018).

The emission intensity of BAT processes

The previous sections introduce the two direct emissions sources for basic material production, energy, and process-related emissions. Even though the focus is primarily on CO_2 emissions, all other greenhouse gas, dust, and particle emissions of basic material production can be linked to the combustion of carbon-based energy sources or the transformation reactions within the production process.[12]

BAT steelmaking by using BF-BOF permits emission levels as low as 1.89 tCO_2 per ton of crude steel (EUROFER, 2013), of which about 40%[13] can be linked to the process reaction. Producing direct reduced iron in the DRI-EAF route by using natural gas is less emission-intensive (< 1.15 tCO_2/t), while process-related emission levels remain (Toktarova et al., 2020).

Direct and indirect emissions (Scope 1 and 2) of Aluminium production depend on the emission intensity of electricity generation. Globally, one ton of aluminium results in 14.40 tCO_2, whereas in the European electricity mix emissions sum 6.70 tCO_2 per ton of product. Emissions would be down to 3.50 tCO_2 if renewable electricity were used for the electrolysis process. About 1.40 tCO_2 of direct emissions are linked to graphite anode consumption (EA, 2020; Saevarsdottir et al., 2020).

For cement, emissions depend on the clinker to cement ratio. Cement clinker is mixed with additives like gypsum to obtain cement. The benchmark used by the European Union and the International Energy Agency is a clinker to cement ratio of 73.7%. Using BAT kilns, emissions can be as low as 0.67 tCO_2 per ton of cement, of which 0.47 tCO_2 are process-related (IEAGHG, 2013a; Schorcht et al., 2013).

Differentiating between energy and process emissions is less straightforward for the remaining industries. Based on EU production data from 2007, Croezen et al. (Croezen and Korteland, 2010) estimate that about 30% of total emissions from steam cracking of crude oil and 75% of ammonia

[11] These two groups account for about 80% of EU ceramics production according to the same source. Specific consumption data is based on 2003 values since no more recent estimates have been found in literature.

[12] CO_2 is used to refer to carbon-dioxide emissions. Whenever possible, a differentiation between CO_2 and CO_2e is made.

[13] Based on the main reaction production molten iron and the molar mass of Fe_2O_3 and $3CO_2$. This value corresponds to the estimations by Croezen et al. (Croezen and Korteland, 2010) based on 2007 EU production data.

production are process emissions. These percentages can be applied to the total BAT emission intensity of ethylene (1.14 tCO_2/t) and ammonia (1.90 tCO_2/t) (Batool and Wetzels, 2019; Ghanta et al., 2014).

Data for the total emission intensity of glass production is based on the average for minimum process and energy emission intensity from European production in 2007 (Schmitz et al., 2011).[14] Fo natural gas-based glass production, about 0.33 tCO_2 of energy-related emissions and 0.11 tCO_2 of process emissions occur per ton of glass. Due to the variety of ceramic products and temperature ranges required for their production, a clear differentiation between process and energy-related emissions cannot be done. The BAT emission intensity of the ceramic industry is given as a range of 0.11 to 0.15 tCO_2/t, based on historic block, brick and tile production plant data (Ecofys, 2009).

Paper production has no relevant process-related emissions. Emission intensity varies for different paper types. The EU paper industry accounts for 0.30 to 0.40 tCO_2 of fossil emission per ton of paper (Croezen and Korteland, 2010).

Theoretical energy need

The theoretical efficiency gains obtained after implementing BAT in all existing plants is more of a thought experiment, highlighting that basic material production would remain highly emission and energy-intensive even under ideal conditions and trigger a carbon lock-in (section 5.3). Note that the focus is mainly on energy efficiency gains since little to no improvements of process emissions intensity compared to BAT are feasible. Process emissions are primarily based on chemical reactions, which are the basis for transforming raw materials into basic materials.

Compared to BAT, the theoretical energy savings for primary steel production using blast furnaces is approximately -24.9% of thermal energy consumption, derived from data published in (McBrien et al., 2016).[15] Aluminium production needs at least 22.7 GJ/t of energy to facilitate the process reaction (IEA ESTAP, 2012), and the theoretical minimum for cement making is stated with 1.7 to 1.8 GJ/t of cement clinker.[16] For ethylene production, the hypothetical reaction energy is 6.7 GJ/t, whereas process emissions could be entirely avoided and only result from transformation inefficiencies (Neelis et al., 2007). Smith et al. (Smith et al., 2020) compare different production routes for ammonia and conclude that ammonia production from methane consumes at least 4.5 GJ/t of thermal energy, limiting CO_2 emissions to process emissions only. For glass production, the theoretical energy requirements vary for the different glass types and are within the range of 2.1 to 3.2 GJ/t (Scalet et al., 2013). Given the different products' energy intensities and temperature ranges, no valid estimations can be made for the ceramics and paper industry.[17]

2.1.3. Mapping emissions for basic material production processes

The quantification of BAT and theoretical energy-intensive and emissions stated in the previous sections can be summarised as shown in Figure 2-3. Whenever possible, I distinguish between energy and process emissions for BAT technologies.

The overview demonstrates how conventional primary production processes are inadequate to decarbonise the basic materials sector. Even under ideal conditions, the production of basic materials remains highly emission-intensive with currently used process designs. The production of steel, aluminium, cement, ammonia and, to some extent, glass causes process-based CO_2 emissions, which already make up a significant share of their total emissions using BAT.

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[14] The 2006 IPCC guidelines for national greenhouse gas inventories states a lower emission value of 0.21 tCO_2 per ton of flat and container glass (IPCC, 2006), which remains the most cited benchmark in recent scientific publications, e.g. (Lechtenböhmer et al., 2016), but only seems to capture process related emissions.

[15] Theoretical maximum thermal energy reduction of 4.3 GJ/t, given that BAT thermal energy consumption is 17.3 GJ/t.

[16] Given a clinker to cement ratio of 73.7% this translates to a theoretical energy demand of 1.3 GJ per ton of cement.

[17] Energy and emission intensity for the ceramics industry is based on (EC, 2017a)

Literature indicates that untapped energy efficiency potential seems to exist in all industries. Even if efficiency gains could approach theoretical limits, these energy savings would not translate into a corresponding emission reduction.[18]

Industries with a minor or negligible share of process-based emissions, such as ethylene, glass, ceramics, and paper production, will not reduce their energy intensity to the theoretical minimum. Here, the usage of fossil-based thermal processes inevitably results in CO_2 emissions that remain substantial for ideal process designs.[19]

New process designs might help to reduce and eliminate process-based emissions[20]. Still, the energy intensity of basic material production will prevail if industrial production, manufacturing, and material use are based on raw materials such as iron ore, bauxite, limestone, and crude oil. Energy will have to be used to trigger non-spontaneous process reactions without resulting in energy-related emissions. This challenge is not only a technical one. It also implies that we rethink energy use within the basic materials sector.

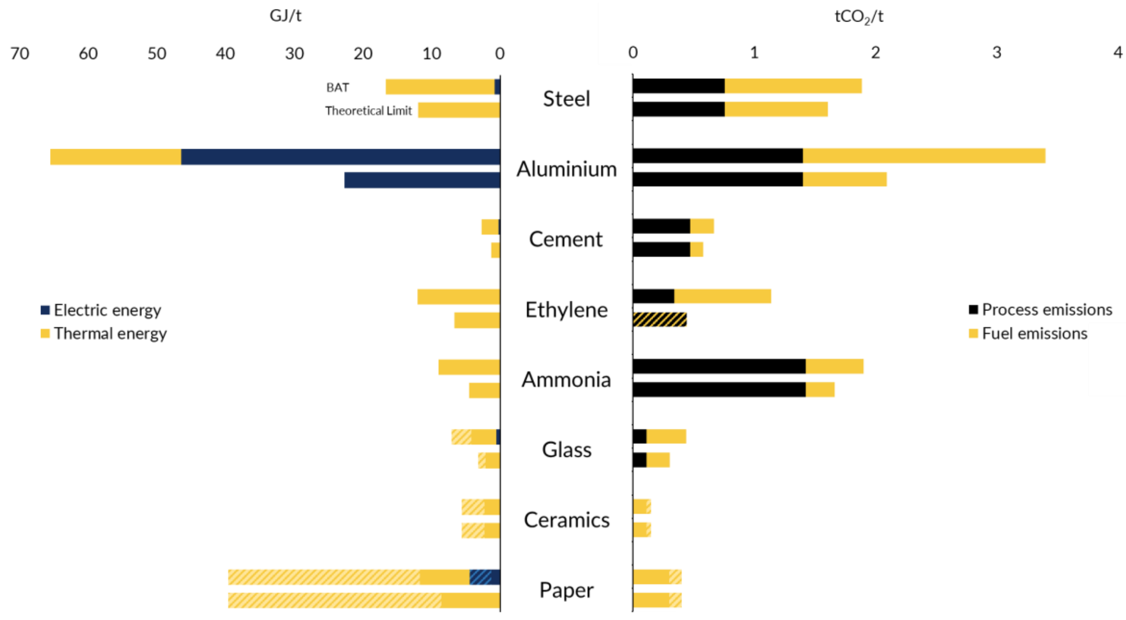

Figure 2-3: Energy intensity and direct emissions for BAT and theoretical limits of the conventional primary production.[21]

[18] The resulting theoretical minimum emission intensity of existing processes is not practically feasible even if optimising energy efficiency. Thermal optima require the use of all excess heat, meaning that the temperature of exhaust gases corresponds to the ambient temperature.

[19] CO_2 emissions originating from the use of biomass could be disregarded in case of paper production, which would make the process carbon neutral with BAT.

[20] *See*, Chapter 3

[21] Ranges are indicated as crosshatched. In case of ethylene the referenced sources don´t differentiated between process and energy emission for the theoriteical optimum.

2.2. Energy use in industry today and tomorrow

Today, emission and energy intensities correlate since 84% of our global energy mix comes from fossil fuels (Ritchie and Roser, 2017). The paradigm that increasing energy consumption inevitably causes more fossil fuel emissions is not sustainable and requires our society to shift towards non-emission intensive energy use. A closer look at how the industrial sector consumes energy within the EU and their currently used processes allows me to distinguish between the transition of the basic material sector and other industrial energy demand in section 2.2.1. I then present a brief overview of parameters that will determine how and what type of energy are going to be used by the industrial sector in the future (section 2.2.2) and conclude this section with closing remarks on how the industrial transition is determined by its future energy consumption in section 2.2.3.

2.2.1. Energy consumption today

Industrial energy consumption represents a share of the European energy mix that assembles its emission intensity, accounting for about one-quarter of all energy consumption in 2018 (Figure 2-4). It is therefore essential to understand how energy is used in the industrial sector. Electric energy is primarily suited for non-thermal applications or low-temperature heat processes, whereas burning solid, liquid, or gaseous energy carriers is commonly used to reach high process temperatures.

Across all industrial sectors, the temperatures range of required process heat differs significantly. By analysing publicly available data from EUROSTAT, the heat demand of different industries can be segregated in different temperature ranges, as shown in Figure 2-5. Here, process heat ranges are displayed with a higher degree of detail than categories recommended by the European Commission[22] and show how the basic material sector primarily relies on high-temperature heat demand while other industries rarely exceed temperature ranges beyond 500 °C (Kosmadakis, 2019). The temperature ranges of the processes used within the different industries are decisive for their energy mix and energy intensities. In Spain, the industries with the highest heat demand, namely the iron & steel, chemical, non-metallic minerals and paper industry, accounted for about half of the total industrial energy demand in 2018 (IDAE, 2020). To what extent high-temperature ranges limit the choice of energy carriers can be shown by analysing the energy mix of various industries across different European countries.

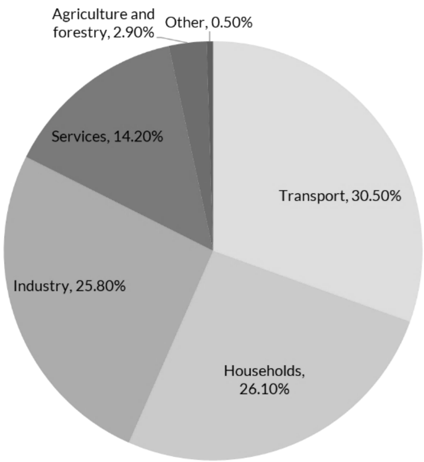

Figure 2-4: EU-27 final energy consumption by sector in 2018 (EUROSTAT, 2021a)

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[22] *See*, Commission Recommendation (EU) 2019/1659 of 25 September 2019 on the content of the comprehensive assessment of the potential for efficient heating and cooling under Article 14 of Directive 2012/27/EU

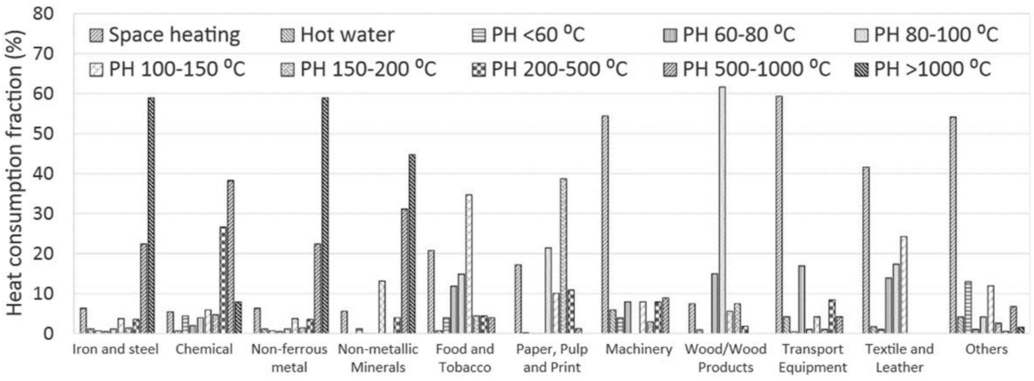

Figure 2-5: Process heat (PH) consumption fractions in EU industries per temperature band (adapted from (Kosmadakis, 2019))

Food and tobacco

Due to their relative size, sectors like the food industry are major energy consumers but mainly require process temperatures below 150 °C (Hita et al., 2011). Different technology options are available for delivering such low-temperature heat, and the food industry of various European countries does not use a similar energy mix for their required process heat (Figure 2-6). In Finland, biomass plays a decisive role in the national energy strategy. It is an important source for heat provision via cogeneration in the food industry, accounting for more than 40% of all energy used in 2018 (Kujanpää et al., 2018). In southern European countries like Greece (EL), direct biomass combustion for heat generation made up 24.8% of the energy mix in 2018. About 90% of this biomass originates from agricultural residues, and its prominence in the energy mix depends on resource availability and cost (Camia et al., 2018). The island economy of Malta (MT), with a small but industrialised food sector ("Agriculture & Food Insights and Sector Profile 2018 - MaltaProfile.info," 2018; "Benna Fresh Milk Products," 2019), shows that heat demand for all required temperature ranges can be electrified already. These observations are in line with the findings of Jermann et al. (Jermann et al., 2015), highlighting that technology trends in the food processing industry move towards sector electrification.

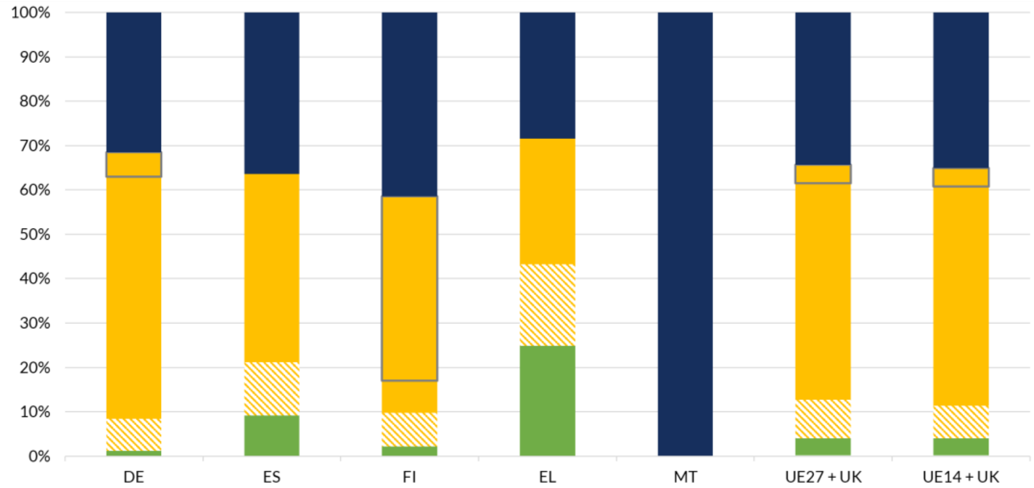

Figure 2-6: Relative energy consumption of the food and tobacco industry in selected European countries[23]

[23] According to EUROSTAT data for 2018 (EUROSTAT, 2021b) (yellow = thermal energy sources (gaseous), yellow hatched = thermal energy sources (solid/liquid), blue = electricity, green = biobased energy sources). Cogeneration outlined in blue as share of heat consumption.

Transport Equipment

The transport equipment industry, which includes the entire automotive sector, displays similar country-specific differences in the energy mix to cover their mostly low and medium temperature energy demand (Figure 2-7). While biomass use is non-existent, electricity and mostly gaseous energy carriers satisfy the energy demand for all European countries with significant transport industries such as Germany, Spain or Italy (ANFAC, 2019). In Romania, the share of natural gas use reaches up to 50.6 %, while in countries such as Italy (74.9%) or Sweden (79.9%), electricity dominates the energy mix.

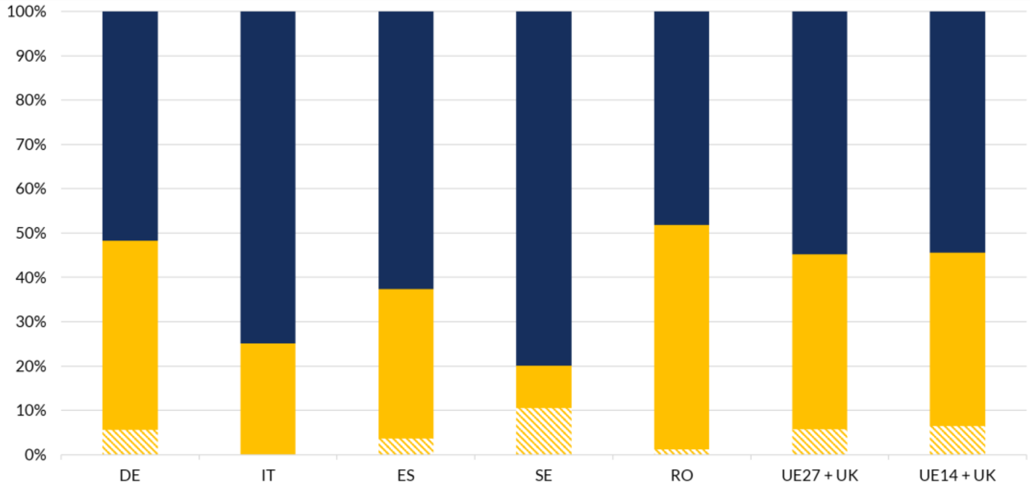

Figure 2-7: Relative energy consumption of the transport equipment sector in selected European countries[23]

Textile and leather

The higher the thermal energy demand, the more a sector relies on solid, liquid, or gaseous energy carriers. According to Figure 2-5, about 50% of heat demand in the textile and leather industry is for temperatures exceeding 500 °C. Natural gas, liquid, and solid fuels, such as coal in Turkey[24], account for at least half of the energy demand across European producers. Other than in industries requiring lower temperatures with significant variance in national energy mixes, the current energy demand of European textile and leather producers is very similar. The EU27 + UK average consumption of thermal energy carriers was 50.7% in 2018, while major producing countries vary no more than ten percentage points from this figure (Figure 2-8).

Iron & Steel

The role of standardised production processes in determining the energy mix of different industries becomes more evident when contrasting consumption data for basic material sectors that rely primarily on high-temperature heat (Figure 2-5). For production, differences in national energy consumption can be linked to the share of steel recycling using electric arc furnaces (EAF). In Spain (ESP), secondary recycling production accounted for 65.7% of national output in 2018, totalling 14.320 Mt (World Steel, 2020). Nevertheless, almost half of the energy consumption stems from natural gas and gaseous co-products from coke processing, used mainly for primary steelmaking. In countries producing only secondary recycling steel like Portugal (PT), electricity consumption account for up to 72.1% of the total energy demand. On the other hand, countries like the Netherlands and Austria produce almost exclusively primary steel (World Steel, 2020). Natural gas and gaseous co-products account for 77.4% (NL) and 74.6% (AT) of the total energy consumption (Figure 2-9). The difference in consumption patterns for primary production is marginal since the same standardised BF-BOF process is used. Mayor changes to the energy consumption patterns of the steel industry, therefore, require major changes to the production process.

[24] Turkey has been included in this review, being one of the ten biggest global textile producers exceeding any European country in sales and production in 2018 (CESCE, 2019).

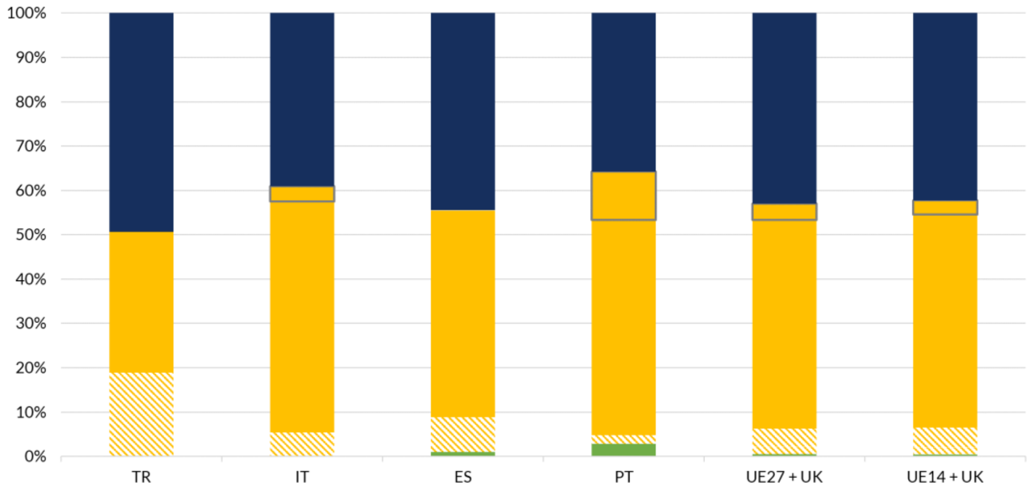

Figure 2-8: Relative energy consumption of the textile and leather industry in selected European countries[23]

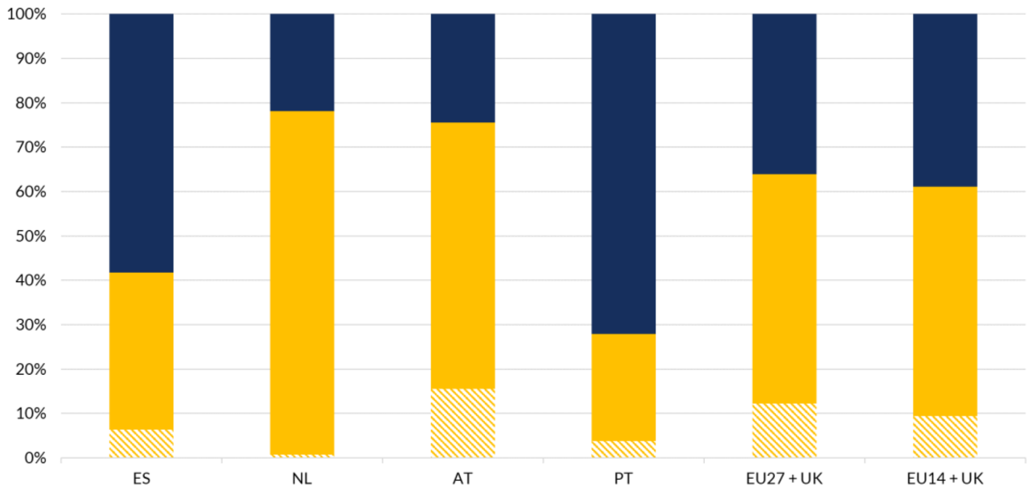

Figure 2-9: Relative energy consumption of the iron & steel sector in selected European countries[23]

Non-ferrous metals

Together with copper, nickel, titanium, gold or zinc, aluminium production forms part of the non-ferrous metal sector within the EUROSTAT database. Like the iron & steel sector, process heat exceeding 1000 °C accounts for close to 60% of their thermal energy demand (Figure 2-5). Even though the available data does not allow for a segregated view of the different non-ferrous metal industries, the size and energy intensity of aluminium production makes it by far the most relevant energy consumer. The industry´s energy consumption in Spain is similar to the German (DE) and average European energy mix, with electricity accounting for approximately 60.0% of the energy demand (Figure 2-10). Processes are highly standardised, implying that changes in demand patterns will require novel process designs. Island, known for its cheap geothermal electricity supply, is an outliner. The country has an entirely electrified non-ferrous metal industry, consisting of alumina electrolysis only, the final production step in the aluminium industry. Alumina is obtained by bauxite refining that relies on thermal energy. Other European countries, such as Spain or Germany, cover the entire value chain of aluminium making and other non-ferrous metal industries (MITECO, 2019).

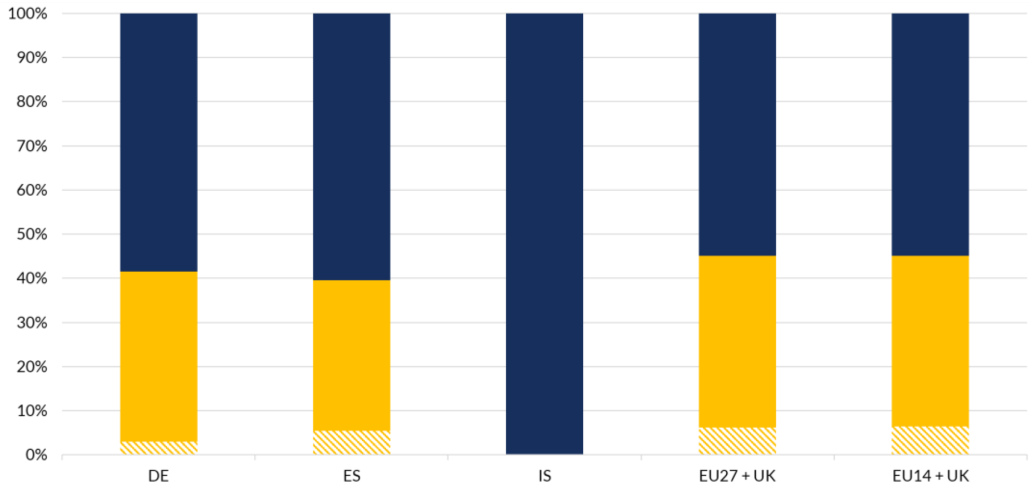

Figure 2-10: Relative energy consumption of the non-ferrous metal sector in selected European countries[23]

Non-metallic minerals

The EUROSTAT database makes no distinction between the production of cement, ceramics, and glass. Consumption data for non-metallic minerals are aggregated. Cumulative cost assessments of both sectors by the European Commission show that both industries primarily use natural gas and electricity as primary energy sources (EC, 2017a, 2017b). In the cement sector, natural gas consumption is insignificant, primarily linked to the relatively high cost of natural gas compared to other options such as pet coke and residuals (OFICEMEN, 2016). The predominant use of natural gas in the ceramics and glass industry is reflected by the Dutch sector data for 2018 (NL). After the country´s last cement plant´s closure, the non-metallic minerals industry only constitutes ceramics and glass producers (Global Cement, 2019). Consequently, 73.2% of energy demand is met with natural gas (Figure 2-11). Consumption patterns across the European non-metallic minerals sector are highly similar, relying to about 80 to 90% on thermal energy carriers. As such, the sector data confirms the observations about the energy and emission intensity of currently used processes presented in section 2.1.3.

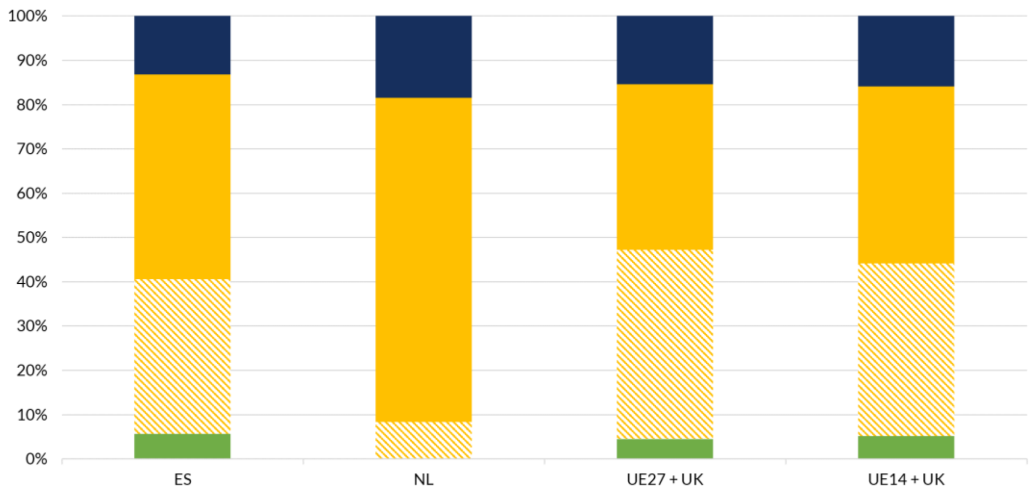

Figure 2-11: Relative energy consumption of the non-metallic minerals sector in selected European countries[23]

(Petro)chemicals

Compared to other basic materials, the chemical sector produces a wide range of products. High-temperature steam cracking and catalytic steam reforming of hydrocarbons form the basis of most production routes and mainly require heat in the range between 200 to 1000 °C, as shown in Figure 2-5. Energy use by the industry has been highly optimised over the last decades so that since 1990 absolute sector emissions fell by nearly 61% while production increased by 83% (CEFIC, 2019). In Spain, this transition led to a decline of solid and liquid fossil fuels from 40.5% of total energy demand in 1990 to 7.4% in 2018 (IDAE, 2020). Today, the Spanish industry is considered to be one of the most efficient in Europe. In other countries, such as Italy and France, the share of solid and liquid fuels remains higher than in Spain, but it completely vanished from the energy mix in the Netherlands (Figure 2-12). Compared to other countries, the French industry has a significantly higher share of electrification (43.6%), which could be due to electricity prices for industrial consumers that are among the lowest in Europe (ACER/CEER, 2019). EUROSTAT data shows that heat consumption plays a significant role in the energy mix reported for some countries. Cogeneration facilities most likely provide this heat, consuming natural gas to generate electricity and heat. Since cogeneration facilities are as common in the Spanish (petro)chemical industry as in Italy or the Netherlands (ChemicalPark.eu, 2020), their role in Spain is anticipated to be similar.[25] Due to the heterogeneity of processes used, the chemical industry shows a higher consumption variance than other basic material sectors across different EU member states. However, this does not affect the predominant role of thermal energy carriers in its energy mix, which also serve as feedstock for production.

2.2.2. Defining parameters for the future energy mix

The analysis of industrial energy demand for various sectors across Europe shows a greater choice of energy carriers and related process technologies for low-temperature heat applications. Options that allow the switch to a non-fossil energy carrier, primarily low emission electricity, are already on the market, and more prospective alternatives will be available soon. Especially the development of high-temperature heat pumps (HTHP) is seen as an economically feasible alternative for providing process heat of up to 160 ºC (Schlosser et al., 2020). The prospective looks less promising for high-temperature processes, especially those in the basic materials sector, as introduced in section 2.1.2. Their decarbonisation requires different production routes to satisfy future demand for basic materials.[26] The future technology and energy mix of these industries depends on one of the following factors:

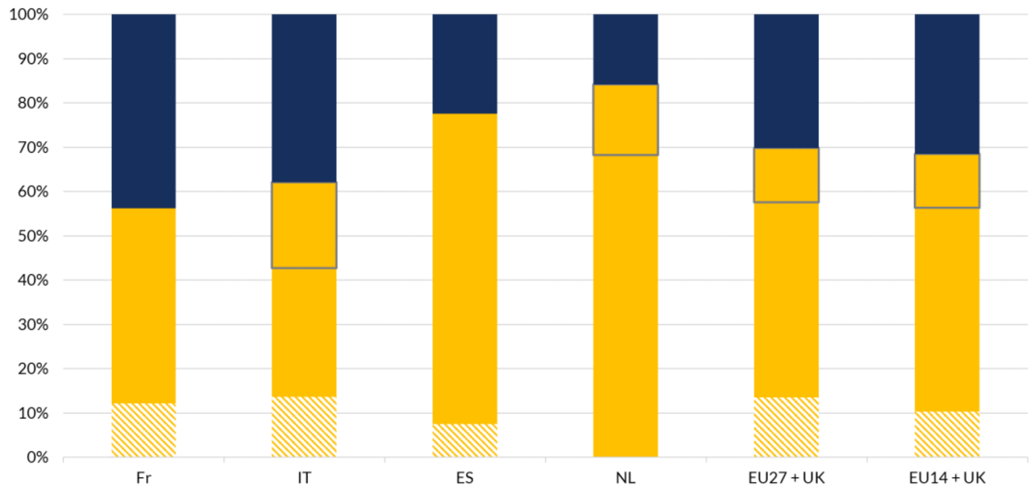

Figure 2-12: Relative energy consumption of the (petro)chemicals sector in selected European countries[23]

[25] Based on bilateral feedback obtained from IDAE, Spain does not report cogeneration as energy source for EUROSTAT data.

[26] *See*, Chapter Chapter 3 for the analysis of technology options

Available energy sources

It is decisive to recall that energy-based emissions have to be reduced to an absolute minimum for a climate-friendly industry. Energy demand currently provided by fossil energy carriers needs to be replaced by one of the following options:[27]

Direct electrification: likely and already competitive for low-temperature ranges, producing high-temperature process heat with electric heating equipment is difficult. Still, it might have its merits for some applications, such as the EAF use in steel making mentioned above.

Biobased energy carriers: biomass and its derivatives do not cause fossil carbon dioxide-equivalent emissions since atmospheric carbon has been processed during plant growth. Biomass availability is limited since it has to stem from sustainable sources to reduce the carbon footprint of industrial processes.

Fossil energy sources with carbon capture and storage or utilisation (CCS/CCU): this option would allow for using fossil-based fuels in the future. Processing captured industrial emissions into synthetic fuels or other carbon-based materials is feasible but might only delay atmospheric emissions if fuels or end-of-life products are burned at a later point. Given that long term storage and utilisation options are available, CCS or CCU would increase industrial energy demand. Depending on the capture technology, additional fossil energy or electricity is needed for the capturing process (see, e.g. (Voldsund et al., 2019) for the cement industry). However, carbon capture might be the only option to reduce those emissions that are not caused by energy use but the chemical transformation of feedstock such as limestone (see section 2.1.3). Direct air capture (DAC) to offset carbon dioxide-equivalent emissions presents an alternative to capturing industrial process emissions, so the process is equally electric and thermal energy-intensive (Fasihi et al., 2019).

Hydrogen and derivatives: solid, liquid, or gaseous energy carriers that are not carbon-based can be used to reach high process temperatures. While CCS and CCU would be required if produced from fossil fuels, hydrogen can be a carbon-neutral energy source if using zero-emission electricity.

Except for biomass, which is limited to its availability, all discussed options are linked to increased direct or indirect energy consumption. CCS and CCU require additional energy for capturing and processing emissions. Hydrogen is produced through electricity or hydrocarbons at imperfect transformation rates, though electricity is a form of energy that does not occur naturally and is subject to prior transformation processes. Additionally, if stemming from water electrolysis, direct electrification and hydrogen mark a shift from fossil energy carriers to electricity as the primary energy source. Furthermore, energy-intensive carbon capture options represent another source for electricity consumption. Regardless of which low emission energy source is used for primary basic materials production in the future, energy and especially electricity intensity of basic materials production is set to increase.

Energy efficiency

Due to its relatively low and expensive natural fossil resource reserves, energy costs for the European industry have been comparably higher compared to other regions in the past. Over the past decades, this gap in variable weights energy price levels (VEPL) to regions with abundant national fossil energy reserves widened (Sato et al., 2019). In combination with a European industrial policy framework directed towards the efficient use of energy (ODYSSEE-MURE, 2015), high energy prices have been one of the main drivers of past efficiency gains in the EU industrial sector, reducing its energy intensity by 38% from 1990 until 2016 (Figure 2-13). As highlighted in the previous section for the petrochemical sector, these improvements have resulted from process optimisations. Having a closer look at individual industrial installations across Europe, a sharp contrast exists across individual plants. In their analysis of energy efficiency improvements in the European Steel sector from 1992 until 2010, Morfeldt and Silveira (Morfeldt and Silveira, 2014) show that some companies push the best practice frontier, increasing the

[27] *See*, Chapter 4 for a more detailed discussion of future energy carriers

innovation gap between installations in inefficient member states. Even though no general applicability of these findings to all basic material sectors can be implied, aggregated historic data for efficiency gains in specific sectors should consider the possibility of this effect in other industries.[28]

Bottom-up studies about further reduction potentials within the European energy-intensive industries state more energy-saving potentials for energy and emission-intensive industrial activities(Chan and Kantamaneni, 2015). However, significant efficiency gains are linked to the replacement of main process equipment components by BAT technology. Especially the design life of kilns, distillation columns and furnaces exceeds 20 years in many industries, e.g. the steel sector (van Laar and Corus, 2016), and can go up to 50 years in the cement industry (Habert et al., 2010). Therefore, focusing on improved energy intensity in these industries might result in a technology lock-in since carbon-neutrality cannot be achieved by currently used process routes (see 2.1.3).

Prospective demand for basic materials

We only need energy to produce basic materials if we consume them. The premise that unlimited growth by non-renewable resource consumption is possible has been prominently questioned by the Club of Rome in their report on the limits to growth back in 1972 (Meadows et al., 1972). Nevertheless, according to OECD data, the global basic materials consumption is expected to double, as shown in Figure 2-14 for the construction sector, the most material-intensive use case (Agrawala et al., 2019). While the biggest driver of this demand growth is linked to emerging economies in Asia, the Middle East and Africa, the European material need is foreseen to double, mainly due to infrastructure investments to facilitate the energy transition.[29]

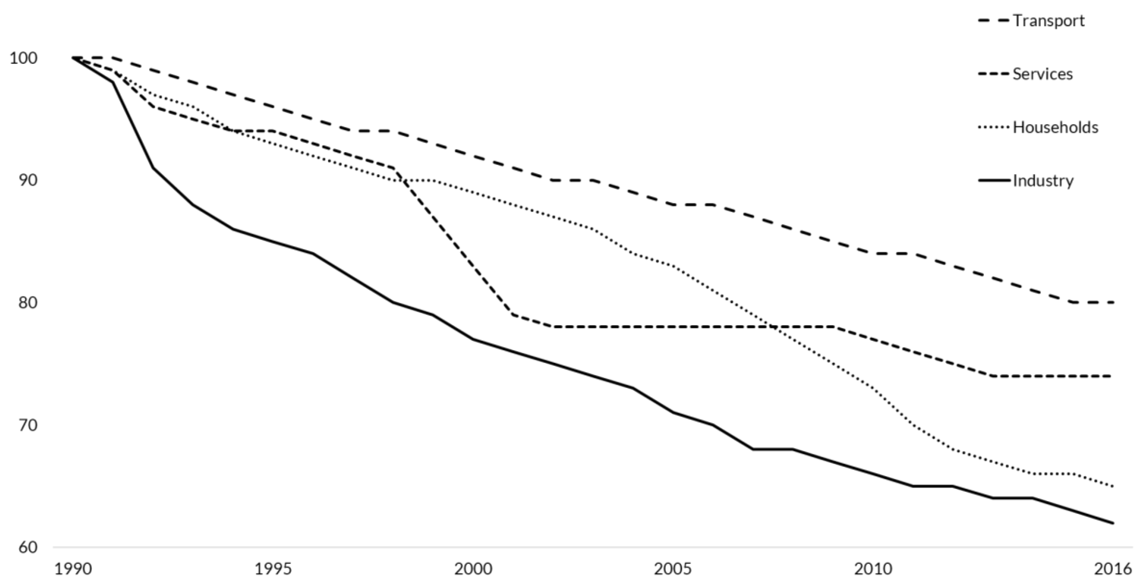

Figure 2-13: Energy efficiency index for final consumers in the EU (EEA, 2021a)

[28] *See*, for example the case of the European chemical industry, which reduced its emission intensity by 54.5 % between 1991 and 2017 (CEFIC, 2020a).
[29] *See*, the analysis presented by Gerres et al. (2019b)

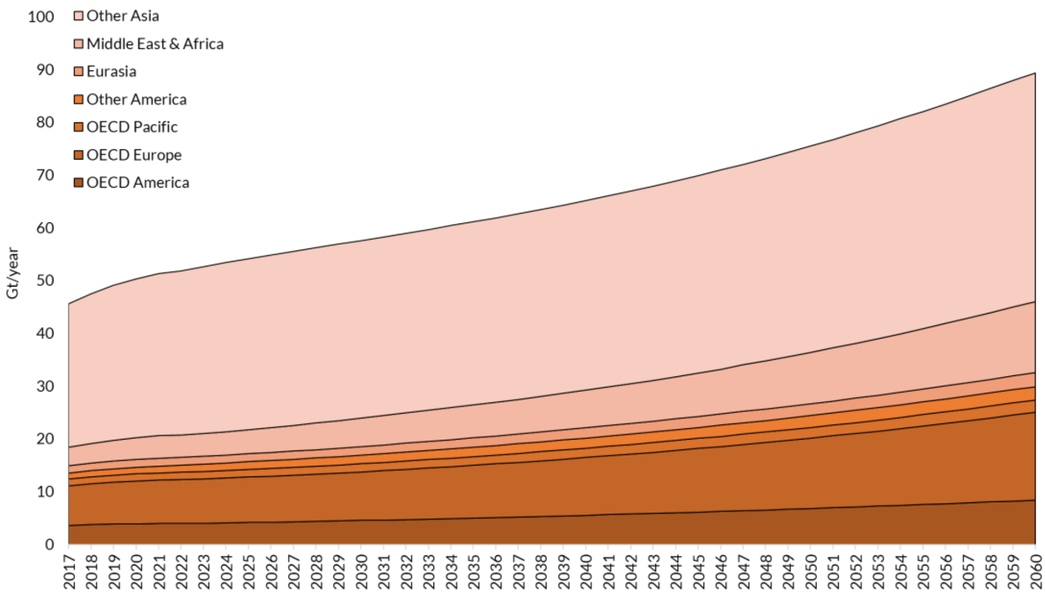

Figure 2-14: Global minerals use in the construction sector until 2060 according to the OECD (Agrawala et al., 2019)

These projections are in sharp contrast to those scenarios underlying the "A Clean Planet for All" strategy announced by the European Commission in 2018 and the basis of the European Green Deal.[30] The underlying modelling results of the FORECAST model state a more stagnant materials consumption in their 95% emission reduction scenarios, though even in the reference scenarios, only cement consumption increases significantly (Fleiter et al., 2019). The CE CIRCular scenario of the European Commission (EC, 2018a) sees future consumption rates between -3% (aluminium) and up to -12% (paper) lower than today´s values. At the same time, non-governmental studies by Material Economics (2018) and (2019) expects more stagnating material demand in 2050.

Even if material consumption within the European Union stagnates over the next decades, the historical development in individual member states may result in national consumption patterns that oppose the general trend on the EU level. In Spain, historical consumption for basic materials peaked before the financial crisis in 2008 and since then remained at low levels.

As shown exemplarily for cement in Figure 2-15, Spain´s per capita consumption is currently one of the lowest among the major European economies. Considering the renewal rate of building stock and especially road and transport infrastructure, the past building boom and current underinvestment may lead to future demand peaks and renewal patterns similar to those shown by Burns et al. (Burns et al., 1999) for Victoria in Australia. In the study "El futuro de las materías primas en España" (Gerres et al., 2019e) conducted for the Spanish Ministry of Ecological Transition (MITECO), we conclude that material demand in Spain is expected to increase, rather than decrease for some of the most consumed basic materials (**Error! Reference source not found.**).

Future demand on the national and European level might vary. Still, the long-term trend of an increasing global material demand means that more primary materials production would consequently lead to an increased energy demand for basic materials.

[30] *See*, Commission (EU), 'A European Green Deal' (Communication) COM(2019) 640 final, 11 December 2019 (EU Green Deal). See also Commission (EU), ´A Clean Plane for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy´ (Communication) COM(2018) 773 final, 28 November 2018 (A Clean Planet for All).

Table 2-A: Future material consumption projections for Spain and Europe as presented in Gerres et al. (2019e)

	Current and future consumption in Spain			**Growth in European consumption until 2050**						
	Current consumption per capita Eurostat data for 2017	**Future consumption per capita in 2050 according to Gerres et al. (2019e)**	**Expected change (%) according to Gerres et al. (2019e)**	OECD (Agrawala et al., 2019)	Intraw (2019)	Lechtenböhmer et al. (2016)	Material Economics (2018)	CE CIRCular (EC, 2018b)	**FORECAST model** (Fleiter et al., 2019) **MIN (95%)**	**MAX (REF)**
Cement	270 kg	300 – 500 kg	+10% to +80%	50% to 100%		+0%	+0%	-8%	-2%	+23%
Steel	220 kg	250 – 300 kg	+15 % to +35%					-6%	-8%	+2%
Aluminium	13 kg	13 – 16 kg	up to +25%	0 %	0%		+33%	-3%	+4%	+6%
Paper	130 kg	130 – 150 kg	-10% to +15%					-12%	+10%	+10%
Plastics	83 kg	80 – 90 kg	- 5% to + 10%			+0%	+25%	-9%		

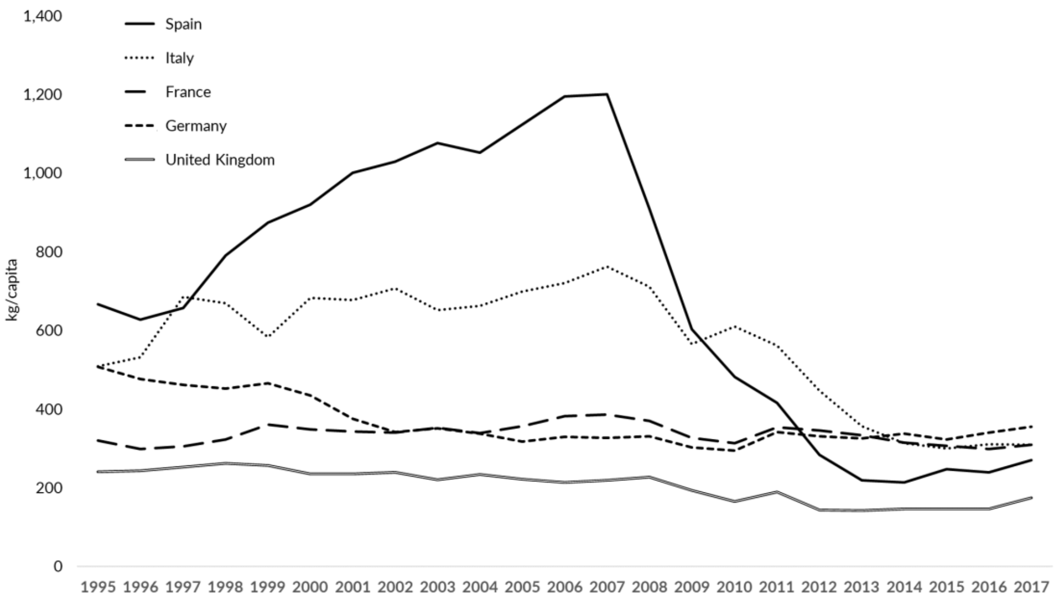

Figure 2-15: National per capita cement consumption in European economies as presented in Gerres et al. (2019e)

Options to provide basic material "services"

Stagnating or increasing material demand in Europe and increasing consumption in developing countries complicates the road towards a decarbonising economy until mid-century. Here, obtaining an equilibrium of consumption would be desirable, but already the Club of Rome was highly critical of technologies and technological optimism to reach this equilibrium.[31] It seems contradictory to accept the limits to growth for a sustainable and decarbonising society while acknowledging a growing global future basic material demand. This dilemma can be addressed by introducing the concept of meeting the demand for basic material "services" rather than basic materials.

[31] *See*, Chapter IV and V in (Meadows et al., 1972)

The underlining idea is that we consume basic materials because of the "services" offered by the final products made from these basic materials. For example, a kitchen knife is made of stainless steel since stainless steel ensures the required product characteristics of sharpness and durability. Therefore, these product characteristics are linked to the "services" of steel when used as basic material for making the knife. In a decarbonising economy, the material demand might therefore be met by a wide range of alternative options that can provide the required basic material service:[32]

Material recycling: Today, most basic material production is primary production from naturally occurring raw materials. Secondary production from recycling feed already plays a significant role in satisfying material demand for steel, aluminium, paper, and glass. Generally speaking, recycling processes are less energy-intensive than primary production but limited by the ability to recover high-quality basic materials from waste streams. Additionally, a significant share of the required energy is needed for collecting, sorting, and pre-conditioning waste streams rather than for high-temperature processes.

Material substitution: Using other sustainable basic materials such as wood in the building sector (Falk, 2009) or clinker substitutes (IEA, 2018b) can reduce the demand for emission and energy-intensive basic materials like cement or steel.

Material efficiency: Higher value and lower volume basic materials can provide the same service while reducing the material intensity of consumption. For example, lightweight designs of steel and aluminium beams require up to 30% less material (Carruth et al., 2011).

Share, repair, reuse: Moving away from individualistic ownership for some basic material end-uses, such as car-sharing, while increasing recyclability and reuse of products compared to today´s throwaway society is vital for enabling a circular economy (Material Economics, 2018).

For the future demand for steel services, climate-friendly basic material production might only be one pillar for decarbonising basic material consumption (Figure 2-16). However, the emergence of these options as an alternative to today´s basic material use primarily depends on their future competitiveness since they are not competitive to primary basic material production in today´s markets. Given that any of the options mentioned above becomes competitive, it would change how we consume basic materials and impact the energy required to provide basic material services. Vice versa, the competitiveness of some alternatives might depend on the availability of zero-emission energy sources introduced earlier in this section.

2.2.3. Some remarks about industrial energy use

The future industrial energy demand remains a big unknown. For many industries, it is not easy to forecast which energy vectors will be used to meet their future energy needs. More so, precisely predicting future consumption trends for industrial goods in a national or European context remains challenging. Having said this, the analysis presented in this section allows for some first remarks about the future interlinkage between industrial transition and the energy system.

First, industries requiring low-temperature heat provisions do not rely on a specific energy carrier for their process energy. Processes operating with potentially renewable electricity seem to be competitive alternatives to thermal energy carriers. At the same time, biomass is already a prominent alternative for process heat provision in some regions and industries. Today, all industries with significant demand for heat exceeding 200 °C have relatively standardised thermal energy demand profiles and require an adequate alternative to deliver high-temperature heat without causing carbon dioxide-equivalent emissions due to the combustion of fossil fuels. Most likely, biomass, hydrogen and carbon capture will be the available alternatives to electrification for high-temperature heat in the industry, mainly required to produce basic materials. Hydrogen production and carbon capture will increase the energy intensity of the industrial output, whereby additional energy required for hydrogen production is likely to be electric.

[32] *See*, Neuhoff et al., (2019) for a more detailed discussion of these basic material services

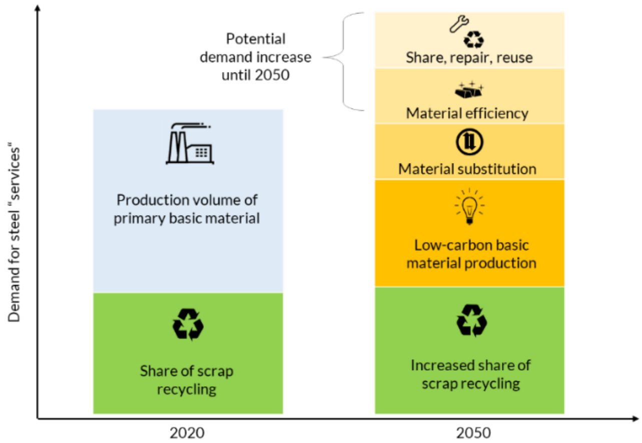

Figure 2-16: Potential mix of services to meet steel demand 2020 and 2050 (based on Figure 2 in Neuhoff et al. (2019)

Scientific research and modelling directed towards industrial decarbonisation do not seem to fully capture the extent of changing energy vectors in the industry.[33] One of the most detailed modelling exercises is the underlying scenarios of the EU "A Clean Planet for All" strategy. These scenarios foresee an increased industrial electricity consumption between 6% in the BAT and 65% in the electrification scenario in 2050 compared to 2015[34] . Still, they account for low hydrogen consumption across all scenarios based on inflated hydrogen cost assumptions (Fleiter et al., 2019).[35]

Alternatives to primary production might play a key role in meeting the future demand of basic material services, though as of today, there seems to be no business case for them. In many aspects, the status quo of alternatives to today´s primary production routes resemble the situation of renewable electricity generation technologies (RES) in the early 2000s (Jacobsson and Johnson, 2000). The potentially increasing interlinkage between the electricity system and industrial energy demand motivates a more detailed comparison between electricity and basic materials.

[33] *See*, section 6.2 for review of industrial modelling approaches.
[34] Industrial electricity consumption is only reduced by 9% compared to 2015 in the biocycle scenario that covers most industrial energy demand with biobased energy carriers.
[35] The low hydrogen utilization rate in (Fleiter et al., 2019) might be linked to underlying cost assumptions of 160 €/MWh and 140 €/MWh of H_2 in 2030 and 2050, which corresponds to a price between 4.6 and 5.3 €/kgH_2, significantly higher than the price of less than $2/kg$H_2$ that is predicted for PV-based hydrogen production by the IEA (IEA, 2019a).

2.3. From one commodity market to another: electricity and basic materials

The energy-intensive industry will need to switch to novel process designs for climate-friendly basic materials production. This industrial transition resembles the emergence of renewable energy generation technologies over the last decades and motivates the comparison of electricity and basic materials as economic commodities. The characteristics of both commodity types are contrasted to highlight similarities and differences regarding their physical characteristics (section 2.3.1) and their markets (section 2.3.2). By summarising the results of this comparison (section 2.3.3), I show that insights from the electricity system transition might have value for understanding the transition of the basic material sector. However, the differences between both commodities make the decarbonisation of the energy-intensive industry a very different type of challenge.

2.3.1. A comparison of electricity and basic materials

Trying to compare apples with pears. This proverb perfectly summarises the task of pointing out similarities and differences between electricity and basic materials. One is a volatile form of energy, whereas the other describes a loosely defined group of tangible goods. A closer look at their production routes, however, illustrates certain similarities between both commodity types.

Both for electricity and basic materials, the production process transforms different types of inputs to produce a commodity. In doing so, fossil thermal electricity generation and basic material production show remarkable parallels and often share the same feedstock. High process temperatures are achieved by burning fossil energy sources, which in the case of the steel and petrochemical industry are also essential inputs to the material transformation process. Secondary outputs of fossil thermal power plants and basic material production processes are similar. High-temperature processes result in residual heat, cause greenhouse gas emissions and waste products directly linked to their fossil material feedstock.

A critical difference between electricity production by fossil thermal generation and basic materials production is the availability of alternatives. Whereas basic material production is highly standardised, and in most cases, today´s commercially operated production routes for each basic material type only differ marginally, alternatives to thermal generation are plentiful. All thermal electricity generation technologies use heat to power rotary turbines. Nuclear fission and concentrated solar power plants (CSP) do so by using non-fossil energy sources. Wind and hydropower make direct use of the forces of nature to transform motion into electricity, and photovoltaics can convert solar radiation into electricity. As such, today´s electricity generation does not have to rely on fossil sources.

Standardised process design for primary production is not based on a thermal but electro-chemical transformation for one basic material.[36] The electrolysis of alumina makes aluminium production one of the most electricity-intensive processes in the industry, and its economics are highly sensitive to developments in the electricity market. In the Spanish context, the struggle of multinational Alcoa for additional electricity price incentives to prevent the closure of their local production facilities highlights this dependency (Monforte, 2018). For the primary production of other basic materials, electricity consumption is secondary to thermal energy use obtained by combustion processes. Electricity is mainly used for rotary process equipment, such as milling, mixing, separation or conveyor technology. However, any change from fossil-based thermal processes towards process technologies with elevated direct or indirect electricity consumption would increase the electricity market exposure of primary steel, cement, petrochemicals, paper, glass, and ceramics production.

[36] Secondary production of steel by electric arc furnaces (EAFs) and primary production by direct reduced induction (EAF-DRI) is highly electricity intensive, but as of today only plays a minor role in Europe (World Steel, 2019).

Both electrical energy and the different basic materials have unique characteristics, making them the choice of input for their current use cases. Electricity is the second choice for applications requiring high thermal energy demand and highly efficient to provide energy of motion. Each basic material has unique characteristics, making it difficult to replace it one-to-one with an alternative material for all use cases. In the case of basic materials, though, alternatives are not only limited to the use of other material types. Alloys and different material compositions can improve material properties and thereby reduce material demand. The re-utilization and reprocessing of waste streams already substitutes some primary basic materials production (Allwood et al., 2013) (see Figure 2-16 in section 2.2.3). Alternatives to provide basic material services are similar to volatile electricity generation in that they require a compromise about the commodity´s characteristics. Electricity systems with a high share of volatility require a more flexible and responsive demand side (section 4.2). Using alternatives to provide basic material services implies a similar degree of flexibility from basic material users about some of the basic material´s characteristics such as material stiffness, ductility or used alloy components or additives.

Due to the different physical characteristics of electricity and basic materials, their transport and storage solutions are highly distinct. Electricity cannot be stored in large volumes without relevant transformation losses and requires a dedicated transport infrastructure. Basic materials are durable goods that can be transported by various means of competing transportation options and cheaply stored both on the production side, along the logistics chain or at premises of the industrial consumer. This major difference in handling both commodity types is decisive for understanding why electricity markets are regional markets, and basic materials are globally traded commodities. Electricity is almost always consumed in the economic area it is generated. Pricing is based on matching regional demand with regionally generated electricity.[37] Electricity transport relies on one common distribution and transmission system, operated as natural monopolies by distribution (DSOs) and transmission system operators (TSOs). It might be technically feasible to interconnect economic areas further, but the business case for such interconnectors diminishes over longer distances since electricity transmission is subject to significant transport losses.[38] Manufacturers that use basic materials, on the other hand, have no economic incentive to rely on regional basic material production exclusively. Basic material procurement does not know national borders, but factors such as lead time and transport cost (by road, rail or ship) may influence purchase decisions.

2.3.2. Electricity and basic material markets

By focusing primarily on the design and functioning of European electricity markets[39], one does note similarities to basic material markets regarding market operation and market participants. Both markets are business-to-business markets.

Unlike basic materials, a significant share of electricity is directly delivered and used by the domestic end-consumers. Nevertheless, domestic consumers do not participate in electricity markets, but retailers do so on their behalf. In both markets, the supply side is dominated by major long-established companies. National champions with origins lasting back to the period before market liberalisation remain powerhouses on European electricity markets (EUROSTAT, 2020; Georges et al., 2018; Thomas, 2003). These companies have been state-owned on a national level, such as EDF in France and ENDESA in Spain, or regional level like RWE and VEBA/VIAG (today E.ON) in Germany. In Spain, Iberdrola, Union Fenosa, and its predecessors were privately funded and owned but operated under a rigid public regulatory regime (Colli et al., 2014; Newbery, 1997).

The production of steel, aluminium, cement, petrochemicals and to a lesser degree, glass, ceramics and paper, is dominated by global players. Global players like ArcelorMittal in the steel sector are

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[37] In this context the European electricity market is considered as one regional market, even though limited interconnector capacity means that prices on national markets still diverge (ACER, 2020).
[38] Long-distance interconnectors gained importance over the last decade, since high voltage direct current (HVDC) connections allow transmission with relatively low losses, see Zhao (2019).
[39] *See*, section 4.2 for a detailed discussion of EU electricity market design.

vertically integrated companies involved in raw material mining, basic material production and offer a product range of specialised alloys. Companies like South Korean POSCO and Indian Tata group, and JSW group are conglomerates operating in the steel, cement or chemical sector. Similar observations can be made for the cement, aluminium and petrochemical sectors. In contrast, the less emission-intensive production of paper, glass and ceramics is much more concentrated on a regional level and often represented by smaller companies (CEPI, 2020; EC, 2017a, 2017b).

The EU electricity markets have welcomed an increasing share of new supply-side participants over the last few years. Especially the ability to scale RES technologies such as wind power and solar PV eases the market entry for new participants. A similar development cannot be observed on primary basic material markets, which rely on investment intensive large-scale plants.

For both markets, long-term bilateral contracting between producers and consumers is the dominant type of market interaction. The price formation on global commodity markets[40] is often used to set prices in bilateral contracts between basic material producers and consumers, the predominant arrangement in commodity trade (Radetzki, 2008). Whereas day-ahead and intraday electricity markets play a key role in physically matching generation and demand, forward markets are dominated by bilateral over-the-counter (OTC) contracts and surpass day-ahead and intra-day markets with regard to market liquidity. The importance of forward contracting varies widely across the different regional markets (ACER, 2020).

2.3.3. Similarities and differences between the commodities

Unsurprisingly, the comparison of electric energy with basic materials highlights the differences between these commodity types. The overview of the main points of comparison in Table 2-B shows that differences heavily outweigh apparent similarities. However, a focus on partially similar categories provides valuable insights about how specific dynamics and developments that have been observed in the electricity sector might show similar effects on the basic material industry and vice versa. As such, questions as the following arise.

1. Fossil-based thermal generation, which has dominated electricity generation within Europe over the last decades, has very similar process characteristics compared to basic material production. The ongoing transition towards non-thermal energy sources is changing the structure of the power plant fleet in Europe and the feedstock used for generating electricity. What would be the effect of implementing non-fossil based basic material production, especially concerning the quantity and type of energy needed for raw material transformation?
2. Electric energy is currently replacing fossil-based thermal energy sources for some applications, such as passenger vehicles. Various options to substitute primary basic material production with alternatives exist, encompassing more efficient use of materials and enhanced recycling processes, which could both be less energy-intensive than primary production. What is the role of such distributional effects in the basic material sector, and can we use lessons learned from RES support mechanisms to support primary material substitution?
3. The structure of actors dominating electricity generation and basic material production is similar. However, market interactions and dynamics are different since electricity is traded on a regional level and basic materials globally. How does this limit the ability to apply lessons learned and best practices from one market to another?
4. End-consumers do not directly purchase electricity and basic materials, but electricity is used directly by the end-consumer, while basic materials are not. To what extend can changing consumer behaviour play a role in the transition of both sectors?

[40] New York Mercantile Exchange (NYMEX), London Metal Exchange (LME), Zhengzhou Commodity Exchange (ZCE) or Tokyo Commodity Exchange (TOCOM) are the most important of the 10 biggest commodity exchanges in the world (Street Finance, 2019).

This work does not aim to address these questions. However, they are closely related to the effects of a likely transition on both markets. Considerations about possible implications will play an important role in the following.

Table 2-B: Comparison of electricity and basic materials as commodities

	Electricity	Basic Materials	Comparison
Type of commodity:	- Temporary energy source - Homogenous	- Tangible goods - Heterogeneous group of materials	different
Production:	- Conversion of energy	- Processing of materials	partially similar
Process input:	- Thermal energy sources - Renewable energy source	- Raw materials - Thermal energy sources - Electric energy	partially similar
Process reaction:	- Transforming energy of motion (obtained by heat in case of thermal generation) - Photovoltaic effect	- Obtaining basic materials by high-temperature reactions of raw materials - Obtaining raw materials via electrochemical processes	partially similar
Process output:	- Electric energy - Heat - Emissions (thermal generation) - Waste products (thermal generation)	- Basic materials - Heat - Emissions - Waste products	partially similar
Commercially available process alternatives:	- Various thermal, nuclear, and renewable options	- Standard emission-intensive processes for each basic material type	different
Commercially available commodity alternative:	- To a limited degree, fossil energy sources	- To a limited degree, alloys/ variants of basic material, other basic materials, and material recycling	partially similar
Supply chain:	- Regional	- Global	different
Transport:	- Dedicated infrastructure monopoly	- Various competing transport providers	different
Storage:	- Limited and expensive - Requires transformation	- Ample and cheap - Does not require processing	different
Markets:	- Bilateral contracting and centrally organised markets on a regional level	- Bilateral contracting (subject to global commodity exchanges)	partially similar
Market participants:	- Electricity generators - Big consumers and retailers representing small consumers - Traders	- Basic material producers - Manufacturing companies - Traders	partially similar
Market structure:	- National champions challenged by new players	- Global markets with major regional players	different
Direct consumers:	- Domestic, services and public institutions - Industrial	- Industrial	partially similar

2.4. A multidimensional view on industrial decarbonisation

Changing how we produce and consume basic materials is a rather complex task. This simple statement summarises the previous sections and is the main argument for studying industrial decarbonisation from more angles than the technological perspective. The transition from emission-intensive processes towards climate-friendly basic material production requires a multi-disciplinary approach. In the following, I show how current plans for decarbonising the European society differ from technocentric initiatives, like Desertec, driven by technological change (section 2.4.1). I then argue that the basic material sector transition and their close interlinkage with future energy systems call for the consideration of a transition triarchy encompassing the technology, economics and policy dimensions (section 2.4.2).

2.4.1. From Desertec to the European Green Deal

In June 2009, the Desertec Initiative (Dii) published a highly ambitious plan (Desertec Foundation, 2009), which echoed widely in media, politics and society. Large concentrated CSP should be installed in Northern Africa. A meshed network of HVDC lines would ensure that electricity consumers in Europe could be supplied with renewable electricity from the desert within the next 40 years. Backed by industrial giants and banks, such as ABB, Bosch, Deutsche Bank, Enel, E.ON, Munich Re, REE, RWE, Siemens and UniCredit, the project presented a complex technical solution to provide carbon-free electricity to European consumers. Right from the start, the project was faced with criticism. Just a couple of days after announcing the project, Gerhard Knies, chairman of Dii´s supervisory board, responded to questions posed by readers of the New York Times, targeting especially the political, economic, and social dimensions of the project. His evasive answers demonstrate how little these dimensions had been considered (Zeller, 2009). Dii renounced their ambitious plans not even four years later, with CEO Paul van Son stating primarily economic reasons and missing markets (Euractiv, 2013). Since then, the project´s failure has been subject to scientific discourse. Nevertheless, conclusions by authors such as Schmitt (2018) and Scheer (2012) do not diverge much from the criticism posted in the comment section of the New York Times back in 2009.

About ten years later, the European Commission published their vision for a climate-neutral European economy by 2050 (EC, 2018c), which served as the basis for the European Green Deal announced in 2019 (EC, 2019a). Equally ambitious in its objective as Dii, one might ask why this European vision is not bound to kick off with great enthusiasm and die a slow death a couple of years later.

The Green Deal sets objectives for a just transition of society, including aspects like the diet and mobility of EU citizens, aims a for resource-efficient and competitive economy and calls for policies to enable the transition (EC, 2019a). The previously published "Clean Planet for All" vision of the European Commission (EC, 2018c) includes an emission trajectory towards 2050 and presents different technology adoption scenarios. However, these emission trajectories are based on indicative top-down assumptions to demonstrate which efforts could be required across all sectors to reach net-zero emissions (EC, 2018a). The Green Deal itself, though, remains relatively technology-neutral[41] by leaving room for technology competition as long as aligned with low emission and societal interests.

As such, the main difference between the European vision and the Dii can be described as follows. While both aim for a carbon-neutral Europe, the Dii proposed a specific technical system and ignored dimensions beyond engineering. In contrast, the European institutional vision states the final objective and defines the multi-dimensional scope of the transition without detailing its technical realisation.

More detailed trajectories are presented in national energy and climate plans such as the Spanish NECP for 2021-2030 (MITECO, 2020a), though these national roadmaps must be understood similarly. These European strategy documents lay out a multi-dimensional vision for future

[41] Some peculiar exceptions to this technology neutrality is the explicit naming of offshore wind power as only specific generation technology mentioned in the entire document.

policymaking rather than detailing and scheduling specific initiatives to reach the set objectives, as the latest Chinese 5-years-plan (Kennedy and Johnson, 2016). Technological system transitions in the context of the long-term European strategy towards a low emission society need to be studied along these dimensions.

2.4.2. The three main dimensions of system transition

The multi-dimensional nature of our transition towards a sustainable society is not a novelty. The United Nations categorise their 17 sustainable development goals along the economic, social and environmental dimensions (UN, 2015), and other classifications additionally consider moral, legal, technical and political dimensions (Pawłowski, 2008). The transition also implies a temporal component since it does not encompass an abrupt but rather a gradual change of the status quo. In their work on the transition of energy systems, Grubb et al. (2014) study these different phases of the system transition towards sustainable development. They identified three pillars on which the transition needs to be based. Standards and engagement for smarter choices (I) aim primarily at changing people and organisations´ behaviour to satisfy their needs most sustainably. Markets and prices for cleaner products and processes (II) reflect the necessity for low emission options to be economically competitive. Strategic investment for innovation and infrastructure (III) is in the realm of institutional efforts to transform systems. As such, system transition is primarily determined by the evolution of the technical, societal, economic, and institutional dimensions and their mutual interference.

The societal aspect brings along some particularities, which require a revaluation of their role in the system transition. Society refers to people, their actions and their interactions with each other. Actions by individuals regarding the transition towards a low-carbon society are based on the value they place on the transition. This value might conflict with other individual values, which means that such conflicts might limit societal adoption (O'Brien, 2001). This can be illustrated by looking at individuals' most significant actions to reduce their carbon footprint, as quantified by Ivanova et al. (2020) (Figure 2-17).

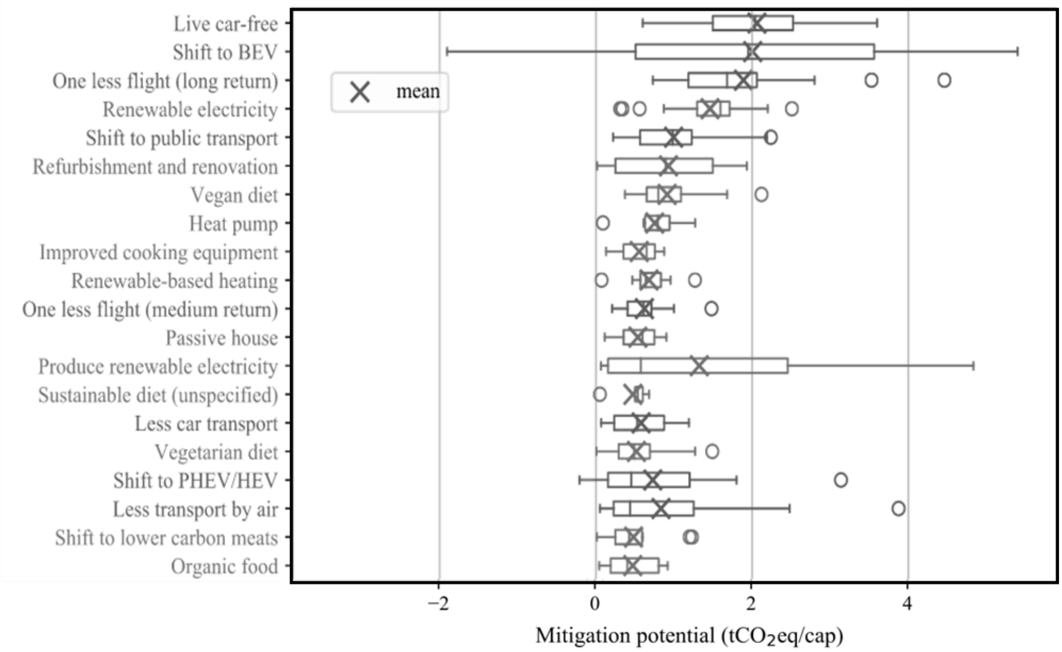

Figure 2-17: Consumption options with the greatest mitigation potential per capita (adapted from Ivanova et al. (2020))

For rethinking our mobility, from using electric vehicles to living car-free, or implementing dietary changes, from low-meat to vegan, a different degree of behavioural change is required, which might be in conflict with our values on mobility and meat consumption. Such actions are directly linked to behavioural changes or would need at least some degree of behavioural adoption. How to change values so that society changes its behaviour? - by behaviour change policies, a field of research on its own (Evans et al., 2020). These policies, though, are implemented by public institutions and governments representing the interests of society. Public institutions, therefore, act as the advocate of the society for the system transition. This advocacy for societal interests also covers one highly emphasised aspect of the European Green Deal, the call for a just transition. The just transition will be a key component of EU policymaking as long as member states support a welfare-oriented European Social Model (ESM) of sharing problems and intervention solutions (Jepsen and Serrano Pascual, 2005).

Therefore, the following three main dimensions of the system transition remain, which will be studied in detail to understand the transition of the basic materials sector on its trajectory towards a net-zero emission society within the European Union by 2050: Technology, Economics, Policy.

Technology

The technology dimension explores the solution space of alternative technology options in the basic materials sector, the electricity system, and a potential hydrogen economy. RES generation options, namely wind and solar power, have been under development over the last decades and reached their market competitiveness over the last years (IEA, 2020c). The excepted rise of these RES sources and their impact on electricity systems needs to be studied considering novel storage solutions and other flexibility options, thermal generation sources, and legacy generation capacity. Alternative technology options for producing basic materials are less straightforward than those available on the electricity system. Covering multiple industrial processes in each of the studied basic material industries, the focus of understanding the technology dimension is to identify cross-sectoral differences and similarities between the different decarbonisation options. Other than in the electricity sector, climate-friendly technology options in the basic material sector cannot yet compete with conventional process designs. As such, emphasis is placed on the technological readiness of different options and their implications.

The technological dimension is primarily covered in Chapter 3, whereas the future role of RES and hydrogen technologies is studied in the context of future electricity systems in Chapter 4.

Economics

Currently, there is no market for low emission basic materials, and as such, there is no business case for the basic material sector to invest in climate-friendly production processes. Therefore, the emphasis in this work will be on the framework conditions for future climate-friendly basic material markets. It encompasses the analysis of future material demand and its implications, the role of imports and exports, carbon pricing, and especially the availability of alternative energy sources. Electrification of production processes might link the economics of basic material production much closer to electricity market dynamics. Additionally, special attention needs to be paid to hydrogen economics, allowing the basic material sector to lower their emissions without changing their current production processes. Results from this analysis require an additional reflection on the future of electricity markets to evaluate the future role of direct or indirect industrial energy consumption. In the European Union, electricity is offered, traded, and purchased on different centrally organized regional markets, based on the European liberalised electricity market design principles. Understanding future electricity markets is closely linked to the interplay between the existing and new generation and storage technologies to be installed. Special emphasis is placed on carbon pricing and other market mechanisms, which might be required to achieve low emission and renewable energy targets while maintaining system security within the Spanish context. The main objective is to understand how electricity markets may develop over the next decades.

A review of techno-economic parameters for climate-friendly basic material production is presented in section 3.3. Insights about the consequences of future electricity market design (section 4.2) motivate a more detailed evaluation of the economics of future energy systems presented in section 4.3.

Policy

As long as climate-friendly production processes for basic materials are not the most economical option, institutional involvement will have to incentivise the transition towards a climate-friendly industry. Today, the most prominent example of institutional involvement in the basic materials sector is pricing externalities, namely CO_2e. It also encompasses any element of the legislative framework that companies have to comply with, covering labour, business and taxation laws, local and national pollution protocols and reporting standards. The role of public governance in the transition of the basic materials sector might have to change substantially over the transition period. First, the basic materials sector might require active public support to bring low-emission technologies to market readiness. Market readiness does not imply market competitiveness, and investments in these technologies will only occur if market conditions create a business case for low-emission technologies. Therefore, the institutional framework must ensure competitive market conditions for climate-friendly basic materials exist in a European and global market framework while safeguarding that the transition is aligned with societal objectives. For this thesis, I will evaluate different policy options and differentiate between the institutional role during the different phases of the transition. Particular emphasis is being paid to similarities in the evolution of electricity markets and the policy implications for the wider energy system.

Different policy options are introduced and evaluated regarding their importance for the different phases of system transition in Chapter 5. The modelling approach presented in 6 explores their role for technology choices taken by industrial actors over the entire transition towards a decarbonised economy.

The transition triarchy

The trajectory towards a low-emission consumption of basic materials requires us to understand how these three dimensions are interlinked and influence each other (Figure 2-18). Technological readiness by itself, even if supported by public spending, might be insufficient. It requires a market-based demand for climate-friendly materials, which might not emerge by itself and may need an institutional framework. Since basic material production is highly energy-intensive, the transition triarchy of technological availability, market economics and industrial policymaking must acknowledge the implications of each of these dimensions regarding the access, availability, and competitiveness of low-emission energy sources.

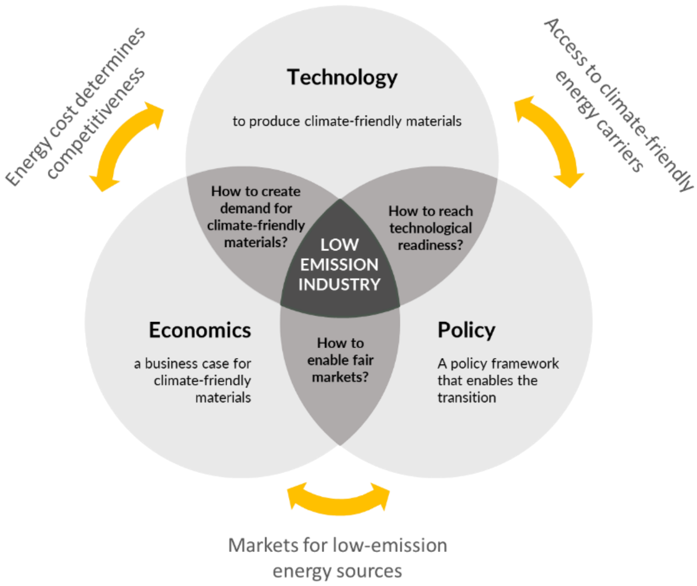

Figure 2-18: The dimension of the transition triarchy for the basic materials sector

Chapter 3
Technology options for industrial decarbonisation

Journal publications and reports used for this chapter:

Gerres, T., Chaves, J.P., Linares, P., Gómez, T., 2019. A review of cross-sector decarbonisation potentials in the European energy-intensive industry. Journal of Cleaner Production. 210, 585–601. 10.1016/j.jclepro.2018.11.036

Chiappinelli, O., Gerres, T., Neuhoff, K., Lettow, F., de Coninck, H., Felsmann, B., Joltreau, E., Khandekar, G., Linares, P., Richstein, J.C., Sniegocki, A., Stede, J., Wyns, T., Zandt, C., 2021. A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions. Climate Policy. 10.1080/14693062.2021.1922340.

Gerres, T., Linares, P., Chaves, J.P., Gómez, T., 2019. Tecnologías para la descarbonización de la industria del uso intensivo de energía. IIT, UP Comillas.

Today´s production processes are unfit for providing climate-friendly basic materials. Awareness about the limitations of conventional production let us question how to reduce energy and process-related emissions to a bare minimum. Changing basic material production to climate-friendly technology options can take two different routes. First, current process designs to obtain basic materials from raw materials, referred to as primary production, need to be replaced by less emission-intensive technology options. Additionally, we have to rethink the role of recycling processes, called secondary production, as an alternative to the consumption of primary basic materials. In the following, I explore these two alternatives for basic material provision with the underlying objective to highlight why neither of these options plays a more significant role for basic material production today. This dive into the boundary conditions of different technologies offers an understanding of the technological dimension of industrial decarbonisation and therefore provides the groundwork for the economic and governance dimension of the system transition.

This chapter recaps the findings published in Gerres et al. (2019b) and Chiappinelli et al. (2021). In Gerres et al. (2019b), I developed a framework to identify and classify different decarbonisation potentials in the basic material sector. This framework highlights and revaluates the areas of emission abatement with the highest emission reduction potential for each basic material sector, focusing primarily on primary production processes. I complement these findings with the techno-economic evaluation of near-term decarbonisation options for both primary and secondary production as published in Chiappinelli et al. (2021), as well as work presented in a technical report made for the Spanish Ministry of Ecological Transition (MITECO) (Gerres et al., 2019d).

Section 3.1 summarises the methods to review the technology options presented in Chiappinelli et al. (2021) and Gerres et al. (2019b, 2019d) and develop the framework presented in 3.2. This framework enables me to identify the most mentioned emission abatement options by public bottom-up roadmap and pathway publications. Based on this, section 3.3 analyses these abatement options by identifying relevant climate-friendly technology options for all reviewed basic material sectors. The discussion in section 3.4 highlights the main findings. Lastly, the conclusions presented in section 3.5 addresses thesis sub-objective I:

Evaluate the principal emission abatement options for the basic material sector, their cross-sector applicability and decarbonisation potential for the European industrial sector.

3.1. Methods

The review of technology options for industrial decarbonisation summarised in this section results from a continuous process that lasted for about four years, from mid-2017 until early 2021.

The basis for obtaining a profound understanding of the different decarbonisation options across various industries is the framework for categorising decarbonisation options published in Gerres et al. (2019b) and described in section 3.2. This framework is based on a structured approach of analysing available public bottom-up roadmap and pathway publications by private and public sector entities for industrial decarbonisation options available by the end of 2018. Since these publications date from 2007 until 2017, they do not fully capture the latest advances or the changing importance of some decarbonisation options. Additionally, the chosen approach is based on alternatives for the primary production route and mainly disregards secondary production alternatives, namely advanced basic materials recycling. Also, the review of emission-intensive industries presented in Gerres et al. (2019b) left out a thorough revision of the aluminium industry.

In section 3.3, I extend the industry-specific findings presented in Gerres et al. (2019b) by a scientific literature review of recycling options, the aluminium sector as published in Chiappinelli et al. (2021) and the techno-economic evaluation of abatement cost as developed in Gerres et al. (2019d). Unlike in Gerres et al. (2019b), I do not contrast the identified abatement options across different industries but present a sector-specific review. This section diverges significantly from the analysis in Gerres et al. (2019b) and introduces a new perspective that is more relevant for developing the modelling framework in Chapter 6. The food sector, included in Gerres et al. (2019b), is not a basic materials industry and does not fulfil the characteristics of a hard-to-abate sector. Therefore, I disregard the food sector for the analysis presented in this chapter.

In this chapter, I take a holistic view of abatement potentials across the various basic material industries, formulating five propositions about the techno-economic dimension of the transition in section 3.4. I use these propositions about the technical readiness of different abatement options in section 6.2 to identify the modelling gap to be addressed with the TRANSid model.

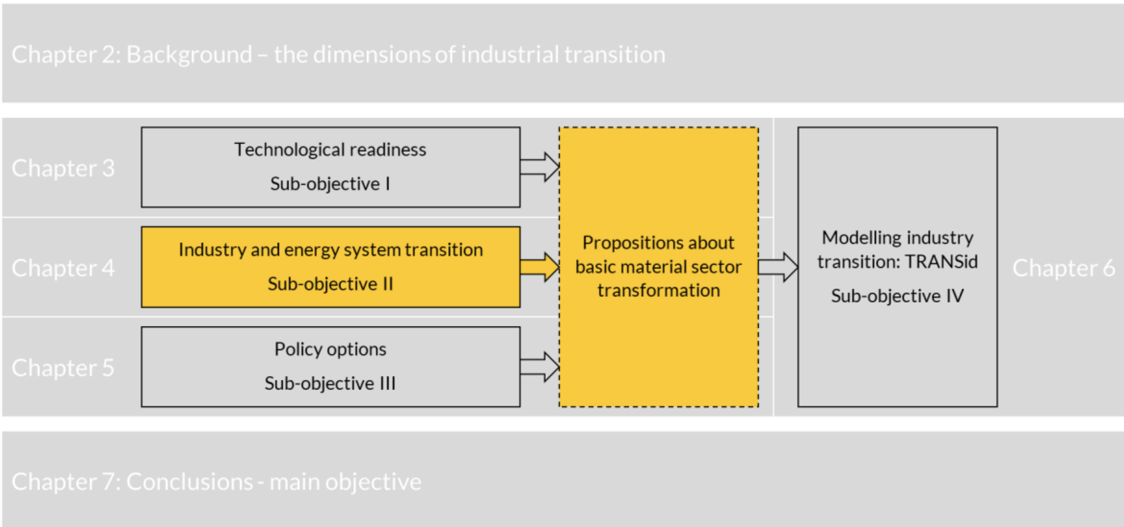

Figure 3-1: Chapter 3 as part of the thesis structure

3.2. A framework for decarbonisation options

Aiming for drastic change requires actions. In light of stricter global and national decarbonisation targets, the last decade has seen a surge in public and private sector reports presenting possible technology pathways towards the climate-friendly production of basic materials. Whereas roadmaps and pathways from national institutions and independent organizations should show technology and sector neutrality, reports published by individual companies or sector associations need to be evaluated with consciousness and cautiousness about their authors´ interests and commercial agenda. Yet, in its entirety, these reports can provide a holistic overview of emission abatement options for the different basic material industries.

Publicly available reports published until late 2018 served as the basis for understanding where and how industries might reduce their energy and emission intensity over the following decades. These reports include governmental and non-governmental publications focusing on the deep decarbonisation of national industries in Germany (Umweltbundesamt, 2014), the UK (Pye et al., 2015; WSP and DNV GL, 2015), US (Williams et al., 2015), the Netherlands (Berenschot, 2017) or Sweden (Brolin et al., 2017), as well as private sector roadmaps by sector associations such as by EUROFER (2013), CEMBUREAU (2013), Cerame-Unie (2012) and CEFIC (2013). I also reviewed technical details about alternative technology options from the EC JRC BAT sector reports and numerous other industry-specific publications.[42]

The quantity and quality of findings required a structured approach to categorise and map emission abatement options. First, all findings were grouped based on whether they aim to reduce emissions by changing the inputs of industrial processes, the process itself or process outputs. Here, we needed to differentiate further between the dispositive dimensions of abatement potentials. Applying the dimensions identified in Gutenberg´s theory of production factors (Gutenberg, 1951), I distinguished between feedstock, energy and information flows over the entire industrial process. Using the resulting matrix framework, I could categorise abatement options and specific areas of emission abatement (Figure 3-2). By far, the most extensive number of abatement options are targeting the process itself, which motivated the introduction of an additional layer for categorising process innovations based on the work on manufacturing processes by Groover (2010).

By applying this framework, I identified and characterised different abatement options, as shown in Figure 3-3. In the following, these areas and the most frequently mentioned abatement options are briefly introduced.

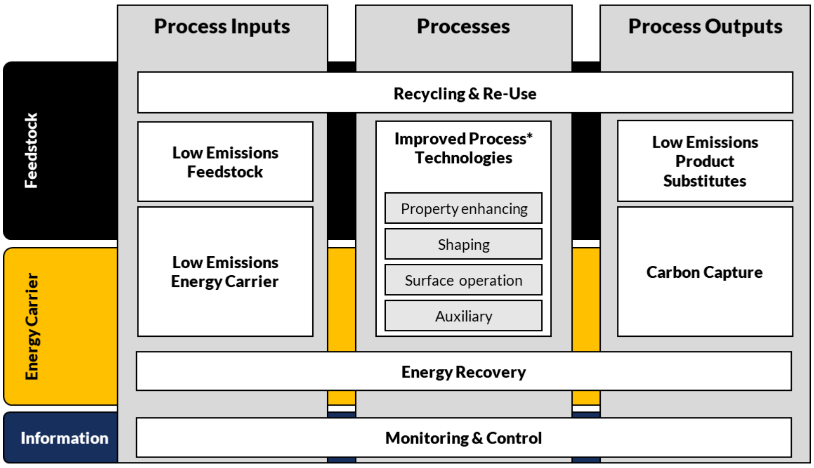

Figure 3-2: Framework for categorising decarbonisation (Gerres et al., 2019b)[43]

[42] *See*, Table 2 in Gerres et al. (2019b) for the full list of reviewed publications.
[43] One category (*) has been renamed since the original wording “manufacturing” refers to the production of subassemblies and final products from basic materials.

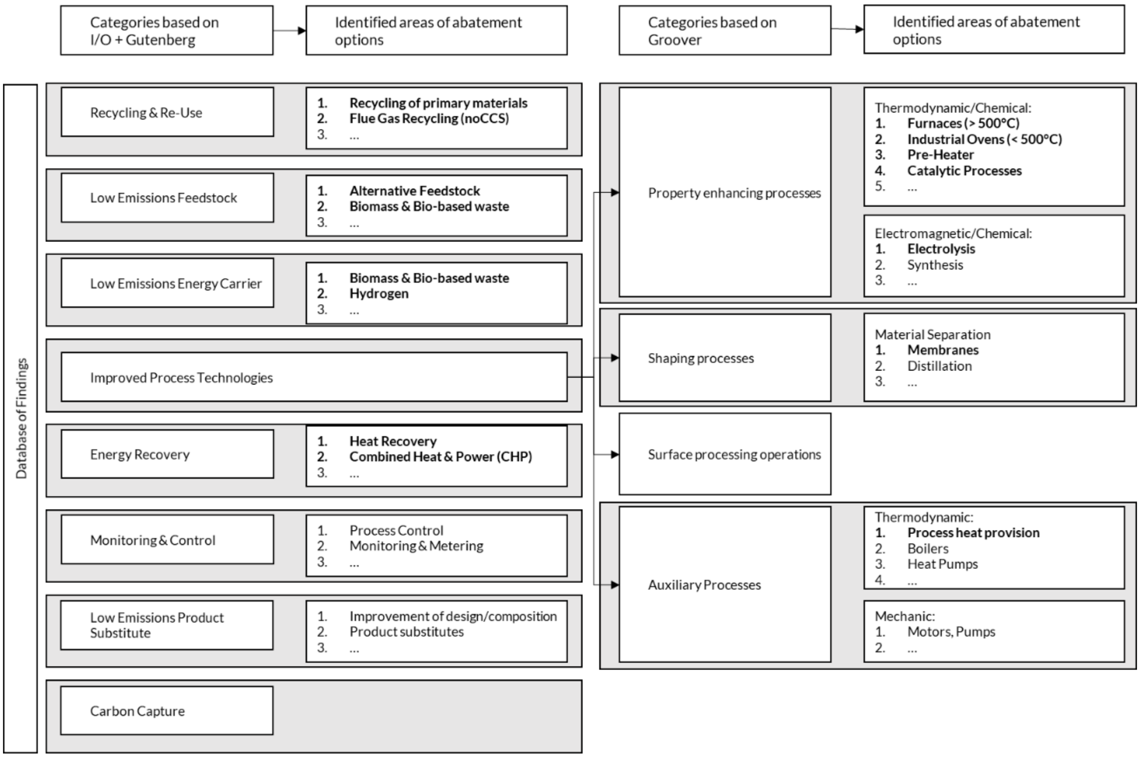

Figure 3-3: Identification of areas of abatement options with most discussed areas highlighted in bold (Gerres et al., 2019b)

3.2.1. Low emission feedstock

Multiple basic materials have in common that emissions are processes related, therefore directly linked to the choice of raw materials used. Entirely replacing the primary material stream of iron ore, bauxite or limestone would mean replacing existing basic materials with other material choices, which this group of abatement options does not cover. Instead, this category covers the use of additives and secondary feedstock streams that could significantly lower the emissions of production processes. Their role is highly prominent in the non-metallic mineral sectors, namely cement and ceramics production and the pulp & paper industry. All have in common that final products contain a relatively high share of secondary feedstock. These additives could be replaced by alternative feedstock types or bio-based alternatives, lowering process emissions.

3.2.2. Low emission energy carrier

Covering thermal energy demand by fossil fuels is the primary source of carbon dioxide-equivalent emissions in several basic material industries. Some industries could decarbonise without changing their production processes by simply replacing these fuels with other non-fossil energy sources. In 2018, biomass as an energy carrier was highly discussed across many basic material sectors, whereas hydrogen was less mentioned. For steel production and the (petro)chemical sector, the development of new hydrogen-based processes is an option that could substitute fossil carbon-based energy and feedstock (Chiappinelli et al., 2021). Nevertheless, hydrogen was not seen as a prominent alternative energy source and direct fuel replacement for natural gas in many sectors.

As reflected in Gerres et al. (2019d) and further detailed in Chiappinelli et al. (2021), this perspective has changed over the last few years. Fuelled by the competitiveness of renewable energy sources, expected cost reductions, efficiency improvements of electrolysis technology and the absence of other non-fossil alternatives that can potentially provide high-temperature process heat, hydrogen has emerged as a solution for applications that are hard to electrify (IEA, 2019a). Recently published national hydrogen roadmaps also reflected this trend for Spain (MITECO, 2020b) and Germany (BMWi, 2020).[44] These findings motivate European natural gas networks operators to re-think the role of their networks as future transport infrastructure for hydrogen (Gas for Climate, 2020). Hydrogen could replace natural gas like natural gas replaced coal and crude oil for heat generation in the European industry since the 1970s (IEA, 2019b).

3.2.3. Improved process technologies

The most exhaustive list of decarbonisation options concerns the emission-intensive production processes in use today. With reference to Groover´s categories of manufacturing operations (Groover, 2010), the main processes used in the basic materials sector can be divided into two different groups. First, property enhancing processes, where several different materials are joined, merged and transformed to create a basic material with enhanced characteristics. This type of process is the basis of most basic material production processes. Furnaces and ovens are used to trigger thermo-chemical reactions at high temperatures in the steel, cement, ceramics, glass, and paper industry. Improved and novel designs are key for emission reduction in these industries. Electrolysis or synthesis processes currently used in the aluminium industry use electrochemical principles to provide reaction energy and could also be used for steel making. Distillation and possibly novel membranes are processes used to separate raw materials into their different components. Both processes are key to the portfolio of decarbonisation options in the petrochemical industry. Additionally, the emission reduction of auxiliary processes, especially the provision of process heat without relying on carbon-intensive energy sources, presents another important field of emission reduction within the basic material industry. Options such as combined heat and power (CHP) are not only limited to the specific sector or the basic material production but could also play an important role in other industries.

3.2.4. Low emission product substitutes

Diverging from basic materials in use today and seeking more sustainable alternatives has its virtue. Why just do not stop using materials with such a big carbon footprint? The list of promising alternatives, though, is relatively short. While crowding-out effects between basic materials have taken place in the past and might also play a role in reducing emissions, there are only very few alternatives to the basic materials. Most prominent is the discussion about alternatives to cement, yet, alternatives struggle to live up to the durability and strength of limestone-based clinker (Amato, 2013). Wood might replace steel for some applications in the construction sector, but this is limited due to its characteristics (Karlsson et al., 2020; Sandin et al., 2014).

3.2.5. Carbon capture

Like the use of low emission energy carriers, carbon capture potentially allows for the operation of today´s processes without emitting greenhouse gases. Carbon capture seems to be an easy fix for decarbonisation by reducing energy-related emissions and all process emissions. Relatively pure CO_2 streams facilitate their separation from exhaust gases. Carbon capture is often mentioned for steel, ammonia, cement, and paper production processes. Latter mentioned could capture bio-based emissions and operate with a net-negative carbon footprint, serving as a carbon feedstock provider for other industries. That said, the question about what to do with captured fossil-based emissions remains the big unknown for this technology. Not in my backyard (NIMBY), and unknown long-term efficacy remains a significant hurdle for long term storage (Terwel and ter Mors, 2015).[45]

3.2.6. Recycling and reuse

What happens with waste is highly relevant for emission reduction in all basic material industries. Scrap, rejects, and flue gas streams can occur along the entire production chain. Areas of abatement include efficiency improvements to reduce waste and the utilisation of production

[44] Our own work for national Colombian hydrogen roadmap (Minenergía, 2021), developed by i-deals, IIT and Montoya & Asociados on behalf of the Inter-American Development Bank (IDB) for the Colombian Government confirms these findings.
[45] *See*, section 4.3.3 for further discussion about carbon capture options for energy provision.

waste. Additionally, post-consumer waste can serve as a feedstock alternative to primary processes or can be recycled by secondary production to reduce the demand for carbon-intensive primary basic materials. As shown in Chiappinelli et al. (2021), recycling options can significantly reduce the emission intensity of steel, plastics, and aluminium consumption. They might have the potential to replace some of the primary cement demand. Recycling rates of paper and container glass already exceed 70.0% on a European level and could increase even further (EPRC, 2020; FEVE, 2020).[46] On the way towards a circular economy, though, waste must not be downcycled to lower-value materials.

3.2.7. Energy recovery

Reducing the amount of excess heat created by the different production steps and released via the exhaust stream is vital for increasing the efficiency of currently used processes. Any heat released to the outside is a loss, which increases energy consumption compared to the theoretical optimum.[47] Heat recovery is one of the most discussed options for all reviewed basic material sectors to reduce emissions. As various sources suggest, recovered heat can be used internally for other process steps or sold to external consumers.[48] This heat is not emission neutral, as long as the energy used to generate process heat originates from fossil sources. Another option to recover heat is high temperature electric industrial heat pumps, potentially lifting low-temperature heat to higher temperature streams. Heat pumps operate at low and medium temperature ranges. Therefore, their application is limited in the basic material sector but could help decarbonise industries operating at lower temperature ranges. Any energy recovery option can only accompany a low emission technology transition since efficiency improvements will not decarbonise the industry.

3.2.8. Monitoring and control

The tools available to collect and process data to improve the operational control of production processes has never been better than today. This trend will continue in the upcoming years, thanks to increased digitalization and relatively cheap sensor technology. Monitoring production processes can help control them better, increase accuracy, reduce material demand and waste and decrease energy intensity. While the importance of the information dimension should not be disregarded and digitalization is highlighted in many of the reviewed pathway publications, it can only play a secondary role in decarbonising the basic material sector. Energy and process emissions cannot be reduced to the levels required for climate-friendly production by optimising the process control.

3.2.9. Areas of abatement potentials in basic material production

Based on the review of bottom-up roadmap and pathway publications by private and public sector entities presented in Gerres et al. (2019b), I identified the most discussed abatement areas and corresponding abatement options. Figure 3-4 summarises these abatement options for the different basic material sectors studied within the thesis's scope. Technical solutions for each of the listed industries are further detailed in 3.3.

As mentioned in section 2.2, one of the common features of basic material production is their heat and energy intensity, requiring process temperatures exceeding 500°C in most reviewed industries. As highlighted in Figure 3-4, abatement options addressing process heat provision, use and reduction of heat intensity dominate this overview of the most discussed abatement options across all industries.[49] Abatement options that do not or only indirectly address the heat intensity

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[46] According to the cited publications from FEVE and EPRC, the recycling rate was 72.0% for paper in 2019 and 76.0% for container glass in 2018.
[47] *See*, section 2.1.3 for the difference between current BAT and theoretical optima for different basic materials.
[48] Among others, provision of excess heat to external sources is considered to be a feasible option for the steel (Schaper, 2017) and cement industry (European Cement Research Academy, 2017).
[49] Though, the aluminium industry has not been included in this review, the analysis presented in sections 2.1.3, 2.2.1 and 3.3.2 shows that the energy and heat intensity of aluminium production would show similar

of basic material production were particularly mentioned in those industries that require the highest process heat (section 2.2.1) and are the most emission-intensive (section 2.1.3).[50] Abatement options such as carbon capture and storage, alternative (biobased) feedstock and energy carriers, and internal and external recycling options are mentioned for various industries. Abatement options addressing the heat intensity of current processes range from new furnaces and oven designs, heat recovery, and pre-heater options to CHP in industries with a significant share of medium to low-temperature heat requirements (section 2.2.1).

	Iron & Steel	Aluminum	(Petro)-Chemical	Cement	Ceramics	Glass	Pulp & Paper
1. Most mentioned	Furnaces	not reviewed	Catalytic Processes	Alternative Feedstock	Furnaces	Furnaces	Industrial Ovens
2.	Electrolysis		Heat Recovery	Biomass & Bio-based Waste	Heat Recovery	Heat Recovery	Heat Recovery
3.	Flue Gas Recycling		Membrane Separation	CCS	CHP	Pre-Heater	CCS
4.	CCS		CHP	Furnaces	Biomass & Bio-based Waste	Oxyfuels	Biomass & Bio-based Waste
5. Least mentioned	Heat Recovery		CCS	Heat Recovery	Alternative Feedstock	Recycled Primary Materials	Process Heat Provision

Figure 3-4: Areas of most discussed abatement potentials presented in (Gerres et al., 2019b) [50]

pattern as observed for the other basic material production processes with alternatives to carbon-intensive graphite anodes offering the highest emission reduction potential.

[50] One of the most mentioned new furnace designs in the steel industry aims at using alternative feedstock, namely H_2 and non-fossil-carbon in the DRI-EAF route, thereby also changing the way process heat is provided within the process. Abatement areas focusing primarily on heat intensity reduction are highlighted in yellow.

3.3. Climate-friendly technology options for the basic material sectors

Emission reductions will rely on new production methods. Potential technology options and prospective innovations are the underlying foundation for any argument supporting future climate-friendly material production. In the following, I recap the emission abatement potentials for technology options in the different basic material industries, as identified in Gerres et al. (2019b) for each of the major basic material industries. Where necessary, information is revised based on the work published in Chiappinelli et al. (2021) and Gerres et al. (2019d) and extended by referenced cost estimations of different abatement options. Saving potentials are always stated relative to BAT technology. Instead of simply restating the literature review to estimate saving potentials in Gerres et al. (2019b), this section revaluates the most suitable decarbonisation options identified for each industry.

3.3.1. Iron & Steel

As of today, blast furnace designs are the most common technology for producing primary steel. The emission intensity of BAT technology is 1.89 tCO_2/t of crude steel (EUROFER, 2013). As shown in Figure 3-5, carbon capture and storage, novel furnace designs and electrolysis are the three main alternatives enabling deep decarbonisation of primary steel production.[51] Electrolysis could allow for the near-zero emission production of steel from iron ore, but the technology has not left the laboratory development stage (Agora Energiewende and Wuppertal Institut, 2019). Estimations about the likely cost increase per avoided tCO_2 compared to today´s production methods are highly uncertain (Figure 3-6). Installing carbon capture equipment on existing blast furnaces does not allow for capturing emissions originating from other process steps. As such, they cannot reduce emissions beyond 65.0%. Higher rates are feasible with novel blast furnace designs, such as Hlsarna (TATA Steel, 2017). Cost estimations for this technology are difficult since only a small pilot plant has been installed so far. Not providing price references for the year 2030 and only for the year 2050, Agora Energiewende and Wuppertal Institut (2019) estimate an abatement cost between 25-45 €/tCO_2e might be feasible. By using hydrogen for the direct reduction of iron ore in combination with electric arc furnaces (DRI-EAF), a technology option exists that is already available on a commercial scale today. While certain modifications are necessary, commercially available DRI-EAF technology can be used with hydrogen (Chevrier, 2020). Given that hydrogen is available at a price that corresponds current natural gas prices, estimated abatement costs below 60 €/tCO_2e are feasible and by using renewable electricity steel production would cause near-zero emission.

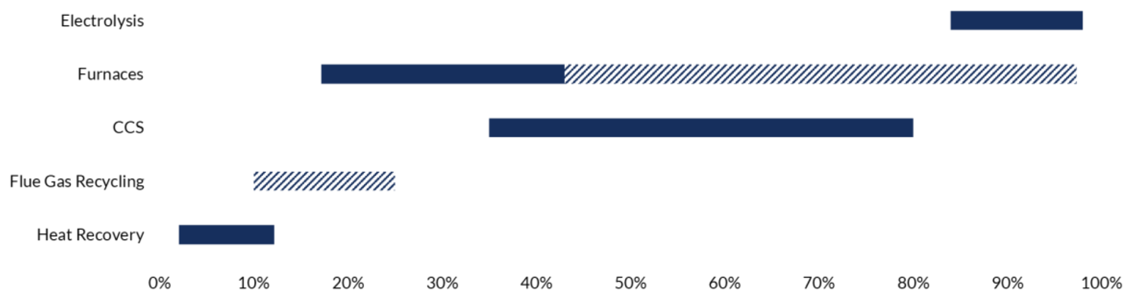

Figure 3-5: Emission reduction potential by abatement options for the primary steel production compared to BAT[52]

[51] This corresponds to the short list of abatement options for the steel sector as published in SWD(2021) 353 final by the European Commission (EC, 2021a)

[52] Adapted from Figure 5 in Gerres et al.,(2019b) and extended (hashed) by DRI-EAF furnaces reduction potential (Chiappinelli et al., 2021) and flue gas recycling without CCS (Gerres et al., 2019d).

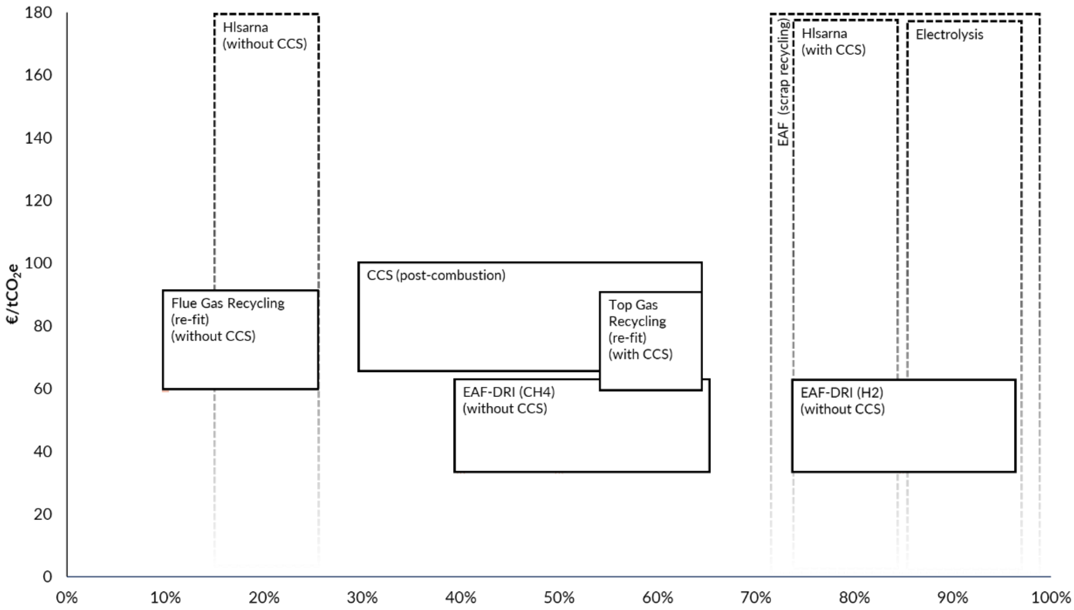

Figure 3-6: Deep decarbonisation costs for options in the iron & steel industry[53]

EAFs have already been used on an industrial scale for decades to remelt scrap and produce secondary recycling steel. Currently, secondary steel makes up about 40.2% of steel production in the EU (World Steel, 2019). The availability of scrap could increase due to extensive building and manufacturing activities in the past. Secondary production might cover the equivalent of the total EU steel production of 2019 by 2050 (Material Economics, 2018). As of today, impurities such a nickel and chrome alloys in end-of-life steel hinder their recyclability. Secondary steel is generally of lower quality than primary steel and cannot replace primary steel in many applications. Enhanced sorting, separation and scrap processing can increase the recycling share but result in higher costs (Allwood et al., 2013). As concluded in Chiappinelli et al. (2021) and displayed in Figure 3-6, higher recycling rates are associated with increased costs.

3.3.2. Aluminium

The direct emission intensity of aluminium production is closely linked to two different process steps, which account for almost all direct emissions. The Bayer process used for alumina production from bauxite requires process temperatures of up to 1000°C, reached by the combustion of natural gas in BAT facilities. Emissions from the electrolysis process originate from the consumption of graphite anodes (Moya et al., 2015). As highlighted in section 2.1.3, its production process makes aluminium the most energy and emission-intensive basic material, causing 4.5 tCO_2 per ton of aluminium of direct and indirect emissions in the current EU electricity mix (Saevarsdottir et al., 2020).[54] These emissions can be avoided by recycling aluminium, up to 98% less energy and more than 90% less emission-intensive than primary production.[55] Especially this extreme difference in energy intensity explains why primary aluminium only accounts for 24.4% of the annual output in the EU, and production is dominated by secondary production. Primary aluminium imports are responsible for about one third on aluminium supply in Europe (EA, 2020). Like steel recycling, a more circular aluminium consumption requires additional sorting, separation, and scrap processing. At the same time, full decarbonisation additionally implies that alternatives to fossil energy carriers are used in

[53] As presented in Gerres et al. (2019b, 2019d) and corresponding emission abatement potential compared to BAT.

[54] Given the high electricity consumption of the electrolysis process, the emission intensity of Aluminium is normally expressed as the sum of direct emissions and indirect electricity related emissions (e.g. (Saevarsdottir et al., 2020)).

[55] *See*, Table 5 in Annex 1.2 of Chiappinelli et al. (2020). Due to impurities the energy and emission intensity is slightly higher for end-of-life recycling than for resmelting of aluminium scrap from manufacturing processes.

resmelting plants. Lately, manufacturers have highlighted the possibility of hydrogen as an alternative energy source, which could also reduce emissions from primary alumina production (Burton and Biesheuvel, 2020).

Alternatives to graphite anodes have been the most mentioned abatement option in publications reviewed for Gerres et al. (2019b).[56] Advanced inert anodes and wettable cathodes were mentioned by various sources (Åhman and Nilsson, 2015; Fleiter et al., 2013; Gellings, 2009; Haydock and Napp, 2013). Rio Tinto and Alcoa, two leading global aluminium producers, have formed a joint venture to bring this technology to an industrial scale by 2024 (ELYSIS, 2020). Though most information about the project is non-disclosed, the partners claim that all direct greenhouse gas emissions could be eliminated while lowering production costs. Inert anodes can be used in existing electrolysers (Alcoa, 2021). The abatement options mentioned above address different emission sources within the production process for primary aluminium making. Therefore, close to 90% of direct and indirect emissions could be reduced without any additional abatement cost, given competitive prices for renewable electricity (section 4.3.2) and hydrogen (section 4.3.4) as an alternative energy source for alumina production (Figure 3-7). Hydrogen or any alternative to provide low emission energy sources such as natural gas with carbon capture could also reduce the remaining emissions related to aluminium recycling.

3.3.3. Cement

Compared to other basic materials, the emission intensity of BAT cement production seems low, causing only 0.67 tCO_2 emissions per ton of cement (section 2.1.2). Nevertheless, the high production and consumption volumes make it the most emission-intensive basic material in the EU (section 2.1.1). A major challenge for reducing these emissions is the high share of CO_2 resulting from the chemical reaction that creates cement clinker from limestone. For cement to clinker ratios of 73.7%, these process-related emissions account for 0.47 tCO_2 per ton of cement (Schorcht et al., 2013). As such, carbon capture is the only option for the deep decarbonisation of the sector to date (Figure 3-8). Various capture alternatives exist. They differ in their trade-off between achievable capture rate, additional process complexity, energy intensity, and resulting abatement costs (Gardarsdottir et al., 2019; Voldsund et al., 2019). Industrial-scale pilot projects for carbon capture technology are planned or already operating in Europe (Agora Energiewende and Wuppertal Institut, 2019). Novel designs proposed in the LEILAC pilot project could reduce emissions by up to 95% without significantly increasing the energy demand (Hills et al., 2017). Only a partial reduction of carbon dioxide-equivalent emissions is feasible by changing the energy carrier since process emissions remain. Potential by biomass use does not exceed 35% (Figure 3-9), whereas biomass costs and competitiveness depend highly on the local availability of biobased resources (sections 2.2.1 & 4.3.5). Cement manufacturers have recently turned to hydrogen usage in first pilot installations (Frangoul, 2021). Disregarding the potential economics of hydrogen production and associated additional costs (section 4.3.4), the suitability of hydrogen for clinker making seems more than questionable.

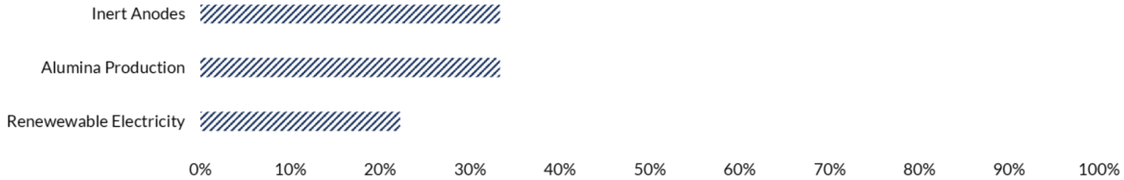

Figure 3-7: Reduction potential by abatement option for the primary aluminium production compared to BAT

[56] Even though it was not included in the final version of Gerres et al. (2019b), the review process included abatement options for the aluminium industry.

As concluded in a recent feasibility study on behalf of the UK government, the flame characteristics of hydrogen make it a suboptimal alternative compared to biomass and other alternative fuel sources (Mineral Products Association et al., 2019). Alternative feedstock can facilitate higher emission reductions if it partially replaces clinker in cement, such as Celitement binders that are in an early development phase (Achternbosch et al., 2016). Its potential and associated costs are highly uncertain, given that limestone-based clinker has been used for centuries due to its material characteristics. Replacing clinker with other alternatives can impact cement's durability, strength, and formability, limiting its applicability to specific use cases.

As discussed in Chiappinelli et al. (2021), requirements concerning material properties also limit the use of cementitious construction waste as an alternative feedstock. Currently, cement recycling that goes beyond its use as a landfill or filling material for new construction sides is negligible (van Lieshout, 2015). Some technology options for recovering clinker components from cement have been explored in recent years, most prominently the SmartCrusher implemented on a pilot scale in 2013 (SmartCrusher, 2013). The mechanical crushing process can be operated with low-emission electricity and near-carbon neutral, though associated abatement costs and economic feasibility remain highly uncertain.

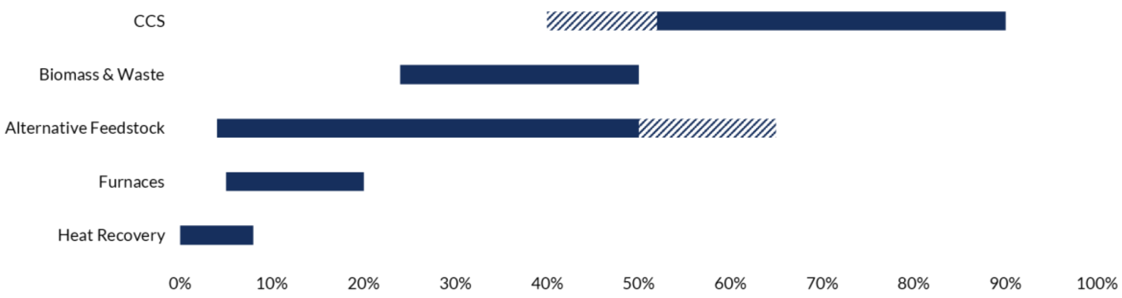

Figure 3-8: Reduction potential by abatement option for the primary cement production compared to BAT[57]

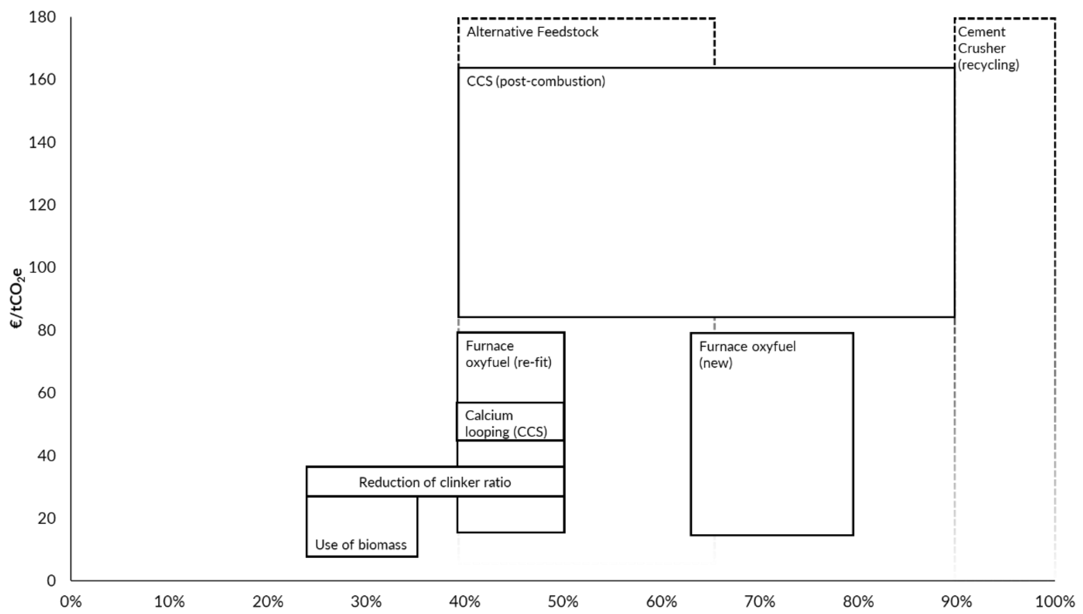

Figure 3-9: Deep decarbonisation costs for options in the cement industry [58]

[57] Adapted from Figure 5 in Gerres et al. (2019b) and extended (hashed) by additional CCS options (Chiappinelli et al., 2021) and updated potential of alternative feedstock (Gerres et al., 2019d).

[58] As presented in Chiappinelli et al. (2021) and Gerres et al. (2019d) and their corresponding emission abatement potential compared to BAT.

3.3.4. (Petro)chemicals

Propylene, ethylene, chlorine, methanol, urea, ammonia, benzene, toluene, other aromatic hydrocarbons and polymers are all products of the chemical industry. At first sight, production processes for making this wide range of basic chemicals are far more complex than in other basic material sectors, potentially complicating the identification of abatement options at the ability to reduce emissions. Additionally, the production of basic chemicals relies entirely on fossil carbon, using either crude oil or natural gas as feedstock for the refining process (see 2.1.2). A closer look at the underlying processes reveals that energy use and point sources of emissions from two main processes account for about 70% of the industry´s emission and energy intensity (DECHEMA, 2017). In the European chemical industry, approximately 60% of direct and indirect emissions are caused by steam cracking and distillation of naphtha (VCI, 2019). BAT naphtha cracking has a net energy consumption of 12.0 GJ/t (IEA, 2018a), almost entirely in the form of heat, and emits 1.14 tCO_2 per ton of product (Ghanta et al., 2014). Producing ammonia and methanol from natural gas is responsible for another 10% of sector emission, which causes 1.9 tCO_2 per ton of product for ammonia production.

Abatement options in the chemical industry encompass alternatives that modify these existing processes and novel technologies that could replace the most energy and emission-intensive process steps. As shown in Gerres et al. (2019b), further process optimisation, such as heat recovery and CHP, can only reduce emissions marginally (Figure 3-10). Due to the purity of CO_2 exhaust streams, carbon capture on existing process steps can reach very high capture rates. Emissions of processes, such as ethylene production, can be reduced to an absolute minimum with an abatement cost of below 100 €/tCO_2e, but would only address about 40% of total process emissions (Figure 3-11). Pure CO_2 streams are required to produce synthetic hydrocarbons in hydrogen-to-x processes so that for proposed novel process designs captured carbon is to be utilised as feedstock (CCU) (Kätelhön et al., 2019). Here, hydrogen-to-x refers to those processes that use low-emission hydrogen as a building block for virgin chemicals. As highlighted in Chiappinelli et al. (2021), Hydrogen-to-Ammonia by the Haber-Bosch process is already the standard production method in the industry. However, natural gas without carbon capture technologies is used to produce the needed hydrogen feedstock. Steam cracker and distillation of fossil hydrocarbon could be replaced by hydrogen-to-x designs, using methanol as an intermediary to obtain olefins or aromatics, as proposed in the Horizon 2020 Carbon4Pur (Carbon4PUR, 2017) or the Carbon2Chem (Deerberg et al., 2018) projects. As shown in Figure 3-11, cost estimates for these technologies remain highly uncertain.

Given that these processes´ energy intensity is considered quantifiable (Chiappinelli et al., 2021), these uncertainties are rooted in the uncertainty of feedstock cost, namely low-emission hydrogen and CO_2. Using captured fossil carbon from other processes, as described above, also raises the question about the life-cycle emissions of these chemical products (Pérez-Fortes et al., 2016). If plastics produced from captured fossil carbon are incinerated at the end of their design life, fossil carbon dioxide-equivalent emissions are only delayed rather than avoided. The case is similar for chemicals used as consumables, such as engine oil. One alternative here is the use of direct air capture (DAC) of atmospheric CO_2. This technology has been tested in pilots but remains relatively expensive compared to other capture options (Fasihi et al., 2019). However, DAC could experience a steep learning and cost reduction curve in the upcoming decades (Tollefson, 2018).

An alternative approach toward emission reduction in the chemical industry is minimising process heat by modifying current distillation and cracking processes. Heat demand can be reduced by using novel catalysts that lower process temperatures. However, its potential is limited and advances achieved over the last decades are minor (Rahimpour et al., 2013). Things look a bit different in the case of novel nano-membranes. This pressure-based technology can fully or partially (hybrid distillation) replace current heat-intensive distillation and cracking operations and has the potential to reduce the energy intensity by 90% (Sholl and Lively, 2016). Membrane technology is also crucial for other activities linked to industrial energy provisions in decarbonising economies, such as separating natural gas and hydrogen mixtures in combined transport infrastructures (Liemberger et al., 2017).

Besides novel production routes for primary production, secondary recycling of (petro)chemicals, most notably plastics, can partially replace fossil-carbon feedstock in the chemical industry. Secondary production can reduce the emissions associated with primary production and avoid about 0.5 tCO_2, which would be released when incinerating end-of-life plastics (Zheng and Suh, 2019). As argued in Chiappinelli et al. (2021), current collection rates of end-of-life plastics in the EU of 30% only results in a 6% quota of recycled material end-use (EC, 2018d) and presents a significant untapped potential for emission reduction. Both mechanical and chemical recycling processes are currently used to recover feedstock for the chemical industry. Still, their commercial application is limited due to the high share of composite materials in recyclate streams. Mechanical recycling by itself is neither energy, emission, nor cost-intensive but requires relative pure recyclate streams and results in thermal-mechanical degradation (Ragaert et al., 2017). Advanced chemical recycling, such as hydrocracking, can dissolve plastic streams to a molecular level but requires an external hydrogen supply (Solis and Silveira, 2020). With reference to the interviews conducted for Chiappinelli et al. (2021), the cost, competitiveness and availability of these options highly depend on how plastic is used in future applications. Separating and sorting activities for waste streams and a potentially increasing complexity of material recovery are the big unknowns for secondary production costs (Figure 3-11).

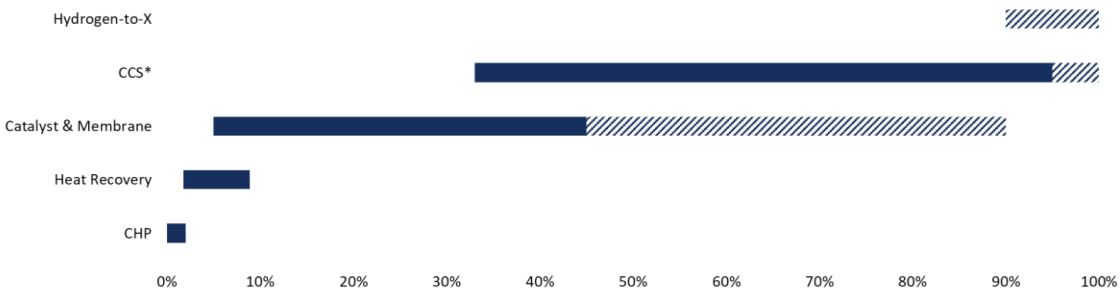

Figure 3-10: Reduction potential by abatement option for the primary (petro)chemicals production compared to BAT[59]

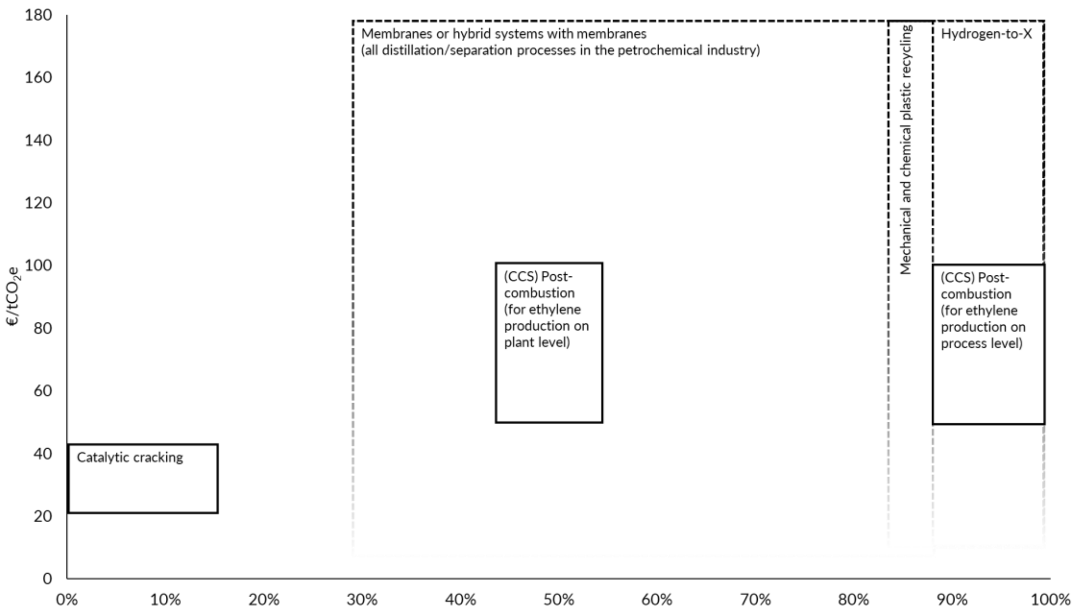

Figure 3-11: Deep decarbonisation costs for options in the (petro)chemical industry[60]

[59] Adapted from Figure 5 in Gerres et al. (2019b) and extended (hashed) to include hydrogen-to-X options presented in Chiappinelli et al. (2021) and updated estimations for process-specific carbon capture* and membrane technology as presented in Gerres et al. (2019d).

[60] As presented in Chiappinelli et al. (2021) and Gerres et al. (2019d) and their corresponding emission abatement potential compared to BAT.

3.3.5. Ceramics & Glass

Similar to cement in their composition, ceramics and glass are basic materials produced from non-metallic minerals. As highlighted in section 2.1.2, both have in common that they are based on silicate minerals. Here, they differ from limestone-based cement in that their raw material does not contain fossil carbon. Fossil-carbon is used as a reduction agent in both industries (section 2.1.2), with thermal transformation processes requiring a similar range of process energy. Heat demand accounts for 2.1 to 3.2 GJ/t (Scalet et al., 2013) in the glass industry and can exceed 7.0 GJ/t for some applications in the ceramic industry.[61] Due to their similarities, abatement options for both sectors are reviewed together, combining and extending the results presented in (Gerres et al., 2019b).

Like any of the other basic material sectors, heat recovery and CHPs can only optimise the use of heat in both industries and offer a limited emission reduction potential. Also, alternative feedstock could reduce the need for carbon-intensive feedstock such as silicate minerals. Using alternative material additives during the process can impact the material characteristics of the final product, which are highly decisive for the material choice in different end-use applications. As such, alternative fuels and furnaces are the two main decarbonisation options in both industries. Both options are highly interlinked, meaning that some alternative fuels require new furnace designs and vice versa. Furnaces account for about 80% of the energy and point emissions in the ceramic and 75-80% in the glass industry (Fleiter et al., 2013), meaning that novel furnace design will not allow for fully decarbonising production processes. As highlighted in (Gerres et al., 2019b), partial electrification might play a role for both industries. According to ASCER, fully electrified large-scale ceramic ovens have been used in Spain but were replaced by gas-fired furnaces for economic reasons.[62] In both industries, process temperatures need to be controlled at a stable level. Therefore, it is not easy to switch between alternative fuels and might require furnace redesigns. Recent projects for ceramics in Spain (ORANGE.BAT) and glass in the UK (HyNet) explore how to adapt current furnace designs for hydrogen combustion (El Independiente, 2021; HyNet, 2020). Another consideration is the use of biomass as bio-based syngas that is relatively similar to currently used natural gas but could potentially reduce the burner efficiency of current installations (Duclos et al., 2014).

The ceramic and glass industries differ regarding recycling potentials. Glass is a relatively homogenous product that facilitates recycling and closed-loop recycling. In 2018 about 76% of all container glass in the EU was recycled, with quotas reaching up to 99% in Northern European countries (FEVE, 2020). Compared to this, ceramics recycling is limited by the different compositions and variety of ceramics in use. Efforts to increase recycling in the ceramics industry focus on other waste streams as alternative feedstock, like glass waste (Andreola et al., 2016). Like cement, tiles and bricks are the main constituent of construction and demolition waste and end up in landfills or filling material for new construction sides (Islam et al., 2019).

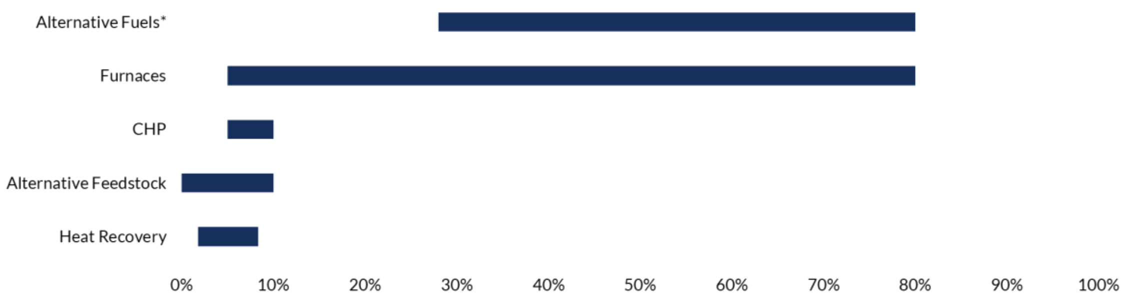

Figure 3-12: Reduction potential by abatement option for the primary ceramics & glass production compared to BAT[63]

[61] Energy intensity in the ceramic industry depends on the final product, e.g. ranging between 1.1 GJ/t for bricks to consumption exceeding 7.0 GJ/t for some tiles and fired refractories ceramics (EC, 2017a)
[62] Interview with representatives from the Spanish ceramic industry association (ASCAR) on 17.11.2020.
[63] Adapted from Figure 5 in Gerres et al.(2019b), reframing the biomass & waste category to alternative fuels* for ceramics.

3.3.6. Pulp & Paper

Any of the previously discussed basic materials are being made from fossil or mineral raw materials. Their consumption depletes natural resources formed over millions of years. In contrast to this, paper is the only principal energy-intensive basic material made primarily from renewable biobased resources.[64] Relative to its weight, paper is one of the most energy-intensive basic materials (section 2.1.3), requiring process heat ranging from 150 to 500 °C (section 2.2.1). Nevertheless, using biobased residuals of the pulp & paper making process as an energy source, paper production´s average fossil emission intensity in the EU is around 0.3 to 0.4 tCO_2/t of paper (Croezen and Korteland, 2010). Applying emission reduction measures discussed for the other basic material sectors, such as CCS, combined with higher shares of low-emission energy carriers, can make paper production carbon negative (Figure 3-13). Pulp & paper plants as biorefineries include the gasification of residual black liquor and other biobased waste streams to produce carbon-neutral biogas (Moshkelani et al., 2013; Pettersson and Harvey, 2012). Here, biobased resources are not necessarily used for low to medium temperature heat for cooking and drying processes which could be easily electrified. As discussed in (Gerres et al., 2019b), the pulp & paper industry accounts for a wide range of energy efficiency potentials, potentially leading to an emission reduction surplus in the pulp & paper industry. Biorefineries could abate the equivalent of 1.6% of current annual transport sector emissions on the European level (Mora and Pavel, 2018). As of 2019, most demonstration and pilot plants and the first large-scale installation have been implemented in North America (Consoli, 2019).

As shown in Figure 3-14, the abatement costs for surplus emission reductions are relatively low compared to those options available for the climate-friendly basic material production of steel, aluminium, cement, chemicals, ceramics, and glass. Reviewed sources state costs below 35 € per ton of avoided fossil CO_2. Implementing measures in the pulp & paper industry could offset hard to abate emissions in other industrial sectors. Having said this, the feasibility of such a biorefinery concept highly depends on locational factors. Carbon capture storage or utilization of biobased pulp & paper emissions requires a close vicinity to storage facilities or other industrial consumers that can process CO_2, such as the chemical industry (section 3.3.4). Pulp & paper factories are traditionally located in areas with forests and not necessarily in industrialised regions. For example, most Spanish paper production facilities are concentrated close to the Pyrenees mountains, with only some facilities near the industrial clusters in Catalunya and the Basque Country (ASPAPEL, 2021). Additionally, the availability of biomass already restricts its use as a fuel source in some European regions.[65] EUROSTAT data for 2018 (EUROSTAT, 2021b) shows that in countries with ample forest resources like Sweden and Portugal, more than 80% of thermal energy demand is met by biomass. However, the Spanish pulp & paper industry relies primarily on natural gas instead of biomass for heat provision.

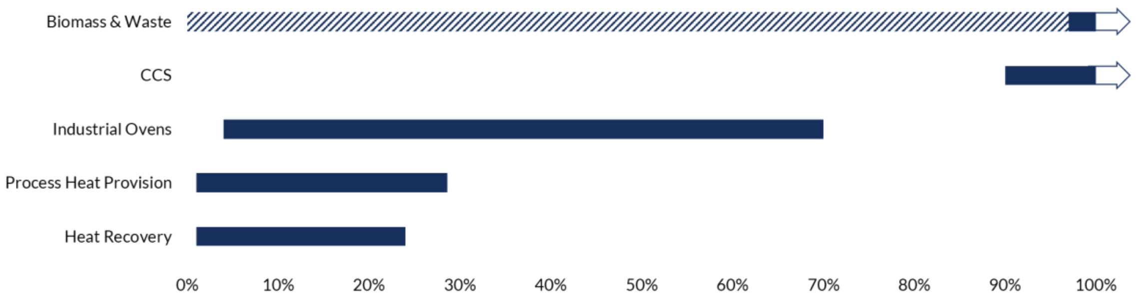

Figure 3-13: Reduction potential by abatement option for the primary paper production compared to BAT[66]

[64] Other biobased raw and basic materials are used, but the pulp & paper production is the only energy-intensive industry with a significantly high share of current EU industrial emissions (section 2.1.1)

[65] *See*, section 4.3.5 for biomass economics.

[66] Adapted from Figure 5 in Gerres et al. (2019b) and extended (hashed) to reflect the potentially gradual increase in biomass and waste used as presented in Chiappinelli et al. (2021).

Paper recycling can be considered a success story. In 2019, the paper industry recollected 71.7% of the paper consumed in the EU, UK, Norway, and Switzerland. The recycling rate increased from 40% in 1990 but has stagnated since 2010 (CEPI, 2020). The production of pulp from recycled paper, referred to as repulping, has its physical limitations since fibres degrade and shorten during the recycling process. As such, wood fibre recycling is always a downcycling process (Ihnat et al., 2020), starting, e.g. with fine paper and ending with card boxes and packaging material. Fibres can only be recycled somewhere between 5 to 7 times (Howard, 2018). Higher recycling rates are feasible, and new technologies can help recover close to 100% of fibres from waste streams (EPRC, 2020). Still, they will always be subject to the physical limits of biobased fibre degradation. Grossmann (2016) highlighted that recycling rates are also subject to the economics of repulping with increasing production costs for high recovery rates that face the competition of virgin pulp. Other than for other basic materials, paper recycling is not necessarily less energy-intensive than virgin pulp production. Consequently, the maximization of circularity might not be optimal for deep decarbonisation scenarios (van Ewijk et al., 2021).

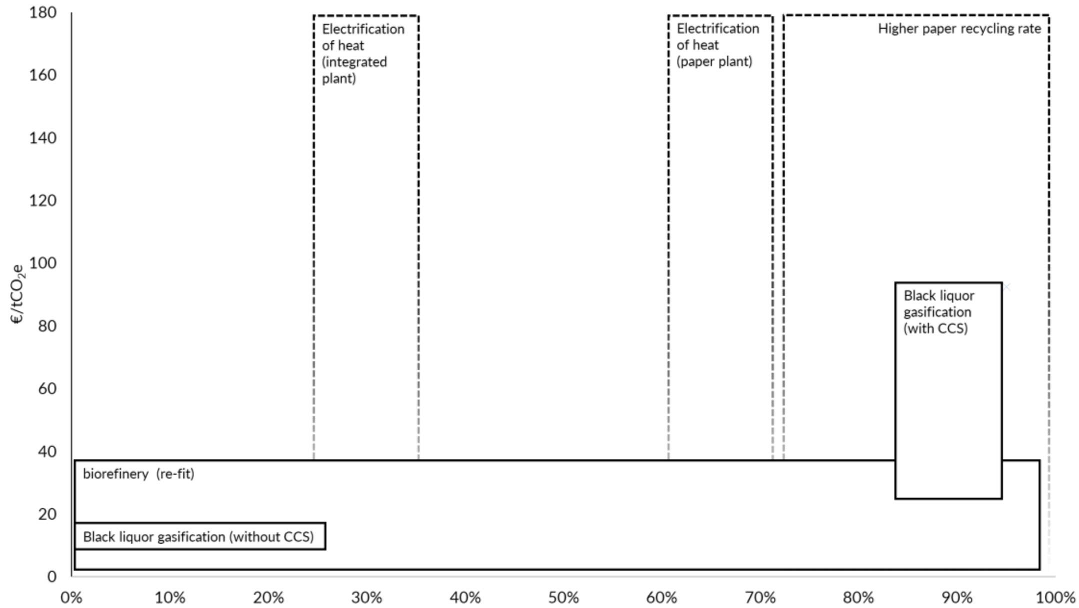

Figure 3-14: Deep decarbonisation costs for options in the pulp & paper industry[67]

[67] As presented in Chiappinelli et al. (2021) and Gerres et al. (2019d) and their corresponding emission abatement potential compared to BAT

3.4. Discussion

The good news is that there are promising abatement options to reduce emissions in the basic material sector drastically, but they will not come along easily. By extending my work for Chiappinelli et al. (2021) and Gerres et al. (2019b, 2019d), I revisit the decarbonisation challenges of the different basic material sectors. This analysis allows for a revaluation of our main findings concerning industrial decarbonisation processes in 2050, as initially stated in Gerres et al. (2019b). While these five main findings still hold, I can refine their message based on the work published in Chiappinelli et al. (2021) and Gerres et al. (2019d) and the additional analysis presented in Chapters and Chapter 3. Based on the three dimensions of the system transition (Figure 2-18: Technology, Economics, Policy), I formulate five propositions about industrial and energy system transition.

Maximised process optimisation by standardised equipment

Further improving existing processes and maximising energy and emission efficiency is a double-edged sword, a solution for some but a dead-end for other industries. As highlighted in section 2.2 and discussed in further detail for the food industry in Gerres et al. (2019b), those industries requiring mainly low and medium temperature process heat below 200°C or energy input for mechanical transformation processes already have climate-friendly technology options commercially available. Further optimising low-temperature heating and auxiliary processes with heat exchangers, heat pumps, or new boiler technology will help these industries gradually reduce their carbon footprint. The high share of standardised energy use cases in these sectors and the number of companies with non-energy or moderately energy-intensive processes with a smaller financial impact of energy consumption on their business operation make the transition less challenging than for energy-intensive businesses.[68] Electronification of the industries is likely given the availability of commercially competitive technologies and decreasing costs for renewable electricity (Atuonwu and Tassou, 2021; Wei et al., 2019). The question about the decarbonisation of these industries is rather focused on how the available energy sources are consumed. In light of the intermittency of wind of solar power generation, demand response might be essential for electricity consumption (Shoreh et al., 2016). Also, it could potentially be of significance if hydrogen obtained from intermittent sources is used in combustion processes.

As shown for all reviewed industries in section 3.3 and further detailed in Gerres et al. (2019b, 2019d), abatement options covering standardised low-temperature process heat provision and heat recovery have also been mentioned in pathways and roadmap publications for basic material production. In none of these energy-intensive industries, such solutions can pave the way for a deep-decarbonisation of the currently used processes. As highlighted for the petrochemical industry (section 3.3.4), process optimisation and energy efficiency measures have been critical in reducing these industries´ emissions and energy consumption over the last decades. Achieving intermediate targets such as for 2030 might be possible by additional optimisation and new technologies to provide low-temperature head demand. However, intensifying optimisation efforts can also trigger a technology lock-in since the design life of renewed optimised equipment can exceed 20 or even 30 years (Erumban, 2008). With reference to Figure 2-3 in section 2.1.3, maximised process optimisation by standardised equipment can only bring the current process design of the energy and emission-intensive basic material sector closer to the theoretical emission minimum. It hinders, rather than fosters, the transition in the energy and emission-intensive basic material towards climate-friendly production processes.

[68] *See*, for example, the results of the representative Energy Efficiency Index of German Industry in (Büttner et al., 2020): only 1.5% of the companies are considered very energy intensive (>10kWh/EUR of revenue) and an additional 9.7% energy intensive (1 - 10kWh/EUR of revenue). The barometer also shows that in case of Germany less energy intensive companies have timelier and more ambitious decarbonisation plans that more energy intensive businesses.

III.I: Conventional processes should be incentivised for industries that can reach deep decarbonisation by gradual optimisation. In contrast, optimisation of current process designs shall not define the transition in the emission-intensive basic materials sector.

Key breakthrough technologies for decarbonisation are required

The logical consequence of the first proposition is that profound technological changes are imperative for climate-friendly basic material production. In section 3.3, I highlight this need for breakthrough technologies for all primary basic material production.[69] With reference to Gerres et al. (2019b), four key technology areas can be identified across all sectors: new designs for the main processes (furnaces, smelters, alternatives to distillation columns,…), carbon-capture, alternative materials and energy sources.[70] While often framed as stand-alone abatement options and in competition with each other, the review of their likely emission abatement potentials highlights the interdependency between all of these technologies for climate-friendly basic material production. Individually, none of these options might enable deep decarbonisation of basic materials. As highlighted in section 2.1, most basic materials have in common that some of their process emissions are not linked to the energy sources used. Motivated by low-carbon energy sources and alternative feedstock use, the redesign of the main process equipment cannot avoid all emissions. However, in none of the industries, carbon-capture technology is expected to reach a near 100% capture efficiency, especially when considering the emissions over the entire process chain. The potential to combine emission abatement options has been highlighted for the aluminium industry (section 3.3.2), which requires different approaches towards emission reduction for each process step from bauxite via alumina to aluminium. The importance of alternative material sources is not to be underestimated since it also encompasses using waste streams and secondary production processes instead of virgin raw material. With some exceptions, namely cement (section 3.3.3) and ceramics (section 3.3.5), industrial-scale recycling is well established. Still, new technologies could improve upcycling capabilities and increase the share of basic material produced from waste streams. The need for combining all four technology areas might be perceived as less urgent for those industries for which one technology option can achieve high emission reductions. Competition between different approaches towards emission abatement is expectable, for example, CCS, DRI-EAF and advanced steel recycling for climate-friendly steel making (section 3.3.1).

III.II: Specific technologies with high emission reduction potential offer alternative pathways to reduce emissions, but deep decarbonisation may imply the joint implementation of various specific technology solutions simultaneously.

Technological readiness and investment cycles of technology adoption

For each basic material sector, references to the latest pilot projects and installations have been made in section 3.3. Many of the proposed deep decarbonisation options are already in an advanced development stage. As confirmed in the interviews with industrial stakeholders conducted for Chiappinelli et al. (2021), many primary and secondary production processes could potentially be implemented in first-of-a-kind industrial installations during the COVID-19 recovery period. Consequently, climate-friendly primary and secondary basic material production could replace 10% to 20% of EU primary production by 2025 (Figure 3-15).

Such installations could be a first step for the industrial transition towards climate-friendly materials, which faces the difficulty to overcome the presence of long-investment and innovation cycles in the industrial sector. These range from 5 years for end-of-pipe solutions, 10-15 years for process and product adjustments, and exceed 20 years for entire production system changes (Vellinga, 1999). As such, we conclude in Gerres et al. (2019b) that sector-wide implementation

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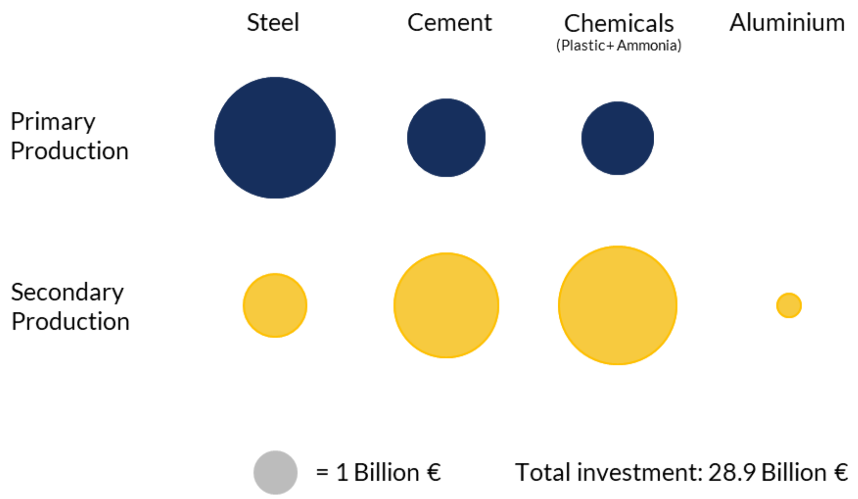
[69] One exception is the pulp & paper industry due to the mainly biogenic emissions in the EU. This cannot be said for paper making on global scale, given that for example the Colombian paper industry consumes only primarily coal to satisfy their energy demand (UPME, 2021).

[70] In (Gerres et al., 2019b) the four technology areas were framed as: novel membrane technology, carbon-neutral steelmaking, alternative clinker materials in the cement industry and CCS. This formulation has been revised to reflect the cross-sectoral relevance of these key-technologies.

of technologies will only happen over a time horizon of 20 years or more after technologies reach market readiness, and could take even longer for equipment with an economic lifetime of 40-50 years in the cement industry (Habert et al., 2010). As proposed in Chiappinelli et al. (2021), first-of-a-kind installations are not necessarily market-ready. Economic feasibility may rely primarily on public support and subsidy schemes.[71] Also, steel companies´ accelerating rate of new announcements for climate-friendly production projects needs to be seen in this context (Vogl et al., 2021). These long-term investment cycles in the basic material sector and the missing market-readiness of technologies to date mean that European decarbonisation targets for 2050 might not be feasible with current technology renewal rates.

Besides transforming existing facilities, the potential ramp-up of secondary production from waste streams would rely on new greenfield installations. Existing recycling facilities are not prepared to handle secondary production levels not seen to date. Nevertheless, building up the recycling sector does not happen overnight and has to be accelerated compared to stable or modestly increasing recycling rates observed over the last decade.[72]

III.III: A transition of the basic materials sector until 2050 can only be achieved if current industrial renewal rates are accelerated compared to current and past investment cycles within the industry.



	Capacity replacements by **new low-emission primary processes** relative to 2018 production		Capacity additions **new low-emission secondary processes** relative to 2018 production	
Steel	10%	of EU primary production to be renewed	10%	of EU primary replaced by secondary production
Cement	10%	of EU primary production retrofitted with CCS	5%	of EU primary replaced by secondary production
Plastics	10%	of EU primary ethylene production renewed	10%	of EU plastic demand additionally met with recycling
Ammonia	20%	of EU primary production retrofitted with CCS		
Aluminium			10%	of EU primary replaced by secondary production

Figure 3-15: Estimation of investment volumes and adoption rates for climate-friendly production until 2025[73]

[71] See, section 5.4.1 for the policies to jump-start the transition of the basic materials sector.
[72] EU waste recycling excluding major mineral waste increased from 54.7% (2010) to 57.3% (2016) (EEA, 2021b)
[73] Assuming that indicated production share will be replaced with new climate-friendly production processes (primary production and recycling, relative to 2018 data) (Chiappinelli et al., 2021).

Uncertainty of emission reduction potential and its cost

Various technology options could significantly reduce emissions across the different basic material sectors, but an exact quantification of these reduction potentials is difficult. Especially concerning technologies in early development, reviewed pathway and roadmap publications and scientific literature seem to lean towards techno-optimism about emission reduction rates. Electrolysis for steel production (section 3.3.1), possible power-to-x processes and the use of next-generation nano-membranes in the chemical industry are very far from market readiness (section 3.3.4). Nevertheless, literature gives a relatively narrow band of high emission reduction potentials. Here, there are certain parallels to the findings by Asayama and Ishii (2017) about the CCS narrative in Japanese media between the years 2006 and 2013 that largely blinds out risks and uncertainties linked to the technology in early development stages.

A high degree of cost uncertainty exists for most abatement options across all basic material sectors reviewed in section 3.3. Besides the imperfect knowledge about technical characteristics of new technologies, the dependency of operational costs on external energy cost positions such as electricity, biomass and hydrogen make abatement cost estimations a problematic task. Especially for secondary production, final abatement costs depend on the complexity of sorting, pre-conditioning and recycling operations necessary to transform heterogeneous waste streams into feedstocks that allow for the production of the required basic materials. With reference to the interviews conducted for Chiappinelli et al. (2021), recycling options were always mentioned together with the availability of adequate waste streams or waste streams that allow for an economically feasible recovery of feedstock for secondary production. Mechanical, chemical, and advanced hydrocracking recycling processes for plastics (section 3.3.4) show that more secondary production is achievable with today´s waste streams but almost always comes at a higher cost. Suppose the way we consume and process basic materials to final products does not change and is not adjusted towards a more recyclable material. In that case, the cost for obtaining higher recovery rates from waste streams may increase exponentially, as displayed indicatively in Figure 3-16.

The level of detail about emission abatement potential and cost estimates is higher for those technologies which have already reached advanced technological readiness levels and have been tested in larger pilots. Costs and abatement potentials are relatively well defined for specific carbon capture and novel furnace technologies in the cement and steel industry. The more details there are available about a particular technology option, the more constraint its reduction potential given its operational characteristics. In contrast, there are no operational experiences about technologies based on conceptual design studies or technologies have been tested in a highly controlled laboratory environment, such as steel productions via electrolysis. Assumptions about their operational characteristics often seem to be over-optimistic.

In Gerres et al. (2019b), we also showed the high uncertainties regarding the abatement potential for standardised technologies and those options with very high maturity. There is missing knowledge about how these technologies have been implemented in the industrial park. Different reference points for emission and energy efficiency improvements have the consequence that cost and potential of CHP, heat recovery, process heat provision, biomass utilisation, and BAT furnace design differ significantly across available academic and non-academic sources.

III.IV: Underlying assumptions for future industrial transition scenarios need to correctly reflect the cost and emission reduction potential of market-ready and near market-ready technologies while balancing the uncertainties and prospects of future technology options.

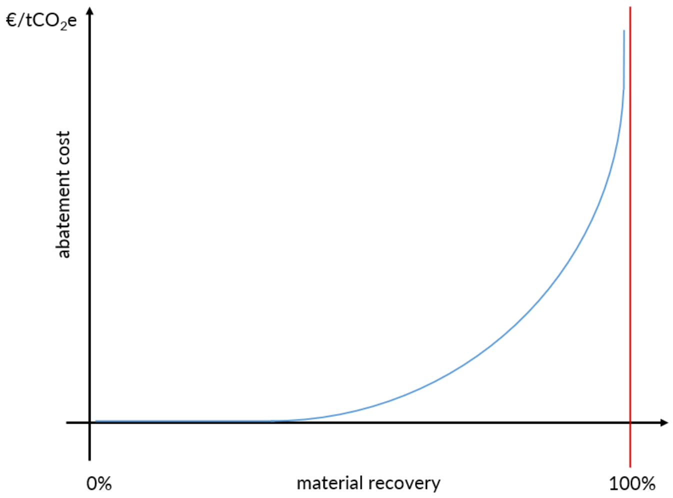


Figure 3-16: Indicative cost curve for increasing recycling rates without changing material use

Cross-sectoral implications of innovations

Each specific basic material sector has its own set of solutions for achieving decarbonisation. These solutions are often presented independently from their cross-sectoral implications, determining each abatement option´s emission reduction and cost potential. Cross-sectoral implications exist for all elements relying on developing physical, economic, and organisational systems beyond the scope of a particular basic material industry. As highlighted in Gerres et al. (2019b), abatement options in many basic material sectors require the emergence of external infrastructure. Captured carbon in the steel, cement, chemical and paper industry needs to be transported and stored or requires new interconnections with industrial consumers that could use CO_2 as feedstock in their production processes. The underlying premises of electrification options for non-energy intensive industries (section 3.3), the aluminium and steel industry, are the abundant availability of low-emission electricity and the required infrastructure to deliver such additional demand. For multiple technologies that allow for a fuel switch to hydrogen or biomass, I have pointed out that the availability and cost of these alternative energy sources are essential for both emission abatement and economic feasibility across all reviewed basic material sectors.

While all of the aforementioned cross-sectoral implications mainly address deep decarbonisation options, it is important to highlight that the same dependence on external systems occurs for optimised heat recovery and heat provision options. Potentially recoverable process heat would only be of use if there were a demand to be satisfied. Examples of such cross-sectoral projects are the use of off-heat from a steel plant to fuel local district heating networks in Salzgitter, Germany (Schaper, 2017), and the shared heat network infrastructure in the Tarragona industrial cluster in Spain (ChemicalPark.eu, 2020). Such infrastructure-based clusterisation can benefit a concentrated regional transition encompassing the required changes to energy and feedstock value chains and requires a coordinated effort of all involved actors within the cluster (van der Reijden et al., 2021). Vice versa, the dependence on cross-sectoral coordination and infrastructure investments might pose a challenge to those basic material industries traditionally not organised in clusters. Besides the pulp & paper industry, concentrated near forest resources (section 3.3.6), companies associated with the Spanish cement association are evenly distributed across the entire country and not necessarily associated with major industrial clusters (Figure 3-17).

Cross-sectoral implications should not be reduced to physical infrastructure. However, enhanced recycling processes need to cover the entire value chain to improve the recyclability of basic materials. I highlighted in section 3.3 that the increasing importance of secondary production for all reviewed basic material sectors depends on the availability of waste streams. The recycling industry has little influence on how basic materials are transformed and used in final products and consumer goods. The economic feasibility depends on organisational changes over the entire life cycle of basic materials, foremost whether the manufacturing industry adapts recycling-friendly product designs.

III.V proposition: The transition of a particular basic material industry and its emission reductions are subject to the cross-sectoral interdependencies with other basic material sectors, the entire value-chain of basic material use and the energy system.

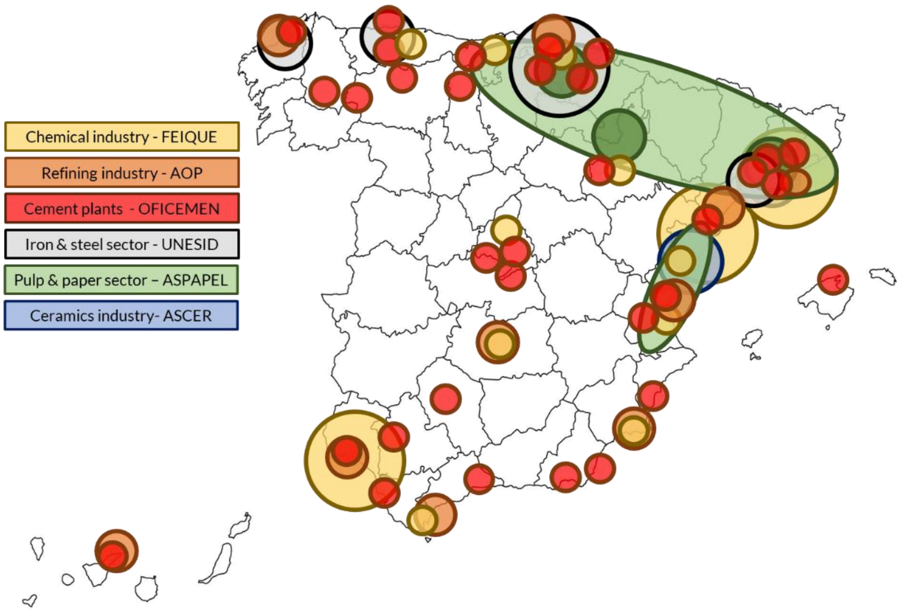


Figure 3-17: Approximate locational distribution of facilities associated with the Spanish basic material sector[74]

[74] Mapping based on data available from the national industrial associations FEIQUE in Spain (data from CEFIC (2020b), AOP (2019), OFICEMEN (2021), UNESID (2021), ASPAPEL (2021) and ASCER (2021).

3.5. Conclusions

Research findings, public and private sector publications and the news are full of buzzwords that announce “efficient”, “green”, “low-emission”, “circular”, or “climate-friendly” technology options for industrial applications. The first part of this thesis project aims to provide an overview of these technology options, understanding what, where, and how different abatement options can change basic material production. Based on a structured review, I presented and applied a framework to classify and differentiate emission abatement areas in the industrial sector in section 3.2. This framework allowed me to identify, characterise and quantify potential abatement options for the most emission-intensive basic materials industries, covering primary and secondary production processes in section 3.3. This work is no holy grail for industrial decarbonisation across the reviewed industries, and it is also not novel in discussing technology options and their potential emission reductions and costs. But what I do provide with the research work published in Chiappinelli et al. (2021) and Gerres et al. (2019b, 2019d) and the additional analysis presented in this chapter is an in-depth understanding of the technological and cross-sectoral implications and consequences of transforming the basic material industry until 2050. These have been formulated as five propositions in section 3.4:

III.I: Conventional processes should be incentivised for industries that can reach deep decarbonisation by gradual optimisation. In contrast, optimisation of current process designs shall not define the transition in the emission-intensive basic materials sector.

III.II: Specific technologies with high emission reduction potential offer alternative pathways to reduce emissions, but deep decarbonisation may imply the joint implementation of various specific technology solutions simultaneously.

III.III A transition of the basic materials sector until 2050 can only be achieved if current industrial renewal rates are accelerated compared to current and past investment cycles within the industry.

III.IV: Underlying assumptions for future industrial transition scenarios need to correctly reflect the cost and emission reduction potential of market-ready and near market-ready technologies while balancing the uncertainties and prospects of future technology options.

III.V: The transition of a particular basic material industry and its emission reductions are subject to the cross-sectoral interdependencies with other basic material sectors, the entire value-chain of basic material use and the energy system.

These propositions summarise the results of my research efforts to address the first thesis sub-objective of this thesis.

I. Evaluate the principal emission abatement options for the basic material sector, their cross-sector applicability and decarbonisation potential for the European industrial sector.

The strong reliance on the energy system to make emission abatement technologies economically feasible for the basic material sector motivates the work presented in Chapter 4.

Chapter 4

Implications from the energy system transition

Journal publications and reports used for this chapter:[75]

Gerres, T., Chaves, J.P., Martín, F., Rivier, M., Cossent, R., Sánchez, Á., Gómez, T., 2019. Rethinking the electricity market design: Remuneration mechanisms to reach high RES shares. Results from a Spanish case study. Energy Policy. 129, 1320-1330. 10.1016/j.enpol.2019.03.034

Gerres, T., Chaves, J.P., Martín, F., Rivier, M., Gómez, T.,2019. The Role of Nuclear Power Plants in Electricity Systems with High RES Share. *2019 IEEE Milan PowerTech*, Milan, Italy. 10.1109/PTC.2019.8810545

Rivier, M., Gómez, T., Chaves, J.P., Cossent, R., Sánchez, Á., Martin, F., Gerres, T., 2018. Análisis de escenarios futuros para el sector eléctrico en España para el período 2025-2050. IIT, UP Comillas.

Gómez, T., Rivier, M., Chaves, J.P., Martín, F., Gerres T., 2018. Señales de precio a la inversión en un mercado eléctrico con elevada penetración de renovables. Papeles de Energía.

[75] Analysis presented about the hydrogen economy is partially based on non-disclosed research done for Enagás S.A. and the Colombian government on behalf of the Interamerican Development Bank (IDB) to develop the national Colombian hydrogen strategy (Minenergía, 2021).

By using alternative process designs, we change the way industry consumes energy. Replacing old equipment with new ones almost implicitly means that energy consumption is changing. These changes might be minor to insignificant if we talk about replacing a broken lightbulb on a shop floor. However, changing the main processes in the energy-intensive basic material industries to climate-friendly alternative designs can significantly impact the consumption patterns of the entire industrial sector. Switching from fossil fuels to hydrogen, electricity, or biobased resources means that the demand for fossil energy carriers diminishes while the need for low-emission alternatives increases. On the other hand, carbon capture technologies might not represent a move away from fossil energy sources but require significantly more energy to capture and process fossil CO_2. An industry-wide transition can impact the markets for the different low-emission alternatives. Increasing demand for specific energy carriers can lead to scarcity and higher prices, changing the operational costs and economics of alternative low emission process designs. This chapter explores such interlinkages with the different energy markets by identifying the role of the energy system and market design choices for the transition of the basic materials sector.

Given the importance of the electricity system for two primary low-emission energy sources, namely direct electrification and hydrogen consumption, the work presented in this chapter foremost focuses on the results published in Gerres et al. (2019a, 2019b), Gómez et al. (2018) and Rivier et al. (2018) about operations and investments in the future Spanish electricity market. After a summary of the methods used in section 4.1, the first part of this chapter (section 4.2) introduces a new case study that takes the findings from the previous publications one step further. By identifying market design challenges for decarbonising electricity markets with particular emphasis on the role of RES support schemes and carbon pricing, the analysis outlines the framework conditions for the direct or indirect electrification of industrial processes. The second part of this chapter (section 4.3) contrasts these findings for the electricity market with the drivers that may determine the future cost and availability of the other three main energy options for the industry. The use of hydrogen, biomass, and fossil fuels with or without carbon capture and storage has different implications for future energy markets that mirror electricity market design challenges (section 4.4). Analysing the interplay of the energy system evolution and industrial transformation, I summarise the results presented in this chapter and address thesis sub-objective II in section in section 4.5:

Analyse the interplay of the energy system evolution and industrial transformation, emphasising the role of the electricity markets and a potential hydrogen economy.

4.1. Methods

This chapter encompasses two distinct parts that build upon each other. The following section 4.2 presents a detailed analysis of the design challenges in decarbonising electricity markets. This work is a stand-alone contribution with an introduction, literature review and knowledge gap analysis that includes a detailed description of the methods in subsection 4.2.5. I obtained the Spanish case study results with the SPLODER model presented in Martín-Martínez et al. (2017) and run by Francisco Martín-Martínez. The analysis is centred around the three electricity system objectives of affordability, adequacy, and emission avoidance. It encompasses a detailed discussion of carbon pricing mechanisms and their role as a policy mechanism. Based on the results, I identify five main challenges for the future electricity market design, formulated as propositions.

I use the insights obtained by this analysis in the second part of this chapter (section 4.3) for a qualitative review of the most relevant energy carriers for the different technology alternatives discussed in Chapter 3. First, I analyse each energy carrier and its ability to meet affordably, adequacy and emission avoidance objectives for industrial applications. Besides identifying corresponding market design implications, I evaluate the significances of these implications for industrial applications. Even though these system objectives have first been identified in the context of electricity system transition in section 4.2, I argue that these objectives and arising market design challenges apply to all energy carriers.

In the discussion section 4.4, I reflect upon my observations about the energy system transition and propose that the main design challenges identified for electricity markets in section 4.2 are also relevant for the other energy markets. I use my propositions about the energy system transformation in Chapter 6 to identify the modelling gap to be addressed with the TRANSid model.

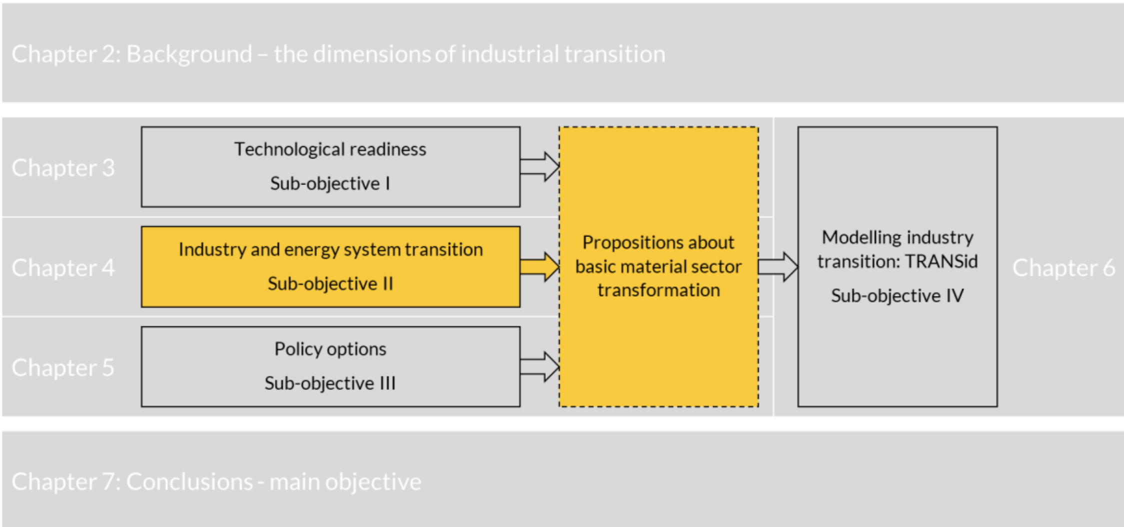


Figure 4-1: Chapter 4 as part of the thesis structure

4.2. Guiding the transition: design challenges in decarbonising electricity markets

The analysis of the model results presented in this chapter has been a collaborative effort together with Jose-Pablo Chaves, Francisco Martín, Michel Rivier, Álvaro Sánchez, and Tomás Gómez. A modified version of this chapter is currently under review to be published in a forthcoming book about the economics of renewable energy.

4.2.1. Introduction

Intermittent renewable energy sources (RES) are set to transform the way we generate and consume electricity. Today, solar photovoltaic (PV) plants are the cheapest option to obtain electric energy almost everywhere worldwide, closely followed by wind power plants installed at locations with good wind yields. RES generation provides cheap electricity, but it does so without relying on the emission-intensive combustion of fossil fuels. The low cost of RES makes the switch from carbon-based to RES-based electricity generation one of the cornerstones of the transition towards a low-emission society aligned with the objectives of the Paris Agreement. Looking at the global boom of RES capacity additions, one might consider that the full decarbonisation of our electricity supply is only a question of time. However, such a view overlooks the difficulty of matching intermittent RES generation with fluctuating and limited controllable electricity demand. Electrification of industrial processes and other applications, energy efficiency improvements, and demand-side response activation may significantly increase the share of controllable consumption. As such, it can improve the system´s capabilities to respond to generation intermittency. Neither a fully flexible demand-side nor an electricity system with intermittent RES covering demand peaks of a highly inflexible consumption are likely. In the latter case, RES overcapacities could result in unutilised generation, putting the cost recovery for such RES would be in jeopardy. As such, intermittent RES by itself is inadequate to cover the demand within our national electricity systems.

In the following, we address how to design electricity markets that enable a high share of RES generation at the lowest total system cost while providing adequate generation and storage capacity to meet the demand. Based on the European electricity market design evolution, we argue that electricity systems must meet at least the three system objectives of **affordable** electricity costs, **adequacy** to ensure supply security and **emission avoidance** aligned with long-term decarbonisation targets (section 4.2.2). We then briefly recap the energy-only market design principles and highlight why, in practice, energy-only markets struggle to ensure capacity adequacy and emission avoidance (section 4.2.3). In subsection 4.2.4, we discuss the role of different energy system policies[76] and underline the importance to align policies with the system objectives. Based on this analysis, we introduce a Spanish case study (section 4.2.5), for which we explore the interplay of different policies, namely capacity mechanisms, emission pricing[77], RES quota requirements and energy efficiency policies and their role in meeting changing system objectives (section 4.2.6). By reflecting on these results, we name design challenges that must be addressed to avoid undesirable market outcomes caused by policies not stringently aligned with the system objectives (section 4.2.7). Policies addressing each of the system objectives need to be well-coordinated, balanced, and technology-neutral to guide the electricity system towards decarbonisation.

This chapter focuses primarily on generation and storage technologies that are available at the system level. Nevertheless, design challenges and insights about alternative design options, backed by the model results for the Spanish case study, equally apply to the economics of other demand-side options and future sources for system flexibility.

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[76] In scope of this chapter the term policy refers to any regulatory change that has a potential effect on the price formation on the electricity market (section 4.2.4).

[77] In the following chapters, “emission pricing” is used to refer to CO_2e emission pricing mechanisms.

4.2.2. Electricity system objectives

Over the past decades, the story of electricity systems has been closely linked to the emergence of electricity markets. In the European Union, electricity systems had been state-controlled natural monopolies, which entered a phase of market liberalisation from 1996 onwards. In its initial design, the internal EU electricity market aimed to ensure the movement of goods, services, and capital by reinforcing competitiveness and establishing price transparency (Directive 96/92/EC). Therefore, market liberalisation was driven by the objective to reduce prices for end-consumers by allowing for more competition between market participants.

Over time, the EU-wide implementation of the internal market progressed, and all member states currently have operating electricity markets in place. However, it has been a contentious issue whether these electricity markets provide adequate investment incentives for new generation capacity. In Europe, a significant share of thermal generation capacity in use was installed before market liberalisation (Farfan and Breyer, 2017), and RES generation added in the 2000s was subject to direct subsidies and public interventions. Market-driven large-scale investments in new generation have mainly been directed towards Combined Cycle Gas Turbine (CCGT) technology. However, by 2012, nearly 51 GW of CCGT capacity had been mothballed and are considered by some authors as stranded assets (Caldecott and McDaniels, 2014). To incentivise sufficient investments and ensure that adequate generation capacity can meet the future energy demand, the electricity market design was revised by establishing the system objective to safeguard supply adequacy (Directive 2005/89/EC). Many EU markets designs encompass firm capacity mechanisms to guarantee that this system objective is met (Söder et al., 2020).

Latest since the European Green Deal (EC, 2019a), electricity systems have a third main objective, the full decarbonisation of electricity supply over the following decades. Given the global consensus to significantly reduce emissions until mid-century expressed by the 2016 Paris Agreement, this objective is not explicitly inherent to the European electricity system and applies to any human activity resulting in the emission of fossil-based CO_2. Nevertheless, due to the availability and cost competitiveness of RES and the importance of electrification options for decarbonising other economic activities, reducing emissions in the electricity sector as quickly as possible has become a vital objective of the European policy agenda (EC, 2020a).

Guiding the transition towards a low carbon economy, the EU adopted several other policies, directly and indirectly, impacting the electricity system. Above all, this is reflected in the EU Clean Energy Package[78], which targets energy efficiency and aims for global leadership in renewable technologies. Additionally, the EU aims for a 32% share of renewable energy in the final gross consumption by 2030, [79] which translates into, e.g. 74% renewable electricity generation in the case of Spain (MITECO, 2020a). Since all these policies support the overarching system objective of emission avoidance, we consider them as mere policies rather than additional main objectives.

Additionally to the objectives mentioned above, the European Union aims for a fair transition, which must be socially acceptable for all consumers (EC, 2019b), without discriminating or favouring any technology or consumer. However, meeting this objective is to be achieved by consumer empowerment and protection regarding market access and tariff design.[80] So far, the impact of related end-consumer policies on the electricity system is secondary since small consumers participation is still limited. However, their importance is expected to increase in the coming decades. In this chapter, the demand side plays a minor role. The need for additional flexibility resources such as batteries can be seen as representative of any alternative system resource that can provide demand response.

[78] Encompasses Directive (EU) 2018/2001, Directive (EU) 2018/844, Directive (EU) 2018/2002, Regulation (EU) 2018/1999, Regulation (EU) 2019/943, Directive (EU) 2019/944, Regulation (EU) 2019/941, Regulation (EU) 2019/942

[79] *See*, Directive (EU) 2018/2001

[80] *See*, Directive (EU) 2019/944

4.2.3. Electricity market design

The long-term electricity system development towards the main system objectives is closely linked to the electricity market design. Disregarding market imperfections and external market design revisions, new generation and storage capacity investments are triggered by market signals that make such additional capacity investments financially attractive to existing or new market participants. In the following, we review the design aspects of electricity markets and reflect on their capabilities to ensure that system objectives are met. Departing from the principles of energy-only market design, we illustrate how electricity markets require additional market mechanisms to ensure investments for adequate capacity that can avoid emissions at the lowest cost.

Energy-only markets

Building upon the principle that voluntary interactions between the market participants (offering and purchasing electricity) provide sufficient incentives for new investments, energy-only markets have been considered the ideal market design by many. Administrative price caps or other design elements shall not restrict market prices. As such, energy-only markets are not limited to centralised spot markets but cover all transactions from long-term bilateral contracting and day-ahead markets to near real-time trading. Authors arguing for the practicability of energy-only markets acknowledge that remuneration mechanisms for system resources such as operating reserves are required but can be designed to support operating and investment decisions in response to market forces (Hogan, 2005). Following this definition, energy-only markets could be implemented to meet the three main objectives by adequately internalising the cost of environmental externalities.

The practicalities of ensuring capacity adequacy

Without questioning that energy-only markets might live up to the challenge, the practicality of energy-only markets to ensure adequate capacity to meet future demand at any given point in time is uncertain. Even electricity systems considered energy-only markets do not fully comply with energy-market principles, such as the Australian National Electricity Market (NEM). In operation since 1999, NEM is often referred to as a successful model of an energy-only market design (ADIB et al., 2008). The NEM has experienced multiple market design revisions to encourage investment in RES (Byrnes et al., 2013) and gas-fired electricity generation (Scott, 2013). Some authors argue that the Australian energy-only market design could prevail in a fully decarbonised system but acknowledge that this would require a favourable functioning of a bilateral contract and derivative market. These markets would ensure that very high electricity market price caps result in elevated penalty clauses in bilateral hedging agreements, which functions similarly to a capacity mechanism (Riesz and MacGill, 2013). However, any market outcome in such an energy-only market that jeopardises capacity adequacy would require market design revisions. This is also the case for other electricity markets without capacity remuneration mechanisms to meet long-term reliability criteria, such as in Texas and the Netherlands (Söder et al., 2020).

For most system interventions to ensure capacity adequacy, the system operator needs to assess the firm capacity of different generation technologies. It is challenging to evaluate volatile RES contribution to system reliability (Mastropietro et al., 2019)[81], and there is no standard approach to determine the firm capacity factor of batteries, storage solutions or demand response (Byers et al., 2018). Based on the applied capacity factors (a score set by the system operator ex-ante to evaluate the contribution of specific technologies to the supply security), investment and operation of certain generation technologies can be more favourable than others and thereby influence the energy-only market outcome. Depending on the firm capacity contribution of installed RES, the need for additional mechanisms to ensure capacity adequacy changes. Here, the firm capacity contribution of installed RES and the potential contribution of batteries also depend on seasonal

[81] Mastropietro et al., (2019) argue that forward-looking methodologies to forecast RES contribution are needed for an adequate capacity remuneration in systems with high RES share.

energy long-term storage to contribute to the capacity adequacy compared to short-term storage offered by batteries (Schill and Zerrahn, 2018).

The difficulty of incentivising investments

Ideally, the day-to-day operation of energy-only markets provides the right long-term investment incentives for new generation capacity. Concerning investment signals for intermittent RES, the validity of this assumption has been widely discussed in the literature. Intermittent RES has near-zero operational costs, meaning that their elevated contribution to the generation mix can reduce hourly market prices when producing, thereby negatively impacting their long-term cost recovery (Hirth, 2013). In the past, high costs and technological immaturity made additional investment incentives necessary to foster RES investments. In recent years, the ongoing cost decline of wind and solar capacity and their relatively low share of generation has resulted in market conditions favouring investment in these technologies without further remuneration mechanisms (IRENA, 2019). With higher shares of RES capacity installed, resulting energy-only market prices could be so low at instances of RES generation that market design revisions would be required to trigger additional variable RES investments if elevated RES generation targets are to be met (Keay and Robinson, 2019). The relevance of such RES incentives for the economics of new RES installations increases, given that higher RES targets are desired (Djørup et al., 2018).

Aiming for electricity system decarbonisation might require market design revisions to increase the renewable generation´s share further and influence the energy-only market´s ability to ensure capacity adequacy. If electricity demand was indeed highly price-sensitive, additional capacity mechanisms could be avoided. In practice, though, capacity payments may still be required since RES generation is not sufficiently correlated with energy demand (Brown, 2018). As shown by Khan et al. (2018), demand response and electrical energy storage can reduce the importance of additional capacity mechanisms. However, they also state that a robust business case for storage technologies may rely on capacity markets to remunerate their contribution to the system adequacy. This need for capacity markets to achieve elevated RES shares at minimum cost is also highlighted in studies for the Israeli (Weiss et al., 2017) and Spanish (Gerres et al., 2019a) electricity systems. In both cases, investments in storage technologies are incentivised by capacity mechanisms to reduce system costs. The need for additional capacity remuneration is not identified by most publications modelling pathways towards a 100% RES share of generation. Studies, presenting scenarios for Denmark (Djørup et al., 2018) or the entire European electricity market (Gerbaulet et al., 2019) forecast extensive investments in storage capacities without explicitly discussing underlying capacity mechanisms. However, it is noteworthy that the model constraints implemented for firm capacity (Gerbaulet et al., 2019) strictly impose that the installed generation capacity serves all demand. This establishes that market clearance dynamics are highly sensitive towards ensuring resource adequacy.[82]

Capacity markets may assign the cost of generation adequacy in electricity markets with elevated RES shares more adequately. As shown by Chattopadhyay and Alpcan (2016) for a case study of the NEM, capacity markets can even result in lower system costs than energy-only market approaches, given that additional RES investments are not subject to incentivised RES quota targets. It demonstrates that energy-only markets may require additional capacity mechanisms to incentivise investments to comply with affordability and adequacy objectives.

The ineffectiveness of reducing emissions

As their name indicates, energy-only markets establish the exchange of electricity between the supply and demand side by energy-based pricing signals. Per se, the environmental damages of emissions related to electricity generation are not reflected in the market price. Given their intermittent nature, relying on RES generation may not be entirely consistent with emission reduction objectives (Möst and Fichtner, 2010). As such, additional investment incentives for other carbon-neutral technologies are needed. Demand response, batteries, nuclear generation,

[82] The shadow cost associated to strictly match demand and supply could be studied by reviewing the marginal costs associated to meeting this constraint.

cogeneration and carbon capture technologies can reduce the emission intensity of electricity generation (Williams et al., 2012). Based on their elevated installation and operational costs,[83] investments in these technologies in energy-only markets are questionable. Additional emission pricing might be needed to reach the targeted level of emission avoidance.[84] All measures directly or indirectly pricing emissions are market design revisions to an energy-only electricity market since the value of a non-tangible externality influences the market outcome.

For a future electricity system that ensures affordable electricity prices, provides adequate investment incentives to ensure supply security and complies with emission avoidance objectives, an energy-only market design might not be the ideal fit. Safeguarding that system objectives are being met, energy markets need to be accompanied by capacity mechanisms and measures that value the emission reduction of different technology solutions.

4.2.4. How policies affect the electricity market

Policy or policy design are ambivalent terms that can cover a wide range of concepts. Since this chapter focuses on electricity market design, we define policies as any regulatory change that potentially affects the price formation on the electricity market and results in different market prices compared to the energy-only market outcome. In the following, we present different current European policies that directly or indirectly aim to reach the main system objectives. The list of policies is non-exhaustive but highlights how their effects can correlate when jointly implemented. The potentially conflicting nature of the main system objectives and policies has been referred to as the energy trilemma (Newbery, 2016) or the energy policy paradox (Blazquez et al., 2018). While this issue has been identified in the literature, resulting design challenges for decarbonising electricity markets have not been explored.

Capacity mechanisms

Based on the missing energy-market incentives for installing adequate generation capacity, different market mechanisms have been discussed in the literature and implemented within the different national jurisdictions. Batlle and Rodilla (2010) reviewed international practices to ensure the long-term security of supply, highlighting the difficulty of designing efficient capacity mechanisms in practice and identifying relevant design criteria. Approaching the design of capacity mechanisms with a more conceptual approach, De Vries and Heijnen (2008) studied how capacity payments, operating reserve pricing, capacity obligations and reliability options can ensure generation adequacy. All capacity mechanisms improve the stability of the market, resulting in less electricity price volatility. However, operating reserves were the least appropriate option for reducing price volatility. Here, ex-ante capacity payments were identified as a better solution to ensure stable revenue streams for generators. Their disadvantage is that they cannot be adjusted if less capacity is needed than contracted in advance. Capacity obligations imposed on load-serving entities and reliability contracts provide generation adequacy while outperforming the other mechanisms in reducing price volatility.[85] Reliability contracts can be seen as a financial variant of capacity obligations that renumerates capacity provision ex-ante while heavily penalising non-delivery (Vazquez et al., 2002).

Regardless of their design, the different options for capacity mechanisms have in common that capacity requirements are defined ex-ante. Such capacity mechanisms based on the predetermined contribution to the generation adequacy of different technologies are common in European electricity markets. Referring to the practicalities of ensuring capacity adequacy mentioned above, the increasing shares of intermittent RES generation and uncertainty about the contribution of different technologies to the system´s peak demand, the suitability of this approach has been put

[83] *See*, levelized cost estimates for the period between 2021 and 2040 (EIA, 2021a)

[84] In the European Union, the electricity system is part of the EU ETS. Emission pricing can therefore either be the result of higher EU ETS emission allowance prices or an additional emission tax to increase the emission reduction incentive for generation, storage and demand side options (section 4.2.4).

[85] Note that in de Vries and Heijnen (2008) capacity obligations and reliability contracts are modelled in the same way.

in question (Söder et al., 2020).[86] Today, capacity mechanisms are the only alternative to scarcity pricing on energy only-markets to incentivise resource adequacy on European markets. Other risk hedging products are not in use (Hawker et al., 2017).

Direct and indirect emission pricing

Various European countries have introduced emission-based taxation policies (World Bank, 2021). With the EU ETS, there is a common European market for emissions allowance trading from non-diffuse sectors, including the electricity system.[87] Due to ample free allowance and missing long-term price signals, the effectiveness and suitability of the EU ETS to trigger industrial emission reduction are doubtful. Additional policies might be needed to support industrial decarbonisation (Chiappinelli et al., 2021). Nevertheless, increasing prices for emission allowances are considered the main driver behind the rapid decline of coal-based power generation within the EU (Simon, 2019). As such, emission pricing policies already have a significant effect on energy market dynamics.

Without market imperfections, different policies to reduce emissions, such as subsidies or mentioned taxes and tradable allowances, can provide adequate pricing signals to comply with emission avoidance objectives (Stern, 2007). Though, the design of subsidies or taxes to support RES generation is challenging. Over the last decades, the scientific discourse has therefore been directed towards comparing the secondary benefits of popular RES subsidy schemes. Benefits include spill-over learning effects (Batlle et al., 2012), security of supply (Linares et al., 2008), compensatory effects on producer rents (Hirth and Ueckerdt, 2013) and macroeconomic benefits for the domestic economy (del Río et al., 2013). While the argument of technology leadership remains one of the principal pillars of the European Green Deal (EC, 2019a), other secondary benefits focus on the near term impact of RES subsidies. They were formulated against the background of a less aggressive decarbonisation policy that the EU had pursued until 2018.[88] This suggests that imperfect RES subsidies only indirectly reduce emissions, and their alignment with emission avoidance objectives cannot be taken as a given. Understanding the impact of policies that aim for elevated RES quotas in deep decarbonisation scenarios has received little attention in the literature. More stringed emission avoidance objectives and incentivised additional RES investments call for mechanisms to ensure capacity adequacy (Brown, 2018). This need for additional mechanisms is also reflected in the results of various national energy market studies, which rely on additional capacity adequacy remuneration to reach elevated RES shares (Chattopadhyay and Alpcan, 2016; Gerres et al., 2019a; Weiss et al., 2017), but fail to provide an in-depth analysis of the interplay of such additional remuneration mechanisms with the other system objectives.

Various policies aim for emission reduction in the European context while indirectly influencing the energy market outcome and pricing emissions. Some policies foster the technological transition towards the electrification of energy consumption and thereby change electricity demand patterns. Equally, energy efficiency policies can be considered an indirect electricity market design revision that reduces the total demand and contributes to emission avoidance. Similarly, the European push towards increasing demand flexibility is a policy response to cover a higher demand share by intermittent RES generation, thereby avoiding emissions and ensuring generation adequacy.[89] Vice versa, demand response might reduce the need for capacity mechanisms (Khan et al., 2018).

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[86] Additionally, it´s questionable that the technology mix that can meet peek demand is adequate to cover all other seasonal demand peaks, e.g. wind generation contributing to the winter peak might not be available for the summer peak.

[87] *See*, Directive (EU) 2003/87/EC, among others amended with Directive (EU) 2018/410 for Phase IV (2021-2030)

[88] The EU roadmap published in 2011 foresaw a total emission reduction of 80% until 2050 (EC, 2011), whereas the revised long term vision published in 2018 aims for a full decarbonisation of the economy by 2050 (EC, 2018c).

[89] *See*, Energy Efficiency Directive (2012/27/EU)

Achieving the system objectives of providing affordable electricity with adequate generation while avoiding emissions is subject to the coordination of all policies. Since the suitability of market design revisions differs given interdependencies with other market mechanisms and future uncertainties (Robinson et al., 2017), a thorough understanding of these policy interactions is missing. Such knowledge is vital for evaluating the future economics of RES generation capacity from an electricity system perspective.

4.2.5. A methodology to evaluate energy system policies

All policies mentioned in the previous sections either impact energy market outcomes or encompass mechanisms that can be seen as a departure from energy-only market principles. This means that the role of different policies can only be studied by comparing them against the energy-only market outcome. In the following, we introduce a case study for the Spanish electricity system in the year 2030 to show how capacity mechanisms, emission pricing, RES quota requirements and energy efficiency policies impact the capability of the electricity markets to comply with the system objectives of affordability, adequacy, and emissions avoidance.

The Spanish case study for 2030

A case study has been designed to represent a likely market scenario with more stringent emission reduction objectives than today´s electricity system requires. For Spain, the national government has announced detailed emission reduction and RES technology targets in their National Energy and Climate Plan (NECP) for 2030 (MITECO, 2020a). An electricity system resource expansion model based on the current market design in Spain is used to analyse how the electricity market could evolve until 2030. The NECP aligned case thereby serves as a relative benchmark that sets the system objectives. In the following, the modelling framework and input data are summarised.

The applied modelling framework SPLODER was initially designed to evaluate the interplay between centralised and distributed generation at optimal total system cost (Martín-Martínez et al., 2017). It was modified to study the optimal investments in low emission technologies during the transition phase of the electricity system towards deep decarbonisation until 2040 (Gerres et al., 2019a) and to evaluate the economics of ageing nuclear power plants in a decarbonising system (Gerres et al., 2019). Based on the available capacity, operational characteristics, and costs of previously installed and available new generation technologies, electricity demand profiles, and weather data, the model optimises the investment decisions for new generation capacity and schedules the optimal operation of all energy resources to minimise the total system cost. For this purpose, the model encompasses a simplified electricity market design, which determines hourly electricity market prices and the dispatch of available resources for a chosen baseline year. Additionally, the model can incorporate optional constraints to meet minimum total installed firm capacity requirements to an energy-only market, potentially resulting in capacity payments (€/kW). The level of capacity payments is linked to the marginal cost for additional generation investment to cover the system´s demand peak. Other optional constraints can ensure that specific RES generation targets are met by providing additional revenues in the form of RES payments (€/kWh) to complement market revenues so that all newly installed RES can recover their investment costs. The main model inputs used for all scenario runs in this model are summarised in Table 4-A.

The economics of RES and batteries, investment, and operational costs, are fundamental input data for the model.

Table 4-A: Summary of input data and sources used for this study

	Input data:	Data type:	Source:
Generation and storage technologies	**Natural Resources:**		
	Generation profiles for solar PV	Three different stochastic hourly maximum generation profiles (kWh)	Evaluation of REE data as presented by (Gerres et al., 2019a)
	Generation profiles for wind	Three different stochastic hourly maximum generation profiles (kWh)	Evaluation of REE data as presented by (Gerres et al., 2019a)
	Seasonal share of hydroelectric generation	Hourly maximum generation profiles (kWh)	Evaluation of REE data as presented by (Gerres et al., 2019a)
	Technical characteristics of power plants	Change of production per hour (%), the emission intensity of production (g/kWh), …	As presented by (Martín-Martínez et al., 2017)
	Technical characteristics of batteries	Capacity in kW, fully discharged after 4 hours and fully recharged after 8 hours.	As presented by (Gerres et al., 2019a)
	Power plants economics:		
	Investment and O&M costs	Annualised installation costs (€/kW) and operational cost [€/kWh)	Table 4-B
	CO_2e price	Emission price is either fixed to 25 €/tCO_2e or an electricity system-based price as model output.	
	Fuel prices	Natural gas and nuclear fuel prices in (€/kWh) per kWh of generated electricity.	As presented by (Gerres et al., 2019a)
	Technology specific taxes	Special tax regimes, levies and charges for generation and demand are disregarded given regulatory uncertainty	As presented by (Gerres et al., 2019a)
System	Firm capacity coefficient of power plants	Contribution to peak demand (%)	Table 4-B
	Overall system characteristics:		
	System losses coefficient	Difference between generation and available supply (%)	As presented by (Martín-Martínez et al., 2017)
	Target RES share in 2030	Percentage of final consumption to be RES (%)	As stated in the Spanish National Energy and Climate Plan (NECP) (MITECO, 2020a)
Demand	Demand profiles	Hourly demand profiles (kWh) based on four representative weeks, further segregated in weekdays and weekend profiles for the industrial, residential and service sectors.	Own evaluation based on REE (2016) by using the clustering algorithm of (Hartigan and Wong, 1979), presented by (Gerres et al., 2019a)
	Additional demand for electric vehicle charging	Additional load (kWh) with one-third of charging load distributed over the entire day, one-third charged during the evening peak, and one-third charged flexible.	EV penetration based on (Bloomberg Finance, 2017), vehicle usage statistics for Spain (MINETUR, 2016), presented by (Gerres et al., 2019a)
	Demand response rate	Share of the total generation that can shift their heating-based demand given that 25% of households install smart thermostats by 2030.	As presented by (Gerres et al., 2019a)

Table 4-B lists installation and operational costs and firm capacity factors based on REE and National Grid (Gerres et al., 2019a; NGET, 2017).[90] The model´s output includes investments in new power plants and storage capacity (MW) and the hourly electricity generation and consumption per technology (MWh). System costs constitute investment, O&M, fuel, and emission allowance costs. The income of each power plant depends on its electricity market remuneration (€/MWh) and, depending on the scenario, additional payments for available firm capacity (€/MW) and RES generation payments (€/MWh).

The existing generation capacity corresponds to the legacy power plant fleet expected to be in operation in Spain by 2030 according to current phase-out plans for coal power and the stepwise closure of the remaining nuclear generation capacity (MITECO, 2020a). There will be no operating coal power plants and a remaining nuclear capacity of 3.1 GW by 2030. Most of the currently installed CCGT capacity is expected to be still operational. Additional to current solar and wind power installations, all planned projects resulting from public auctions until mid-2020 will be in operation by 2030. The resulting legacy capacities are summarised in Figure 4-2.

[90] By fixing firm-capacity ex-ante the potential contribution of different generation technologies to the system´s firm capacity is taken as a given and therefore doesn´t allow to study the effect of changing firm capacity contribution and does not consider how the technologies providing firm capacity can contribute to seasonal demand peaks.

Table 4-B: Techno-economic characteristics of available power plant options in the year 2030

Technology	Investment costs	Annual Maintenance Cost	Maintenance Variable Cost	Fuel Cost	Taxes	Firm capacity coefficient		
	(€/kW)	(€/kW-year)	(€/MWhe)	(€/MWhe)	(€/MWhe)	(%)		
Nuclear	4116	108.30		8.72	15.02	97%		
OCGT	544	18.40	11.00	85.07	4.68	96%		
CCGT	845	19.30	2.00	56.69	4.68	96%		
Hydropower	2978	68.80	3.00			44%	25%	77%
						(reservoir)	(run-of-river)	(Pumped storage)
Solar PV	500	10.00				0%		
Wind	950	29.00				7%		
Battery	800					96%		

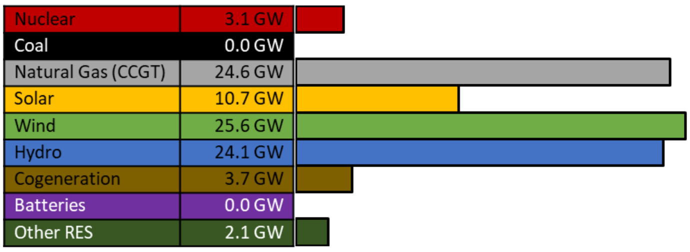


Figure 4-2: Legacy generation capacities and planned projects from past public auctions expected to be in operation in Spain by 2030

Policy scenarios

The SPLODER model allows studying the implementation of various policies departing from an energy-only market design. The following policy scenarios (Figure 4-3) enable us to reflect on the policies and policy interdependencies that have been analysed in Sections 4.2.3 and 4.2.4 to evaluate their performance relative to a benchmark case.

The benchmark case must comply with relative emission avoidance objectives for 2030 while reaching at least the 74% RES quota stated in the NECP. General practice is that the generation adequacy objective covers 110% of the annual peak demand. A benchmark set for capacity adequacy refers to a scenario in which a capacity auction mechanism determines the marginal annual capacity payments (€/kW) to meet the adequacy objective (**+CAP** scenario). In contrast, the **EnergyOnly** scenario illustrates the system development of an energy-only market with no additional policies implemented to reach the system objectives. As such, generation investments are based on scarcity pricing. Except for scarcity pricing defined by the cost of non-served energy, the **EnergyOnly** scenario does not include any additional policy costs and results in the most affordable average electricity prices. Therefore, the outcome of the **EnergyOnly** scenario is used to benchmark affordability. The unit for affordability is the average system cost per MWh of electricity demand (€/MWh) and is calculated by dividing the total system cost by the annual consumption.

Three different policies to increase emission avoidance are reflected by the selected policy scenarios. The **+CAP+RES** scenario explores the effect of increasing emission reductions by aiming for a slightly higher RES quota compared to the benchmark case by introducing additional RES generation payments (€/kWh). In contrast, the **+CAP+CO2** scenario shows how the same level of emission avoidance could be achieved while introducing electricity market-based emission pricing to complement EU ETS allowance pricing. Here we diverge from the current policy design of pricing emissions across all non-diffuse sectors to explore the advantage of remunerating the technology-neutral contribution to emission avoidance objectives. All scenarios are analysed for the case of 0% demand growth and the 2% annual growth foreseen in the NECP to reflect the impact of energy efficiency policies on the energy market dynamics (MITECO, 2020a).

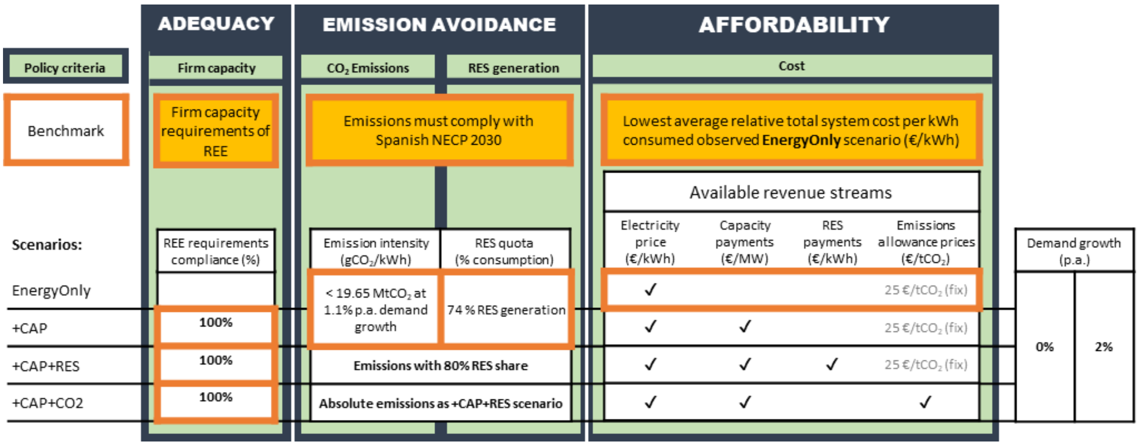


Figure 4-3: Policy scenarios and the benchmark case[91]

4.2.6. Results for different policy scenarios

In the following, we explore the impact of different policy choices on the ability of the system to comply with the main system objectives for the benchmark case. Results are discussed relative to the benchmark case. The benchmark case complies with relative generation adequacy and emission avoidance objectives according to the NECP at the lowest and most affordable energy cost in an energy-only market scenario. Deviations are expressed as percentage deviations from the 100% compliance to these objectives.

Generation adequacy and emission avoidance

In the **EnergyOnly** scenario, the Spanish generation mix is dominated by RES in 2030 (Figure 4-4). Solar and wind power are the cheapest technology options and replace retiring thermal generation capacity. Up to 76% of all generation comes from RES, reducing the emission intensity of production in Spain from 246 gCO_2/kWh in 2018 (REE, 2019) to 65 gCO_2/kWh. While complying with the NCEP based emission avoidance objective, the energy-only market gives insufficient investment incentives contributing to generation adequacy. Available generation meets demand but does not fulfil the adequacy requirements to cover 110% of the annual peak demand. Introducing capacity payments changes investment incentives for different technology options in **+CAP** scenarios. Historically, the peak demand in Spain is observed on winter evenings, so that the contribution of solar PV to the demand peak is zero. Solar PV cannot provide firm capacity, and the technology competition for generation adequacy is between solar and batteries versus wind power. With 0% demand growth, the firm capacity mechanism reduces the emission intensity of electricity generation by 3%, while the actual share of RES generation remains at 76% in the **+CAP** scenario. The positive effect of the firm capacity requirement on emission intensity can also be observed for the **+CAP** scenario with 2% demand growth, elevating the share of RES to 78%, thereby reducing emissions by more than 17% compared to the corresponding energy-only market scenario.

Results highlight the importance of the applied methodology to define ex-ante firm capacity factors of intermittent generation. For this case study, wind and batteries can partially provide firm capacity, which theoretically allows intermittent RES to cover the peak demand. This would not be feasible in market designs that do not acknowledge that RES and batteries ensure supply adequacy. In contrast, higher firm capacity factors for RES and batteries may result in a market outcome where firm capacity payments are no longer necessary. However, the predefined firm capacity factors only consider the expected demand peak and don´t acknowledge the need to cover seasonal peaks, nor the contribution of other technology options to cover these seasonal peaks.

[91] Highlighted within the scenario matrix (orange) with firm capacity requirements based on criteria by Red Eléctrica de España (REE), the Spanish system operator, and emission requirements for 2030 derived from the Spanish National Energy and Climate Plan (NECP).

Another methodology to determine firm capacity factors and remunerate the contribution of different technologies to generation adequacy might significantly impact the model results and market outcome.

Policy options to avoid emissions

More ambitious emission reduction objectives exceeding the benchmark require additional incentives for installing low emission technologies. For this case study, additional RES payments can achieve compliance with an elevated RES generation target of 80%. In scenario **+CAP+RES** with 0% demand growth, additional wind and solar generation investments drive down emissions and provide an additional 20% emission reduction compared to the benchmark (Figure 4-5).

Alternatively, electricity market-based emission pricing (**+CAP+CO2**) can be used to reduce absolute emissions. Fossil fuelled generators internalise emission prices in their market bids and increase electricity market prices. Thus, additional remuneration for RES technologies becomes redundant. Absolute emissions in the **+CAP+RES** scenario with 0% demand growth amount to 13.5 $MtCO_2e$ (Figure 4-6), which can be achieved with an additional electricity system-based price of 54.53 €/tCO_2e in scenario **+CAP+CO2** (Figure 4-7). Compared to scenarios with RES payments, emission pricing penalises fossil generators, by elevated emission pricing benefits both RES and storage technologies.

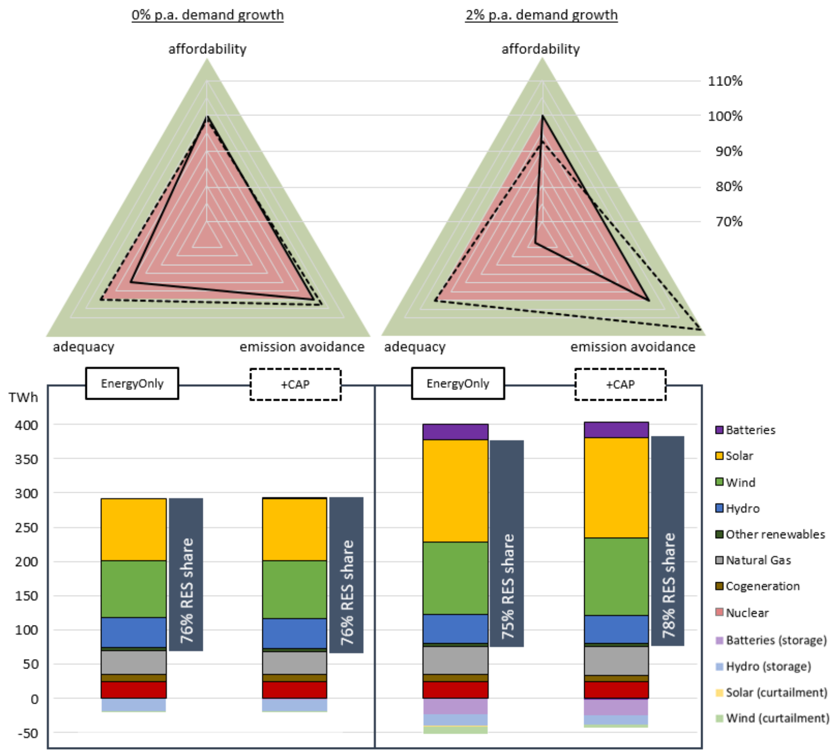


Figure 4-4: Relative comparison of ***EnergyOnly*** *and* ***+CAP*** *scenarios*[92]

[92] 0% and 2% p.a. demand growth with benchmark objectives and resulting generation mix of all scenarios. Objectives are not reached if the level of compliance is < 100 % (red area).

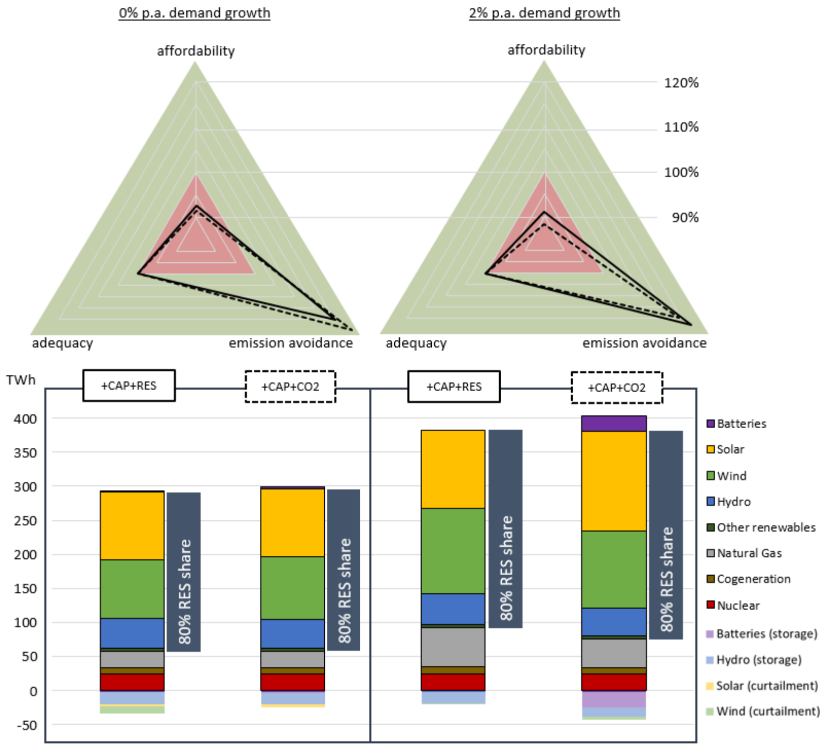


Figure 4-5: Relative comparison of ***+CAP+RES*** *and* ***+CAP+CO2*** *scenarios*[92]

Similar observations can be made in scenarios with demand growth of 2% p.a., though absolute system emissions increase substantially. A peculiarity of the Spanish case study is the presence and increased operation of 24 GW of legacy CCGT plants in 2030. In the **+CAP+RES** scenario, these plants are responsible for a relative emission rise of 9% compared to the 0% growth case, which translates into an increase of absolute emissions by 46% to 19.8 $MtCO_2e$ (Figure 4-6). It highlights the general dilemma of relative emission reduction targets. National (MITECO, 2020a) and European (EC, 2018c) plans describe decarbonisation pathways stating improvements relative to absolute emissions in a historical base year. However, proposed policies like the RES generation share might be insufficient if demand, subject to energy efficiency or electrification policies, develops differently than anticipated.

How policies impact the cost recovery

Reduced affordability in **+CAP+RES** and **+CAP+CO2** scenarios compared to the relative **EnergyOnly** scenario benchmark does not necessarily imply higher energy-only market prices. As shown in Figure 4-7, policies for providing firm capacity and RES generation reduce the importance of energy-only markets as a revenue source for generation capacity (**+CAP+RES**). In both cases, new markets are introduced to pay generators for providing generation adequacy services or electricity generation originating from RES. RES plants require lower electricity market prices to recover their costs by obtaining substantial revenue streams for these two markets. It has a degressive effect on the role of energy-only remuneration to recover the total system cost. In contrast, externality pricing of emissions has the opposite effect and increases the importance of the electricity market to recover the system cost (**+CAP+CO2**). Independently of the emission pricing mechanism, costs for emitting CO_2e are an additional operational cost position for fossil-fuelled power plants that are included in their electricity market bids. Whenever these power plants set the market price, it contains an emission premium and increases the electricity market revenue for all active generation capacity (Figure 4-7).

Affordability of ambitious emission avoidance

Perfectly competitive energy-only markets minimise the total system cost and average end-consumer prices but might fail to meet supply adequacy and emission reduction objectives (**EnergyOnly**). Policies to adequately incentivise sufficient firm capacity and emission avoidance increase the total system cost. Since implementing additional market mechanisms results in higher total system cost (Figure 4-4 and Figure 4-5), it is vital to identify the optimal market design revisions to keep the system affordable.

For the initial **+CAP+RES** and **+CAP+CO2** scenarios, the system´s affordability is very similar. This observation, though, is deceptive. Emission pricing and RES remuneration mechanisms may have stronger effects on system affordability than stricter absolute carbon dioxide-equivalent emission policy targets. It can be visualised by maximising the emission avoidance objective for the **+CAP+RES** and **+CAP+CO2** scenarios, equivalent to covering up to 90% of the demand with intermittent RES generation.

In the **+CAP+RES** scenario, additional payments to RES generation incentivise excessive wind and solar generation installations eligible for RES payments. While this scenario results in the installation of ample battery capacity[93] to shift intermittent generation in hours without RES availability, RES payments reach such a high level that the marginal kilowatt of installed intermittent RES capacity can recover its costs while only providing the marginal required RES generation share. It results in an extreme case where the major share of annual electricity generation by the marginal RES capacity has to be curtailed. Here, the marginal RES capacity is installed to comply with the production quota requirement rather than to optimise load-shifting with battery operations or emission reductions on the system level. Consequently, the average consumption cost increases exponentially since RES payments need to ensure the return of investment for highly curtailed marginal RES generation capacity (

Figure 4-8).

The extreme cases for the **+CAP+CO2** scenario result in significantly lower generation curtailment and only a moderate system cost increase compared to the **+CAP+RES** case. Higher emission prices set technology-neutral incentives to reduce emissions. Intermittent RES is being installed, and battery capacity operated so that the utilization of available intermitted RES by batteries is optimised for reducing emissions and associated emission allowance costs, rather than marginal RES capacity installations to meet quota requirements.

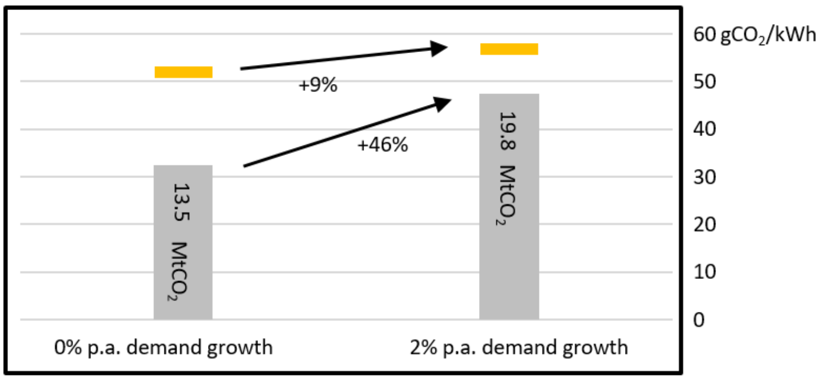


Figure 4-6: Absolute annual emissions compared to relative emissions (yellow) for ***+CAP+RES*** *scenario*

[93] The gap between installed battery capacity in the +CAP+RES and +CAP+CO2 scenarios displayed in Figure 4-8 reaches 27% in the low emission reductions, 0% p.a. growth scenarios and is down to 2% in the high emission reduction 2% p.a. growth scenarios.

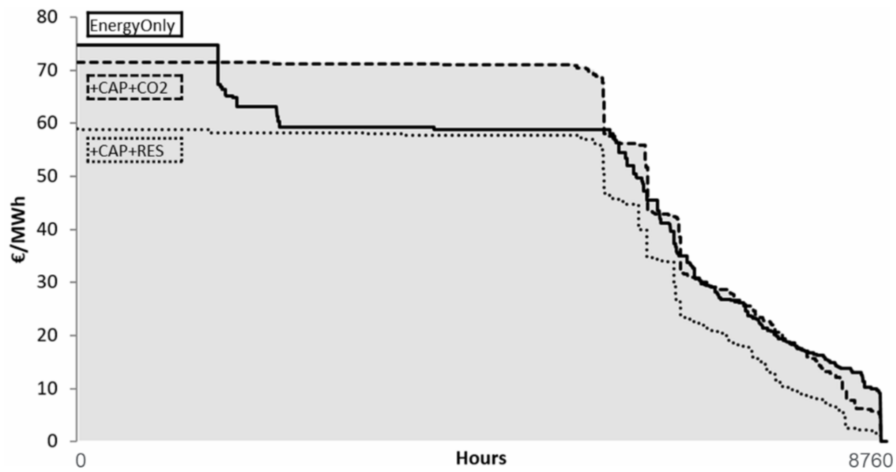
Emission pricing internalises emission allowance costs in the electricity market prices (**+CAP+CO2** in Figure 4-7). Minimising the total system emissions means that higher emission prices increase the marginal price of generation. This price increase creates a business opportunity for demand response. Here batteries consume low-cost generation in hours of low electricity prices and sell at hours with little intermittent generation. It helps avoid an exponential cost increase, and the system in a **+CAP+CO2** would be more affordable than in the equivalent **+CAP+RES** scenario.

For both extreme **+CAP+RES** and **+CAP+CO2** scenarios, it holds that intermittent RES would most likely not be curtailed but could satisfy the expected need for low-cost electricity to produce alternative fuels such as hydrogen (Glenk and Reichelstein, 2019) or aid in electrifying the heavy industry (Lechtenböhmer et al., 2016). Large consumers with demand response capabilities may reduce RES curtailment by shifting their energy demand to absorb excess generation available at near-zero electricity costs. It would avoid exponentially increasing curtailment rates, as shown in

Figure 4-8, but would not reduce the overall system cost difference between **+CAP+RES** and **+CAP+CO2.** In scenarios with high emission avoidance, elevated RES quota payments would remain suboptimal for incentivising generation, storage capacity and other demand response services that can decrease emissions at the lowest system costs.

4.2.7. Discussion: challenges arising from policy design

The transition of our energy systems requires an electricity market design that encourages efficient investments while ensuring emissions reduction and security of supply. Diverging from an energy-only market design, different policies have been implemented or suggested to reach these objectives. By studying the interrelations between capacity mechanisms, emission pricing, RES quota requirements and energy efficiency policies in a Spanish case study for 2030, the following challenges for electricity markets have been identified that originate from policy design choices.



	average marginal price (€/MWh)	capacity payments (€/MW-year)	RES payments (€/MWh)	CO_2 price €/tCO_2
EnergyOnly	51.18	-	-	25
+CAP+CO2	55.94	46642	-	25 + 54.53
+CAP+RES	44.55	54932	8.83	25

*Figure 4-7: Annual hourly marginal energy market prices for the **EnergyOnly**, **+CAP+CO2** and **+CAP+RES** scenarios*[94]

[94] Case of 0% demand growth. Capacity payments, RES payments and emission prices are listed, additionally. Note that higher natural gas prices, as observed in 2021, can significantly change the model

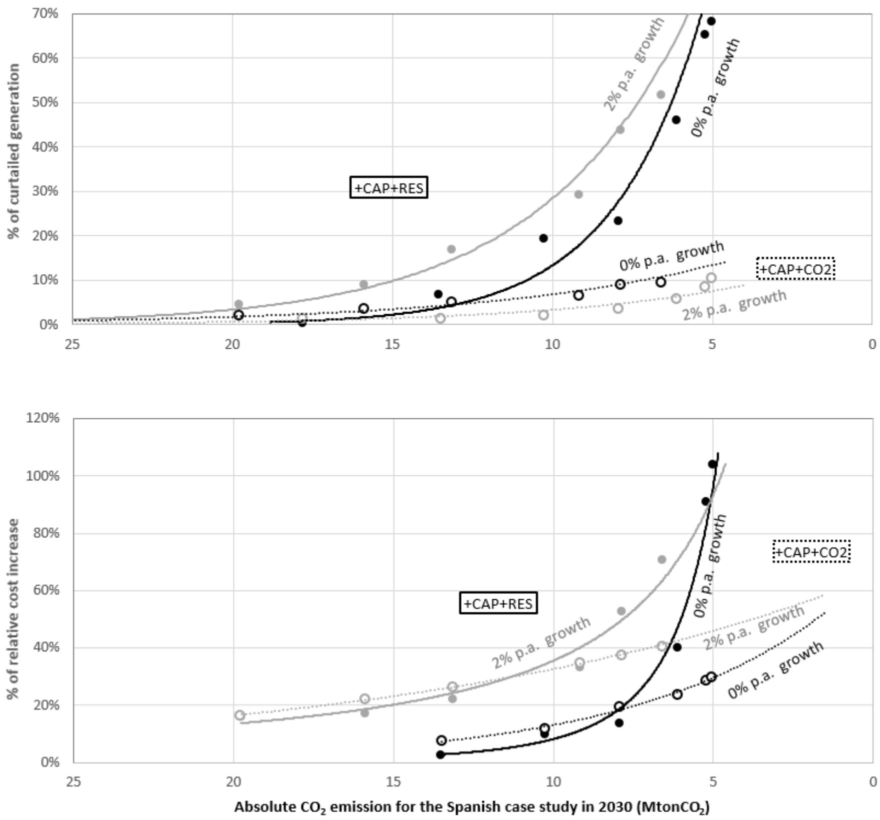


Figure 4-8: Curtailed generation and relative cost increase (%) compared to the benchmark case for ***+CAP+RES*** *and* ***+CAP+CO2***[95]

Results show a clear interdependency among the three objectives. Results for the **EnergyOnly** and **+CAP** scenarios (Figure 4-4) and the **+CAP+RES** and **+CAP+CO2** scenarios (Figure 4) as a triangular equilibrium of system objectives visualise this interdependency. Pushing the system with an additional capacity policy in one direction can simultaneously result in an overachievement of another objective, the emission avoidance, putting pressure on the third objective of affordability. Here, the challenge is whether policies could be balanced to the degree that all objectives are met.

IV.I: The policy design should acknowledge the clear interdependency among the three objectives: affordability, adequacy, and emission avoidance.

The results presented confirm how two alternative policies designed to comply with emission reduction targets lead to very different outcomes in terms of affordability. Indeed, Figure 7 highlights how two policies targeting the same absolute emission reduction, for instance 5 $MtCO_2e$, may entail an increment in the electricity supply cost that is up to five times higher. In that sense, applying a marginal price to emissions (**+CAP+CO2** scenarios) seems much more efficient than using a RES support mechanism based on a RES production quota related marginal price (**+CAP+RES** scenarios). This observation confirms the results of previous studies that highlight the economic adjustment costs of RES support mechanisms (Böhringer and Behrens, 2015) and the interaction between emission trading and renewable electricity support schemes (del Río González, 2007; del Río et al., 2013).

outcome. The maximum electricity price in high-price hours for all scenarios would increase, though, the number of these high-price hours would significantly drop since alternative sources for system flexibility become more cost competetive. Additional sensitivity runs are required to confirm that the general market dynamics described in this chapter are also observed with significantly higher natural gas prices.

[95] When complying with stricter absolute carbon emission policy criteria. Displayed scenarios correspond to resulting shares of RES generation between 80% and 90%.

IV.II: Alternative policies aiming to achieve the same objective may have a different impact on other objectives.

The reason behind the inefficient reduction of emissions by RES production quota is that the measure is not fully aligned with the objective of reducing avoidance. Indeed, the primary objective should be to reduce emissions to a given target and pricing emissions is directly linked to that target. Instead, setting a RES production target, although indirectly linked to an emission reduction, is not, itself, a meaningful objective to reduce emissions. The real issue is to reach the desired emissions reductions and not to reach a RES production quota. Many other drivers may play a role in reducing emissions. Implementing a policy that is indirectly but not fully aligned with the system objectives may distort the efficient achievement of the objective.

IV.III: Policy designs that are not fully aligned with the system objectives may lead to undesirable outcomes.

Even though the different scenario interrelations presented in sections 4.2.5 and 4.2.6 are of limited complexity, results show that policy design should be as technology-neutral as possible to reach any system objectives. Future markets will most likely be dominated by investments in technologies that can provide intermittent but decarbonised electricity and options that can offer flexibility to cope with this intermittency[96]. Policies to assure generation adequacy and emission avoidance need to create business cases for intermittent RES generation and flexibility options while being balanced and not incentivising overinvestments.

By over-incentivising investments with RES quota-based policies (Figure 4-8), we take one policy that is not fully aligned with the system objectives to an unrealistic extreme case. Rather than fuelling criticism of RES specific policies, these results can also be interpreted as a criticism of remuneration that is not directly reflecting the main objectives. Given the current functioning of the EU ETS, similar dynamics could also be observed for emission allowance pricing. As discussed in section 4.2.4, the EU ETS currently prices emissions across all non-diffuse sectors. Decarbonisation technologies for heavy industries, such as steel or cement making, require emission prices well above 100 €/tCO_2e to reach profound emission abatement (Rootzén, 2015). If such high EU ETS prices are becoming a reality by 2030, they might exceed the estimated emission price required for reaching the electricity system emission avoidance objectives for 2030 (Figure 4-7). It could result in higher emission avoidance but might negatively impact the affordability and capacity adequacy of the installed generation.[97] The same can be said if such high emission prices are imposed onto generation in other ways, for example, by additional static emission taxes. Policy instruments that ensure fixed-price and stable cost signals are essential to enable investments into low-emission technologies. Regulators and policymakers face the challenge of balancing long-term commitments and the electricity market design.

IV.IV: Policy design should be as technology-neutral as possible to reach any of the system objectives.

Discussed policies that aim for generation adequacy and emission avoidance provide financial incentives to ensure compliance with the system objectives. These incentives can either take the form of remunerating system services, such as RES generation or capacity adequacy or penalise non-compliance as emission pricing. As shown in section 4.2.6, creating additional markets to

[96] In the presented model runs, the role of flexibility providers corresponds to existing fossil-fuel based combined cycles, hydro generation (including pumping), and new investments in battery technology. Investments in battery technology are only one technology option to address the need of flexibility. None of the other potential alternative technologies that can provide the required flexibility, for example demand response or flexible hydrogen production, has been discussed in detail in section 4.2. Given that their functional characteristics related to the provision of flexibility services differ from batteries, further research is needed to investigate their role in future electricity markets.

[97] A universal emission price might be the most efficient signal for reflecting the emission allowance costs across all economic activities to incentivise decarbonisation at the minimum cost. As further analysed in section 5.4.2, the inability to provide new generation and industrial capacity in the medium term means that a unilateral pricing signal might hinder rather than support efficient investments in climate-friendly technologies.

remunerate system services other than wholesale electricity generation reduces the importance of electricity market prices to recover system costs. In the extreme, power plants might be mainly reimbursed based on their capacity adequacy and renewable generation. In contrast to that, policies that penalise emissions increase the relevance of electricity market prices. It has been highlighted for electricity market-specific pricing but may also hold for capacity mechanisms that oblige the compliance to firm capacity requirements without reimbursing them. Like pricing, the additional cost for such capacity obligations would have to be recovered via the electricity price. The effect of pricing different services such as energy, adequacy, and emissions might significantly impact the role and basis for electricity pricing in future electricity systems.

IV.V: When pricing different services (energy, adequacy, emissions), policy designs impact consumption and thereby change the need for additional services.

All scenarios introduced in section 4.2.5 were analysed for a 0% and 2% demand growth case to evaluate the impact of indirect policies on the system that increase or reduce electricity consumption. Also, other developments closely linked to EU policymaking, such as the possible success of electric cars and their impact on consumption, might result in such different demand growth scenarios. The challenge is to anticipate such effects, design market policies, and set system objectives robust to expected and unexpected impacts on electricity demand.

By contrasting absolute and relative emissions for 0% and 2% demand growth in the **+CAP+RES** scenario (Figure 4-6), we hint at the dilemma of imposing relative intermediate targets on the pathway toward full decarbonisation by 2050. Relative quotas, be it the 32 % of renewable energy consumption in the EU by 2030 (section 4.2.2), do not necessarily reduce emissions if they are not linked to absolute emission reduction objectives. If there is no political support for absolute emission reduction objectives before 2050, policymakers are challenged to design policies based on relative targets that ensure absolute net-zero emission by 2050.

Lastly, all scenarios presented and discussed in this chapter illustrate that the future role of RES generation depends on the investment signals of the electricity system. Therefore, the electricity system design should create conditions that value the contribution of RES generation, low emissions, low operational and installation costs while feathering off the effects of intermittency of these sources. Here, future work should focus on the economically optimal combination of RES generation with resources that can provide system adequacy without increasing emissions. Considering both intra-day and seasonal fluctuations, the economics of RES may be different if combined with demand response options, novel hydro and pump-storage capacity or hydrogen power-to-gas concepts.

4.3. Decarbonising energy markets and its implications beyond the electricity system

The generation and consumption of electricity from renewable wind, solar and hydro resources is only one pathway towards decarbonising the industrial sector. But in parallel to the electricity system, the provision of other energy sources to operate climate-friendly production processes have their very own market implications for an economy moving towards net-zero emissions by mid-century. The following section explores the role of emission avoidance, affordability, and adequacy objectives for fossil fuels, hydrogen, and biomass markets (section 4.3.1). Then I revisit the alternative energy markets individually in sections 4.3.2 to 4.3.5 to identify energy market propositions for competing potential low-emission options in the industrial sector.

This subchapter presents a novel analysis but directly reflects on previous sections, especially section 4.2. Though mainly focussing on the analysis of energy markets, I acknowledge the option to use some of the discussed energy carriers as feedstock throughout this subsection and consider this for my analysis.

4.3.1. Energy system objectives

Emission avoidance, affordability and adequacy are the three main system objectives that we identified for electricity generation and consumption in section 4.2. While electricity systems are unique due to their generation, transport, and storage constraints resulting in regional rather than global markets (section 2.3.2), the main system objectives must apply to all energy sources in a decarbonising economy. Following this logic, future fossil fuel, hydrogen and biomass markets[98] are subject to emission avoidance, affordability and adequacy objectives.

Emission avoidance as energy system objective

Equally to electricity systems and any other human activity, all energy systems must comply with the long-term decarbonisation targets set by governments for their jurisdictions to keep global warming to a minimum under the 2015 Paris Agreement. In the case of the European Union, intermediate 2030 targets are foremost formulated as renewable energy rather than electricity system decarbonisation targets.[99] As such, they shall equally apply to all forms of energy usage, including existing fossil energy sources, biomass, and future hydrogen markets.

Note that net-zero emission reduction targets for energy use do not imply full decarbonisation of the industrial sector since many industries´ emissions are process rather than energy-related (section 2.1.2). That said, emission avoidance in energy markets can reduce industrial emissions beyond energy use. For many industries, fossil energy carriers are equal to the fossil feedstock used in the production process, e.g., crude oil and natural gas in the petrochemical industry and coal in the steel industry. The use of carbon capture technology, on the other hand, does not differentiate between energy and process-based emissions, so its implementation to reduce energy-related emissions also brings down process emissions for most applications.

Affordability as energy system objective

For more than a century, the price formation for solid and liquid energy carriers has been subject to global market dynamics. Supply and demand have been decisive for crude oil and mineral coal market prices. Their low cost has driven economic growth since the beginning of industrialisation more than 150 years ago (O'Rourke and Williamson, 2002).[100] Additionally to the global market price, today´s end-consumer prices for fossil energy carriers highly depend on the national

[98] The analysis focusses on electricity, fossil fuel, hydrogen, and biomass markets as they are considered to be the most relevant energy markets for the system transition. They review and analysis is therefore not envisioned to be complete.
[99] *See*, Directive (EU) 2018/2001
[100] This statement disregards any short-term price fluctuations due to hedging, nor the role of cartels such as OPEC for crude oil.

regulatory regimes. A striking example is the difference between petrol prices across EU member states due to different national taxation schemes (EC, 2020b).

In contrast to global crude oil and coal prices, natural gas markets have developed more regionally. Like the electricity system, natural gas markets rely on a centralised distribution infrastructure undergoing market liberalisation since the late 1990s in the European Union. This liberalisation was primarily motivated by increasing competitiveness and reducing prices.[101] Additionally, the availability of liquefied natural gas (LNG) also levelled costs globally over the last years. This trend is expected to continue in the future (Tsafos, 2020).[102]

Regardless of these different existing market structures for energy carriers in place and the varying degrees of market design revisions on the national level, all energy markets will have to experience a profound transformation to align them with emission avoidance objectives. It shall occur "through a socially fair transition in a cost-efficient manner", as stated in the 2018 "A Clean Planet for all" strategy of the European Commission (EC, 2018c). Affordability, therefore, defines the transition of existing energy markets and the emergence of new markets, such as hydrogen.

Adequacy as energy system objective

Electricity is a volatile form of energy that is difficult to store. As such, intermittent generation capacity might be inadequate to ensure that demand can be met at any time, calling for adequacy of generation and demand to safeguard availability (section 4.2.2). Other energy carriers under consideration do not or, to a much lesser extent, face adequacy limitations related to the intermittency of supply or unavailability of storage options. Nevertheless, in a broader sense, adequacy considerations have dominated and will dominate the market design decisions for all energy resources. As the European Union has been a net importer of energy from the very early days of its existence, supply security and the availability of alternative supply routes has been at the very core of its policy agenda since the emergence of the European Coal and Steel Community in 1952 and the European Atomic Energy Community in 1958 (Wilson and Dobreva, 2019). The 1970´s OPEC oil embargo and the effects of the Russia-Ukraine natural gas disputes between 2005 and 2010 seriously threatened the supply security of the European Union (Nies, 2008), while the adequacy of the Russian-German North Stream 2 project is being challenged on EU level (Adomeit, 2016).

The question about supply adequacy is crucial for hydrogen and biomass as potential low-emission alternative energy sources. While the European Union´s hydrogen strategy states security of supply as one of the main policy objectives (EC, 2020c), national roadmaps, such as for Germany, depart from the premise that "most of the hydrogen needed will have to be imported" (BMWi, 2020). With the limited availability of biomass resources in Europe (Camia et al., 2018), future energy market design needs to encourage adequate use cases for low-emission energy carriers. Simply said, each available energy carrier should be used for the applications they are best suited for to avoid emissions in the most affordable way.

4.3.2. Electricity

The design challenges in decarbonising electricity markets to meet the three main objectives of emission avoidance, affordability and adequacy have been discussed at length in the first part of this chapter in section 4.2. For industrial energy consumption, electricity is assumed to be near-zero emission in the future and can avoid direct and indirect industrial emissions. We also challenge the narrative of universally cheap electricity for end-uses such as industrial production in section 4.2.7. On-site electricity consumption can be a highly affordable energy source thanks to the cost decline of RES generation from solar and wind but requires industrial processes to adjust their consumption pattern to the availability of intermittent RES. If technically feasible, direct electrification is only an adequate decarbonisation option for industries with flexible consumption patterns or industries willing to pay elevated electricity prices due to their

[101] *See,* Directive 98/30/EC

[102] In 2021, the price rally for natural gas on global markets demonstrated the price interdendency. The shortage on globally traded LNG caused price peaks in all regional natural gas markets.

incapability to adjust their consumption. For many industries, though, production output is predominantly determined by the order books, delivery deadlines, capacity utilization rates, material costs and labour, so volatile electricity prices would only be secondary for operational decisions. As such, levelised electricity cost of intermittent RES (LCOE) should only be used as an electricity price benchmark for very few specialised industrial processes that can operate cost-optimal while aligning their production to intermittent RES output.

IV.VI(1): If we evaluate direct electrification as an industrial decarbonisation option, we must consider variable electricity prices from a market design that meets adequacy and emission avoidance objectives.

4.3.3. Fossil fuels

Coal, lignite, natural gas and, to a minor degree, fuel oil are the most important primary energy sources for electricity production. While the share of fossil fuels in the electricity mix of the EU is on the decline and fell from 52% in 2010 to 40% in 2019 (Redl et al., 2020), coal and natural gas have maintained a relatively stable contribution of about 60% in the global energy mix over the same period (IEA, 2020d). This strong link between fossil fuels and electricity markets is expected to change fundamentally, as RES are already cost-competitive nearly everywhere in the world (REN21, 2020). As shown for the electricity market scenarios for Spain for the year 2030 in section 4.2.6 and up to 2045 in Gerres et al. (2019a), the decarbonisation of the electricity system means that fossil fuels are primarily going to be used for covering demand peaks that require relatively little consumption.

Given a global push towards decarbonisation, we would have to abandon fossil fuels for electricity generation and most other end-uses in the transport or industrial sector. Unlike short-term price fluctuations, lower global demand for fossil fuels would mean that market prices move downward on the supply cost curve, as shown exemplarily for coal in Figure 4-9. The global reference price for hard coking coal (Australian prime HCC) dropped significantly in 2020 compared to previous years due to the economic downturn caused by the COVID-19 pandemic. This development could create the paradox that cost-driven decarbonisation reduces the need to exploit costly fossil energy deposits, such as coal, natural gas, or crude oil, thereby bringing down their global market price and improving their competitiveness compared to renewable energy sources. However, future price development cannot shape decarbonising energy markets that comply with affordability and emission avoidance and adequacy objectives.

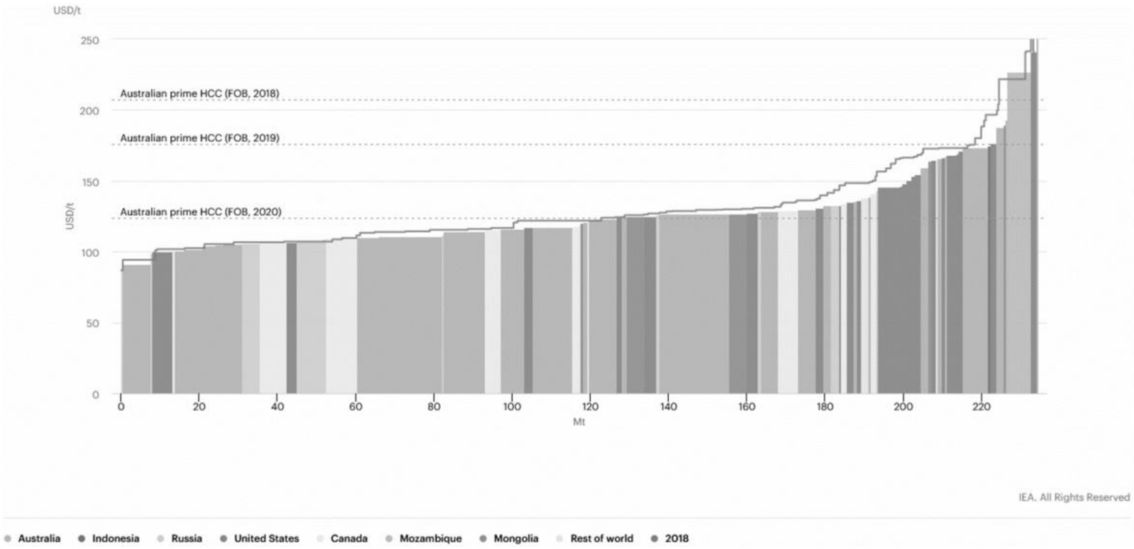


Figure 4-9: Global hard coking coal FOB supply curve 2019 and average FOB marker prices (IEA, 2021a)[103]

[103] FOB (free-on-board) supply curve for 2019 and average FOB marker prices in USD/t for the years 2018, 2019 and 2020.

Emission avoidance with fossil fuels

The use of fossil energy sources is emission-intensive so that fossil fuels cannot be used in applications that directly or indirectly cause emissions in a decarbonising energy system. Nevertheless, for some applications, especially in the industrial sector, fossil energy sources are expected to continue playing an important role (see 3.2.5). For example, installing carbon capture technologies makes it possible to avoid fossil emissions to the atmosphere. The relatively pure fossil CO_2 stream can then either be used as feedstock for materials that bind fossil carbon in basic materials, such as organic compounds or needs to be stored in long-term deposits. However, there is no business case for these alternatives today since carbon capture, storage (CCS) or usage (CCU) infrastructure requires additional capital expenditures and increases the operational costs linked to the consumption of fossil fuels in the industry (section 2.2.2).

Referring to the analysis for electricity markets presented in section 4.2, three principal market mechanisms can limit carbon dioxide-equivalent emissions linked to the use of fossil fuels:

1. Harmonised standards and a subsequent ban on carbon-intensive industrial processes, as proposed in Gerres et al. (2021) and further discussed in section 5.3.5.
2. Disincentivising the usage of processes and technologies that emit fossil carbon to the atmosphere by putting a price on carbon dioxide-equivalent emissions, such as discussed for the electricity system in section 4.2.4.
3. Incentivising the installation and operation of technologies that do not emit fossil carbon, such as RES payments for wind and solar generation (section 4.2.4).

These three principal market design mechanisms are specific for fostering the installation of CCS/CCU and any alternative energy use that can reduce emissions. They will play a prominent role for fossil fuels but also for hydrogen, biomass, and any other alternative energy carrier. The following analysis refers to "emission pricing" as representative of any of these three mechanisms.[104] Nevertheless, market design options are not limited to a unique mechanism that can reduce carbon dioxide-equivalent emissions. Any specific market design for fossil energy carriers shall be aligned with the following proposition.

IV.VI(2): The energy market design shall only incentivise *fossil fuels* as an energy carrier or feedstock for industrial processes if consumption does not result in direct or indirect atmospheric emissions that jeopardise compliance with emission avoidance objectives.

Affordability of fossil fuels

Exploitation, processing, transport, and distribution are the main cost drivers for fossil fuels (Baruya, 2007; Bonhomme et al., 2013). In the case of natural gas and mineral coal, the naturally occurring fossil energy resource does not need to be converted. It can be used with very little treatment in end-use applications. Alternatives such as electricity or hydrogen are the product of a conversion process from a primary energy source and, following the laws of thermodynamics, result in significant transformational losses in the form of heat. The absence of transformational losses makes mineral carbon and natural gas the cheapest option and the first choice for satisfying the energy need of many industrial processes.[105]

As discussed in the previous section, energy market designs shall include provisions limiting carbon dioxide-equivalent emissions linked to the use of fossil fuels. That said, any market mechanism that disincentivises fossil fuel use or incentivises low-emission alternatives negatively impacts the energy affordability for industrial consumers. Regardless of the market mechanism in place, this price difference between today´s most competitive energy source and its low-emission alternative can be expressed by the cost per ton of atmospheric carbon dioxide-equivalent emissions (€/tCO_2e) required to make the low-emission alternative the cheapest option. This cost

[104] "emission pricing" can be representative for each of the three mentioned mechanisms. In case of 1.) a ban this is the financial impact in monetary terms of the penalty received for noncompliance, 2.) refers to a direct emission pricing mechanism and 3.) indirectly prices emissions by subsidising non-emitting technologies.
[105] According to data from EUROSTAT fossil fuels account for 58.4% of industrial energy consumption in Spain and 49.2% in the EU27 + UK (2018) (EUROSTAT, 2021b).

can be represented by a carbon pricing mechanism, such as a flat carbon tax or the cost of tradable carbon dioxide-equivalent emission allowances in an emission trading scheme like the EU ETS (section 4.2.3). But it can also be understood and implemented as the payment needed for not emitting a ton of fossil fuel by using low-emission alternatives. In the latter case, payments for emission avoidance in €/tCO_2e would take the form of a subsidy. For simplicity, we refer to the emission allowance cost in €/tCO_2e as the shadow price necessary to make low-emission alternatives competitive. In the case of fossil energy carriers, the emission cost becomes an additional cost position that must be added to expenditures for exploitation, processing, transport, and distribution to define their competitiveness and might become the predominant factor for fossil fuels with increasing emission costs.

Exemplary, the results for the case study of the Spanish electricity system in section 4.2.6 show the predominance of the costs associated with carbon pricing for the electricity market prices. In the **+CAP+RES** scenario, Natural gas power plants (CCGTs) only operate as peakers at a market price of 71.51 €/MWh (Figure 4-7). With an associated carbon price of 79.53 €/tCO_2e, about 64.5% of the CCGTs´ revenue is used to cover the cost of emissions.[106]

Increasing emission costs take on a similar role in the cost structure of fossil fuels for industrial applications. Energy-intensive industries relying on coal and natural gas can see their energy costs double compared to global and regional energy markets prices at relatively modest emission pricing levels. As shown in Figure 4-10, coking coal cost would double in comparison to the average coal benchmark price for Australian prime HCC in 2019 at an emission price level of 58.3 € per ton, while EU import prices for gas reach twice their 2019 market price average with an emission price below 70€ (67,4 €/tCO_2e), as long as free emissions allowances are not granted to fossil fuel consumers.

Future emission costs for fossil energy carriers have decisive implications for the affordability of energy-intensive production. First, the high share of emission costs in the final price of energy consumption means that global market price fluctuations for coal and natural gas would lose relevance in defining the final cost for industry associated with their consumption. In case local carbon pricing, e.g., within the jurisdiction of the European Union, final industrial energy prices would be decoupled from global market prices for coal, natural gas, or crude oil.

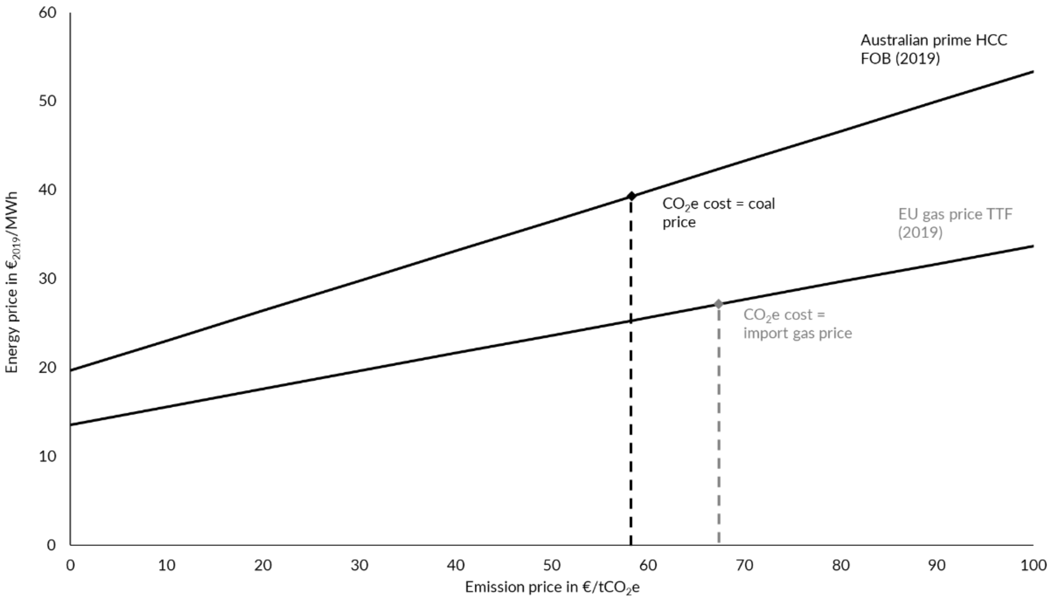


Figure 4-10: Coking coal FOB and EU natural gas import TFF prices (2019) for emission prices (IEA, 2020e, 2021a)[107]

[106] This ex-post calculation is based on an emission factor of 0.575 tCO_2 per MWh for CCGTs (Mearns, 2016)

[107] TFF = title transfer facility (virtual natural gas trading point in the Netherlands)

This decoupling means that energy-intensive industries would face significantly higher energy prices that threaten their competitiveness. Energy consumption is a key cost component in these industries, representing 24% of the gross operating surplus in refineries, 51% in the cement sector, 64% for organic chemicals, and 79% in the steel industry (EP ITRE, 2020).

Energy is a much smaller operational cost factor for the manufacturing industries. Emission prices affect the affordability of industries down the value chain much less than basic material producers. For products like cars, the end-consumer price is primarily defined by the added value based on the functional characteristics of the car. For the exemplary calculations presented in (Rootzén and Johnsson, 2016), steel cost only accounts between 1.7 and 1.8% of the final sales price.[108] That said, an emission price of just 30 € per ton would have a much more significant impact on intermediate products such as gearboxes than on the final consumer product, as shown in Figure 4-11. Higher basic material prices mean that manufacturers opting for or required to use low emission basic material would face higher production costs than competitors, which reduces their competitiveness compared to other producers that operate in energy markets that do not have to comply with the criteria of emission avoidance.

Basic materials are globally traded commodities (section 2.3.2). With only local carbon pricing mechanisms in place, such as the EU ETS in the European Union, the gearbox manufacturer mentioned before could also buy basic materials from basic material producers outside Europe that do not face carbon costs. This profit-maximising behaviour would only reduce direct carbon dioxide-equivalent emissions locally and would not affect the indirect emissions intensity of industrial production. With no global emission pricing in place, additional market mechanisms would be required to prevent such carbon leakage effects.[109] However, local carbon pricing also implies that future energy markets move from a global market to local markets with much higher energy prices for industrial consumers. It raises concerns about whether local economies and industries can afford these additional costs while operating on a global market for manufactured goods.

IV.VI(3): Without pricing emissions globally, emission avoidance would create local fossil energy markets with weak links to global market prices. There may be demand for industrial fossil energy carriers that creates a need for these local markets if other policies prevent carbon leakage of direct and indirect emissions by strengthening industrial competitiveness.

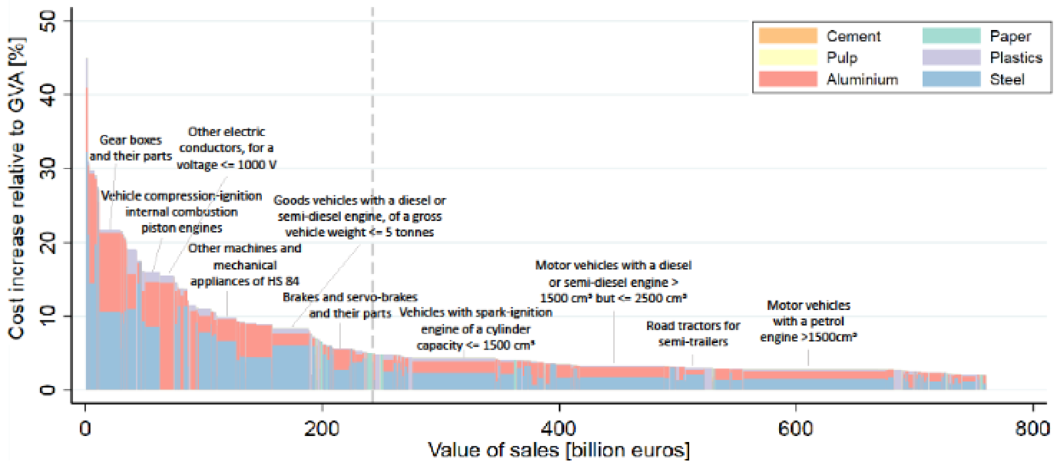


Figure 4-11: Cost increase of different products with a 30 €/tCO_2e emissions cost (adapted from (Stede et al., 2021))[110]

[108] Assumptions: steel price incl. shipping and without emission costs of 485 €/tonne with a steel consumption between 742 and 959 kg per vehicle. Sales price of 20,000 € for gasoline and 27,500 € for diesel cars.

[109] *See*, section 5.4.2 for a more detailed analysis of policies to prevent carbon leakage.

[110] Products and product groups as listed in the EU-27 PRODCOM manufacturing database.

Adequacy of fossil fuels

Burning fossil energy sources has been an adequate way to obtain process heat for high-temperature industrial processes. Direct electrification is not technologically feasible for many applications, so that heat generation by incineration is the only technology option for many industrial processes (section 3.3). Operating these processes without emitting fossil carbon can be achieved if replacing today´s fossil energy carriers with low-emission alternatives.

A one-to-one replacement of fossil fuels by hydrogen might be an easy fix. Even though the flammability characteristics of hydrogen differ from fossil fuels, better process control could permit many of today´s industrial processes to do this switch (McAllister et al., 2011). Technological feasibility by itself does not make hydrogen an adequate low-emission alternative. Extending Figure 4-10 by adding cost estimates for hydrogen that are based on IEA data (IEA, 2019a), we can show that even with low-cost estimations of 2€/kgH_2, emission costs would have to reach the equivalent of 120 € per ton to be competitive with coking coal utilization and 210 € per ton for natural gas (Figure 4-12). Things look different if the transition of a specific industry implies a technology change (steel BF-BOF to DRI-EAF). In section 3.3.1, abatement costs between 40 and 60 €/tCO_2e have been identified in the literature. Energy is used differently and more efficient since coking coal is not used as a reduction agent anymore. Carbon capture options are expected to be economically competitive in the cement and steel industry, with abatement costs below 100 €/tCO_2e (sections 3.3.1 & 3.3.3). Consequently, the continuous use of fossil fuels might be an adequate solution for specific CCS applications. Even though this cost analysis that has been summarised in Figure 4-12 is highly simplified, we can conclude that one of the propositions identified for future electricity markets in section 4.2.7 is also applicable to all other energy markets.

IV.VI(4): Any energy market design should be as technology-neutral as possible to support the implementation of adequate technologies for avoiding emissions most affordably.

4.3.4. Hydrogen

From all the energy carriers we include in this analysis, hydrogen is the only low-emission alternative for which no energy market exists today. As feedstock, hydrogen is one of the most used industrial gases and plays an essential role in the petrochemical and fertiliser industry, mainly to produce ammonia for the fertiliser industry. Approximately 8.2 Mt annually are made from natural gas via steam methane reforming (SMR) within the EU (Kakoulaki et al., 2021). Today´s industrial use also explains the high technological maturity of so-called "grey hydrogen" from fossil energy carriers and its low-emission equivalent "blue hydrogen", for which SMR is combined with carbon capture technologies to reduce its carbon footprint from 8.9 kg to less than 0.9 kg of CO_2 per kg of hydrogen (Collodi et al., 2017). An alternative to SMR that allows for emission-neutral hydrogen production is the electrolysis of water (H_2O). Electricity, rather than heat intensive, so-called "green hydrogen" can potentially replace fossil fuels as an energy source that causes neither direct nor indirect carbon dioxide-equivalent emissions and decarbonise consumption. In the following, we review blue and green hydrogen options and their suitability to comply with emission avoidance, affordability, and adequacy objectives.[111]

Avoiding emissions with hydrogen

The math is quite simple. By substituting a fossil energy carrier with green hydrogen, we can abate their fossil emissions. Since lignite and mineral coal cause more emissions than fuel oil or natural gas, absolute and relative emission reduction differ depending on the fossil energy carrier, we replace with a low or non-emission alternative (Table 4-C). The same holds if we use hydrogen instead of fossil sources as feedstock, for example, in the steel, plastics, or fertiliser industry. New process technologies need to be installed that also change the energy need of the production

[111] Many recent publications state methane pyrolysis or "turquoise hydrogen", the production if hydrogen from natural gas with solid carbon as by-product as another low-emission pathway. This technology, though, is still in early development phases and many challenges, such as lows yields and high process temperatures need to be overcome (Bhaskar et al., 2021).

process and make it more challenging to estimate emission abatement for blue hydrogen consumption or partially decarbonised electricity supply.[112]

Even after substituting all feasible energy and feedstock options with green hydrogen, unabated process emissions would prevail in some industries. Graphite anode consumption in aluminium electrolysis, burning limestone in cement kilns or, to a lesser extent, keep using crude oil as feedstock for high-value chemicals causes fossil carbon dioxide-equivalent emissions that cannot be avoided by hydrogen and energy carrier and feedstock. This observation is not limited to hydrogen only and applies to the consumption of any zero or low emission energy carrier in the industry.

IV.VI(5): Market mechanisms only addressing the emission reductions linked to energy consumption need to be accompanied by non-energy market mechanisms that can abate process emissions.

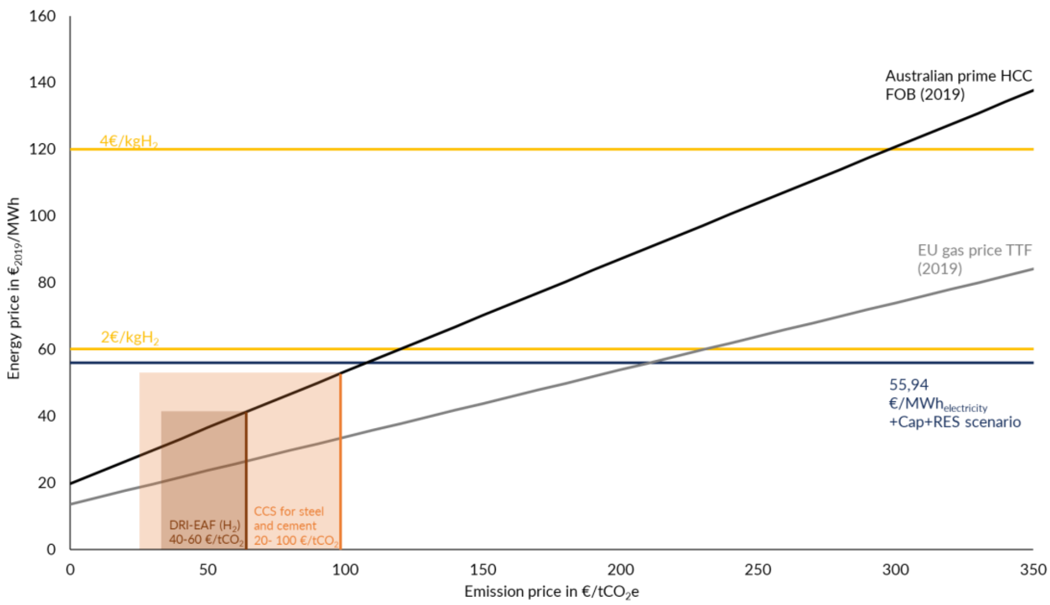


Figure 4-12: Coking coal FOB and EU natural gas import TFF prices for 2019 compared to hydrogen costs (IEA, 2019a)[113]

Table 4-C: Emission reduction if replacing different types of fossil fuels with zero or low emission hydrogen[114]

	Lignite	Mineral coal	Light fuel oil	Natural gas
Green hydrogen from renewable electricity	- 110.9 tCO_2/TJ (100.0% reduction)	- 93.6 tCO_2/TJ (100.0% reduction)	- 74.0 tCO_2/TJ (100.0% reduction)	- 55.9 tCO_2/TJ (100.0% reduction)
Blue hydrogen from natural gas (90% capture)	- 105.3 tCO_2/TJ (95.0% reduction)	-88.0 tCO_2/TJ (94.0% reduction)	- 68.4 tCO_2/TJ (92.4%)	- 50.3 tCO_2/TJ (90.0%)

Affordability of hydrogen

Due to its material characteristics, hydrogen has been the first choice for many commercial applications since the industrial revolution. Playing an essential role as industrial feedstock, especially in the chemical industry, its use as lift gas in airships marked the rise and fall of an

[112] *See*, (Chiappinelli et al., 2021) and in particular Annex 1.2 for the changing energy need for novel industrial processes.
[113] Based on Figure 4-10. All energy costs compared in this figure exclude (carbon) taxes, additional charges, transmission and distribution costs, which are different for each of the energy vectors.
[114] Fuel emission factors in tCO_2/TJ based on (Umweltbundesamt, 2016).

entire transportation sector.[115] But not even airships relied on hydrogen as fuel but were propelled by diesel engines. Likewise, hydrogen has never been used as an energy carrier for large-scale commercial applications. Fossil fuels were more affordable and remain the most competitive energy carrier today. As such, the operator of an industrial production side has little incentive to replace mineral coal, its derivatives or natural gas consumption for heating purposes by hydrogen. With reference to the analysis of fossil fuels in section 4.3.3 (Figure 4-12), hydrogen can only be an affordable option for meeting industrial energy demand if emission-intensive energy consumption is disincentivised, for example, by emission pricing.

The relatively high cost to obtain hydrogen compared to other energy carriers is due to its production process. Fossil fuels are primary energy sources that only need little pre-treatment before being burned to create process heat. On the other hand, hydrogen does not occur in its elementary form on earth, so either methane (CH_4) or water (H_2O) molecules must be split by non-spontaneous reactions requiring external reaction energy. As summarised in Table 4-D, green and blue hydrogen production have an energetic process efficiency with state-of-the-art technology (SOA) of around 50% to slightly above 60%.

Either when transforming water molecules via electrolysis or natural gas to blue hydrogen via methane reforming and CCS. Energetically, the use of hydrogen is always less efficient than the direct consumption of electricity or natural gas. Therefore, the levelised production cost of green hydrogen (LCOH) per unit of energy always exceeds the levelised cost of generation for the consumed electricity (LCOE). Correspondingly, without a market

$$LCOE < LCOH_{green} \text{ and (without emission pricing) } LCONG < LCOH_{blue}.$$

Introducing emission pricing does not affect the relationship between electricity and green hydrogen prices, given that electricity generation would be fully decarbonised. Pricing emissions, though, does change the cost structure of both blue hydrogen and natural gas. Blue hydrogen requires investments in SMR and CCS technology, while the energy consumption of these technologies lowers the nominal efficiency of the process. By capturing 90% of the process emissions, blue hydrogen production facilities would still have to pay for their residual emissions. Natural gas consumers, on the other hand, would have to face the full carbon price. Figure 4-13 visualises how different carbon and natural gas market outcomes influence the competition between blue hydrogen and natural gas for end uses. Without emission pricing, natural gas is always the cheaper option of the two energy carriers.

Nevertheless, blue hydrogen becomes competitive at 105 €/tCO_2e for the hypothetical case that natural gas costs are zero.[116] At first sight, a paradox, the competitiveness of blue hydrogen declines with higher natural gas prices. At the EU 2019 TTF reference price (Figure 4-10), blue hydrogen requires an emission price of 140 €/tCO_2e, and at a natural gas price of 20 €/MWh, blue hydrogen would only be competitive with a carbon price of 150 €/tCO_2e.

Due to its energetic inefficiency, blue hydrogen production requires input energy as natural gas, equivalent to about 145% of the output energy as hydrogen. Therefore, higher natural gas prices disproportionally increase the energy and feedstock costs of blue hydrogen production facilities. Additionally, emission costs reflect the emission intensity of natural gas and not its market prices. With higher natural gas market prices (€/MWh) and constant emission allowance cost (€/tCO_2e), the relative price increase of natural gas consumption due to emission prices decreases. For the same reasons, the final cost of blue hydrogen is much more sensitive to natural gas price changes than to higher carbon prices.

[115] The Hindenburg disaster on May 6th 1937 put an end to regular commercial flight services with airships. The biggest airship ever built used hydrogen as floating gas that inflamed during a landing approach at Manchester Township, New Jersey, United States.

[116] Transport and storage cost for captured carbon emissions have not been taken into consideration for this figurative example. Plant costs by (Collodi et al., 2017) have been used: 3100 €/(m^3/h) installation cost with a 25 years design life and 8000 operational hours per year and an 8% discount rate per year. Additionally fixed O&M costs, equivalent to 18.3% of the capital cost have been included.

While natural gas prices might fluctuate in the medium-term, IEA long-term sustainable development scenarios foresee natural gas prices beyond 20 €/MWh for Europe, potentially reducing the competitiveness of blue hydrogen even further ("Outlook for natural gas," 2017).[117] Since both SMR+CCS technology and natural gas exploitation are relatively mature technologies, significant innovations and associated cost reductions for blue hydrogen are not likely, and long term predictions foresee costs around 1.5 –3 $/kg$H_2$ (IEA, 2019a).

Table 4-D: BAT and prospective future efficiencies in 2050 for green and blue hydrogen production

	Green hydrogen from renewable electricity			Blue hydrogen from natural gas
	AEL	PEM/PEMEL	SOEC/SOEL	SMR+CCS
Energy density H2	120 MJ/kg (lower heating value)			
BAT Electric energy demand	200-235 MJ/kg	200-261 MJ/kg	146-158 MJ/kg	
BAT Thermal energy demand				42 MJ/kg
BAT Natural gas feedstock				149 MJ/kg
BAT Nominal system efficiency	51–60%	46–60%	76–81%	69%
BAT Sources	(Buttler and Spliethoff, 2018)			(Collodi et al., 2017)
2050 Nominal efficiency	> 73 %		> 83 %	<74%
2050 Sources	(Taibi et al., 2020)			(Abad and Dodds, 2017)[118]

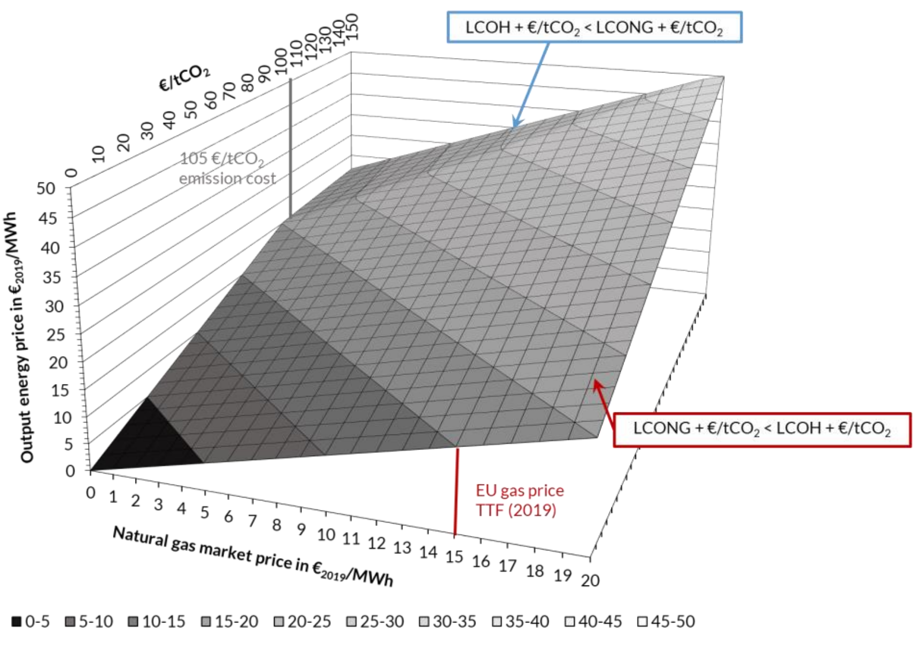


Figure 4-13: Cost competition between direct natural gas consumption and blue hydrogen production[119]

Parallel to blue hydrogen, the cost drivers of green hydrogen are energy and plant costs. The difference is that both operational and investment cost drivers are expected to decline significantly. LCOE for new wind and solar generation capacity may experience further cost

[117] The IEA states prices between 7.9 and 10.4 $(2017)/MBtu for Europe in their different long-term price scenarios from 2025 until 2040. Equivalent natural gas prices of 24.1 and 31.7 €(2019)/MWh require carbon prices of about 95 €/CO_2e and 115 €/CO_2e to make blue hydrogen competitive to natural gas.
[118] The source states that the state-of-the-art system efficiency for steam reforming without CCS is approximately 74%. Given the maturity of the SMR process we expect that future combined SMR+CCS systems will not exceed an energetic efficiency of 69% as for the system presented in (Collodi et al., 2017).
[119] Assuming a SMR+CCS plant with operational costs stated in (Collodi et al., 2017).

reductions in the future (IEA, 2020c). At the same time, electrolyser efficiency is set to increase while their costs decline. Recent estimations by IRENA (Taibi et al., 2020) show that hydrogen production costs of around 1 $/kgH$_2$ are possible long-term. This perspective motivates a closer look at the different cost drivers for green hydrogen and its competitiveness with blue hydrogen.

As shown exemplarily in Figure 4-14, the electrolyzer plant and electricity expenditures affect the production cost of green hydrogen differently. Assuming an annual uptime of 4000 full load hours for an electrolysis plant with dedicated RES electricity generation and an electrolyzer plant cost of 500 €/kW[120], the actual cost-share related to the electrolyser equipment is approximately 11.7 €/MWh of the produced hydrogen. Electricity costs are the main cost driver, so that hydrogen production costs increase proportionally with energy prices. Different electrolyser costs change the baseline component of the total production cost. Still, even in the case of system costs for currently available technology beyond > 1000€/kW, the electrolyser´s capital cost only accounts for > 0.40 €/kgH$_2$. The electricity cost component of green hydrogen production can be reduced by improving the efficiency of available electrolyser technologies. This reduction, however, can only lower the relative electricity cost. In the case of low electricity prices and a relatively high electrolyser cost, these efficiency improvements would have a relatively minor impact on the final production cost of green hydrogen.

Figure 4-14 also shows the reference price for blue hydrogen production with average EU TTF (2019) gas prices. For this illustrative example, the price parity between blue hydrogen and green hydrogen is at 24 €/MWh of zero-emission electricity at an emission price of 50 €/tCO$_2$e.[121] Considering the secondary role of electrolyser costs and average future electricity market prices beyond 55 €/MWh for the +CAP+RES scenario in 2030, green hydrogen from dedicated RES power plants may be the most affordable way to produce hydrogen in the future.[122]

While we must acknowledge a modest degree of uncertainty concerning the stated cost figures,[123] this analysis shows how different components define the cost of hydrogen and its competition to blue hydrogen. The various cost drivers that can change the price parity between blue and green hydrogen and define the competition between these two production routes over the upcoming decades are summarised in Figure 4-15.

Since natural gas prices in Europe are expected to rise rather than decline compared to the 2019 TTF reference, the production cost of blue hydrogen is more likely to increase in the future. Especially when looking at the Spanish case, where carbon capture faces public opposition on a national level (Upham and Roberts, 2011), the availability of largely unused land with low biodiversity and high solar radiation potential makes hydrogen from Spain the most competitive within the European Union (Brändle et al., 2020; IEA, 2019a), a hydrogen economy based solely on green hydrogen is the more likely scenario.

Higher prices for natural gas also mean that the required emission pricing to make green hydrogen competitive to natural gas diminishes. However, competitiveness without any emission pricing remains unlikely but not impossible. For natural gas prices of 15 €/MWh, an LCOE of less than 3 €/MWh would be needed, while doubling the natural gas price requires a RES LCOE of 14 €/MWh for hydrogen to be competitive, assuming an electrolyser cost of 500 €/kW (Figure

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[120] Data published by (Buttler and Spliethoff, 2018; Taibi et al., 2020) is used for formulating these cost estimates to reflect current cost of Alkaline/PEM systems and future cost of various technology options including potential stack replacement costs for this figurative example. Weighted cost of capital: 8%.

[121] An LCOE of 24 €/MWh corresponds to the value forecasted by Goldman Sachs for solar PV in Spain by 2024, while it is expected to reach 19 €/MWh by 2030 (Goldman Sachs, 2018).

[122] *See*, section 4.2.6 for the average reference price of 55.94 €/MWh in the +CAP+RES scenario for 2030. As shown in Figure 4-14, doubling electrolyzer utilization from 4000h to 8000h and thereby reducing relative plant cost by half to 5.85 €/MWh of H$_2$ has not major effect on the competitiveness of green hydrogen. For both load hour scenarios, the same average efficiency is assumed.

[123] Price parity is at 1.42 €$_{2019}$/kgH$_2$. This price is lower than IEA estimates and should not be taken as a reference since no transport costs for gas are included and it should be acknowledge that the EU TTF (2019) gas price was about half of the long term average in 2019 (IEA, 2020e; "Outlook for natural gas," 2017).

4-14). However, bringing down LCOE and thereby LCOH to such low levels is impossible without large-scale technology introduction that fosters innovation and drives down technology costs for electrolysers and RES in the long run.

IV.VI(6): Hydrogen can only become the most affordable energy carrier if fossil fuels are not primarily priced based on exploitation and transport cost, meaning that market mechanisms are needed to improve the competitiveness of hydrogen by reducing the affordability of fossil fuels.

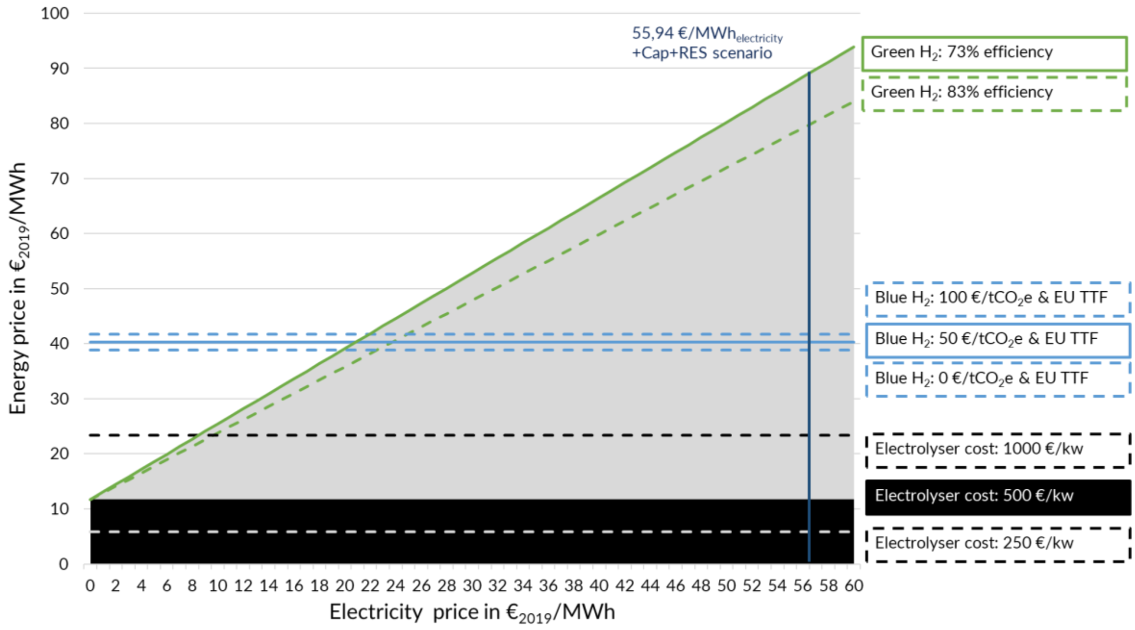

Figure 4-14: Reference costs scenarios for blue and green hydrogen for varying electricity and electrolyser costs

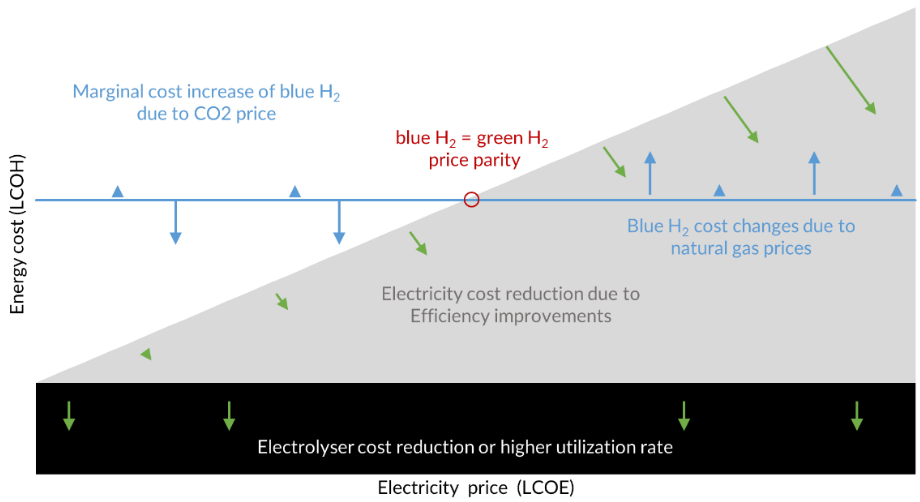

Figure 4-15: Simplified overview of cost drivers that define the price parity of green and blue hydrogen

Adequacy of hydrogen

Hydrogen has very different energetic characteristics than natural gas or mineral coal if used to generate process heat. Due to its different flame velocity and combustion behaviour, the total substitution as an alternative for natural gas is not feasible and blending options are limited (de Santoli et al., 2017). Besides the limited adequacy for replacing fossil fuels without adjusting existing installations, there are processes in some industries that can easily incorporate low-emission hydrogen flows. For example, ammonia production in the chemical industry or novel process designs based on hydrogen as energy and feedstock stream, such as DRI-EAF steelmaking (see section 3.3). Independently from the technical adequacy that might imply replacing equipment and associated investments in new hydrogen-friendly technologies, hydrogen has one additional advantage compared to the electrification of processes: its flexibility.

The flexibility of hydrogen production allows for the operation of electrolysers with electricity costs that correspond to the levelised cost of electricity for new RES installations (LCOE).[124] In contrast, direct electricity consumption by the industry is subject to fluctuating electricity market prices with significantly higher average market costs. Industrial consumers may adapt their electricity consumption profiles to respond to fluctuating electricity market prices, for example, by installing battery storage. Suppose such systems are not technically or economically feasible. In that case, hydrogen might be an adequate option, but only if there are competing technologies for electrification or hydrogen use for the specific industrial use case. Figure 4-16 sketches this competition between direct electricity consumption, the potential of demand response for industrial applications, and hydrogen consumption as a function of the available process flexibility. Note that the completion between hydrogen and other demand response options depends primarily on the use case, given that hydrogen combustion provides thermal energy demand. With reference to section 2.2, this applies mainly to applications with heat demand below 150ºC, primarily used in non-energy intensive industries. Transport and storage are also substantial cost factors in a hydrogen economy, but other than electricity, no prior transformation is needed to store hydrogen within the gas network, caverns or other storage facilities (Gas for Climate, 2020).

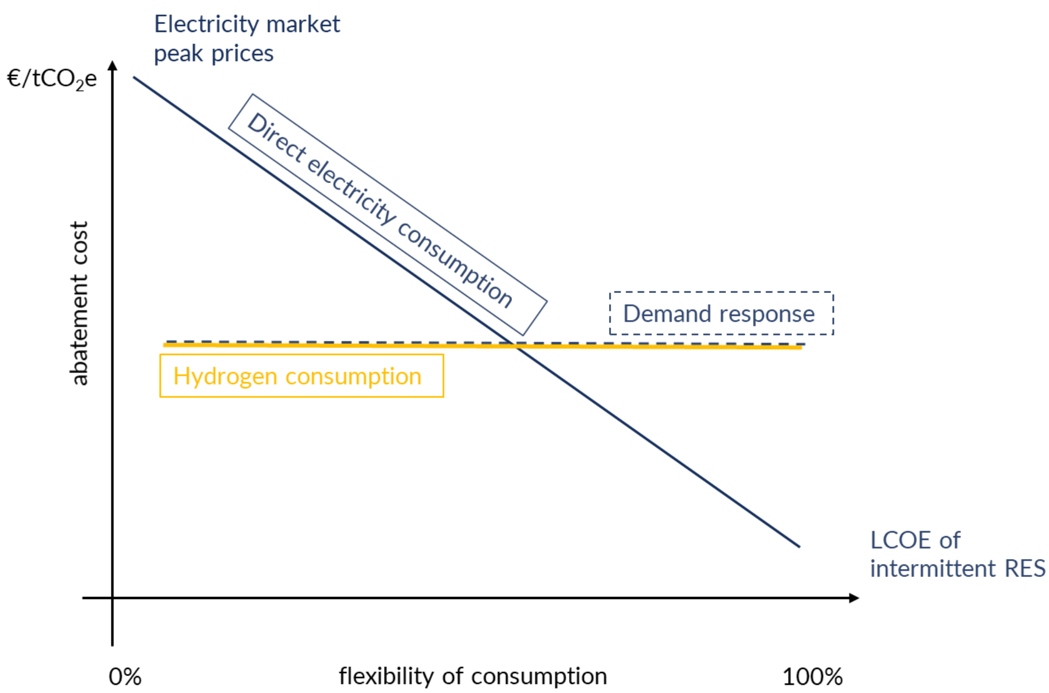

Figure 4-16: The competition between hydrogen and demand response option for offering flexibility

[124] This statement is subject to relatively low storage costs for hydrogen. Other than electricity, hydrogen can be stored without losses but

Though always more expensive than the direct consumption of electricity from intermittent RES sources, this consumption flexibility may make hydrogen the more adequate energy carrier than direct electrification for some industrial applications.

IV.VI(7): Hydrogen can offer consumption flexibility, making it an adequate alternative energy carrier for some industrial applications that could electrify their heat provision, given that markets correctly value the ability of energy carriers for providing flexibility.

4.3.5. Biomass

Energy from biogenic sources is an important energy carrier for the European industry. In Spain, about 7.1% of industrial energy use was met with biomass in 2018[125], used primarily in those industries that process biobased feedstock, such as papermaking, the food industry, furniture and textile. It also plays a vital role in the cement industry (EUROSTAT, 2021b). Estimating the additional potential and related emission abatement of biomass is challenging.

Biomass does not refer to one chemically homogenous material but a heterogeneous group of various biobased energy sources with different energetic potential, degrees of humidity and carbon content. Considering these challenges linked to biomass use, I focus on biomass´s ability to adequately deliver affordable emission avoidance from a holistic perspective to identify the key proposition for evaluating the use of biomass in the industry.

Avoiding emissions with biomass

It is an easy fix to assume that biomass is carbon dioxide-equivalent emission neutral by design. Such generalisation, though, ignores the existence of various emission sources that are linked to the production and the processing of biomass. The use of wheat straw for electricity generation in Spain, for example, causes emissions between 41 and 70 tCO_2/TJ (147.6 – 252.2 $kgCO_2$/MWh) linked to fertiliser use, agricultural machinery operation, and transport (Sastre et al., 2015). Indirect emissions can be even higher if forests and other natural habitats are transformed into agricultural land to produce biomass (Fritsche et al., 2010). The exclusion of some sustainable biofuel certification schemes by the European Union is representative for the difficulty to evaluate the sustainability of biomass (European Court of Auditors, 2016).[126]

Next to the difficulty to evaluate its emission abatement potential, burning biomass causes secondary emissions. Using biomass in furnaces and kilns emits metals in ash and other elements such as silica, sulphur and chlorine that may cause local emissions and are a severe threat to the health of local communities (Demirbas, 2005). Representatives from the cement industry confirmed these challenges related to secondary emissions. This industry could potentially replace all its energy demand with biomass, but avoiding these secondary emissions is a significant barrier.[127]

IV.VI(8): Biomass can avoid emissions, but its potential depends on the use case and cannot fully decarbonise industrial processes.

Affordability of biomass

In parallel to the complexity of estimating its emission reduction potential, the heterogeneity of biomass resources makes it challenging to estimate their costs. Each type of biobased feedstock has different costs associated with preparing, planting, harvesting and exploiting its energetic value. For some industrial sectors, biomass is already the most competitive energy source today. As mentioned before, biomass also serves as feedstock to their production processes for most of

[125] Including biomass, biogas, biofuels and biogenic waste consumption.
[126] *See*, the analysis presented in (Gerres et al., 2021).
[127] These concerns have been mentioned on several instance by Spanish and European cement industry representatives during the round table events that we organized as part of the Climate Friendly Materials Platform (https://climatestrategies.org/projects/european-climate-friendly-materials-platform/) since 2018.

these industries. Their biomass consumption is partially based on the energetic utilization of biobased waste streams (sections 2.2.1 and 3.3.6).

Higher biomass shares in these industries and other applications depend on the characteristics of the available biomass or require biomass conversion to biogas. Biogas, or biomethane, is a homogenous gas with a chemical structure similar to natural gas, consisting primarily of methane (CH_4), which can be used in most natural gas applications as an energy source. In Europe, the average price of biomethane was $16/MMBtu in 2018, equivalent to 49 €$_{2019}$/MWh (IEA, 2020f), about four times the price of natural gas or coal (section 4.3.3). While resource availability is limited, these prices would rise further if biomethane demand increases, implying the exploitation of more expensive biomass sources for biomethane production.

Available literature about the cost of biomass does not give a clear picture of its economics. Based on estimates published by IDAE for Spain (Table 4-E), biomass seems to be a competitive alternative. Nevertheless, these low-cost estimations have to be looked upon carefully. More detailed studies tend to identify more cost drivers for biomass exploitation. Agar et al. (2020) estimate the cost of retrieving surplus forestal biomass including collection and transport operations in Sweden to be between 7.528 €/TJ and 10.250 €/TJ (27 - 36 €/MWh), about double the cost of natural gas or coal and up to three times the estimates for the same biomass resource by IDAE. Furthermore, potential exploitation costs do not reflect the market price.

In the case of Spain, actual market data, also published by IDAE, show that the market price for one ton of wood for thermal use was 109 € in 2015 and increased to 146 € in the first trimester of 2019 (IDAE, 2019).[128] Also, record-high lumber prices for non-energetic use cases, such as construction, that could be observed in Europe and on global markets in April 2021 (Arnold, 2021) can inflate the price of other biobased resources and reduce the competitiveness of biomass as an alternative energy carrier.

All these different factors and market dynamics that determine the price of biomass make its economic evaluation for industrial applications highly complex. Biomass economics is a field of research by itself with many open questions that concern its competitiveness. Therefore, when evaluating scenarios with biomass use for industrial applications, results should be contrasted and studied together with other decarbonisation options.

IV.VI(9): Scenarios that consider biomass as an alternative energy carrier for specific industrial applications should be compared to alternative decarbonisation options to identify the maximum marginal cost for biomass that would justify its use case.

Table 4-E: Maximum biomass potential in Spain and average associated cost[129]

		Available biomass		Average Cost		
		kt/year	TJ/year	€/t	€/TJ	€/MWh
Existing forestal stock	Wood debris	2.984	26.628	30	3.362	12.10
	Entire trees	15.731	142.937	49	5.393	19.41
Agricultural debris	crops	14.435	1.279.193	24	573	2.06
	woody	16.118				
Bioenergy (crops) from agricultural land		17.738	742.655	61	1.458	5.25
Bioenergy (woody) from agricultural land		6.599	276.287	41	979	3.52
Bioenergy (woody) from forestal stock		15.072	631.034	48	1.146	4.13
Total		88.677	723.772			

[128] Another report by IDAE (IDAE, 2009) states that wood for thermal use (leña) has an energy content of 4.0-4.5 kWh/kg so that a price of 146€/t is equivalent to 32.4 - 36.5 €/MWh.

[129] According to the 2011 report by IDAE (applying a 14.21% inflation factor for the period between 2010 and 2019) (Margarit i Roset, 2011).

Adequacy of biomass

Similar to hydrogen, the adequacy of biomass for future energy uses has at least two different dimensions. Firstly, biomass is only an adequate low-emission alternative for delivering process heat for some industrial applications due to its heterogeneous characteristics. Many processes such as steel, glass or ceramic production require rigid temperature control (section 3.3). They cannot use heterogeneous fuels that might cause impurities within the final product. Biomass could only be used in the form of biogas. Biomass already plays an essential role in some sectors that can fully or partially cope with its burning characteristics. Besides industries that process biobased feedstock, like paper making or the food industry, cement can be produced using biomass as the only energy carrier. Already demonstrated at the former Maastricht cement plant in the Netherlands back in 2008 (Zhu, 2011), high biomass utilization rates require relatively pure feeds and adequate measures to reduce secondary process emissions. The previously cited report also states that nearly 100% biomass shares were not achieved in 2009 due to missing biomass availability, which is exemplary for the second dimension of biomass adequacy.

Sustainable biomass is only of limited availability. As highlighted by (Material Economics, 2021), there is a 40-70% gap for sustainable biomass supply for a decarbonising economy in the European Union, with 18-19 EJ demand derived from the latest long-term climate scenarios compared to merely 11 -13 EJ of available supply.[130] Here, industrial applications compete with potential demand growth for biomass and biofuels in other sectors. Especially the decarbonisation for maritime shipping and air travel contemplate an elevated share of biobased fuels (IEA, 2021b). Since resource scarcity already leads to net imports of biofuels to the EU, accounting for roughly 4% of consumption in 2019 (EC, 2019c), biomass use for industrial applications should be evaluated along with the following proposition.

IV.VI(10): Sustainable biomass is a limited resource and shall be reserved for applications with no or only very cost-intensive second-best alternatives to decarbonise.

[130] Other estimates for Spain contemplate a technical potential for biomethane production below 70 PJ by 2030 (Baldino et al., 2018), only 0.6% of the EU estimates presented in (Material Economics, 2021).

4.4. Discussion

Over this chapter, we looked upon the transition of energy systems from two slightly different angles. Whereas the first part (section 4.2) presents a case study of the Spanish electricity system and, based on the results, identifies challenges for future electricity market designs, the analysis presented in the second part (section 4.3) is a more holistic analysis of emission avoidance, affordability and adequacy objectives in energy markets and their implication for decarbonising industrial energy demand. In the following discussion section, I use the propositions I made for decarbonising industrial energy demand in section 3.4 to show that future electricity market design challenges identified in section 4.2 may also apply to the transition of other energy systems.

IV.I: The policy design should acknowledge the clear interdependency among the three objectives: affordability, adequacy, and emission avoidance.

Section 4.3.1 shows that these three objectives must equally apply to all energy markets, not only the electricity market. As such, additional policies might be necessary to ensure that all energy markets comply with these objectives. While the analysis of these different energy carriers primarily focuses on its implication for industrial end-uses, it nevertheless hints at the interdependencies of these objectives for other energy carriers.

The call for market mechanisms to improve the competitiveness of hydrogen in comparison to fossil fuels in proposition IV.VI(6) highlights the interlinkage between emission avoidance and affordability objectives. At least for the early phases of the transition towards the decarbonisation of our energy systems, hydrogen would be a more expensive energy source compared to fossil fuels. Policy design can make hydrogen more competitive but results in extra costs. These costs would have to be recovered by a market mechanism, thereby reducing the affordability of energy supply for industrial applications.

Proposition IV.VI(10) also shows that this interdependency affects the adequacy of different energy sources to reduce industrial emissions. Our observation that biomass is a limited resource and should be used for applications with no or only very cost-intensive second-best low-emission alternatives implies prioritising biomass use for some industrial applications over others. However, such prioritisation might result in higher sector-specific abatement costs for those industries that consider biomass their cheapest decarbonisation pathway but would not have access to biomass as an energy carrier due to its limited availability. One notable example of this proposition´s implications is the recommendation by (Material Economics, 2021) to stop using biomass as a transport fuel additive and rather electrify the transport sector to make limited biomass resources available for other end-uses.

IV.II: Alternative policies aiming to achieve the same objective may have a different impact on other objectives.

Since the analysis in section 4.3 does not focus on contrasting different policy designs, one needs to take proposition IV.VI(3) about industrial energy consumption one step further and foreshadow some findings presented in Chapter 5.[131] Based on proposition IV.VI(3), we can outline the different impacts of two emission avoidance policy designs on affordability and adequacy objectives. The proposition contrasts the role of global and local emission pricing for fossil fuels, stating that in the latter case, there would only be local industrial demand for fossil fuels if other policies prevent carbon leakage.

Global and local emission pricing are two policies that aim to avoid emissions by putting a price on fossil carbon. With global emission pricing in place, the competition between industries from different jurisdictions changes based on the emission intensity of production. European steel producers, for example, could maintain their competitiveness compared to imports if switching to low-emission production routes. Affordability for steel products from all competitors would be lower since emission pricing would affect the worldwide market. Implementing only local emission pricing, though, would only impact the competitiveness of local emission-intensive

[131] *See*, discussion about carbon leakage in section 5.4.2.

companies. The European steel producers mentioned before would face additional costs for emission pricing that reduce the affordability of their products compared to global competitors. Without any additional policies in place, local emission pricing would reduce emissions locally by jeopardising the business case of local emission-intensive companies and, *in extremo*, putting them out of business. It would have a negligible impact on the affordability of emission-intensive products for local consumers since imports would replace local production since transport costs are of minor importance for bulk materials.

Given that global warming and the need for emission avoidance are global challenges, a local emission pricing policy would be inadequate to reduce emissions. It could even cause higher global carbon dioxide-equivalent emissions by replacing domestic production with more affordable emission-intensive alternatives from unregulated jurisdictions available on the global market (OECD, 2006). Without policies preventing carbon leakage (section 5.3), local industrial demand would disappear, and in line with proposition IV.VI(3), the need for local fossil fuel markets serving industrial consumers.

IV.III: Policy designs that are not fully aligned with the system objectives may lead to undesirable outcomes.

Based on the findings in the first part of this chapter (section 4.2), this proposition was motivated by the partial incompatibility of RES quota policies with the three main objectives in electricity markets. By analysing the other energy markets and especially their role for industrial demand, I highlight with proposition IV.VI(5) that market mechanisms cannot be limited solely to energy consumption to achieve emission avoidance objectives. For some industries, emissions are also linked to chemical reactions during the production process, so market mechanisms that only focus on reducing energy-related emissions would fail to meet decarbonisation targets. This proposition shows that even policy design that targets only emission avoidance might lead to undesirable outcomes if it does not cover all but only a specific group of emissions.

Similar concerns arise in the context of proposition IV.VI(8), acknowledging that biomass can avoid emissions but that its reduction potential depends primarily on the use case, and full decarbonisation with biomass would not be achievable. Like RES quota requirements, policies that only target higher biomass shares disregard the emission intensity that might be linked to its production and use and might foster its consumption by industries for which biomass is inadequate for reducing emissions. As such, the implications of the 3rd proposition may also universally apply to other energy markets and not just the electricity market.

IV.IV: Policy design should be as technology-neutral as possible to reach any of the system objectives.

With proposition IV.VI(4), I show that technology-neutrality is equally important for other energy markets as for the electricity market to avoid emissions most affordably. Two other propositions provide more specific examples of how technology-neutrality is needed to meet the three main objectives.

Proposition IV.VI(7) highlights that hydrogen might be an adequate alternative to offer flexibility for some industrial applications, therefore justifying higher energy costs than other low-emission alternatives. However, such flexibility services must be valued by the market design. This proposition references the results presented in section 4.2.7 that call for a technology-neutral remuneration of flexibility services to comply with adequacy objectives. Also, on the (industrial) demand side, consumption adequacy must be valued technology-neutral to allow energy markets to comply with three main objectives.

Proposition IV.VI(9) primarily targets difficulty to evaluate the affordability of biomass, calling for a comparison of biobased decarbonisation options with other alternatives to identify the maximum marginal cost for biomass that would justify the use case. Not directly targeting technology-neutrality, this position highlights the importance of being open to various technology alternatives that potentially can avoid emissions most adequately at the lowest cost while not discriminating between them.

IV.V: When pricing different services (energy, adequacy, emissions), policy designs impact consumption and thereby the need for additional services.

The industry is a major energy consumer and subject to market mechanisms that price energy, adequacy, and emission avoidance. As stated in proposition IV.VI(1), when evaluating the direct electrification of industrial applications, we should contemplate variable electricity prices subject to adequacy pricing. As such, the suitability of electrification options for industrial applications also depends on their ability to operate cost-efficiently given variable prices and their ability to adjust production based on these price fluctuations. An industrial demand sensitive to electricity price fluctuations would reduce the need for additional mechanisms to ensure generation adequacy.

Proposition IV.VI(2) identifies a similar causality for fossil fuel markets that are exemplary for the effect of mechanisms in other energy markets. Fossil fuels might play an essential role in decarbonising some industrial applications with carbon capture technology that can partially avoid the emissions linked to fossil energy consumption. By adequately pricing emissions, fossil fuel consumption would be reduced to levels that comply with emission avoidance objectives. Abating emissions by using other energy carriers, such as electrification, hydrogen or biomass, would reduce total fossil fuel consumption, thereby supporting the business case for carbon capture technologies by lowering the associated emission pricing required to comply with emission avoidance objectives.

4.5. Conclusions

This chapter marks a departure from engineering and technologies to decarbonise the emission-intensive basic material sector. Instead of asking how to reduce industrial emissions, the second part of this thesis project looks at the energy system and analyses why its market design is decisive for industry-wide adoption of climate-friendly processes. Basic material production is emission-intensive because it is, first of all, energy-intensive. Without access to affordable low-emission energy resources, the industrial transition would remain wishful thinking. Therefore, this chapter is driven by the motivation to understand how energy market design can enable the decarbonisation of emission-intensive and hard to abate industries.

Section 4.2 first examines the electricity market and uses a Spanish case study to show that future electricity systems complying with emission avoidance, affordability and adequacy objectives require additional market mechanisms. Based on the results of this case study, we conclude that policies for introducing these mechanisms to the electricity markets face five main challenges, formulated as propositions. We then show that other energy markets are also subject to three main objectives for a decarbonising economy (section 4.4). Revisiting the most relevant alternatives for decarbonising the energy system, namely electricity, fossil fuels, hydrogen and biomass, we identify the implications of the three main objectives for industrial energy demand. Based on this analysis, I formulate ten propositions that shall define the role of alternative energy resources for enabling a climate-friendly industry. Lastly, in section 4.4, we use these ten propositions to argue that all energy systems face the five challenges for designing market mechanisms to comply with emissions avoidance, affordability, and adequacy objectives identified for electricity markets in section 4.2.

For the transition towards a decarbonised economy, the market design for current and future energy systems must be revised to make low-emission technologies and practices the most competitive alternatives in the industrial sector. Therefore, the transition towards climate-friendly industrial processes should be subject to the changes of the energy markets design and need to be studied while acknowledging the 15 propositions formulated in this chapter. An energy market design in line with these propositions is critical for making low-emission technologies and practices competitive. However, it might not be enough to create markets for climate-friendly basic materials.

These propositions summarise the results of my research efforts to address the second thesis sub-objective of this thesis.

> II. *Analyse the interplay of the energy system evolution and industrial transformation, emphasising the role of the electricity markets and a potential hydrogen economy.*

In the following chapter, I look at policies that can accompany the transition of energy markets towards such climate-friendly basic material markets.

Chapter 5

Policies to support the industrial transition

Journal publications and reports used for this chapter:

Chiappinelli, O., Gerres, T., Neuhoff, K., Lettow, F., de Coninck, H., Felsmann, B., Joltreau, E., Khandekar, G., Linares, P., Richstein, J.C., Sniegocki, A., Stede, J., Wyns, T., Zandt, C., 2021. A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions. Climate Policy. 10.1080/14693062.2021.1922340.

Gerres, T., Haussner, M., Neuhoff, K., Pirlot, A., 2021. To Ban or Not to Ban Carbon-intensive Materials: A Legal and Administrative Assessment of Product Carbon Requirements. Review of European, Comparative & International Environmental Law. 10.1111/reel.12395

Cosbey, A., Das, K., Fischer, C., Gerres, T., Ismer, R., Linares, P., Mehling, M., Neuhoff, K., Pirlot, P., Sato, M., Sniegocki, A., 2020. Designing Border Carbon Adjustments and Alternative Measures: An Overview.

Gerres, T., Chaves, J.P., Linares, P., 2019. The transformation of the Spanish basic materials sector towards a low carbon economy. Papeles de Energía.

Chiappinelli, O., Bartek-Lesi, M., Błocka, M., Chaves Ávila, J.P., Felsmann, B., Gerres, T., Linares, P., Neuhoff, K., Śniegocki, A., Szajkó, G., Wetmańska, Z., 2019. Inclusive Transformation of the European Materials Sector. EUKI.

Neuhoff, K., Chiappinelli, O., Gerres, T., Haussner, M., Ismer, R., May, N., Pirlot, A., Richstein, J., 2019. Building blocks for a climate-neutral European industrial sector. Climate Strategies.

Gerres, T., Linares, P., 2020. Carbon Contracts for Differences: their role in European industrial decarbonisation. Climate Strategies.

Neuhoff, K., Chiappinelli, O., Richstein, J.C., de Coninck, H., Linares, P., Gerres, T., Khandekar, G., Wyns, T., Zetterberg, L., Felsmann, B., Sniegocki, A., 2021. Closing the Green Deal for Industry. Climate Strategies.

We have the technologies, but we need markets for them. This statement resonates with the results from Chapter 3 and our discussions with industrial partners during the multiple workshops I organised together with the other members of the Climate Friendly Material Platform (CFMP) in Madrid, Berlin, Brussels and online. Implementing a new production process on an industrial scale is almost always a costly endeavour. Besides higher implementation costs for doing something without prior experience for the first time, uncertainties about technological reliability and performance translate into financial long term risks. In addition, climate-friendly production faces different operational costs than conventional processes in use today. As analysed in-depth in Chapter 4, the changing cost structure, particularly for energy carriers, implies that the economics of climate-friendly production routes depend on very different energy, emissions, and material market dynamics than their conventional counterparts.

This chapter explores how policymakers can support and guide the transition towards climate-friendly basic materials markets. I first review the academic literature on industrial policymaking (section 5.2) to demonstrate why climate-friendly basic materials require industrial policy support. Furthermore, I reflect on the difference between horizontal and specific policymaking in the transition towards decarbonised markets. Section 5.3 introduces the policy package developed and promoted as part of the CFMP. Since the audience for reports published by the CFMP is mainly non-academic, I present a novel analysis of these policy options and their capabilities to address investment and operational cost uncertainties. This analysis enhances the ongoing academic discussion of these policy options, differentiating between the horizontal and sector-specific nature and their role in the different phases of the transition. Based on my findings, I identify those policy elements that are key for kick-starting the transition, creating competitive markets and ensuring the long-term climate-neutrality of basic material markets (section 0). By identifying long-term policy design needs for transitioning the industrial park towards a decarbonised basic material sector, my conclusions in section 5.5 provide a first answer to thesis sub-objective III:

Contrast long-term policy options that can foster desirable transitions of the industrial park to reach decarbonisation targets without jeopardising the economic viability of all stakeholders.

5.1. Methods

This chapter builds upon work realised as part of the CFMP during the development of this thesis. Under the umbrella of the independent policy and economic research organisation Climate Strategies, the CFMP brings together universities and think tanks that collaborate to enhance the analytical understanding of industrial policy design. As part of the CFMP, I have actively participated in designing and developing different industrial policy concepts to support the industrial transition towards a decarbonised basis material industry. The wide range of reports and publications authored by up to 14 authors requires some clarification regarding its relevance for the contributions of this chapter.

The industrial policy package that forms the basis of the analysis presented in this chapter was first introduced with the "Building blocks for a climate-neutral European industrial sector" (Neuhoff et al., 2019) report published in October 2019. The first author and main driver behind this synthesis report is Karsten Neuhoff. My principal contribution to this report has been designing and analysing product carbon requirements (PCRs) and their legal review. Results of this cooperative research are presented in a journal paper (Gerres et al., 2021), authored by Alice Pirlot, Manuel Haussner, Karsten Neuhoff and myself, Gerres. Based on academic work and stakeholder consultations, together with the other members of the CFMP, we detailed and developed this policy package in various reports (Chiappinelli et al., 2019a; Cosbey et al., 2020; Gerres et al., 2019c; Gerres and Linares, 2020; Neuhoff et al., 2021). In our latest journal paper (Chiappinelli et al., 2021), we refine these insights and apply them to the perceived needs of industrial stakeholders for enabling a climate-friendly COVID-19 recovery of the European basic material sector. Olga Chiappinelli and I authored this publication with 12 co-authors who supported us in designing the research methodology, conducting interviews, and analysing research findings.

Drawing upon the findings of the CFMP, I analyse the proposed policies to identify their role during the different phases of the transition towards a climate-friendly basic material industry. First, I briefly reflect on the academic literature on industrial policymaking and introduce the difference between horizontal policies applying to all industries equally and specific policies targeting individual sectors. This review motivates a revaluation of different policies presented in our journal papers and the various CFMP reports (section 5.2). Section 5.3 introduces this revaluation emphasising the interrelations and interdependencies between different policies for addressing the competitiveness of climate-friendly basic material production. Doing so, I suggest various design variations for Green Public Procurement (GPP), Contracts for Differences (CfDs) and product carbon requirements (PCRs) that have not been discussed in previous publications. Based on these findings, I revisit the results of our latest journal paper (Chiappinelli et al., 2021). Here, I differentiate between policies that could kick-start the transition (section 5.4.1), policies that may enable a global competition of climate-friendly basic material production (section 5.4.2) and implications for climate-neutral basic material markets (section 5.4.3), thereby adding a new perspective to work published as part of the CFMP. I formulate one proposition about industrial policy needs for each of these three transition phases. These three propositions are the basis of my concluding remarks on the policy pathway towards a decarbonised basic material sector in section 5.5. I use these propositions about industrial policymaking in Chapter 6 to identify the modelling gap to be addressed with the TRANSid model.

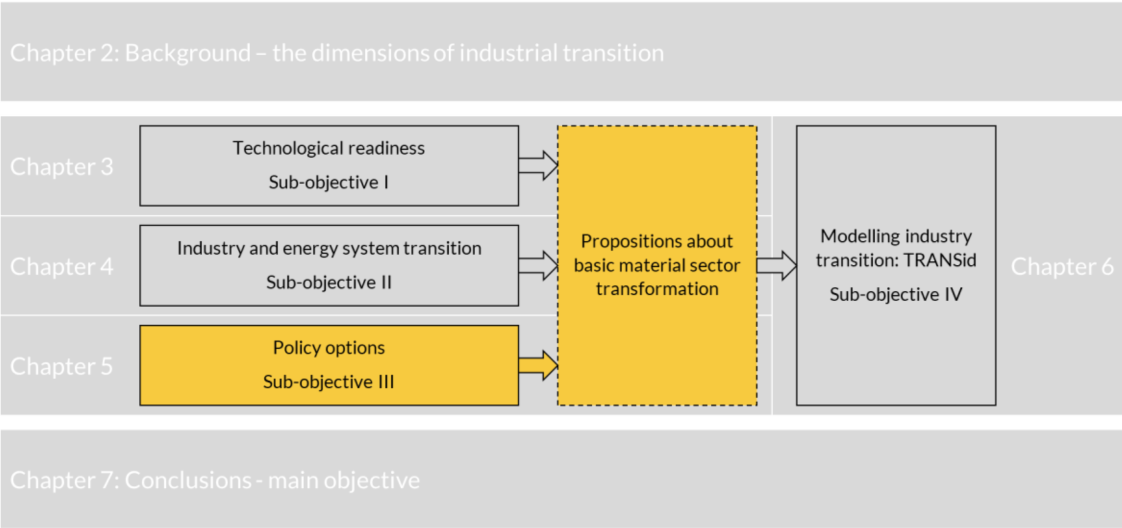

Figure 5-1: Chapter 5 as part of the thesis structure

5.2. The need for basic material market policies

We can refer to "industry" as any human activity aimed at manufacturing or producing goods.[132] The term is so broad that an exact definition of industrial policymaking and its optimal design can always be subject to debate. In the following, we use Dani Rodrik´s work on normalising industrial policy, published as an OECD working paper in 2008 (Rodrik, 2008), to motivate the need for specific policies that can create climate-friendly basic material markets.[133]

There is a need for policies if markets fail. Market imperfections for credit, labour, products, and knowledge are the main motivations to create policies that re-establish a competitive market. According to Lewis (1954), industrial policy is about developing and structurally changing markets, and it involves new technologies to produce new goods, thereby changing from traditional activities to new ones. The need for industrial policymaking, though, is highly case-specific. Whether producers require public input by industrial policy depends on each economic activity and the market served (Hausmann and Rodrik, 2006). Recent publications on the empirics of industrial policies support this view by analysing particular cases, industries, and policy episodes, rather than general policies applicable to all industries (Lane, 2020). General policies that apply equally to all market participants and do not differentiate between economic activities imply that they address a market failure impacting all market participants. Rodrik refers to these general policies as "horizontal" policies. In the following, we differentiate between such horizontal policies and policy designs that are more case-specific, addressing specific regional contexts, sectors or projects.

In a European context, the general principles of EU industrial policy, aiming for an integrated policy that creates "general conditions" (Gouardères, 2021) for equality on the EU single market, present more of a "horizontal" ideology. Nevertheless, EU industrial policy shall also "take into account the specific needs and characteristics of individual sectors" (Gouardères, 2021), acknowledging the specificity of industrial policymaking. Examples of EU industrial policy show that these general principles are more of a framework to address specific industrial policy needs. The transition of the fishery industry in regions of current and former EU countries such as Cornwall (UK) and Tuscany (Italy) can only be understood and addressed when looking at the very distinct regional context (Prosperi et al., 2019). With reference to the struggling Romanian textile industry shows that even the initial competitiveness of a business within the single market can originate from regional specificities, like the availability of cheap labour in Romania compared to other European countries (Ştefãnuţ, 2018). The EU´s approach to financing coal region transition could be an example of a horizontal industrial policy. But looking at the different national phase-out plans, a genuinely horizontal policy seems little likely. Policies must cover countries that are already coal-free (Sweden, Austria, …), those that are aiming for a phase-out by 2025 (Portugal, Greece, Hungary, …), beyond 2030 (Germany, Belgium, …) and those so far only taking in consideration a phase-out, like Poland (EC, 2020d). The comparison of coal regions and their role within the national context only manifests this impression. A region like Asturias with a decade long decline of mining operations, geographically isolated in the north of Spain and an unemployment rate of 14.1%, would require a different industrial policy than the Lausitz region in Eastern Germany with its operating open pit lignite mines, strategically positioned close to major production centres in Germany, Poland, and the Czech Republic and an unemployment rate around 7%.[134]

Is a horizontal industrial policy on the EU level feasible to guide the transition towards a decarbonising economy? Based on my analysis in Chapter 5, horizontal EU policymaking is decisive for current and future electricity and natural gas systems, which have been shaped by a common European approach towards market liberalisation since the 1990s. Here, the energy industry is one relatively large sector of the entire economy that provides different energy

[132] *See*, the definition of industry, noun, in the Oxford English Dictionary (OED Online, 2021)

[133] Rodrik´s more recent work on green industrial policy (Rodrik, 2014) is used in section 5.5 for the concluding remarks on the implications of our analysis in this chapter.

[134] Unemployment rates in Q1 2021 based on data published by the regional agency IDEPA (2021)for Asturias and the German National Employment Agency (Arbeitsagentur, 2021)

resources that are commodities. Equally, basic materials are commodities, and their markets include industries with relatively similar characteristics (section 2.3). This raises the question of whether market policies similar to those for energy systems can be implemented in the basic material sector.

Compared to other industries, production processes for basic materials have in common that they are material, emission, and energy-intensive, but not necessarily labour intensive. I use these characteristics to group these sectors (Chiappinelli et al., 2021; Gerres et al., 2019b), as commonly applied in other academic, public or private sector publications. However, a more detailed comparison highlights significant discrepancies.

For primary steel making, labour costs represent less than 10% of production costs within the EU, while steel recycling is slightly more labour intensive (Medarac et al., 2020). The share of labour costs in the cement industry can be more than twice that value, averaging 18% across the EU in 2014 with values as low as 7% in Romania and as high as 23% in Italy (EC, 2018e). In the chemical industry, labour cost is higher for ammonia and methanol production (11%). Still, it only accounts for a minor fraction of the production costs for hydrocarbon steam cracking and refining high-value chemicals (Boulamanti and Moya, 2017b).

Energy is one of the leading cost factors for all basic materials sectors. Its impact on the final sales prices and gross operating surplus varies significantly for the different industries. In the chemical industry, the effect of changing energy costs on operating surplus can vary between 24% for refineries and 64% for organic chemical production and reaches up to 79% for basic iron and steel production (Table 5-A).[135] These differences are linked to the individual energy intensity of each basic material production route (section 2.1.3), the different costs for feedstock and their share of the total production costs and revenues. Raw materials accounted for 65% of total primary hot rolled steel production costs (458€/t) in the EU in 2019 (Medarac et al., 2020), while raw materials made up only 20% of the total average production cost of 48 €/t for cement in 2012 (EC, 2018e) and can make up to 90% in the chemical industry (Boulamanti and Moya, 2017b).

Though the importance of individual cost factors mentioned above differs across industries, EU basic material markets have in common that a relatively small number of companies dominates domestic production. Given that market shares are non-disclosed and public data is sparse, recent publications by competition authorities can serve as an indication for market concentration.[136] The economic analysis by the OECD (2020) of the approved sale of a former CEMEX cement plant to Çimsa shows the high degree of market concentration within the cement sector in Spain. Germany´s six largest cement producers have been subject to cartel formation investigations since the early 2000s (Harrington et al., 2014; Naumann, 2018). At the same time, the final report of the EU Commissions assessment about the rejected merger between Tata Steel and ThyssenKrupp mentions the dominant market power of the potential joint venture as the main reason for its disapproval (EC, 2019d). The raw chemical sector seems to be less concentrated, with a total of 90 companies responsible for 90% of the EU market share and 50 steam crackers in operation to process hydrocarbons into raw materials (Arns, 2018). With the common EU single market in place for all sectors, exports to third countries, and vice versa imports, basic

[135] Energy intensity as share of gross operating surplus demonstrates the sensitivity of profit/surplus with regard to energy prices. Taking 2017 figures, an energy cost increase of about 50% in the steel sector reduces profit by about 40% (79% share of fuel prices of gross operating surplus) given global market prices remain the same.

[136] According to the SFI Global Cement Database (McCarten et al., 2021a), there are 207 integrated cement plants in operation in the EU27+UK owned by 42 different companies. 178 of these plants are owned by 19 companies with more than one side, while the four biggest companies combined own 129 sides. According to the SFI Global Steel and Iron Database (McCarten et al., 2021b), there are 97 steel plants in operation in the EU27+UK of which 30 are integrated primary production plants owned by 15 different companies. 21 of these plants are owned by 7 companies with more than one side, while the ArcelorMittal owns 10 of these sides.

material industries face similar market conditions that define their domestic and global competitiveness.[137]

Moving towards a decarbonising economy might differently impact the competitiveness of basic materials. This observation is based not only on the different economics of these industries but also on the implications of a decarbonising industry presented in the previous chapters. I discussed in section 3.4 how the availability of technologies for decarbonising basic material sectors varies, as do their decarbonisation potential and relative abatement costs. I then argued in section 4.3 that due to the characteristics of decarbonisation options across industrial sectors, we would need to restrict the use of limited resources, such as biomass, to those industrial applications with no or only very cost-intensive second-best alternatives to decarbonise (15th proposition, section 4.3.5). These observations hint at specific rather than horizontal policies to create markets for climate-friendly basic materials. Without questioning the need for energy markets that comply with emission avoidance, affordability, and adequacy objectives (section 4.4), we need to re-evaluate the role of different policies to guide the transition towards climate-friendly basic material markets. By doing so, one can identify specific policies and policies that could be implemented across different basic material industries to enable a decarbonising economy.

Table 5-A: Estimated share of energy costs (excluding feedstock) in the EU-27 in 2017 (EP ITRE, 2020)

	As % of sales prices	As % of gross operating surplus
Refineries	2%	24%
Organic Chemicals	4%	64%
Fertilisers	4%	35%
Cement	5%	51%
Basic iron and steel	11%	79%

[137] Based on 2008-2017 data for steel (EUROFER, 2018), 2003 – 2016 data for Portland cement (EC, 2018e) and 2008 – 2018 data for the chemical Industry (CEFIC, 2020a) the EU is net importer of raw Steel and both the EU cement and chemical industry have a positive export balance.

5.3. A policy package for the basic materials sector

In a decarbonised economy, materials and products would compete without industry or sector-specific public support. As of today, such markets are wishful thinking. We know which technologies are needed to decarbonise emission-intensive industrial processes (Chapter 3). Still, we do not know how they can become competitive and dominate their markets in the long run. This gap is referred to in the literature as "technology-valley-of-death" and has also been present for renewable electricity generation like solar PV, onshore and offshore wind (Grubb, 2014). Government subsidies are part of the success story of solar PV and have driven module costs towards grid-parity.[138,139] A policy package for the basic materials sector should aim to break the valley of death and allow for a transition towards decarbonised basic material markets. The design of such support is crucial to create long-term efficiency.

Technologies analysed in Chapter 3 face higher investment and operational expenditures, mainly because of higher energy costs than currently used processes. Policies can therefore address investment costs, operational costs or both to make investments in these technologies attractive. In the following, I present different policies that we studied as part of the Climate Friendly Materials Platform in various reports (Chiappinelli et al., 2019a; Cosbey et al., 2020; Gerres et al., 2019c; Gerres and Linares, 2020; Neuhoff et al., 2019, 2021) and in our latest journal paper (Chiappinelli et al., 2021). This policy package includes direct investment support (section 5.3.1), green public procurement (section 5.3.2), contracts for differences (section 5.3.3), measures to ensure carbon pricing across the entire value chain (section 5.3.4) and standards and product carbon requirements (section 5.3.5). These policies are not exclusive but cover various measures to address investment and operational cost uncertainties for climate-friendly basic-material production. The analysis presented in the following evaluates how these measures can support the transition of the basic material sector and whether they could be implemented as specific or horizontal policies. Results are summarized in section 5.4.3. As such, insights are also valid for proposed industrial policy packages with slightly different measures, for example, presented by Agora Energiewende and Wuppertal Institute (2021).

5.3.1. Direct investment support

Subsidies, tax rebates, discounted loans, rent of land and buildings below market value, and other forms of state aid lower the direct investment needs for new climate-friendly industrial production facilities. The Treaty on the Functioning of the European Union permits state aid or direct investment support in some cases, like research, environmental protection and energy.[140] Projects, such as the Swedish HYBRIT hydrogen-based steel making pilot plant, can rely on public funding of the Swedish Energy Agency, or in case of scale-up, on the European Innovation Fund (Olsson and Nykvist, 2020). Additionally, temporarily available funds, such as NextGenerationEU adopted as a response to the COVID-19 health crisis, can also support the development of new industrial facilities (Chiappinelli et al., 2021).

Direct investment support by itself, though, would not be enough to ensure the financial attractiveness of large-scale industrial installations with a long design life. As discussed in the previous section, energy cost defines the competitiveness of production processes in the basic materials industry. While emission allowance costs represented a minor cost factor for existing industrial installations in the past, less than 2% of the total production cost in the steel industry (Medarac et al., 2020), future emission allowance prices are another source of operational cost

[138] In case of solar PV, the development of a national industry has been closely linked to governmental support (Haley and Schuler, 2011), while the cost decline of solar PV is seen as a result from the industry build-up and move from niche to mass market production ("How governments spurred the rise of solar power," 2021).
[139] Some scholars, including ourselves (section 4.2) have argue that additional policy measures would be required to address market uncertainty risks for new investments (Karneyeva and Wüstenhagen, 2017; Polzin et al., 2019).
[140] *See*, (2014/C 200/01) `Guidelines on State aid for environmental protection and energy 2014-202´

uncertainty. Operational cost uncertainty follows production cost uncertainty, creating the risk of no demand for low-emission basic materials priced significantly higher than the market price.

5.3.2. Green Public Procurement (GPP)

Public spending accounts for a considerable share of the total economic activity within Europe. Encompassing all purchasing activities of governmental institutions and other public entities that need to follow EU public procurement regulations,[141] government expenditures made up between 7.2% (Ireland) and 19.5% (the Netherlands) of the national GDP within the EU in 2017 (EC, 2019e).[142] The state budget encompasses, among others, education, construction activities, health and social work, public administration, defence and social security expenditures. In the case of Germany, these activities were responsible for 12% of the national carbon footprint in 2011 (Chiappinelli et al., 2019b).

Other than private investments bound to financial returns on invested capital, public procurement follows other award criteria. First of all, expenditures shall ensure the functioning of the state. That said, public procurement practices can also be a policy tool to foster developments of public interest. By leveraging purchasing decisions to create demand for climate-friendly and recycled materials and incentivising material efficiency, governments can use GPP as a policy to support the development of climate-friendly basic material markets.

Many countries already practise GPP. For example, the Dutch Directorate-General for Public Works and Water Management (Rijkswaterstaat) has evaluated project proposals based on sustainability criteria since 2010 (OECD, 2014) and applies a shadow price on reported carbon intensities for awarding contracts (Chiappinelli et al., 2019b). GGP can be based on one or several of four different policy goals (Hasanbeigi et al., 2021):

1. Adaption targets for a relative or absolute GPP quota, such as the 60% GGP adoption target for the public sector in South Korea by 2020 (UNEP and KEITI, 2019).
2. Industry targets that are linked to the emission reduction or efficiency targets for specific industrial sectors.
3. Project-based targets, such as the evaluation of proposals based on its carbon intensity by Rijkswaterstaat.
4. Product-based targets, for example, with sustainability criteria for basic materials like cement or steel.

By aligning public expenditure to one or several of these goals, GGP is essential for creating climate-friendly basic materials demand. By doing so, the share of basic material consumption for public construction may be significant enough to create sufficient demand for justifying investments in first-of-a-kind industrial-scale facilities for climate-friendly basic materials production, but at the same time also limits the role of GGP for transitioning entire sectors towards a decarbonised economy (Chiappinelli et al., 2021).

Shadow prices for carbon dioxide-equivalent emissions to monetise sustainability when awarding public contracts are one "horizontal" policy option to implement GGP. Discussing the limitation of emission pricing in more detail in sections 5.3.4 and 5.4.2, note that GGP design can take many alternative forms. GGP can also be subject to a combination of measurement and requirements to evaluate the sustainability of public spending. Based on a series of interviews with stakeholders for public construction projects, Kadefors et al. (2021) conclude that GGP should additionally consider the local implementation setting, making GGP a rather project-specific policy option. Some of the following policies can be the basis for designing alternative "horizontal" or specific GPP strategies.

[141] *See*, Directives 2014/23/EU, 2014/24/EU, and 2014/25/EU

[142] 13.3% on average across all EU member states in 2017.

5.3.3. Contracts for Differences (CfD)

The prevailing uncertainty about future energy, emission and material prices presents a major difficulty when evaluating the long-term viability of investments into climate-friendly basic material production processes. Long-term energy price scenarios for coal, natural gas and crude oil, such as presented annually by the U.S. Energy Information Administration (EIA, 2021b), demonstrate the vast uncertainty gap in price forecasts for globally traded energy carriers. Additionally, local markets, such as electricity, face the uncertainties discussed at length in Chapter 4. For conventional basic material production, the impact of these market uncertainties is well known and has only minor effects on the market structure for basic materials. Production routes are highly standardised. All competitors face changing commodity prices equally, e.g. for energy carriers and raw materials, and construction projects often include price adjustment clauses for materials such as steel (Pierce et al., 2012).[143] As analysed in Chapter 3, changing the production process usually results in increased energy demand and often implies a change of energy carrier by replacing a fossil energy source with potentially higher-priced electricity or hydrogen. Climate-friendly production processes are therefore exposed to other market uncertainties than conventional basic material production routes. Additionally, the economic viability of climate-friendly basic material processes relies on future emission allowance prices, which may be essential for climate-friendly basic materials to compete with conventional products in a market with supply and demand sensitive pricing.

As discussed in the following, Contracts for Difference (CfDs) can help overcome these uncertainties for climate-friendly basic material production. By design, CfDs are long-term contracts between a private entity and a public stakeholder to mitigate the market price uncertainty for the operation of new climate-friendly assets.[144] A well-established policy for electricity markets, I argue that the concept of CfDs can also be used to hedge any tradable good (X) against market price dynamics. In the following, we briefly discuss the role of CfDs for electricity (E-CfD), emission (C-CfD), and material prices (M-CfD), exemplary for any other operational cost and revenue positions of an industrial process (X-CfD).

CfDs for electricity markets (E-CfD)

CfDs have been well studied and put in practice to support investments in new RES generation capacity, such as wind and solar PV, by establishing project-based selling strike prices for electricity over a long period of up to 15 years and longer (ARUP, 2018). By using public auctioning, governments award E-CfDs to those bidders that require the lowest generation cost. Though national auction design can vary significantly (Dukan et al., 2019), at its core, an E-CfD is a hedging instrument with the public stakeholder taking over future electricity market pricing risks. Governments could also sign supply-side E-CfDs for electricity consumption with industrial consumers to strengthen the business case of electrification options (Chiappinelli et al., 2021). With regard to the business case of EAF-DRI steel making in Vogl et al. (2018), lower electricity cost for electrification options means that lower carbon price levels are needed to make climate-friendly basic material production processes competitive with conventional ones.

CfD for emission trading schemes (C-CfD)

The CfD concept can also be used to hedge against carbon price uncertainty with a Carbon Contract for Differences (C-CfD). Basic-material producers and the government agree on a strike price for emission allowances. The producer can then sell his free emission allowances for a climate-friendly materials production facility at the agreed strike price rather than the market price. Figure 5-2 demonstrates the functioning of such C-CfD. By granting a strike price significantly above the current price for emission allowances over a contractual period of many

[143] Based on my personal work experience as project manager in offshore construction projects I can confirm this observation with steel being purchased based on global market prices at a contractually agreed milestone date during the projects executional phase.

[144] By design, a Power Purchase Agreement (PPA) is also a CfD. PPAs between private sector parties are no governmental industrial policy. Nevertheless, publicly backed PPAs that include public institutions as risk hedging parties may fulfil a similar role as CfDs (Neuhoff et al., 2018).

years, the government would pay the climate-friendly basic materials producer the difference between the current market price for emission allowances and the strike price. Vice versa, as soon as emission allowance prices surpass the strike price, the basic material producer would have to return additional profits obtained by selling its free allowances. Like E-CfDs, an auction-based mechanism could be used to award C-CfDs.

Whether the design scope covers electricity, emissions, or basic materials, any CfD is hedging the price of a tradable good against market price dynamics. Whereas future industries procure energy and raw materials to produce and sell basic materials in a market environment, the situation is different for C-CfDs. For a C-CfD to work, the operators of climate-friendly basic material production facilities need to receive free allowances that they can sell. Free allowances are a specific feature of some current carbon market designs, such as the EU ETS, to prevent carbon leakage. An emission-intensive industry fully exposed to carbon pricing faces higher operational costs than global competitors and loses competitiveness. On the EU ETS, all plants belonging to industries with a perceived carbon leakage risk receive free allowances based on sector-specific benchmarks and the total emission cap.[145] This means that a climate-friendly basic material production facility gets the same free emission allowances as its conventional competitor, but rather than using these allowances to compensate for emissions, they can sell them on the market (Figure 5-3). Without free allowances, such C-CfD would be of no value in future carbon markets since climate-friendly basic material facilities receive no allowances. An alternative C-CfD design could grant free allowances to climate-friendly production facilities after phasing out free allowance allocation to conventional processes. Such a C-CfD design, though, would correspond to a direct subsidy scheme. Climate-friendly production facilities receive free allowances that they can sell at a fixed strike price, while conventional installations face the full emission allowance market prices. In the following, I focus on CfD schemes subject to equal free allowance allocations to all eligible market participants.

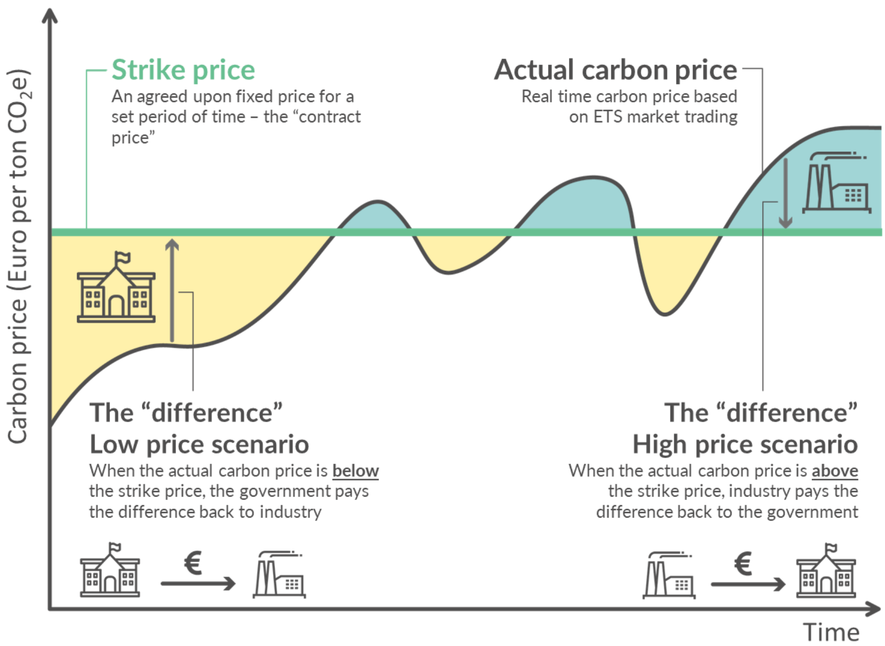

Figure 5-2: Schematic functioning of a C-CfD[146]

[145] *See*, functioning of EU ETS phase 4, as detailed by Directive (EU) 2018/410.
[146] Developed as part of the CFMP consortium: https://climatestrategies.org/publication/unlocking-the-low-carbon-transition-of-the-basic-materials-sector/

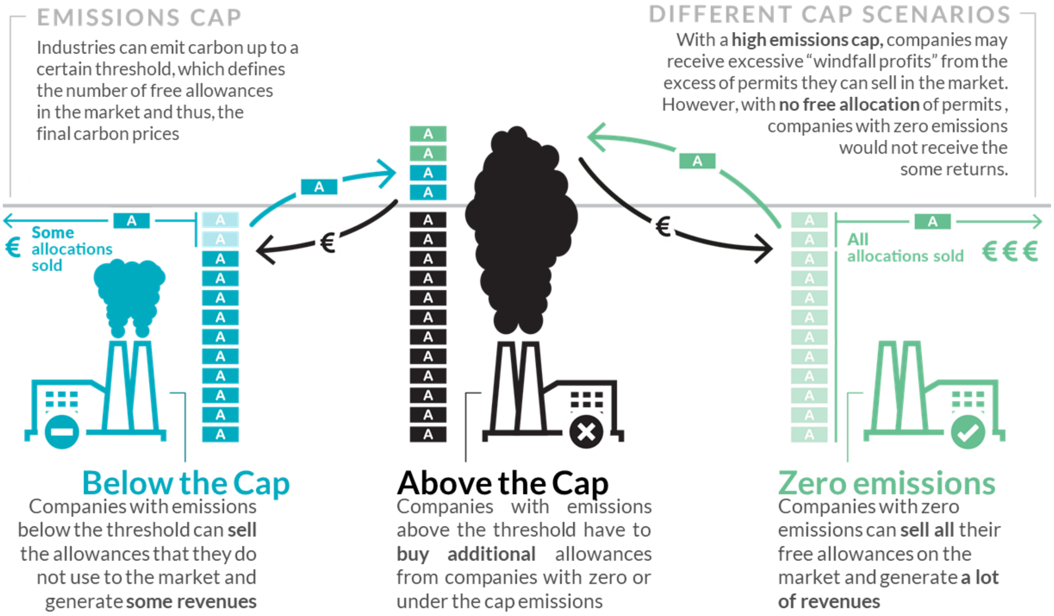

Figure 5-3: Schematic functioning of free allowance allocation[116]

Though the economic concept was introduced by Richstein (2017), I contributed to the understanding of C-CfDs by further analysing their potential benefits in Gerres and Linares (2020). C-CfD as an industrial policy would mean that the government takes over the hedging risk for future carbon prices and the cost linked to the risk of technology failure that reduces along the learning curve for operating novel processes. On the other hand, government-backed C-CfDs enable producers to obtain better financing conditions by allowing for a higher debt ratio of low-carbon projects, thereby reducing the carbon price required to make the investment competitive. C-CfDs could therefore help to reduce the total transition cost for the society and at the same time serve as a commitment device of the government to strengthen carbon markets, which would be needed to partially or fully recuperate the policy costs in the long run (Sartor and Bataille, 2019).

CfD for material prices (M-CfD)

While existing literature has not framed them as CfDs, I propose that long term supply contracts can fulfil the role of M-CfDs for stabilising revenue flows for new climate-friendly production facilities. In Olsson and Nykvist (2020), the authors discuss the feasibility of a first-mover hydrogen steelmaking plant on an industrial scale and consider long-term purchasing agreements for public projects and the private sector as key. Such purchasing agreements could potentially take the form of an M-CfD with public institutions hedging the risk of fluctuating material prices in the long run. If the market prices were below the strike price, the government would pay the climate-friendly basic materials producer the difference between the current price for the basic material and the strike price. Vice versa, as soon as market prices surpass the strike price, the basic material producer would have to return additional market profits. Such M-CfD design based on basic material prices has not been explored in the literature yet and might prove less practical and efficient than long-term purchasing agreements. Additionally to the common design challenges of CfDs presented in the following, the evaluation of the M-CfD option requires further investigation and is subject to future research.

Common design challenges for CfDs

CfDs can help mitigate future operational cost risks and improve investment conditions into new climate-friendly basic material production processes. Nevertheless, CfDs for industrial applications face some common challenges, whether for electricity prices, as already implemented, for emission allowances, as discussed in the literature and suggested by national policymakers[147], or only hypothetically for basic materials. The following challenges need to be addressed by any CfD design.

First, long-term price agreements might reduce the risk of price volatility but can seriously hamper the economic viability of climate-friendly production subject to a CfD. Such a scenario can occur if markets develop very differently than expected when signing the CfD. Literature about the chances and risks of electricity price E-CfDs between two private sector parties, namely power purchase agreements (PPAs), state this risk for signing parties for price agreements over long periods between 5 and 20 years (Baines et al., 2019; Mosovsky and Titus, 2018). Assuming an arbitrary numeric example of a C-CfD with an agreed carbon price of 100 €/tCO_2e for 15 years for a first-mover for a climate-friendly basic materials production facility.[148] Such a production facility may see its entire business model in jeopardy if emission prices stabilise at a level significantly higher than 100 €/tCO_2e, for example, 150 €/tCO_2e, after signing the C-CfD. Second-mover installations with a higher technological maturity and without a C-CfD could benefit from elevated prices and therefore produce climate-friendly basic materials at much lower costs than the first-mover installation subject to the agreed strike price of 100 €/tCO_2e for the upcoming years since they receive 50 € more per obtained free emission allowance certificate.

The underlying premise of the first challenge is that free allowance allocation is based on benchmark allocation. All production facilities for each basic material type receive the same quantity of free allowances regardless of their production process. Departing from benchmark allocation and combining CfDs for the first-mover installation with additional free allowances would require an updated EU ETS design. This first challenge could be addressed with a CfD only covering these non-benchmark additional free allowances.

Second, the share of total demand that is subject to a CfD may not be subject to market price signals anymore and can jeopardise the long-term functioning of the market itself. Stabilising the energy, emission or material cost and revenues with CfDs for some climate-friendly basic material production facilities means that they participate in the market by selling or buying tradable goods but do not react to market price signals anymore. The difference between the market price and the agreed CfD strike price is balanced via the CfD with the public stakeholder. Let´s take the example of a C-CfD awarded to a climate-friendly production facility that is not emission neutral, such as first-mover carbon capture installations in the cement industry that avoids less than 90% of its emissions (see 3.3.3). Such cement plant would receive the strike price for those emissions allowances that are not needed to cover the cost for its residual emissions of 10%. Given that the market price for allowances is significantly higher than the strike price, there is no additional incentive for the cement plant to reduce its emissions beyond 90%. The emission price signal is frozen at the strike price of the C-CfD. In contrast, a comparable cement plant with CCS subject to the market price has an additional incentive to reduce emissions further since it can maximise the return on selling free allowances at the market price (Figure 5-4).

CfD design can reestablish the price signal if the public stakeholder and industrial plant operators contractually fix the volume to be exchanged between both parties. For the example shown in Figure 5-4, a C-CfD could only cover 90% of free allowances obtained by the CCS cement plant operator since 10% of the emissions are not captured with the current process design. Emission allowances not captured by the CfD are subject to market prices, providing an investment signal for further improving the capture efficiency of the CCS equipment. This challenge is less relevant for long-term delivery contracts for electricity since E-CfDs are generally designed with contractual stipulations for both delivered electricity and the strike price (Szabó et al., 2020).

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[147] CCfDs are, for example, mentioned as a policy option in the national German hydrogen roadmap (BMWi, 2020).
[148] A strike price of 100 €/tCO_2e would allow for the implementation of climate-friendly processes in all of the basic material sectors reviewed in section 3.3.

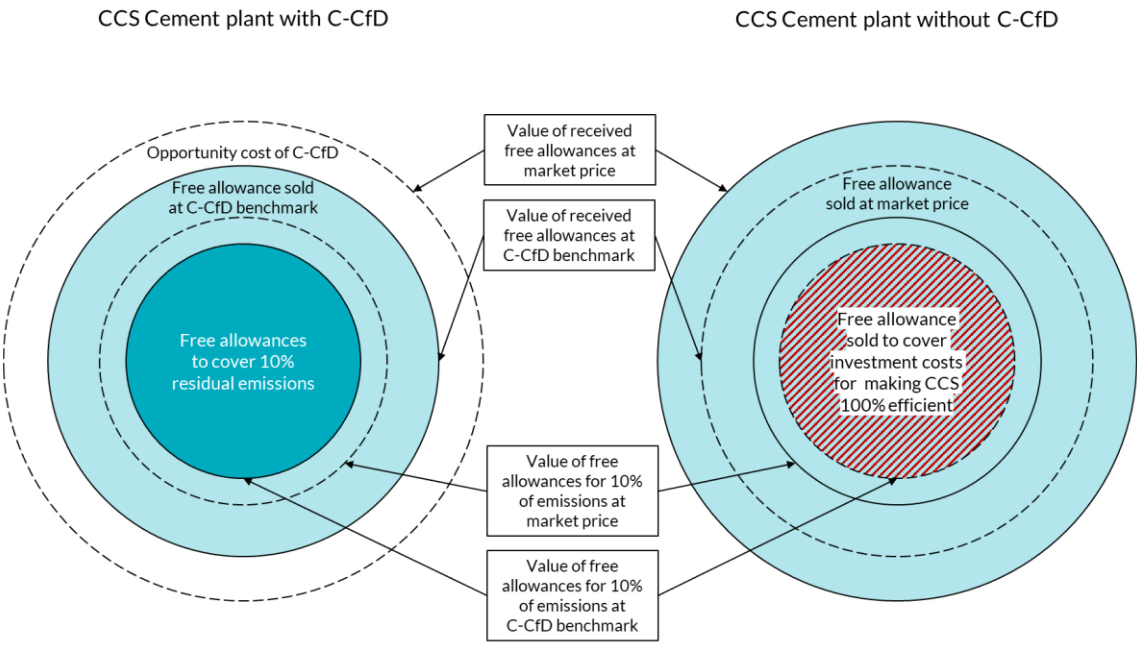

Figure 5-4: Emission allowance revenues (light blue) in a high carbon price scenario[149]

As advised for PPAs (EFET, 2019), contractual fall-back clauses might also help to respond to the two previously described challenges. Fall-back clauses could, for example, introduce flexible C-CfD benchmark prices for selling free allowances. The flexible benchmark could reflect the market price differences to the most competitive production process in use. In the steel industry, benchmarks could be linked to fossil fuel price dynamics of carbon as long as blast furnaces set the market price for primary steel. Revenue from selling their allowance allows first-mover climate-friendly alternatives to compete with conventional and second-generation climate-friendly processes on future basic material market prices. This would be similar to long-term supply contracts for electricity provision indexed to financial parameters, such as the fossil fuel market price, and used for long-term auction mechanisms in Latin America, East Asia and Australia (Reus et al., 2018). Any form of fall-back clause means that climate-friendly production facilities have greater exposure to market price dynamics. The design and functioning of such flexible fall-back clauses have not been studied so far. Further investigation is needed to understand whether they could be designed in a way that sufficiently strengthens the business case of new climate-friendly production facilities.

Third, it is unclear how to award CfDs to the basic-material industry with a competitive auction mechanism. As noted in section 5.2, the production of basic materials such as steel, cement or petrochemicals is a business with a relatively concentrated market structure, a small number of installations and high production capacities. Also, industrial-scale climate-friendly production facilities would operate with an annual output of about 1 Mt for cement (IEAGHG, 2013a), 4 Mt for steel (IEAGHG, 2013b) or 1 to 1.5 Mt for each steam cracker in petrochemical plants (Benchaita, 2013). Here, climate-friendly basic material production differs significantly from low-emission RES generation of electricity, scalable with little additional cost. In 2020 capacities of individual commercial solar panel modules reached up to 600 W, and installed wind turbines have average capacities between 2-4 MW onshore and 3-9 MW offshore (IRENA, 2020). The scalability of RES allows for competitive CfD auctioning on a national level. Project developers bid turnkey power plants of varying scales using off-the-shelf solar panels and wind turbines.[150]

[149] The premise is that the high carbon price scenario would disincentives additional investments in a CCS cement plant with CCfDs in place.

[150] The latest RES auctions in Spain from January 2021 awarded 78 solar PV projects ranging between 10 kW and 125 MW to 26 different companies and 42 onshore wind projects ranging between 1 kW and 180 MW to 8 different companies (MITECO, 2021)

As I highlighted in Gerres and Linares (2020), auctioning E-CfDs or C-CfDs to new climate-friendly material production facilities on the national level might not result in competitive tenders due to the small number of companies dominating the national markets.[151] Other than electricity consumed locally with cross-border transport restricted by the available interconnector capacity, basic materials are sold on national, European and global markets. National tendering of CfDs, either for a specific sector or across various basic-material types, can lead to a race between different EU member states to grant higher subsidies in the form of CfDs to companies willing to open new production facilities within their jurisdictions. Here, we echo the concerns formulated by Edh Hasselgård (2017) about the potential competition distortions in the internal market caused by state aid when using environmental award criteria for public tendering procedures.[152] To maximise competition, CfDs for new basic material production facilities could instead be awarded by the European Commission on the EU level, similar to the 95.5 billion € in research funding under the Horizon Europe programme between 2021 and 2027.[153] By benefitting regions with high availability of low emission energy sources, it would also weaken the perspective of basic-material production in those regions that are currently highly industrialised but with limited access to low-emission alternatives to fossil feedstock and energy carriers.

For awarding CfDs on a European level, a sector-specific tendering procedure would be more adequate to support the development of climate-friendly technologies for all basic materials. The expected cost of decarbonisation options within the different industries varies (see section 3.3). As such, a "horizontal" tendering procedure that allows competition between different basic material types would favour those industries that face the lowest abatement costs and risk that industries with higher abatement costs drift into a carbon lock-in. Instead of investing in climate-friendly new processes, these industries would keep or renew conventional production routes (Chiappinelli et al., 2021). Given that enhanced recycling and recovery of basic materials via secondary production routes also provide climate-friendly basic materials, one option could be to allow primary and secondary production routes to compete in CfD auctions. Such an approach could still lead to a carbon lock-in for primary production routes, given that secondary production does not allow for fully circular basic material streams. In other words, as long as secondary production routes cannot recycle all waste streams and cannot fully recover basic materials, secondary production would always be of lower quality than primary production. As such, future basic material demand still relies on primary production.

Lastly, the interplay of combining different CfD designs and the economics and competitiveness of climate-friendly basic material production facilities remains unknown. It is vital to understand whether and how M-CfDs could be implemented in parallel with E-CfDs or C-CfDs without double-accounting or remuneration of emission reduction efforts. For any discussed CfD design, a public stakeholder takes over hedging and financing costs to cover the premium of producing climate-friendly compared to conventional emission-intensive production routes. If several different types of CfDs are in place in parallel, the public stakeholder risks providing aggregated financial benefits to the climate-friendly producers that exceed the actual premium.

The list of identified challenges to the practicality of CfDs is not exhaustive. Nevertheless, my analysis shows that CfDs for climate-friendly industrial processes shall fit application-specific needs for stabilising energy, emissions or material costs, thereby reducing operational uncertainties. Here, the impact of CfD design elements on its functioning and effectiveness

[151] According to the SFI Global Cement Database (McCarten et al., 2021a), there are 27 integrated cement plants in operation in Spain, of which 25 owned by 6 different companies. According to the SFI Global Steel and Iron Database (McCarten et al., 2021b), there are 6 steel plants in operation in Spain of which only one is integrated primary production plant and five EAF plants for secondary production. Half of the plants, including the primary production plant in Gijón are owned by Arcelor Mittal SA.
[152] Hasselgård (2017) analyses tendering procedures under the EU 2014 Procurement Directive, though the argumentation presented by the author can also be applied to publicly funded C-CfD and CfD support schemes.
[153] Regulation (EU) 2021/695 of the European Parliament and of the Council of 28 April 2021 establishing Horizon Europe

remains a field of research that has not been explored in-depth so far. The identified design challenges can help to frame characteristics of future CfDs.

The difficulties faced when designing CfDs and extending their reach to several operational cost and revenue positions of climate-friendly basic material production facilities (X-CfDs) is also a call for other policy instruments that might be a better fit to ensure the operational viability of these installations over their entire design life. Theoretically, CfDs could cover any functional aspect of climate-friendly basic materials production and consequently make the economics for operating these plants utterly indifferent to any market dynamics.[154] Out of multiple reasons that speak against creating an "alternative market universe" for climate-friendly production processes, probably the most important one is that CfDs reduce market uncertainties but do not mitigate their impact on the existing markets for energy, emissions, or materials. Competitive tenders for CfDs should ensure that CfDs only cover some of the market risks for basic material producers rather than making them risk indifferent. Therefore, CfDs should primarily serve as a supportive and well-proportioned measure.

5.3.4. Carbon pricing across the value chain

Putting a price on carbon dioxide-equivalent emissions makes emission-intensive products more expensive and climate-friendly alternatives more competitive. This simple idea is the motivation for any policy that associates a cost to carbon dioxide-equivalent emissions. As I already highlighted in section 4.2.4, in theory, it does not matter whether we charge end-consumers the emission price equivalent to the total carbon footprint of a product or oblige companies involved in the production process to pay for their equivalent direct emissions. In the end, consumer-based policies of taxing the emissions intensity of final products or charging producers for the emissions caused by basic material, intermediate or final product production would have the same effect on end-consumer prices (Stern, 2007). In practice, the polluter pays principle or consumption charges are imperfect for pricing emissions for globally traded products as long as some regions, such as the European Union, have a stricter carbon market in place than their global trade partners (Jakob et al., 2014). Determining the carbon price to be imposed on a final product requires perfect knowledge about the global value chain of each product, and the polluter pays principle for domestic production does not cover the consumption of imported products.

Under the EU ETS, covered emitters need to buy allowances in proportion to their emissions unless they benefit from free allowances. Due to the EU ETS, emitters, including European steel, cement or petrochemical producers, could face additional emission-related costs than competitors from regions with a less rigid or no emission pricing system in place. Empirical ex-post evidence shows that European producers of these basic materials forwarded additional emission-related costs to their customers. However, due to the prevailing share of free allowances for industrial sectors, this emission premium on the final product price is relatively small (Cludius et al., 2020). The carbon cost pass-through is subject to free allowances that, to a certain degree, mute the emission price signal. If domestic producers participating in the EU ETS faced higher emission allowance costs and forwarded these to the consumers, they would lose their competitiveness to imports. Just continuing with free allocation, though, is no option either. Carbon pricing needs to be maintained and reinforced because of the EU ambition to decarbonise the European economy by 2050. In that case, the emission cost needs to be reflected in the final product price, regardless of whether basic materials stem from domestic or international producers.

In the following, I review the current EU ETS design and its free allocation mechanism for phase 4 in operation from 2021 until 2030. Then I discuss available design options for the proposed border carbon adjustment mechanism (CBAM) and present the climate contribution (CC) that we promote as part of the CFMP as an alternative approach to introduce the carbon price to the value chain. Here, I do not aim to present a solution for designing a carbon border adjustment mechanism but rather discuss different approaches to highlight their implications for industrial stakeholders.

[154] For this thought experiment, the concept of CfDs could be extended and applied to any operational cost position, covering among others labour costs (L-CfD), raw materials (R-CfD).

Current EU ETS design

Introduced with Directive 2003/87/EC, the EU ETS started its phase 1 operation in 2005, covering the power sector and some basic material industries. Since then, the market design and sector coverage have been revised for each new phase, with phase 4 starting in 2021. The market design of past phases has been far from perfect and was under scrutiny for, amongst others, low prices and dynamic inefficiency, insufficient coverage and competitiveness concerns (Hepburn et al., 2017). Even though EU ETS emission allowances have experienced a price rally since 2017, jumping from about 4 €/tCO_2e to price peaks beyond 60 €/tCO_2e in 2021[155], insufficient coverage and competitiveness concerns remain.

Phase 4 of the EU ETS sets the stage for emission trading in the 2021 to 2030 period. The objective of phase 4 is to align the absolute annual emissions within the covered sectors with the general target of a 40% emission reduction compared to 1990. In line with this target, free allowances across shall be reduced by 2.2 % annually.[156] In total, 57% of the allowances stock shall be auctioned and the remainder granted as free allowances to the different sectors covered by the EU ETS (ICAP, 2021). As such, a total of about 6 billion free allowances will be available until 2030 (EC, 2016a). For the manufacturing and basic material industry, free allocation is based on absolute sector-specific benchmarks adjusted annually with a 0.2 to 1.6% reduction rate depending on technological progress. Additionally, a free allocation buffer of 450 million allowances shall mitigate the potential effects of carbon leakage. Nevertheless, free allowances shall be fully phased out by 2030 (ICAP, 2021).

By presenting their "Fit for 55" strategy in July 2021, the European Commission recognised that phase 4 of the EU ETS might be insufficient to reach more ambitious climate targets, namely a 55% emission reduction compared to 1990 by 2030. Gradually phasing out emissions for the basic material industries increases their operational costs compared to international competitors. Consequently, the EU ETS could rather encourage decarbonisation by deindustrialisation instead of inducing "the relevant sectors to modernise, become more sustainable, and drive down their carbon content." (EC, 2021b). A CBAM shall safeguard this objective, gradually phased in while free allocation is phased out in line with clear sector-specific targets. Ensuring that domestic and imported products pay the same carbon price, a CBAM shall ensure that the final products price reflects the product´s carbon intensity.

Without offering a solution for a CBAM mechanism, the "Fit for 55" strategy hints at a sector-specific approach to address carbon leakage concerns. Free allowance allocation and CBAM would be accompanied by clear sector-specific targets that shall drive the transition. Additionally, the Commission plans to increase the carbon market participation of the domestic aviation industry and extend the carbon market to maritime, road transport and buildings (EC, 2021b). While businesses need to meet sector-specific targets, the cross-sectoral emission allowance price would also depend on the emission reduction performance and growth of various other economic activities. Based on these requirements derived from the "Fit for 55" strategy, a potential CBAM design would have to offer an answer to multiple design aspects.

Carbon Border Adjustment Mechanism (CBAM)

One of the principal challenges of a potential CBAM design is its compatibility with international trade law, namely the General Agreement on Tariffs and Trade (GATT) and Technical Barriers to Trade (TBT) Agreement of the World Trade Organisation (WTO). These agreements shall promote international trade by ensuring that different countries do not impose discriminatory trade barriers or introduce protectionary measures for their industries. According to the "Fit for 55" strategy, compatibility with WTO rules and international obligations is a prerequisite for CBAM implementation (EC, 2021b). As such, legal scholars have evaluated potential design implications for CBAM mechanisms to a great extent over the last years. Early works, such as Cosbey (2008), have been complemented and extended by more recent legal evaluations of CBAM design (Mehling et al., 2019) and its alternatives (Cosbey et al., 2020; Ismer et al., 2020). The

[155] In October 2021 the peak price for EU ETS futures reached 64.72 €/tCO_2e (05.10.2021)
[156] Directive (EU) 2018/410 amending Directive 2003/87/EC and Decision (EU) 2015/1814

following design scope of a potential CBAM identified by Mehling et al. (2019) can serve as a guide for understanding the principal design challenges:

1. Imports vs exports
2. Sectoral coverage
3. Geographic scope
4. Policy coverage
5. Carbon content

For transforming both the domestic industry and ensuring a carbon-friendly domestic basic materials consumption, a CBAM shall cover imports or both imports and exports. Imported goods would face a carbon price. Exports exemptions for carbon pricing allow domestic producers to sell their products at the global market price. These exemptions might be considered an export subsidy (Mehling et al., 2019) and provide no carbon price incentive for export-oriented businesses to implement carbon-friendly production processes. Without these exemptions, exports would face higher costs than competitors not subject to carbon pricing. It would endanger the business model of export-oriented industries and could result in carbon leakage risks (Ismer et al., 2020). A continued free allowance allocation for exports could mitigate this effect but would imply complex bookkeeping and tracking of domestic production flows. Additionally, continued free allocation might be incompatible with the WTO Agreement on Subsidies and Countervailing Measures (ACSM) (Ismer et al., 2020). As explicitly stated in the "Fit for 55" strategy, CBAMs would most likely mean an end to free allowance allocation for those sectors covered by a CBAM.

A CBAM should cover emission-intensive material flows. Reducing a CBAM to basic materials flows from those sectors already covered in the EU ETS reduces administrative complexity but might impact the global competitiveness of domestic producers of intermediate products. The effect of CBAM design considerations studied in greater detail in the literature includes a product-group-specific (Rocchi et al., 2018) and a sector-specific approach (Allevi et al., 2017). Still, its effect on the value chain has received little attention.[157] Given a carbon price pass-through for all basic materials sold within the EU, material-intensive manufacturers of intermediate products face significantly higher operational costs than their international competitors, as we described in Cosbey et al. (2020). Preventing carbon leakage for basic material production does not imply carbon leakage protection for the entire value chain. Nevertheless, the resulting administrative complexity might make it practically impossible to extend the CBAM to the manufacturing sector.[158]

Scholars highlight the need for a CBAM with a geographical scope covering all countries equally to avoid transhipment strategies of importers but remain open to certain exemptions for least developed countries (Mehling et al., 2019). CBAMs would cover carbon dioxide-equivalent emissions, equally as the domestic carbon market, the EU ETS. Fossil CO_2 is not the only greenhouse gas, and if the scope of emission pricing were extended to the likes of methane or nitrous oxides to prevent global warming, border adjustment measures for all these gases would be required.

The method used to evaluate the carbon content of imported products determines the effectiveness of the CBAM to reflect the full carbon cost on domestic markets. Benchmark options range from facility, technology, or country-specific default values to uniform values based on best-available technology or sector-based global averages. Setting these default values would always require a sound methodology. Country specific and sector-based averages can be quantified with globally accepted standard methods used by the IPCC or the IEA. In Cosbey et al. (2020), we evaluate options and trade-offs between these different emission intensity values, as shown in Table 5-B.

In theory, country, technology, or facility-specific values may allow for a better carbon cost internalisation. One concern, though, is that it incentives companies to reshuffle their production.

[157] See, Stede et al. (2021) for a first evaluation of incentives and risks for carbon pricing of basic materials for the value chain and consumers.
[158] *See*, the exemplary the flows within international value chains in the automotive industry operating under a combined strategy, as described in Schmid and Grosche (2008).

Production from countries, technologies or facilities with a low-carbon footprint would serve European markets, while emission-intensive facilities supply other international markets. Technology and facility-specific default values could also discriminate production from countries with a low-emission energy mix. As such, uniform default values based on a sector average or best available technology average for emissions caused by one ton of the product might be the better design choice. A best available technology benchmark means that older and less efficient production facilities face carbon costs heavily deflated compared to their actual emissions. Therefore, CBAM would only reflect part of their actual emissions and give these facilities a competitive edge compared to domestic production facing the full carbon cost. This effect can be partially mitigated by establishing a CBAM based on the global average. Here, foreign cleaner production facilities must have the opportunity to reduce the CBAM surcharges by proving that their emissions are significantly below the sector average.

Table 5-B: Options and trade-offs for default emissions intensity values, their potential to strengthen climate actions (green), risks and costs (yellow)[159]

			Benchmarks with uniform default values		Benchmarks with differentiated default values		
			based on sector average	based on best available technology	by country	by technology	by facility
Strengthen mitigation incentives	Carbon cost internalisation	For imports	✓✓	✓	✓✓✓	✓✓✓	✓✓✓
Strengthen mitigation incentives	Carbon cost internalisation	For domestic producers with export rebates	✓✓	✓✓	N/A	✗	✗✗
Strengthen mitigation incentives	Leakage protection	Level playing field for exporters	✓✓	✓	N/A	✓✓	✓✓
Strengthen mitigation incentives	Leakage protection; Support global climate action	Avoids foreign production reshuffling	✓✓	✓✓	✗	✗	✗✗
Strengthen mitigation incentives	Leakage protection; Support global climate action	Incentives for foreign producers to improve	(with option to certify)		(with option to certify)	✓	✓✓
Strengthen mitigation incentives; Legal and political risk	Support global climate action	Incentives for foreign governments to regulate			✓		
Legal and political risk		Avoids over-charging clean importers	(with option to certify)	✓✓	(with option to certify)	✓	✓✓
Legal and political risk		Avoids over-compensating exporters		✓✓		✓✓	✓✓
Legal and political risk	Complexity and cost	Avoids discriminating by country of origin	✓✓	✓✓		?	?
	Complexity and cost	Uses domestically available data	✓✓	✓✓	✓		

The optimal design of a CBAM robust to WTO rules remains an unsolved issue, known since early carbon pricing considerations on the verge of the Kyoto protocol in the early 1990s (Poterba, 1991). Given the identified design challenges, I conclude that a proposed CBAM will not fully reflect the imported products´ carbon content and associated emission allowance costs. A CBAM design would always rely on additional policies, among others, to address carbon leakage concerns by those sectors not covered by the EU ETS (or CBAM) and compensate for potential trade-offs with regard to carbon cost internalisation due to applied benchmarks. A CBAM is a highly sector-

[159] The default value (with current EU ETS benchmark approaches) is two ticks, three ticks presenting better performance, and a cross indicates adverse effects. Developed with an international team of researchers to respond to the public European Commission consultation on the EU Green Deal (carbon border adjustment mechanism) initiative (Cosbey et al., 2020).

specific policy whereby policy design choices about its scope impact the future markets of basic materials and the business model of industries covered by a CBAM and those that are not.

Climate Contribution (CC)

Free allowances are the status-quo of emission pricing for basic materials in the EU ETS. Introducing a CBAM without free allowances means that at 30 €/tCO_2e, cement, steel, and aluminium producers would have to charge between 17.6 and 49.3% more for their production (Stede et al., 2021).[160] As such, their competitiveness would rely on the functioning of the CBAM to assign adequate carbon costs to imports. Even if implemented gradually, industry representatives vehemently oppose such direct exposure to emission prices and market dynamics. Spanish companies echoed this concern during our roundtable consultations as part of the CFMP (Gerres et al., 2019c). Furthermore, industry responses to the European Commission consultation procedure on carbon border adjustment mechanisms highlight industrial opposition to CBAMs (Euractiv and Reuters, 2020).[161]

The Climate Contribution (CC), co-developed and further detailed by the CFMP (Neuhoff et al., 2019), is an alternative approach to a CBAM that can introduce a carbon price signal to the entire value chain while addressing industry concerns by maintaining free allowance allocation. First of all, the CC is an additional surcharge on basic material use. All basic material flows, covered by the EU ETS and entering the EU single market, are charged a fee that corresponds to the weight of the basic material multiplied by a material-specific emission benchmark and current EU ETS allowance price. The benchmark can be based, for example, on the product-specific emission default values for basic materials stated in Annex 1 of Commission Decision 2011/278/EU. As shown in Figure 5-5, the CC would ensure that final consumers would pay the equivalent CC for their material use. By itself, the CC incentivises smarter material use because the only way to reduce the surcharge across the value chain is to minimise basic material intensity. Since this charge would not discriminate between imports or exports based on their production process or origin, it would also conform with WTO trade law (Ismer et al., 2020). It would act more like a domestic material tax that varies depending on the current market price for emission allowances rather than a carbon pricing mechanism that would differentiate between production processes. Consequently, basic material exports are exempt from the CC while imports are covered.

By maintaining free allowance allocation after introducing the CC, domestic producers with conventional basic material production processes would not experience price changes for their products in domestic and international markets, given that its emission intensity corresponds to the benchmark set for free emission allocation. Their carbon price signal would remain muted (Figure 5-6). That said, any new climate-friendly basic material facility would be equally eligible to free allowance allocations like their emission-intensive conventional counterparts. This free allowance would be sold to generate an extra revenue stream and, backed up by C-CfDs, can guarantee stable long-term returns (Chiappinelli et al., 2021; Neuhoff et al., 2021). Conventional production would thereby primarily be pushed out of the market by the improved competitiveness of climate-friendly alternatives. A CC would additionally rely on other policies to create and strengthen markets for climate-friendly basic materials.

[160] Mean carbon cost increase (%) over all basic material product categories in the EUROSTAT production of manufactured goods data base (PRODCOM) is 23.0%

[161] The Euractiv/Reuter report (Euractiv and Reuters, 2020) refers to consultation procedure on the EU Green Deal (carbon border adjustment mechanism) initiative that I contributed to with (Cosbey et al., 2020).

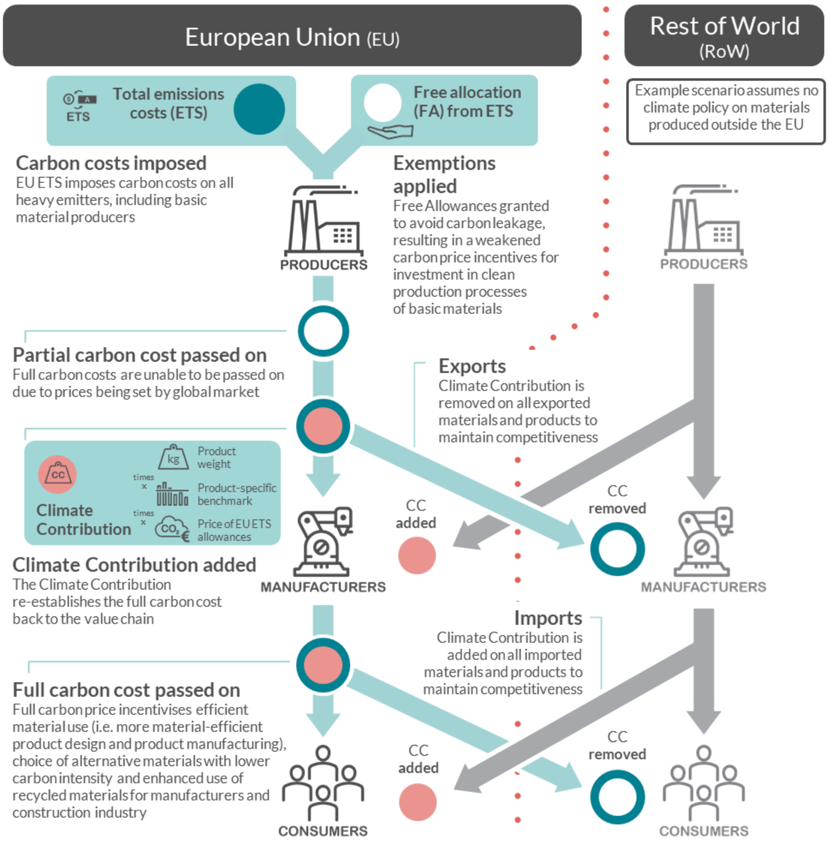

Figure 5-5: Schematic functioning of the Climate Contribution (CC)[146]

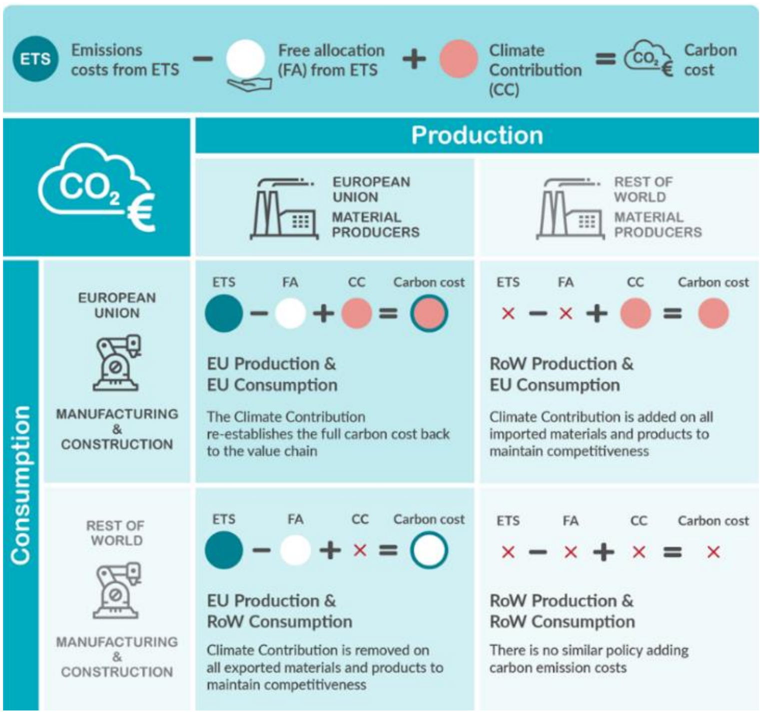

Figure 5-6: Emission pricing for domestic and foreign producers with a Carbon Contribution (CC)[146]

The CC would introduce a carbon price to the value chain equivalent to the chosen benchmarks for different basic materials used to calculate the CC. Other than for the CBAM, the functioning of the CC is less sensitive to changes in these benchmarks. Setting the benchmarks might also be less controversial than for a CBAM, especially concerning WTO law concerns, since it equally applies to domestic production and imports. Administrational complexity would also be reduced, given that the only product-specific characteristics used to calculate the CC for imports are its weight and material type. Under the proposed CBAM by the European Commission[162], benchmarks apply to imports only, thereby treating foreign producers differently from domestic production with emission pricing corresponding to their actual emission intensities.

Apart from these differences, the discussed CBAM designs and CC may share one common feature. The function of these mechanisms is based on the market price for emission allowances. The emission allowance price itself, though, is subject to the transition across all sectors covered by the EU ETS. Besides the demand from the industrial sector, the power sector, aviation and, in line with "Fit for 55" propositions, shipping, road transport and the building sector set the market price for emission allowances. It might be questionable that one "horizontal" carbon price across all these sectors can orchestrate a transition that safeguards that very different intermediate transition targets are met in each industry. Intermediate target setting can be crucial for those sectors that are harder to abate and risk carbon lock-in since current and new technologies have long design life, often exceeding 20 years (section 3.3). The gradual implementation of such measures might also incentivise only gradual and incremental improvements rather than introducing climate-friendly production processes. Therefore, carbon market designs and mechanisms to ensure a carbon price pass through within the value chain cannot be the only policy to comply with decarbonisation objectives.

5.3.5. Standards and product carbon requirements (PCRs)

Governments deciding what is good for their citizens and banning what is bad is a highly emotional topic. In German, we even have a word for it. "Verbotskultur", a cancelling culture that creates a nanny state. But rather than patronising citizens, voluntary standards, mandatory requirements, and bans can foster innovations, shape markets, and create new ones. Empirical studies have demonstrated how regulation stimulates innovation (Ambec et al., 2013; Calel and Dechezleprêtre, 2016; Pelkmans and Renda, 2014). In sharp contrast to previously reviewed policies, rigid regulatory requirements can also ensure that each basic material sector can meet agreed emission reduction targets. Rather than incentivising potential incremental improvements, such product carbon requirements (PCR) would send a strong signal for investments in climate-friendly production processes. In the following, I summarise the findings presented in our journal paper on PCRs (Gerres et al., 2021). First, I recap the role of environmental standards and regulations for products and processes on the EU single market. I then describe how policymakers could implement product carbon requirements based on best practices from current legislation.

Environmental standards and technical regulations: examples from the EU

By setting criteria and limits, the CE (Conformité Européenne) legislation[163] ensures that a wide range of products sold and used within the EU conform with safety, health, and environmental protection requirements. Relevant CE directives and regulations[164] motivated the development of harmonised voluntary standards that can be used to demonstrate compliance (EC, 2016b). CE legislation ensures producer liability for goods sold on the EU single market but does not set any criteria on the production process itself. Here, they are similar to Euro emission standards for road vehicles like Euro 6. The relevant regulation specifies quantitative emission limits for exhaust gases that any new vehicle must comply with when sold in the EU.[165] Although EU emission standards primarily apply to the EU single market, the "World Harmonised Light Vehicle Test Procedure" (WLTP) used to validate compliance is the outcome of a global initiative led by the United Nations (UNECE, 2019). Product requirements impact domestic and foreign

[162] See, Proposal for a Regulation of the European Parliament and of the Council establishing a carbon border adjustment mechanism. COM(2021) 564 final in July 2021.
[163] *See*, Regulation (EC) No 765/2008
[164] For a complete list of the relevant directives, see: https://ec.europa.eu/growt h/single-market/ce-marking/manufacturers_en.
[165] *See*, Regulation (EC) No 715/2007

producers who want to sell goods on the European market, but only concern the operational characteristics, such as emissions caused by using the final product.

In contrast, legislation that addresses production processes sets rules for domestic production facilities and those of importers situated outside the EU. One example of such legislation is the EU biofuel certification scheme. Biofuel importers need to comply with different environmental impact criteria and land-use practices for growing biofuel crops. Only then, their biofuel is considered to be sustainable under the Renewable Energy Directive.[166] They can certify their production using one of the voluntary certification schemes recognised by the EU (European Court of Auditors, 2016). Whereas the biofuel certification scheme requires importers to certify their production processes, the EU Timber Regulation (995/2010) only requires companies to exercise "due diligence". By keeping records of their suppliers and customers, importers need to demonstrate that imported timber and timber products do not stem from illegal sources. Timber from countries that signed Forest Law Enforcement, Governance and Trade Voluntary Partnership Agreements (FLEGT VPAs) with the EU is considered legally harvested.

Compared to the biofuel and timber regulation, the Ecodesign Directive[167] and the Energy Labelling Regulation[168] may have more relevance for basic material production. The Ecodesign Directive covers a wide range of products and provides a framework for detailing product-specific regulations containing binding requirements on product design and functioning. In the past, these regulations primarily detailed energy efficiency and labelling requirements for products such as non-directional household lamps[169] or televisions[170]. That said, the Ecodesign Directive encompasses provisions for requirements beyond product characteristics, like recyclability and material circularity provision. New regulations, for example, initiated by the EU sustainable product initiative[171], could extend the reach of the Ecodesign Directive, covering both product and production process related environmental standards and requirements. Criteria set by such regulations would go beyond monitoring requirements, such as defined in the Eco-Management and Audit Scheme (EMAS). Introduced by Regulation 1836/93[172], EMAS is a voluntary standard for environmental management systems. EU Green public procurement guidelines advise public authorities to oblige contractors to certify their environmental management system accordingly (EC, 2016c).

Implementing PCRs

The following paragraphs are part of our journal paper "To ban or not to ban carbon-intensive materials: A legal and administrative assessment of product carbon requirements" (Gerres et al., 2021), with minor modifications to the published version.

Our review[173] of selected examples of EU legislation demonstrates that product-specific policies, such as CE marking, Euro vehicle emissions standards and the Ecodesign Directive, have a long history and are well established in EU policymaking. Moreover, it shows that the EU has experience with standards related to the production process, for example, to ensure the sustainability of biofuels and timber products. These findings can help to outline the general design of PCRs.

In comparison to reviewed legislation, PCRs would be mandatory and be implemented through an assessment of the carbon intensity of the production process. Only near-zero carbon products

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[166] *See*, Directive 2009/28/EC, now recast Renewable Energy Directive (EU) 2018/2001
[167] *See*, Directive 2009/125/EC
[168] *See*, Regulation (EU) 2017/1369
[169] *See*, Commission Regulation (EC) No 244/2009
[170] *See*, Commission Regulation (EC) No 642/2009
[171] Our contribution to the public consultation on the sustainable products initiative can be downloaded from the website of the European Commission: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative/F890179_en
[172] *See*, now, Regulation (EC) No 1221/2009
[173] For the full review of the selected legislation introduced in the previous paragraph, see Gerres et al. (2021).

would be allowed on the EU market. Such a measure could be a drastic but necessary step towards a carbon-neutral Europe. An elaborate body of emission standards would be needed to determine the climate neutrality of production processes, which could be developed internationally through the ISO or under the umbrella of the United Nations or at the EU level as EN standards or EU regulation.[174]

To smoothen the transition towards such a measure, initially, these standards could be introduced as a labelling standard for basic materials linked to their emissions intensity. This could be the first possible (voluntary) step towards implementing PCRs, though these standards could also be used to introduce quota schemes for domestic consumption.[175] These quota schemes could set minimum shares of basic material use for final consumption and apply these standards to demonstrate compliance. Such standards would set emissions criteria for traditional carbon-intensive materials to evaluate whether their production is near climate neutral. As such, it would go beyond the provisions of EMAS, which only requires emissions auditing and does not set emission criteria. Materials complying with the standard and products exclusively containing such materials could obtain a label.

Such a label would benefit and enable businesses to provide evidence of the climate impact of their materials to final consumers and demonstrate the viability of their business model to financial investors in a carbon-constrained economy. Provisions for introducing such standards could be implemented as part of the EU sustainable products initiative, aiming to revise the Ecodesign Directive.

In a second step, mandatory PCRs could complement voluntary standards (Figure 5-7). One option for implementation would be to allow companies to use the previously described voluntary standards to demonstrate the climate neutrality of their basic materials, adopting them as harmonised standards as used for EU product rules.

At the same time, lawmakers could draw from experience with non-product related processes and production methods, such as the sustainability criteria for biofuels production and timber products. For example, administrative complexity could be reduced by obliging companies to exercise due diligence, as it is already done with CE marking and the Timber Regulation. In parallel, carbon-intensive domestic production processes of basic materials would also need to be banned within the EU to avoid that producer export materials previously dedicated to the domestic market and therefore jeopardise the political legitimacy of PCRs.

As further demonstrated by us in Gerres et al. (2021), PCRs could be implemented within the EU or any other jurisdiction without violating WTO rules provided they are designed and adopted in a manner consistent with the main legal tests of the GATT and TBT. That said, the unilateral introduction of PCRs might create bilateral tensions with trade partners of the European Union since they could be perceived as sanctions for carbon-intensive basic materials. Without entering a detailed discussion, measures and countermeasures in the trade conflict between China and the US on tariffs and unequal treatment of imports and exports demonstrate how unilateral actions can escalate.[176] As such, the decision for introducing PCRs is subject to other policy considerations that are beyond its consistency with WTO rules.

Even though we see PCRs as enablers of a transition towards climate-friendly production processes, their introduction might face opposition by those that perceive them as part of a "Verbotskultur". Critics might refer to the bureaucratic burden for companies and additional costs

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[174] European Standards (EN) are voluntary specifications for products, production processes, services or test-methods, developed by the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI) to support EU single market legislation and policies: https://ec.europa.eu/growt h/single-market/european-standards_en

[175] A voluntary standard would leave the choice to importers to require non-EU producers to comply with the EU standard or opt for not labelling their products.

[176] For a detailed economic analysis of the causes and effects of this conflict, see this WTO staff working paper (Bekkers and Schroeter, 2020).

for tracking, accounting and certifying the emission intensity of production. However, PCRs imply less administrational efforts than implementing, for example, a CBAM. Both PCRs and emission pricing mechanisms require emission monitoring, whereby carbon pricing and their border adjustments represent an additional dimension of complexity compared to PCRs. That said, all domestic and foreign producers that are subject to domestic carbon pricing mechanisms are already required to monitor their emissions. Also, any company implementing environmental management systems such as EMAS or ISO 14000 monitor their emissions already.

ISO 14000, a voluntary international standard developed by the International Organisation for Standardization, is used by companies across the globe. Though the relative share of certified companies globally is difficult to estimate, absolute numbers indicate that 319.324 companies had valid certifications in place by 2015 and 396.242 companies by 2019. In 2015, EU companies accounted for 37.50 %, and Chinese companies for 36.13 % of all certificates issued (Boiral and Allur, 2018; ISO, 2020). Chinese companies dominate the global market for basic materials such as steel(World Steel, 2020). Therefore, the global reach of environmental monitoring schemes is highly relevant for the successful implementation of PCRs. Its introduction could also benefit from more manufacturing industries requiring global suppliers to certify their production according to the ISO standard (Chiarini, 2012).

By announcing the implementation of PCRs, the EU would signal their commitment to intermediate and final decarbonisation targets. Preliminary findings from our work on industrial finance in the basic material sector[177] indicate that publicly listed companies commit to emission reduction targets announced by national governments. Examples are the commitment of Swedish steelmaker SSAB to full decarbonisation by 2045 (SSAB, 2020) in line with the Swedish national climate policy framework (Government of Sweden, 2021), 2030 emission intensity targets for steel production by conglomerate JSW (JSW Steel, 2019), following targets set by the Indian Ministry of Steel (Ministry of Steel, 2021) and Korean producer POSCO explicitly stating in their Annual Corporate Citizenship Report 2019 (POSCO, 2019) to align their decarbonisation strategy with the national 2050 plans that were to be presented in 2020.

Since we envisioned PCRs as a policy approach to ban the production and import of carbon-intensive basic materials in the EU, PCRs would be a horizontal policy measure that applies to all industries equally. On the other hand, the described pathway towards implementing PCRs via voluntary standard would be more sector-specific to account for the different characteristics of industrial processes.

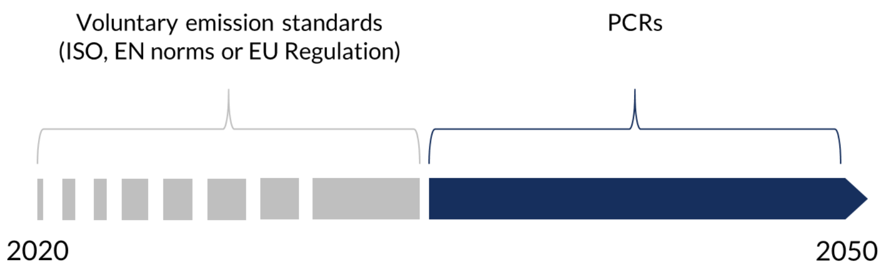

Figure 5-7: PCR phase-in with increased availability of climate-friendly production processes (Gerres et al., 2021)

5.3.6. Project, sector-specific and horizontal policy elements

The analysis of the different policy elements in this section shows that each policy has its strength and weaknesses in addressing project, sector-specific and cross-sectorial policy needs. As summarised in Table 5-C, direct investment support and GGP are suitable to address project-specific needs. However, their role in transforming entire sectors is limited. While sectorial-wide investment support translates into full subsidisation of whole industries, green public

[177] The ongoing research project is a cooperation with Elisa María Aracil Fernández (University Comillas, ICADE) and Anna-Joy Kühlwein analysing how financial markets value climate commitments by publicly listed basic material producers.

procurement is limited by its share of final demand. Contracts for Differences (CfD) for energy, carbon or in the form of long-term delivery contracts for basic material production are risk hedging instruments that can make investments in climate-friendly basic material production facilities attractive. CfDs might have relatively little total public costs and could support the transition across industries as a risk-hedging instrument. It remains unclear how competitive tenders could be designed in a national and European context. By design, market-based carbon pricing is a horizontal policy. However, one carbon price signal across various sectors is the most effective if all these sectors have low-emission alternatives available to perform all economic activities required by our society. As long as this is not the case, free allowances combined with a CBAM make carbon pricing a rather sector-specific policy that relies on other policy instruments to support the transition of the basic materials industries. The climate contribution is an additional carbon pricing policy that could help the transition with sector-specific incentives to improve material efficiency across the value chain and provide funding for other policy instruments. Voluntary standards can support other project and sector-specific policies. The introduction of mandatory PCRs is a horizontal policy that would set the rules for market access in a decarbonised economy. Such standards or requirements can be used to ensure compliance with intermediate and long-term decarbonisation targets.

Table 5-C: Project, sector-specific and horizontal policy elements of the policy package[178]

<table>
<tr><th></th><th>Project-specific</th><th>Sector-specific</th><th>Cross-sectorial (horizontal)</th></tr>
<tr><td>Direct investment support</td><td>+ fund and finance novel technologies
- does not address operational uncertainties
- costly</td><td>- sector-wide subsidies could be unfair competition on global markets
- increased public cost</td><td></td></tr>
<tr><td>Green public procurement (GGP)</td><td>+ long-term demand stability for first-mover installations
o GPP criteria to foster low-emission options over efficiency improvements
- costly</td><td>o can provide enough demand for a significant share of current production
- does not provide enough demand to transform sectors</td><td></td></tr>
<tr><td>Contracts for Differences (CfDs)</td><td colspan="2">+ can make new projects financially attractive
+ reduce operational cost uncertainties
o design to hedge against volatile operational cost difference with conventional processes
- unclear how to ensure competitive tenders for projects or sector-specific awards on national or European level</td><td>- only supports the transition if award criteria aligned to sector-specific needs</td></tr>
<tr><td>Carbon pricing across the value chain</td><td>o basis for C-CfDs
- first-mover projects are price-taker for market-based emission pricing</td><td>+ free allowance allocation allows for sector-specific emission price signals
+ create revenues to finance other policy instruments
- uncertainty about future allowance costs</td><td rowspan="3">o horizontal emission pricing requires the availability of low-emission technologies for all economic activities</td></tr>
<tr><td>Carbon Border Adjustment (CBAM)</td><td colspan="2">+ strengthens the carbon price signal by reducing the need for free allowances
o CBAM design should not discriminate between imports and domestic production
- full CBAM is highly bureaucratic and not practical
- partial CBAM may result in undesired policy effects on the value chain</td></tr>
<tr><td>Climate Contribution</td><td colspan="2">+ strengthens the carbon price signal by reducing the need for free allowances
+ additional revenue stream to finance policy instruments
- only incentivises material efficiency across the value chain</td></tr>
<tr><td>Standards and product carbon requirements</td><td>o voluntary standards can define the climate-friendliness of processes</td><td>+ standards can be used to strengthen and support other policy instruments</td><td>+ PCRs to set sunset clause (target setting) for market access in a decarbonised economy
- risk of premature bans without sufficient low-emission production capacity available</td></tr>
</table>

[178] The table lists results for the analysis of the policy package presented in section 5.3 by differentiating between strictly positive (+), potential positive or hindering (o), and negative (-) aspects of policy elements.

5.4. A pathway towards decarbonised basic material markets

How to get from A to B, "A" being the status-quo and "B" a decarbonised basic material industry. In section5.3, I revisited the design elements of a policy package that provides us with the tools to guide the transition towards climate-friendly basic material productions. I explained the functioning and implications of these policies and characterised them by differentiating between horizontal and specific policies. As we have highlighted in our reports with the CFMP, especially in (Neuhoff et al., 2019), these policies are tools that need to be well aligned to guide an inclusive transition of basic material markets. However, our work with the CFMP has remained rather unspecific on how and when these policies shall be implemented. In Neuhoff et al. (2019), we only provide a rough indication of the implementation order. We then detailed policies that can kick-start the transition towards climate-friendly basic material production as part of a green Covid-19 economic recovery in our latest journal paper (Chiappinelli et al., 2021). In the following, I first recap and revaluate our findings related to policies that could kick-start the transition (section 5.4.1). Then I extend our analysis to evaluate those policies that may enable a global competition of climate-friendly basic material production (section 5.4.2) on the pathway towards long-term climate-neutrality of basic material markets (section 5.4.3). As a result of this analysis, I formulate propositions about the policy need during these three transition phases.

5.4.1. Policies to kick-start the transition

Most climate-friendly technologies for basic materials have not been implemented on an industrial scale yet. Based on interviews with industrial stakeholders and a literature review covering both primary production and secondary recycling options for the steel, cement, petrochemicals and aluminium industry, I show in the first part of Chiappinelli et al. (2021) that climate-friendly alternatives are commercially available or have been implemented as pilot plants today. So far, though, there is no business case for changing conventional production processes to new ones. In the second part of our paper, we analysed 31 semi-structured interviews with industry experts across 6 European countries (Germany, Netherlands, Belgium, Spain, Hungary, Poland) to identify the main barriers to implementing climate-friendly basic material production (Table 5-D).[179]

As shown in Figure 5-8, more than 80% of the interviewees stated that the unpredictability and effectiveness of carbon pricing mechanisms was the main barrier to implementing climate-friendly basic material production and recycling options. As almost half of the respondents stated, the limited availability of affordable green electricity was the second most mentioned barrier. Primarily relevant to industries with direct or indirect electrification options, responses highlights the perceived electricity price (section 4.2) and energy supply uncertainty (section 4.4) that we analysed in Chapter 4. On positions three to six, each mentioned by about one-third of the interviewees, we find barriers that refer to the lack of regulatory certainty, adequate infrastructure and demand for clean and recycled materials and the perceived low technology readiness and funding. Here, low technology readiness is closely linked to funding difficulties. Missing industrial-scale implementation and operational experiences increase the risk of failure, making the projects more costly so that they rely on public support (Nemet et al., 2018). Lacking infrastructure for hydrogen, CO_2, or electricity can be another showstopper for new climate-friendly projects. The operational economics of such infrastructures require demand from multiple consumers, while the lack of such infrastructures is a primary barrier to implementing first-mover projects. Challenges are similar to the "chicken-egg-problem" of installing electric hydrogen vehicle charging infrastructure (Tollefson, 2010). The lacking regulatory framework for circularity is specific to enhanced recyclability. Here, the availability of purer recycling streams is a prerequisite for a higher share of secondary production. Whether produced with primary or secondary production route, demand for climate-friendly basic materials remains a significant barrier, especially if conventional options are cheaper than climate-friendly alternatives.

[179] *See*, Annex 1.1 of Chiappinelli et al. (2021) for a detailed description of the research method and the interview guide.

Table 5-D: Categorization of interviewees by industry, type of company and country from Annex 1.1 of Chiappinelli et al. (2021)

Number of interviewees by	
Industry	
Steel	9
Cement	5
Chemicals	12
Aluminium	2
Sorting and recycling	3
Type of company	
Material producer	20
Technology provider	6
Other (e.g. associations)	5
Country	
Belgium	6
Germany	14
Hungary	2
Netherlands	3
Poland	2
Spain	3
United Kingdom	1
Total	31

The most mentioned barriers of effective carbon pricing and affordable green electricity reflect the cost uncertainty of emissions and energy pricing. Combined with the perceived funding difficulties, half of the six most mentioned barriers are related to installation and operational cost uncertainties. A fourth barrier, the lack of demand, is a logical consequence of these cost uncertainties by putting the competitiveness of climate-friendly materials in question. In the following, we focus on policies that can address these four barriers.

From the discussed policy options in section 5.3, green public procurement (GPP) is an ideal candidate for creating long-term demand certainty for first and second mover installations. These installations for climate-friendly basic materials may utilise very different production processes than conventional processes. Both investment and operational costs, latter especially for energy, exceed those of conventional technologies. Using shadow emission prices in GPP might encourage further investment in optimising existing technologies that lead to carbon lock-in. Using target-based green public procurement criteria for climate-friendly basic materials from primary or secondary production might create a stronger demand signal (Hasanbeigi et al., 2021). Here, GPP could act like quota schemes, such as adopting recycled content in plastic beverage bottles by Directive (EU) 2019/904 and strengthening their role.[180] Such quotas would be highly sector-specific, concerning the scope of basic material processes considered climate-friendly for each industry and the quota that would depend on availability and planned production capacities. As suggested in Gerres et al. (2021) and mentioned as a possible step towards introducing PCRs (section 5.3.5), labelling schemes can support but cannot ensure demand growth for climate-friendly basic materials. Due to their voluntary character, their success depends on the willingness to pay for climate-friendly basic materials of industrial and final consumers.

Carbon and energy price uncertainties can be addressed from a more general market-based or a project-based perspective, both discussed in Chiappinelli et al. (2021). However, modifying the EU ETS, the introduction of CBAM or CC are all changes to the general market design that may provide framework conditions for making climate-friendly materials production more competitive in the long run. As such, they do not necessarily help early projects to ensure their economic viability.

In contrast, project-based Contracts for Differences (CfDs) fit the individual needs of early projects and ensure their long-term viability. CFD design for electricity (E-CFD), carbon allowance pricing (C-CfD) or even materials (M-CfD) should address the three challenges that we identified in section 4.4. Concerning price-fixing mechanisms, the long-term competitiveness of

[180] Quotas for climate-friendly basic material are included in the industrial policy package for industrial decarbonisation presented by Agora Energiewende and Wuppertal Institute (2021).

climate-friendly production facilities with CfDs, their potentially market disturbing effect and the difficulty of organising competitive tenders.

Since public CfDs for first and second mover installations would be project-specific long-term agreements, the European Union should provide common framework conditions for CfD design. Their objective is to ensure competitive tenders and avoid the misuse of CfDs by national and regional governments as a vehicle to channel subsidies to political motivated uneconomic projects. Here, EU wide tenders might be a good approach, especially for first or second mover installations in each industry. A wider choice of technology providers and locations incentives cost-competitive bids and provides a better indication about their expected economics. The same holds for any direct investment support (section 5.3.1) that might be required to bridge the funding gap of these first-mover projects.

Early projects would require substantial financial support. GPP funding would most likely stem from the general budget of the European Union and its member states. As highlighted by us in Chiappinelli et al. (2021) and by other CFMP reports (Brzeziński and Śniegocki, 2020; Gerres and Linares, 2020; Neuhoff et al., 2021), revenues from the EU ETS, CBAMs or a CC should be redirected to fund CfDs for climate-friendly basic materials production. Resources obtained from climate policies should finance climate mitigation measures, and as such, could be circulated within the basic material industry. That said, the origin of financing has little effect on the economics of first and second mover installations since their market share would be negligible. With an average plant size of 1 Mt for cement, 4 Mt for steel or 1 to 1.5 Mt for individual steam crackers in petrochemical plants (section 2.3), early projects would provide only a fraction of European basic material demand. As such, concerns regarding funding and operational revenues have little impact on global basic material markets and would not raise cross-border issues. Here, my analysis of policies to kick-start the transition differs from the work presented by us in Chiappinelli et al. (2021), which also includes measures that address the competitiveness of climate-friendly basic materials in global markets. I, therefore, conclude that an appropriate policy design for kick-starting the transition would primarily focus on creating just and competitive funding conditions across companies and sectors in all European regions for successfully implementing first industrial-scale projects.

V.I: For kick-starting the transition, a horizontal policy framework needs to detail how governments can design sector- and project-specific policies that strengthen the business case for first industrial-scale installations serving the domestic basic materials market.

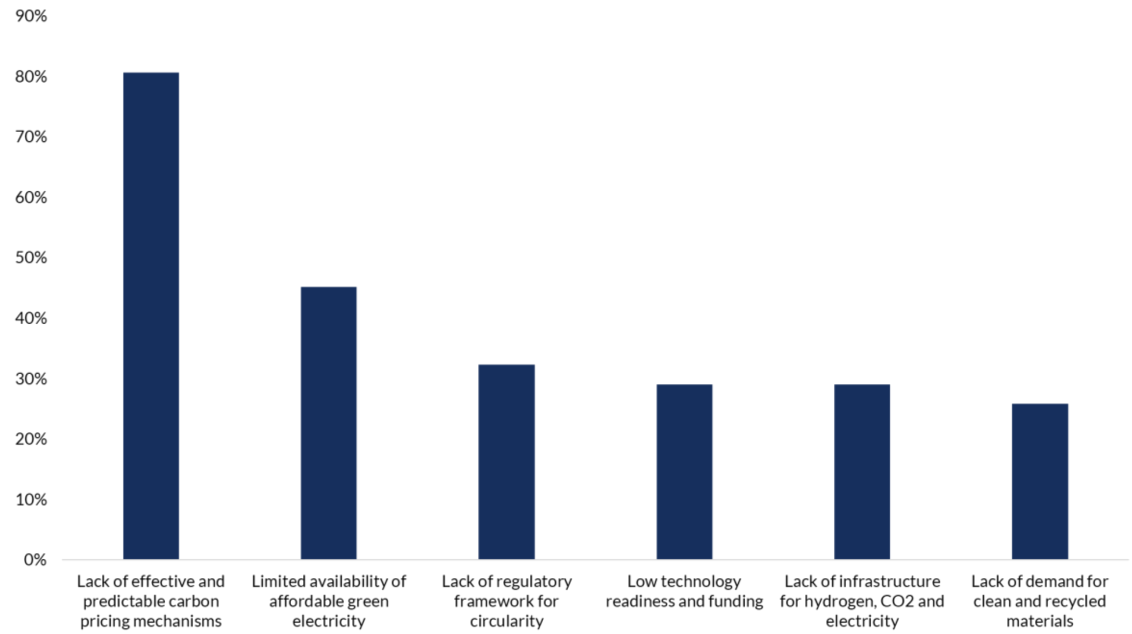

Figure 5-8: Ranking of barriers based on interviewees responses (Chiappinelli et al., 2021)

5.4.2. Policies favouring global competition

Climate-friendly basic material production could only reduce absolute and relative emissions if they make up a significant consumption share. Our journal paper (Chiappinelli et al., 2021) contemplates a 20% share of climate-friendly basic materials production in the EU that could be reached by 2025, originating both from novel primary and secondary production processes (section 3.4). Without fixing a time horizon for reaching such production quotas, I focus on policies necessary to reach a level of sector transformation beyond the first industrial-scale implementations of climate-friendly basic material production routes.

Many policies to kick-start the transition can also help to make climate-friendly material production competitive in the long run. Extending the reach of green public procurement towards the use of only climate-friendly basic materials is vital for creating a stable demand for novel low-emission processes. However, public expenditure only accounts for less than 15% of all economic activities in the EU (section 5.3.2) and by itself would not be able to create competitive climate-friendly basic material markets. Direct investment support that is essential for financing early projects cannot be a cornerstone for building up an entire climate-friendly industry. Such public investments would require vast funding, oppose free-market principles, and disturb trade with international partners. According to WTO Agreement on Subsidies and Countervailing Measures ("SCM Agreement"), such direct subsidies may allow foreign countries to evoke measures to counter the effects of such subsidies. Even if WTO rules permitted such subsidies as part of environmental policymaking, it is doubtful that foreign trade partners would approve such unilateral actions (section 5.3.5).

In this context, even CfDs for new climate-friendly production facilities could be seen as a subsidy. Primarily a risk hedging instrument, additional revenue streams for buying or selling energy, emission allowances or materials at rates more favourable than the actual market conditions might be considered state aid. This might be the case if other countries or regions with more favourable locational factors, such as access to low-cost renewable energy sources, would move towards producing climate-friendly basic materials to export their goods to the European Union. Countries like Australia and Chile have already announced export-oriented strategies, not for basic materials but the production of green hydrogen (Hydrogen Council, 2021). These regions could see their strategies jeopardised if instruments like CfDs protect domestic climate-friendly production. Legal experts should carefully assess CfD designs to make sure that measures are consistent with WTO rules.

In particular, C-CfDs would protect new climate-friendly production facilities against low, volatile and unpredictable emission allowance pricing on the EU ETS. Implementing CBAMs or a CC may help ensure that carbon prices are reflected within the value chain so that manufacturers are incentivised to choose basic materials with a lower carbon footprint. However, as I show in the following, carbon pricing across the value chain does not mean that allowance pricing incentives investments in climate-friendly basic material production.

As explained in 5.3.4, carbon pricing is a horizontal policy measure with a price formation mechanism for a single carbon price across all sectors participating in the EU ETS. Therefore, the changing emission intensity in one sector may influence the competitiveness of climate-friendly technologies in others. An accelerated transition in one sector may reduce the total emission price, thereby disincentivising the transition of other sectors. For EU ETS design, free allowance allocation is used as an instrument to counteract such potential imbalances by using sector-specific volumes and shares of free allowances (ICAP, 2021).[181] The adjustment of free allocations is slow, only done ex-post and on a yearly basis, therefore inadequate for avoiding the undesired side effects, such as detailed in the following.

Emission allowance prices form by matching supply and demand. Neither free allowance supply nor demand is highly price-sensitive but subject to macroeconomic volatility across the sectors included in the EU ETS. Airlines require fewer free allowances when global air travel demand is low, though, at the same time, the energy and emission demand of other economic activities might

[181] *See*, Directive (EU) 2018/410 amending Directive 2003/87/EC and Decision (EU) 2015/1814

remain relatively stable, such as observed during the COVID-19 pandemic (Jiang et al., 2021; Mofijur et al., 2021; Prol and O, 2020). Additionally, sectors such as the power and basic-material industries have rather long planning horizons for new projects that could significantly shift the emission intensity of individual sectors. For renewable generation capacities, the planning, licensing and construction can take seven years or more (Portwain, 2018). Similar figures can be found about the construction of new hydroelectric power plants (AQPER, 2021). Utility-scale solar PV farms can be constructed within months, but obtaining licences and permits before starting the construction may take years (ICF, 2015). Aggregated data for industrial projects are hard to come by, though the project timeline for a new aluminium plant shows industrial greenfield development requires similar time horizons.[182] The long lead times for new projects can cause long term market imbalances that completely dominate the functioning of the market, given the 9-year period for phase 4 of the EU ETS.

The illustrative case presented in Figure 5-9 shows the effect of a temporary imbalance if two very different sectors, the power system and climate-friendly basic material production, are coupled by the same emission allowance price. The emission allowance price that results in the optimal market balance in the electricity system would ensure that all technologies, here CCGT and RES, operate close to their financial break-even. Suppose the resulting emission allowance price is at 80.94 €/tCO_2e, such as in the +CAP+RES scenario in section 4.2.6 and would determine the price of all emission allowances. In this case, a climate-friendly basic material production facility cannot be cost-efficiently operated if it requires additional revenues of 100 €/tCO_2e for their free allowances to compete with conventional producers. Compared to conventional basic material producers, the new climate-friendly production facility would face the issue of missing revenues. Vice versa, if basic material producers set the marginal emission allowance price, here 100 €/tCO_2e, emission-intensive CCGT plants would have to pay more for their emission allowance. By adding higher emission allowance costs to the operational costs of CCGTs and elevating their markets bids, higher emission allowance prices temporary inflate electricity market prices that lead to higher profits for RES generation.

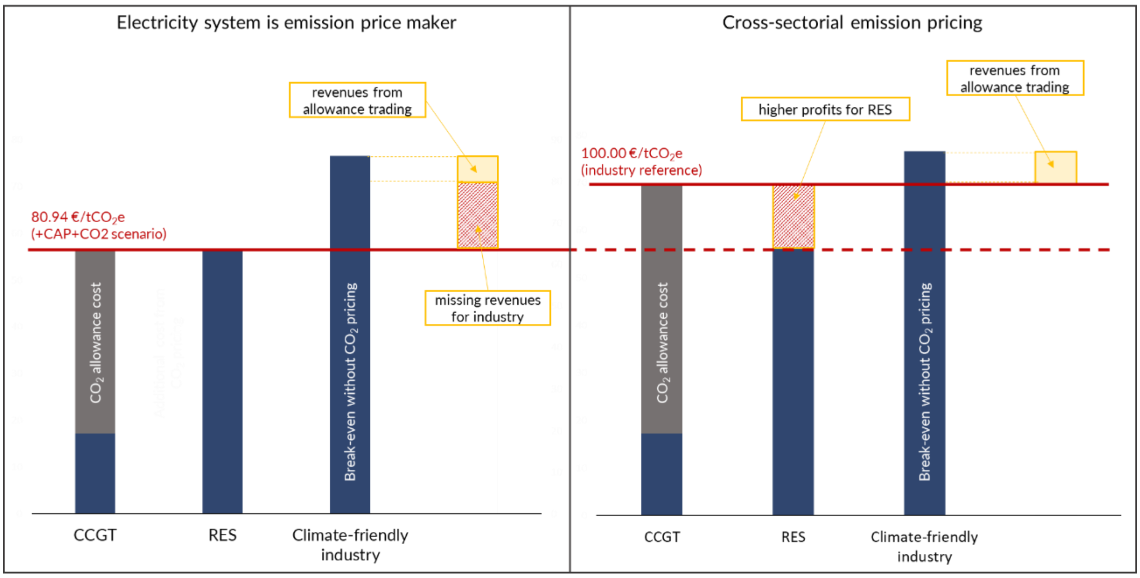

Figure 5-9: Temporary market for two indicative emission price scenarios

[182] The integrated GALTCO aluminium plant shall be fully operational in 2027, 7 years after selecting the technology suppliers (GALTCO, 2021).

This example ignores the mitigating effect of different free allowance allocations between these two sectors and does not anticipate that higher emission allowance prices impact the market outcome in the electricity system. Nevertheless, long project timelines for constructing new RES generation and climate-friendly basic material production facilities mean that the described situation could be more the rule than the exception on future carbon markets. First indications of such dynamics might even be observed today already.[183]

To conclude, carbon pricing across the value chain does not ensure that investments in low-emission technologies are incentivised within a specific sector. At the same time, CfDs as a horizontal policy for all new climate-friendly basic material production facilities might be incompatible for businesses that operate in a global market. Additionally, carbon pricing and potential border adjustment mechanisms, highlighted in the previous paragraphs and detailed for CBAM and CC in section 5.3.4, are imperfect for complying with intermediate and long-term emission reduction targets. Consequently, policymakers would face the increasingly complex task of steering the EU ETS with sector-specific policies like CfDs and CBAMs towards emission reduction in line with 2030 and 2050 targets.[184]

We can simplify this task by introducing regulatory measures like green public procurement (GPP) and later product carbon requirements (PCRs). As explained at the beginning of this section, the impact of GGP is limited by the scope of economic activity subject to public procurement rules. On the other hand, PCRs are not envisioned as a short-term solution but aim to introduce legally binding requirements for intermediate emission reduction. A step to reinforce compliance with reduction targets, PCRs would complement current emission pricing mechanisms and ensure that the horizontal carbon price reflects at least the specific emission reduction target in each sector. As highlighted in section 5.3.5, PCRs can be implemented via voluntary standards. These standards would demonstrate that the required share of production stems from climate-friendly production processes necessary for meeting intermediate targets. Strict near-zero-emission PCRs require novel primary or secondary production processes in all basic material sectors, so that also importers need to invest in novel process designs to comply. Intermediate targets might only set climate-friendly production quotas, for example, 20% with climate-friendly processes by 2030. In that case, PCRs could create a secondary market for pooling production volumes from different producers to comply with intermediate targets without incentivising production reshuffling. Such a secondary market is similar to those incentivised by the sustainability quota of biofuels (section 5.3.5) or the compliance with Regulation (EU) 2019/631 about EU fleet-wide emission targets for new passenger cars or vans.[185]

PCRs would set clear market entry conditions that apply to both domestic and international producers equally. By strengthening the carbon price signal, PCRs would also reduce the need for C-CfDs as risk hedging and funding instrument that could favour domestic producers over international competitors. I conclude that by implementing PCRs and a robust CBAM, either in the form of a CBAM or CC, policymakers could create market conditions that allow for

[183] During the third semester of 2021, the Spanish electricity market experienced record price peaks that have been linked to the price peaks for EU ETS emission allowances, as mentioned in section 5.3.4. Natural gas-fired CCGT power plants provided 21.5% of the total generation in October (El periódico de la energía, 2021), setting the marginal price based on their operational costs, including emission pricing. Consequently, the highest ever average monthly electricity market price of 204,09 €/MWh was observed on a national level (La Vanguardia, 2021), benefitting all other mainly carbon-neutral generation. Given that emission allowance prices remain high, electricity prices will only lower as soon as the demand drops or new RES generation enters the system and reduces the hours CCGTs set the marginal generation cost. As reference, according to a recent industry survey the 25th percentile offering price for solar PV PPAs was at 30.50€/MWh during Q2/2021 in Spain (LevelTen Energy, 2021). However, this interpretation ignores the presence of market power and gaming behaviour of electricity market participants.
[184] *See*, for example, the new provisions of the "Fit for 55" package that would imply a re-adjustment of phase IV of the EU ETS (EC, 2021b).
[185] *See*, for example, the financial agreement between electric vehicle producer Tesla and Fiat Chrysler Automobiles for pooling their fleets to comply with European fleet-wide emission targets (McGee and Campbell, 2019).

competitive markets between domestic and international conventional production and new climate-friendly basic material producers.

V.II: Ensuring compliance with sector-specific intermediate emission reduction targets implies a level playing field for domestic producers and importers. Policies shall foster climate-friendly basic material consumption without favouring domestic producers nor distorting competition with imports.

5.4.3. Policies to ensure long-term climate neutrality

No emissions know no exceptions. In a decarbonised economy, neither consumption nor production shall cause atmospheric carbon dioxide-equivalent emissions. All basic material production needs to be climate-friendly, contemplating a ban of emission-intensive production methods. In general, such horizontal net-zero emission policies would not allow for exceptions and would mean the end to sector-specific benchmarks. In the following, we focus on the implications of a decarbonised economy for phasing out transition policies discussed in sections 5.4.1 and 5.4.2.

Carbon markets are the backbone for emission reduction policies for the basic material sector. The availability of emission allowances makes the right of emitting fossil carbon a tradeable commodity. Allowances are granted via free allowance allocation or auctioning the available allowance stock (section 5.3.4). However, absolute emission targets diminish the allowance stock over time. As such, a decarbonised economy may not have an emission allowance market operating with free allocation or auctioning schemes.

New allowance could only be obtained by carbon-negative processes, like carbon capture and storage of non-fossil emissions or offsetting emissions by re-forestation or other carbon sink options. However, the availability of carbon-offsets comes at a certain cost and is limited (Van Kooten et al., 2004). Market-based mechanisms to sell available offsets incentivise the use of offsets in all sectors. As a result, some industries with carbon-neutral options available might be willing to pay a high price for offsets instead of decarbonising their processes. Other industries without carbon-neutral options would face higher costs for offsetting if the price is determined by a market-based shortage of offsets rather than the actual cost of realising the carbon sink. By looking at the technology options in the basic-material sector, primary cement making might be a process that cannot be fully decarbonised by 2050 (section 3.3.3). Cement producers would therefore rely on offsetting their residual emissions. Without banning offsets for specific applications, near-zero-emission PCRs could be designed so that only those basic materials with residual emission intensities but without available zero-emission options are allowed on the domestic market. This measure would significantly reduce the price for offsetting emissions if emission allowances are traded and sold domestically rather than in global markets. Other regions and countries would have implemented policies to reduce emissions, so offset allowances would become a globally traded commodity.

Deep decarbonisation to mitigate climate change is a global effort, but the domestic transition is first of all subject to changing intermediate and final targets. As visualised in Figure 5-10, efforts to reduce emissions might have to accelerate significantly until 2030 if the EU adopts the "Fit for 55" strategy. Accelerating the transition compared to other regions makes it more eminent to introduce the policies outlined in sections 5.4.1 and 5.4.2 to allow for a competitive climate-friendly basic material sector. Nevertheless, if emission reduction targets were applied to domestic consumption only, export-oriented basic-material producers would only reduce emissions in line with the emission reduction trends in their foreign target markets. They would keep emitting even if EU consumption decarbonised already. If reduction targets include all domestic emissions, exporters might depend on sector-specific transition policies to safeguard their economic viability in foreign markets, even after the EU reached climate neutrality. Without maintaining transition policies outlined in sections 5.4.1 and 5.4.2, EU decarbonisation would lead to the deindustrialisation of export-oriented basic-material production.

The speed and scope of decarbonisation in other regions impact the effectiveness of domestic transition policies. Climate-neutrality in the EU, covering consumption and production, can only lead to a globally competitive domestic industry if global trade partners commit and move towards climate-neutrality. I, therefore, conclude that global climate-action is a premise for a fully decarbonised EU economy, leading to the following proposition for climate-neutral basic material markets.

V.III: Product carbon requirements for all basic materials, resulting in a de facto ban of carbon-intensive basic material production, is the predominant policy in a global decarbonised basic materials market. Horizontal emission-pricing policies shall only define the cost for offsetting non-abatable emissions with available carbon sink options.

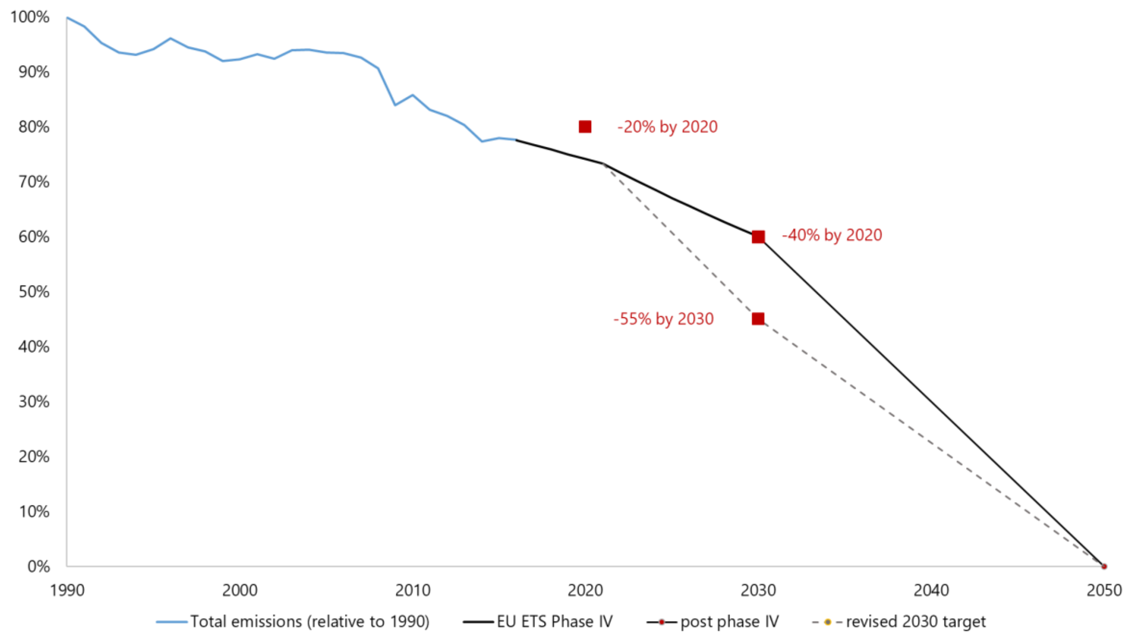

Figure 5-10: EU-28 emission reductions for the target scope (incl. aviation) since 1990 and targets for 2030 and 2050[186]

[186] Historical emission data according to the EEA (2018) and indicative reductions in line with EU ETS phase IV 2030 targets, revised emission reduction targets for 2030 and long-term net-zero emission targets.

5.5. Conclusions

In the introduction to this thesis, I stated that climate-friendly basic material production and consumption is a question of technologies, economics and policies that foster technological readiness and enable fair markets. Based on the motivations for industrial policies, as stated in section 5.2, one could argue that the apparent need for such policies is due to the market failure that emissions have not been priced adequately so far. By analysing the policy package developed by the CFMP in section 5.3, I show that a combination of various specific and horizontal policies is needed to address this apparent market failure. It might be inadequate only to use emission pricing to address this market failure, and it is questionable whether effective emission prices can be introduced on a domestic level in practice.

The transition from current conventional to climate-friendly basic material markets is subject to changing policy needs. Policies shall first kick-start the transition with first industrial-scale climate-friendly projects (section 5.4.1), then create competitive markets (section 5.4.2), and finally, ensure climate-neutrality of basic material production and consumption in the long run (section 5.4.3). Here, I argue that kick-starting the transition relies primarily on project-specific and sector-specific policies. However, since project-specific policies distort competition, sector-specific policies will be less important for decarbonising basic material markets.

Figure 5-11 shows the different policies discussed in this section for the three phases of the transition. This overview shall not serve as a design guide for industrial policy towards decarbonisation. Instead, it maps the solution space for potential industrial policies to meet policy needs that can either focus on enabling specific projects, address sector-level changes, or transform the entire economy across all sectors.

According to the rules of industrial policymaking identified by Rodrik (2014), the transition will discover which combination of these policies works with institutional mechanisms needed to carefully adjust and revise the policy package. During the transition, though, I conclude that the revision of the policy package for each phase would be guided by one of the following propositions about policy needs:

V.I: For kick-starting the transition, a horizontal policy framework needs to detail how governments can design sector- and project-specific policies that strengthen the business case for first industrial-scale installation, serving the domestic basic materials market.

V.II: Ensuring compliance with sector-specific intermediate emission reduction targets implies a level playing field for domestic producers and importers. Policies shall foster climate-friendly basic material consumption without favouring domestic producers nor distorting competition with imports.

V.III: Product carbon requirements for all basic materials, resulting in a de facto ban of carbon-intensive basic material production, is the only policy in a global decarbonised basic materials market. Horizontal emission-pricing policies shall only define the cost for offsetting non-abatable emissions with available carbon sink options.

Project-specific, sector-specific, and horizontal policies can be complementary in some phases of the transition, though, hinder it in others. Among others, this raises the question of how to transition between these phases while avoiding market distortions. Sections 5.3 and 5.4 highlight interdependencies between policies like horizontal carbon dioxide-equivalent emission pricing to ensure transitions in different sectors. However, to address research objective IV and refine the policy design for a transition towards climate-friendly basic material markets, we need to understand the interplay between different policies better.

V.IV: The effectiveness of horizontal and specific industrial policies for climate-friendly basic material market needs to be evaluated based on their impact on the cross-sectoral interdependencies of emissions, energy and material use in basic material industries and other emission-intensive sectors.

These propositions summarise the results of my research efforts to address the third thesis sub-objective of this thesis.

I. Contrast long-term policy options that can foster desirable transitions of the industrial park to reach decarbonisation targets without jeopardising the economic viability of all stakeholders.

In the following chapter, I revisit these propositions and those formulated at the end of the previous two chapters to evaluate how the industrial transition can be modelled.

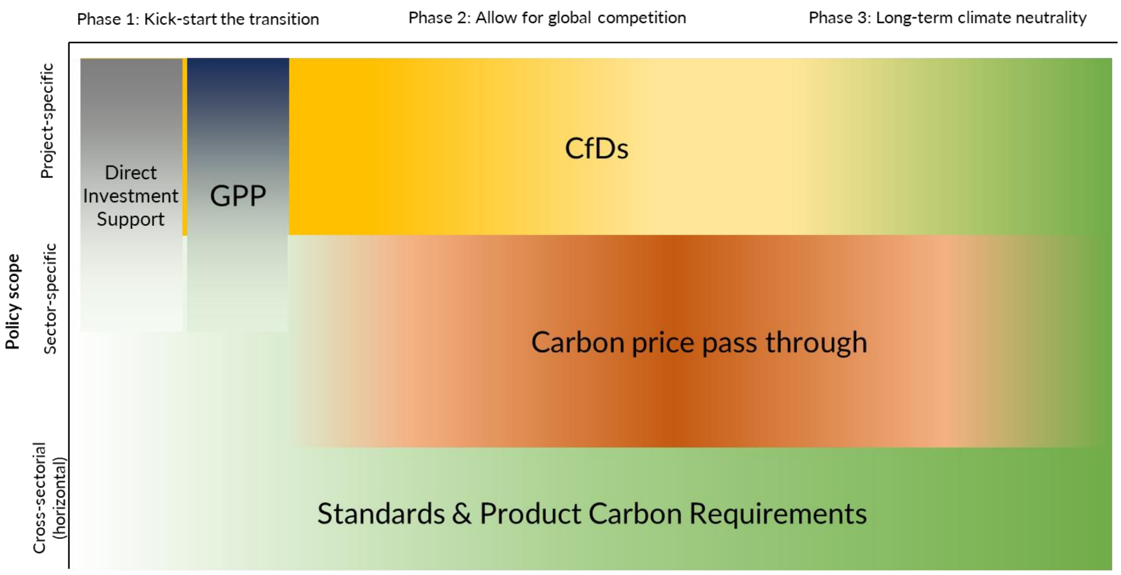

Figure 5-11: A policy pathway towards basic material decarbonisation (colour intensity = role of each policy)

Chapter 6

TRANSid: a model for quantifying the transition

Neither the conceptual model nor the mathematical formulation have been presented in any previous publication and are novel. Preliminary model results have been presented at the ECEEE Industrial Summer Study (Gerres et al., 2020).

A decarbonised society needs decarbonised basic material production. This underlying premise has been the motivation for studying the technologies that can deliver the required emission reductions (Chapter 3), the economic implications of switching to renewable energy carriers (Chapter 4) and industrial policies needed to create a business case for climate-friendly basic material production (Chapter 5). My analysis along the technological, economic and policy dimensions shows that the decarbonisation of industrial processes is, first of all, a transition challenge. It implies moving from technologically mature and emission-intensive production routes towards climate-friendly processes that, as of today, cannot compete with conventional technologies.

The different propositions formulated throughout this thesis about technology options, energy economics and industrial policies frame the transition process, its prerequisites, and the uncertainties we are facing on the way towards a decarbonised basic materials industry. This chapter builds upon these propositions to show that we need a new modelling approach to understand better the framework conditions for the transition towards industrial decarbonisation. Based on a current energy and industrial models review, I first identify a technology, economics, and policy gap in existing modelling approaches (section 6.2). In section 6.3, I introduce the conceptual model design for TRANSid, a model for studying the **trans**ition towards **i**ndustrial **d**ecarbonisation that addresses this modelling gap. An exemplary translation of the conceptual model design into a mathematical formulation (section 6.4) is used for a case study of the cement sector (section 6.5). In section 6.6, I reflect on the contributions and limitations of the model design and identify the step needed to validate and verify the model. In my concluding remarks (section 6.7), I reflect on the contributions of this chapter to address thesis sub-objective IV:

Explore how the energy demand and characteristics of the basic material sector can evolve by introducing new process innovations under various premises concerning available technologies, market scenarios and policies.

6.1. Methods

This chapter presents the current state of the TRANSid model design, which I developed over four years.

The motivation for developing a basic material sector model originates from the findings of an initial review of currently used modelling frameworks and approaches revised and extended by industry and sector-specific modelling approaches. In section 6.2, I contrast the insights obtained by the model review with the propositions about technologies (section 3.5), energy economics (section 4.4), and industrial policies (section 5.5) identified across the different chapters of this thesis. The propositions demonstrate the need for a novel modelling approach to study the transition towards a decarbonised basic material industry.

The model development has undergone a recursive process with various iterations. The conceptual model, detailed in section 6.3, addresses the modelling gap identified in section 6.2.3.

Section 6.4 introduces a linear programming (LP) problem that translates the conceptual model design into a mathematical optimisation model. The case study (section 6.5) based on the cement industry is of limited complexity and can only demonstrate the basic functionality of the proposed mathematical model. As I discuss in section 6.6, further steps are necessary to validate and verify the suitability of this mathematical formulation to obtain valid results about the impact of industrial policies on the long-term business case of climate-friendly basic material options. Concluding remarks in section 6.7 summarise how the model presented can address thesis sub-objective IV.

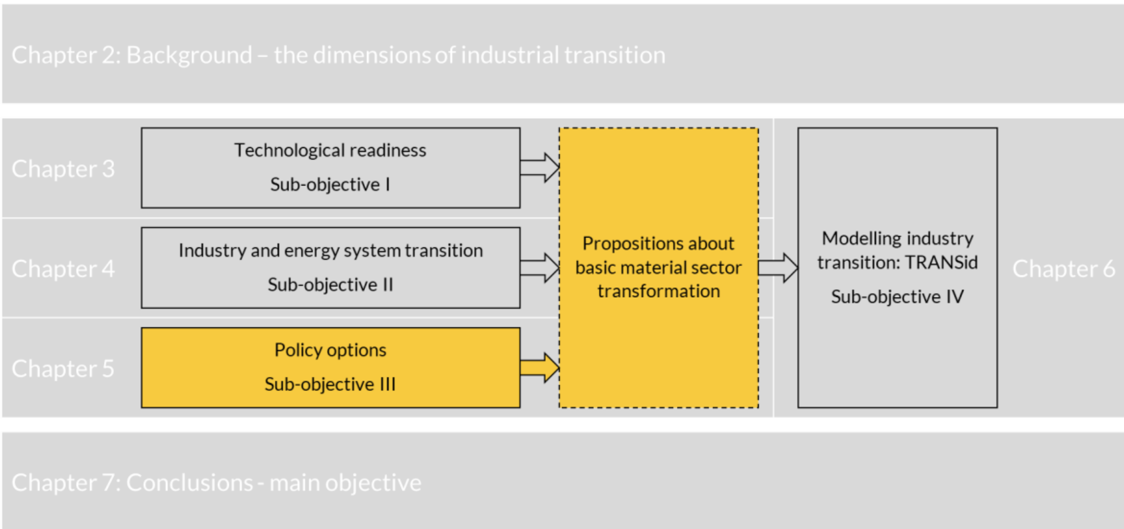

Figure 6-1: Chapter 6 as part of the thesis structure

6.2. A call for a basic materials sector model

The basic material sector is one of the most energy-intensive industrial activities. Therefore, it is no surprise that modelling the consumption of energy-intensive industrial processes has been an essential element of energy system models used to evaluate the potential evolution of energy supply and consumption. In the following, I look at energy models and how they detail industrial demand (section 6.2.1). I then contrast my observations with publications that evaluate the potential of different technology options for the various basic material sectors, relying on the references used in Chiappinelli et al. (2021) and Gerres et al. (2019b, 2019e) for Chapter 3 of this thesis (section 6.2.2). By reflecting on the propositions made across the different chapters, I then identify the gaps that justify a novel approach towards modelling the basic material sector transition given the positions specified in previous sections of this thesis (section 6.2.3).

6.2.1. Industrial demand in bottom-up energy models

As of 2011, bottom-up energy models had considered technologies and processes within the industrial sector in an aggregated form (Fleiter et al., 2011). The question is whether this observation still holds. I use two more recent reviews of energy system models (Hilpert et al., 2017; Pfenninger et al., 2014) to highlight how models represent the industrial sector.[187] I also include the MASTER.SO model developed at the Pontifical University Comillas. This overview does not aim to cover all bottom-up energy models. However, it provides sufficient evidence to point out the limitations of energy modelling approaches to understand the industrial transition.

According to Fleiter et al. (2011), one can differentiate between three different types of bottom-up models. Accounting models are the first generation of energy system models. These models strongly rely on external assumptions about technological change, and most do not consider parameters like energy prices and firm behaviour regarding possible investments in new technologies. Optimisation models aim to achieve a partial equilibrium on energy markets with interactions between demand and supply. Most of these models were initially designed as linear optimisation problems to minimise total energy system cost. Later approaches also include non-linear and mixed-integer formulations and may optimise emission[188] rather than energy costs (Pfenninger et al., 2014). Thirdly, simulation models are an extension of accounting models (Fleiter et al., 2011). The evolution of the industrial park is simulated using technology adoption algorithms that do not optimise for minimised system costs. The definition of simulation models in Pfenninger et al. (2014) differs slightly, extending the simulation concept to modular approaches in which sub-models, like for industrial subsectors, can again incorporate optimisation algorithms. In their review, Hilpert et al. (2017) distinguish between models, model generators and frameworks while focusing on optimisation approaches.

For this overview, I consider the models and modelling generators, as summarised in Table 6-A. Accounting models were disregarded due to their limited capability to capture the complexity of industrial processes. I also included optimisation and simulation models mentioned by Fleiter et al. (2011) and Pfenninger et al. (2014), but I disregarded energy models only focusing on short term and operational aspects, like Dispa-SET (Quoilin, 2017). As presented by Hilpert et al. (2017), model generators are tools for building novel energy models. [189] Therefore, I also look at studies using different modelling generators to evaluate their current capabilities.

From the 17 models, modelling generators and frameworks reviewed, five approaches encompass a highly aggregated representation of industrial demand. Novel modelling generators like OSeMOSYS (Moksnes et al., 2015) and PyPSA (Brown et al., 2018) are prepared to detail the industrial sector demand. Some case studies with these modelling generators have considered

[187] These review papers have been chosen as reference since they cover all relevant modelling approaches found in literature. Additional models that have not been listed in these papers have been included in the review and highlighted in the following sections.
[188] All energy-models enable the representation of emissions, either by applying energy carrier specific emission intensities or combing those with process related emission factors for the industrial sector.
[189] Model generators are toolboxes to simplify the implementation of optimization problems. Mostly open-source, common programming languages as Python are used for providing modules and classes.

industrial applications without extending the modelling framework, such as identifying robust energy and climate indicators for the steel industry in the OSeMOSYS project (Morfeldt et al., 2015).

The remaining 12 modelling approaches include a more detailed disaggregation of the industrial demand. The DNE21(RITE, 2008) and AIM (Hanaoka et al., 2015) optimisation models and the LIEF (Ross et al., 1993) and POLES (Keramidas et al., 2017) simulation models use technology packages to represent possible efficiency improvements. Reviewed sources do not further specify the level of detail of these packages.

The SAVE Production model (Daniëls and Van Dril, 2007), (Boonekamp, 2013) is a microeconomic investment simulation focusing mainly on CHP implementation as a driver for changing industrial demand. The dynamic accounting models CEF-NEMS (EIA, 2018) and ENUSIM (Fletcher and Marshall, 1995) replace existing technologies based on an economic evaluation and comparison with a dataset of novel technologies. Given that the ENUSIM model was developed more than 20 years ago, it is questionable that underlying datasets are still of value today.

For the MESSAGE optimisation model (IIASA, 2016), researchers defined coherent socio-economic pathways with sets of innovations made available to the optimisation algorithm of the model to determine the future industrial demand. Based on the currently available documentation, whether the model introduces innovations to the industry deterministically or based on an underlying optimisation function is unclear. The TIMES model (Loulou et al., 2016; Vaillancourt and Giannakidis, 2013), used by the European Commission, has a separate module for the industrial sector demand. Different industrial products are understood energetically as industrial service demand to satisfy the demand for steam, heat, machine drive, electrochemical processes, and other processes. Within related projects, this has been segregated further and permits to study competing technologies.

Three modelling approaches provide a detailed set of industrial processes to represent changes in industrial demand. The CIMS model (Murphy et al., 2007) specifies sub-processes for each industrial subsector and sets of competing technologies. The optimisation model is an economic equilibrium model. Decisions on the subsector level consider cost, performance and subsector specific socio-economic factors. FORECAST is a simulation model (Frassine et al., 2016; Herbst et al., n.d.; Rehfeld and Fleiter, 2017; Rehfeldt et al., 2016) with high granularity for industrial processes. It encompasses characteristics of eight different industries with 64 sub-processes and can evaluate the competition between conventional and novel technologies. The most detailed optimisation model so far is the PRIMES model (E3MLab, 2016). In this hybrid model, agents take subsector optimal decisions for or against novel technologies in 30 different industries and for 235 types of process technologies. Emphasis is on heat provision and related processes. The model is executed in timesteps of five years to study the evolution of the EU energy system.

Independently of the depth of industrial process representation, all approaches follow slightly distinctive ways of characterising industrial processes and their possible substitute within the model. The PRIMES model uses upfront and variable costs depending on energy performance, stock turnover, and equipment age. In CIMS, time preference, intangible costs, and marketplace heterogeneity affect technology choices, whereas the TIMES model´s energy service demand approach emphasises energy intensity per unit of the final product.

This overview is not a full literature review, given that I only looked at recent publications about the models mentioned in three different review papers. Though one cannot guarantee its completeness, findings align with the categorization of energy systems models in the UK, published in Hall and Buckley (2016). Besides the UK specific ESME optimisation model (Heaton, 2014), which uses exogenous data for industrial demand, the modelling approaches presented in Table 6-A have been used for quantitative, bottom-up studies of long-term energy system evolutions that included industrial sector transformations in the UK context.

Table 6-A: Industrial demand in energy system models

	Discussed in review:	Reference:	Industry modelled:	Methodological approach:	Optimisation function:	Comments:
DNE21+	(Fleiter et al., 2011)	(RITE, 2008)	Iron & Steel	4 different production routes with individual fuel and electricity demands	Total system cost (partial equilibrium)	Global dimension, legacy model (<2008)
MARKAL (2011) TIMES (2018)	(Fleiter et al., 2011; Pfenninger et al., 2014)	(Loulou et al., 2016; Vaillancourt and Giannakidis, 2013)	Energy intensive industries (EII)	Separate module for industry demand. It can be extended according to use. The key parameter is energy service demand.	Total system cost (partial equilibrium)	The framework was extended within different projects. For the EU (Simoes et al., 2013), industrial energy demand is an external value.
AIM	(Fleiter et al., 2011)	(Hanaoka et al., 2015)	EII products defined as energy service	Products (like steel) are considered an energy service provided by competing technology packages.	Total system cost (partial equilibrium)	Focus on the Asia-Pacific region
PRIMES	(Fleiter et al., 2011; Pfenninger et al., 2014)	(E3MLab, 2016)	18 industrial sectors	Sector-specific agents with microeconomic benefit maximization, 30 subsectors, 235 types of energy process technologies (options to shift to more efficient ones)	Hybrid model / MIP (partial equilibrium)	Base for EU 2016 reference scenarios (Capros et al., 2017)
CEF-NEMS	(Fleiter et al., 2011; Pfenninger et al., 2014)	(EIA, 2018)	EII on disaggregat e level	Consumption/throughput/ lifetime data for processes. Reparation/replacement based on accounting principle	No optimisation - Dynamic accounting model	The base scenario of US Energy Information Administration
ENUSIM (UK)	(Fleiter et al., 2011)	(Fletcher and Marshall, 1995)	EII in Midlands (UK)	Technology stock on device level that is retrofitted at the end of life	No optimisation – predefined pathways	Regional for Midlands (UK), legacy model (<1995)
SAVE Production	(Fleiter et al., 2011)	(Daniëls and Van Dril, 2007), (Boonekamp, 2013)	Industry & agriculture	Focus mainly on the implementation and penetration of CHP technology.	No optimisation – microeconomic investment behaviour based on historical data	A national model for the Netherlands, key publication from 2007, continuously updated.
POLES	(Fleiter et al., 2011)	(Keramidas et al., 2017)	EII	Legacy/ retired plants are replaced by deterministically provided more efficient infrastructure (no evaluation on process level)	No optimisation - Econometric partial equilibrium	In-house tool of the EC for long-term analysis of GHG mitigation policies and evolution of energy markets,
IS Industry (2011) FORECAST (2018)	(Fleiter et al., 2011)	(Frassine et al., 2016; Herbst et al., n.d.; Rehfeld and Fleiter, 2017; Rehfeldt et al., 2016)	EII	8 subsectors, 64 subprocesses + cross-cutting technologies, technologies are replaced at the end of their lifetime	No optimisation – simulation with high granularity	Used to benchmark EU 2016 reference scenario in (Herbst et al., n.d.).
LIEF	(Fleiter et al., 2011)	(Ross et al., 1993)	EII grouped in 10 subsectors	Combination of historical data and bottom-up modelling, but technology stock not explicitly considered (aggregation)	No optimisation - econometric simulation	A national model for the US, legacy model (<1992)
CIMS	(Fleiter et al., 2011)	(Murphy et al., 2007)	EII	8 subsectors, 41 processes with 191 technology competitions at the lowest level of stimulation.	No optimisation – energy economic equilibrium and decision-maker factors.	Hybrid model, the key publication is from 2007, but continuously updated (Jaccard, 2015).
MESSAGE	(Pfenninger et al., 2014)	(IIASA, 2016)	EII	Sector-specific energy demand – fuel switching possible but constrained for technologies that cannot provide high-level temperatures. Specific switching technologies defined in Shared Socioeconomic Pathways "storylines".	Total system cost (partial equilibrium)	Modelling framework - part of a wider modelling environment. Unclear whether industrial demand is deterministic or part of the optimisation.
OSeMOSYS	(Hilpert et al., 2017; Pfenninger et al., 2014)	(Moksnes et al., 2015)	NA	No project with industrial sector implementation was identified.	Total system optimisation	Model generator: an open-source alternative to MARKAL/TIMES, MESSAGE, PRIMES and POLES
EnergyPlan/B almorel	(Hilpert et al., 2017)	(Lund et al., 2014; Wiese et al., 2018)	NA	Industry as annual demand (external data)	Total system cost (partial equilibrium)	EnergyPlan is a simulation model, and Balmorel is an optimisation model by the same group.
Calliope	(Hilpert et al., 2017)	(Pfenninger, 2018), (Pfenninger and Keirstead, 2015)	NA	Demand as an externality. Spacial-temporal focus.	Total system cost (partial equilibrium)	Modelling framework
EMMA	(Hilpert et al., 2017)	(Hirth, 2017)	NA	Demand is inelastic. Focus on generation investment.	Total system cost (partial-equilibrium)	
PyPSA	(Hilpert et al., 2017)	(Brown et al., 2018)	NA	Interface to introduce demand-side management. Only investment in generation.	Total system cost (partial equilibrium)	Model generator – modular/ can be extended.

None of the reviews included the MASTER.SO model developed at the Pontifical University Comillas (Linares and Declercq, 2017; Peña Fernández, 2014). The development of this bottom-up optimisation model was motivated by the limitations identified from the MARKAL/TIMES, POLES, PRIMES and CEF-NEMS. Introduced as a tool based on public data, a reduced level of detail was chosen to represent industrial demand and its evolution by optimising the energy system for a set of benchmark years. The model characterises the basic material sectors by their thermal and electrical energy demand per unit of final product, referred to as "energy service demand" like the TIMES model. The model grants certain flexibility in choosing the energy source to provide the thermal demand or opt for electrification, satisfying thermal demand with electricity.

The MASTER.SO model and modelling approaches listed in Table 6-A have in common that their primary objective is to evaluate energy supply and demand. Like MASTER.SO, many energy models can optimise the long-term system evolution based on absolute emission reduction targets and contemplate emission pricing, including process and energy-related emissions. However, the development of the industry park is always subject to energy system-wide pricing and emission reduction objectives. Instead of addressing the drivers and enablers of industrial sector transition, the primary focus of energy-system models is on the implications of transition pathways on the macroeconomic level using discrete temporal resolutions. It is possible to study the transition of energy demand and emissions over time by evaluating multiple years but considering temporal dynamics that drive the transition within individual sectors is hard to capture.

6.2.2. Methods for evaluating the techno-economic viability of technologies

Above all, the potential of alternatives for basic material production is based on the characteristics of their processes. How much energy and raw materials do we require to produce one ton of raw materials. Such technology assessments can be combined with operational and investment cost assessments to determine the techno-economic viability of the technology alternative. In the following, I revisit the scientific literature used to analyse the different decarbonisation options in Gerres et al. (2019b) (Chapter 3) to highlight the methods used to evaluate the economics of novel technology options, emphasising the role of energy, raw material, and emission allowance costs.

Most economic assessments of novel technologies follow an accounting approach. First, assumptions about operational characteristics and investment costs are confirmed by literature or other sources. In a second step, changing energy, raw material and emission allowance costs are applied to show the operational cost sensitivity of the climate-friendly basic material production route. Here, the required emission allowance price (€/tCO_2e) for climate-friendly alternatives to be competitive with a conventional production facility is often used as a benchmark. Such assessments do not consider a temporal horizon for implementing novel processes but instead focus on parameters determining the break-even point of climate-friendly technology options.

The IEA published such studies for carbon capture technologies in the steel (IEAGHG, 2013b) and cement sector (IEAGHG, 2013a). For cement making, the EU Horizon 2020 CEMCAP project used a similar approach to contrast the technical characteristics (Voldsund et al., 2019) and economics (Gardarsdottir et al., 2019) for different CCS technology options. For evaluating the economics of hydrogen-based steel making with DRI-EAF furnaces, Vogl et al. (2018) varied operational characteristics, namely scrap furnace charge and contrast conventional primary and secondary production routes. Similar studies exist for other basic-material sectors, like comparing black liquor gasification with other biorefinery concepts for the pulp and paper industry (Ferreira and Balestieri, 2015; Pettersson and Harvey, 2012).

Some assessments have gone beyond determining a potential breakeven point, evaluating technological readiness and competitiveness for future years. Comparative studies, such as Wiertzema et al. (2020) for assessing electrification options exemplary for syngas and steam production in chemical plants, use different IEA energy price scenarios to evaluate future technological competitiveness. Studying the future evolution of the German pulp & paper industry, Fleiter et al. (2012) first identified potential emission reduction technologies. Then they designed scenarios of technological diffusion, namely best-available technology, cost-effective and technical potential scenarios, that determine the introduction of technologies over the time horizon from 2007 until 2035. Here, the technical lifetime of new and existing equipment influenced the potential diffusion rates. For more standardised equipment, such as CO_2 direct air capture as a building block for synthetic chemicals, future economic potential depends primarily on expected efficiency gains and cost reductions. As such, levelised-cost approaches have been proposed to study the economic viability as an isolated system (Fasihi et al., 2019).[190]

The techno-economic analysis of CCS employment in the iron and steel, cement, oil refining and pulp and paper industries is presented by Leeson et al. (2017). Here, the influence of factors such as initial technology costs and initial employment rate on the final abatement cost was calculated for different scenarios that all reach an 80% technology penetration by 2050. Results are relevant for understanding the path-dependency of transition processes but provide little insight into the described scenarios´ technological feasibility.

Various other publications have explored the economic feasibility of climate-friendly decarbonisation options across all basic material sectors. However, my overview is representative of the approaches used to evaluate the economics of novel technologies. Most studies identify marginal cost conditions for climate-friendly material production to compete with conventional technologies. Others consider future operational costs scenarios, like energy costs, but only evaluate the competition for certain target years. These approaches are similar to levelised-cost estimations. Market dynamics do not play a role in determining the result of the economic evaluation. Instead, break-even points represent unique emission, energy and material market outcomes. Approaches that determine market diffusion externally and study technological change over a long time horizon give credit to the current structure of the industrial park and acknowledge the challenges related to transforming existing infrastructures. However, externally defined diffusion rates do not indicate the policies and market dynamics needed to facilitate the technology change.

6.2.3. The technology, economics, and policy modelling gap

In the previous two sections, I recapped how one can model industrial processes in bottom-up models (section 6.2.1) and which methods allow us to evaluate the economics of novel climate-friendly basic material technologies and options (section 6.2.2). In the following, I highlight the limitation of bottom-up energy models and current techno-economic cost assessment methods for evaluating climate-friendly processes and required industrial policies. The basis for this evaluation is the propositions that I formulated throughout this thesis about the implications of an industrial transition in a competitive market environment.

One can frame a modelling gap that would need to be addressed by an alternative approach. I use the MASTER.SO model as a representative for a bottom-up modelling approach, though pointing to the potentially greater capacities of alternative approaches during the analysis. When referring to bottom-up methods, I mean accounting approaches used to evaluate possible investment and operational cost assumptions of novel climate-friendly basic material options to conventional technologies.

Technological transition

The following propositions are stated in section 3.4 and conclude my findings regarding the available technologies and their introduction from Chapter 3. Here, I reflect on how these findings can be translated to energy system models and bottom-up cost methods to study industrial transition.

III.I: Conventional processes should be incentivised for industries that can reach deep decarbonisation by gradual optimisation. In contrast, optimisation of current process designs shall not define the transition in the emission-intensive basic materials sector.

There is a need to identify the sectors that run into a technology lock-in by continuous process optimisation and study the degree of gradual improvements of conventional processes still

[190] Levelized cost of CO_2 direct air capture (LCOD) based on LCOE assumptions for solar PV.

desirable in those industries that will have to switch to climate-friendly technologies later. Such evaluation is not feasible with bottom-up cost models because they lack any temporal component. Energy models that study a particular benchmark year cannot examine whether transition pathways comply with this proposition. Looking at different external diffusion factors might help enhance our understanding of the scope of the sector transition. However, the resolution of energy system models makes it difficult to investigate how the industrial policies introduced in Chapter 5 might avoid technology lock-ins to prevent the optimisation trap.

III.II: Specific technologies with high emission reduction potential offer alternative pathways to reduce emissions, but deep decarbonisation may imply the joint implementation of various specific technology solutions simultaneously.

Bottom-up cost methods often contrast different technology alternatives with each other and currently used conventional process designs. However, each technology alternative consists of a predetermined technology package and is evaluated jointly. One example is the IEA report about the techno-economic evaluation of technologies in the cement industry, studying different CCS technology setups without considering further potential improvements (IEAGHG, 2013a). Post-combustion CCS could be combined with biomass as a fuel source and additional clinker additives to reduce emissions further, innovating inputs, processes, and material output.

Such evaluation is tricky in energy models, especially with those studying only one benchmark year. It implies combining various options and implementing them as greenfield or later on as brownfield plant extension. That said, modelling the joined implementation of multiple options must be restricted to those combinations that are technically feasible. The framework developed in Chapter 3 (Figure 3-2) can be a starting point for systemically identifying potential combinations for each basic material industry.

III.III: A transition of the basic materials sector until 2050 can only be achieved if current industrial renewal rates are accelerated compared to current and past investment cycles within the industry.

Even though this proposition is part of the technical evaluation in Chapter 3, it already foreshadows the need for industrial policies to kick-start the transition, as discussed in Chapter 5. An accelerated transition might require policies that diverge from a cost-optimal scenario for energy systems to ensure that climate-friendly alternatives overcome the technology valley-of-death (section 5.3). Bottom-up energy models might not be suitable to study an industrial policy pull accelerating renewal rates beyond economic investment cycles.

III.IV: Underlying assumptions for future industrial transition scenarios need to correctly reflect the cost and emission reduction potential of market-ready and near market-ready technologies while balancing the uncertainties and prospects of future technology options.

Any method to compare climate-friendly basic material options with conventional technologies relies on valid assumptions concerning currently used processes, conventional optimisation potentials, and future technology options. The best model is of little use if the underlying assumptions are wrong. Technology benchmark studies, such as the best available technology (BAT) reports by the JRCs of the European Commission (JRC, 2007; Scalet et al., 2013; Schorcht et al., 2013), help to characterise conventional technologies but provide little information about the currently installed equipment, age, efficiency, energy and emission intensity. Industry surveys, such as the Energy Efficiency Index of German Industry (EEI) (Büttner et al., 2020) or the Global Steel Plant tracker (Swalec and Shearer, 2021), enhance our understanding of the current industrial park.[191]

Potential climate-friendly processes have very different technology readiness levels. I show in (Chiappinelli et al., 2021) that some technology options are shovel ready, and industry stakeholders can evaluate their economic and technological potentials. In contrast, operational

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[191] Together with the CEOE, Fraunhofer IPA and the University of Stuttgart we currently survey the Spanish energy-intensive Industry to better understand the current situation on the national level.

characteristics and associated investment costs are highly uncertain for options with an expected market entry beyond 2030. Modelling approaches need to reflect these increasing uncertainties for future technology options when studying the industrial transition.

III.V: The transition of a particular basic material industry and its emission reductions are subject to the cross-sectoral interdependencies with other basic material sectors, the entire value-chain of basic material use and the energy system.

This proposition calls for system models that cover the complexity of coupling industrial sectors, infrastructure developments and the energy supply and demand. With reference to the models reviewed in section 6.2.1, models covering these interdependencies go far beyond currently used energy models. A more practical approach is to study regional or cluster transformation rather than transitioning the entire economy. Shared infrastructure like natural gas and electricity networks developed very locally, first. Therefore, the industrial transition might also start with clusters that group industries across the entire value chain to benefit from shared infrastructures for hydrogen or CO_2 (van der Reijden et al., 2021). The novel industrial policies presented in Chapter 5 could also be tested in a regulatory sandbox, as practised in some European countries for electricity system transition (Schittekatte et al., 2021). Neither bottom-up energy models nor techno-economic cost approaches are suitable for studying such interactions between selected industries and policy packages to evaluate these interdependencies. Among others, bottom-up energy models miss representing material flows, necessary to represent cross-sectorial independencies, while bottom-up cost models tend to only study isolated business cases for technical equipment in a individual plant.

Energy market dynamics

Bottom-up cost methods attempt to capture energy market dynamics by operational cost sensitivities or using external pricing scenarios by organisations like the IEA (Wiertzema et al., 2020). Therefore, I focus on the difficulty of breaching the gap between the propositions about energy market policies (section 4.4) and the need for industrial decarbonisation policies (section 5.4) with energy system models.

IV.I: The policy design should acknowledge the clear interdependency among the three objectives: affordability, adequacy, and emission avoidance.

Section 4.2 analysed a Spanish case study using the SPLODER optimisation model and the challenge to design policies that can comply with affordability, adequacy, and emission avoidance objectives of generation and demand on electricity markets. I argue in section 3.4 that the same challenges prevail for all future energy markets. Scenarios studied with energy system models should therefore be able to reflect the interdependencies of objectives covering all energy demand and system emissions, including the basic materials sector. However, I show in section 5.4 that the transition of the basic-materials sectors requires primarily sector-specific rather than horizontal policies to enable the transition. Suppose one studies specific policies with models covering only the industrial sector. In that case, we need to ensure that assumptions about energy, emission allowance and material market dynamics comply with energy system scenarios aligned to emission avoidance, affordability, and adequacy objectives.

IV.II: Alternative policies aiming to achieve the same objective may have a different impact on other objectives.

Sector-specific industrial policies dominate the previously described policy pathway during the early phases of the transition (section 5.4.1). CfDs may take some industrial demand out of the market but can ensure that emission avoidance objectives are met. Green public procurement creates a separate market for climate-friendly production to meet emission reduction targets by establishing low-emission basic material industries. These policies may have a very different impact on other system objectives. Here, energy system models that must comply with affordability, adequacy and emission avoidance objectives for discrete benchmark years might indicate what share of basic-material production need to be climate-neutral. However, they often do not tell us how climate-friendly production is implemented by optimising investments for the single benchmark year rather than over the entire transition period. As such, most energy models might not be suitable for studying the role of alternative policies to the required level of detail.

IV.III: Policy designs that are not fully aligned with the system objectives may lead to undesirable outcomes.

It is crucial to identify undesired long-term effects of implementing certain policies to prepare potential mitigation options or countermeasures. Climate-friendly processes incentivised during the early phases of the transition would still be in operation during later phases due to the long design life of industrial facilities. One example is the current discussion about hydrogen production from natural gas with CCS as transitionary technology, so-called blue hydrogen. It is expected that green hydrogen produced with electrolysis technologies providing carbon-neutral hydrogen will be cheaper in the long run (section 4.3.4). As such, policies that foster blue hydrogen production with inefficient capture rates by today may create stranded assets of tomorrow.[192] Energy system models can be executed recursively so that outputs for one year, such as investments decisions in some technologies, serve as the input for the next one, here as the existing industrial park. This approach might help to identify such technology lock-ins and determine required diffusion rates to prevent them. However, it does not allow us to study the required sector-specific policy design that incentivises the industry to invest.

IV.IV: Policy design should be as technology-neutral as possible to reach any of the system objectives.

No model is technology-neutral. Models are simplifications based on assumptions made about the real-life environment, human interactions, and technologies. By representing entire economies, energy system models face a higher degree of simplifications than models that optimise industrial or sector-specific interactions. Suppose a model determining the cheapest low-emission technology across all energy supply and demand to reduce total system emissions marginally. In the MASTER.SO model, for example, this most affordable climate-friendly technology, let´s say a new steel making process, would be reduced to an energy service demand with a single value for each representing its cost, energy, and emission intensity per unit. Now, let´s assume a more detailed sector-specific model that considers different process steps, optimisation, and replacement options for steel plants. Here, results might show that the furnace´s optimal temperature control is the cheapest option to reduce marginal system emissions. Technology-neutrality is different based on the level of detail included in the model.

IV.V: When pricing different services (energy, adequacy, emissions), policy designs impact consumption and thereby the need for additional services.

Referring to the interdependencies of the system objectives highlighted in proposition IV.I, one needs to model sector-specific industry transition while considering macroeconomic market dynamics for energy, emissions, or materials. However, the resulting industrial demand for energy, materials and emission allowances shall not jeopardise compliance with energy system objectives. In practice, sector-specific policies might incentivise an increased consumption of low-emission energy carriers like electricity or hydrogen, impacting energy system dynamics. Due to this additional consumption, the industry might become the market price maker while driving emission allowance pricing. This effect can be studied with energy system models rather than sector-specific approaches.

Basic material sector policies

In Chapter 5, I analyse different industrial policies and group them according to their role for the three phases of the transition. In the following, I revisit the propositions made for the different phases and devise requirements for modelling the industrial transition.

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[192] *See*, the analysis of blue hydrogen economics in section 4.3.4 and recent publication arguing for blue hydrogen as indispensable to cover future hydrogen demand (Dickel, 2020) versus concerns that blue hydrogen might be a dead-end due to its prevailing emission intensity (Beck et al., 2019; van Renssen, 2020).

V.I: For kick-starting the transition, a horizontal policy framework needs to detail how governments can design sector- and project-specific policies that strengthen the business case for first industrial-scale installations serving the domestic basic materials market.

Sector-specific policies needed for kick-starting the transition aim to support the implementation of precise technical solutions. As I have highlighted for multiple previous propositions, specific policies might oppose some of the underlying assumptions of energy system models. However, early climate-friendly basic materials production supported by these sector-specific policies has little effect on macroeconomic energy, emission allowance, and material markets at the system level. By being a price-taker without impacting commodity markets, projects to kick-start the transition can be studied by considering external market scenarios. Therefore, the right policies for kick-starting the transition could be studied at an industry or sector level with sector-specific models since the emphasis is on how these specific policies interact. Results can then serve as the basis for designing a policy framework on how specific policies can kick-start the transition.

V.II: Ensuring compliance with sector-specific intermediate emission reduction targets implies a level playing field for domestic producers and importers. Policies shall foster climate-friendly basic material consumption without favouring domestic producers nor distorting competition with imports.

The challenge for the second phase lies in a policy design that encompasses sector-specific policy needs without distorting competition within the sector and on energy, emission allowances and material markets. Therefore, sector-specific modelling approaches need to be combined with energy system models to evaluate the role of sector-specific policies on the energy system´s compliance with affordability, emission avoidance and adequacy objectives.

V.III: Product carbon requirements for all basic materials, resulting in a de facto ban of carbon-intensive basic material production, is the predominant policy in a global decarbonised basic materials market. Horizontal emission-pricing policies shall only define the cost for offsetting non-abatable emissions with available carbon sink options.

Market dynamics shall be similar to current markets in the final phase of the transition towards a fully climate-friendly material´s production. Basic materials are priced based on competing operational costs with a new climate-friendly technology equilibrium. Energy system models can determine this equilibrium complying with horizontal affordability, emission avoidance and adequacy objectives. Here, insights gained from studying the sector transition might help refine technology assumptions on the system level. Vice versa, the final goal of a decarbonised global basic materials market needs to determine the transition for each specific industry and sector.

V.IV: The effectiveness of horizontal and specific industrial policies for climate-friendly basic material market needs to be evaluated based on their impact on the cross-sectoral interdependencies of emissions, energy and material use in basic material industries and other emission-intensive sectors.

Industrial policies that can guide the transition towards climate-friendly basic material production have cross-sectoral interdependencies with any market they participate in. Current energy system models would have to be extended to cover emission allowance, material markets along the basic material value chain, and implications for infrastructure demand. Instead of energy systems, I would have to model also material flows within the economy over a period covering the whole transition. However, one cannot model everything. Rather than calling for highly detailed bottom-up energy models, we should focus on the modelling gap that needs to be addressed to study industrial policies´ effectiveness while acknowledging their interdependencies with the energy system and other related markets.

Five key points to address in the proposed modelling framework

In this section, I have revisited the proposition about the technological transition of the basic material sector towards climate-friendly production processes, energy market dynamics and industrial policies. Technological transition requires additional project-specific and sector-specific policies to kick-start the transition (section 5.4.1) and allow for global competition (section 5.4.2). However, the functioning and interplay of these policies might be difficult to capture in bottom-up energy system models, as revised in section 6.2.1. While system models may provide a good understanding of how different generation and consumption options compete for scarce operational resources to meet affordability, emission avoidance and adequacy objectives, system models can face difficulties capturing the transition processes within specific sectors. My review in section 6.2.2 shows that bottom-up cost approaches for estimating the techno-economic feasibility of novel climate-friendly production technologies are inadequate for studying the interplay of different policies, which may prevent the technology carbon lock in the emission-intensive basic material industries.

I propose a new modelling framework for studying the **TRANS**ition towards **I**ndustrial **D**ecarbonisation (**TRANSid**) that addresses this sector-specific modelling gap and allows us to evaluate the impact of introducing different policy designs on the transition of specific industries or the entire basic material sector. As shown in Figure 6-2, sector-specific models would aim to study how policies affect the economics of basic material producers during the early phases of the transition. For studying the later phases of the transition, the model would require coordination and interactions with bottom-up energy system models to understand impacts on energy, material or emission allowance market dynamics. Based on the analysis presented in this section, the new modelling framework would have to address the following five key points:

1. **Study industry and sector transition**
   System models only provide a limited understanding of the industry and sector dimension of basic materials production. Bottom-up cost methods lack the temporal dimension of the transition.
2. **Explore technology pathways**
   System models and techno-economic cost assessment methods tend to study predefined technology packages but struggle to evaluate the potential combination of technologies for achieving emission avoidance.
3. **Differentiate between greenfield installations vs brownfield extension**
   It is difficult to show with system models that the basic material industry is subject to an existing industrial park with installations of different ages and design life.
4. **Avoid the carbon lock-in**
   System models can identify carbon lock-in risks, but their ability to explore policies to avoid them is limited.
5. **Account for the temporal dimension of transition policies**
   For evaluating sector-specific policies, we need to study their role over the entire transition period until 2050. Neither system nor bottom-up cost models are suitable approaches.

A new sector-specific modelling framework would combine the strength of system models and bottom models, representing a hybrid of both approaches. A sector-specific model would cover the dynamics between the different industries in the basic material sector with the level of detail observed for bottom-up evaluation. With long-term scenarios from system models and exploring their effect on sector-specific dynamics, both sector-specific models and system models could be operated in symbiosis using the outputs of one model to fine-tune the assumptions of the other, to enhance our understanding of the industrial transition. Sector-specific models would study the transition on industrial project and sector level, providing valuable insights on how the transition could take place over the first phases, while energy-system models explore the effect of an increasingly climate-friendly basic material consumption on our energy systems (Figure 6-2).

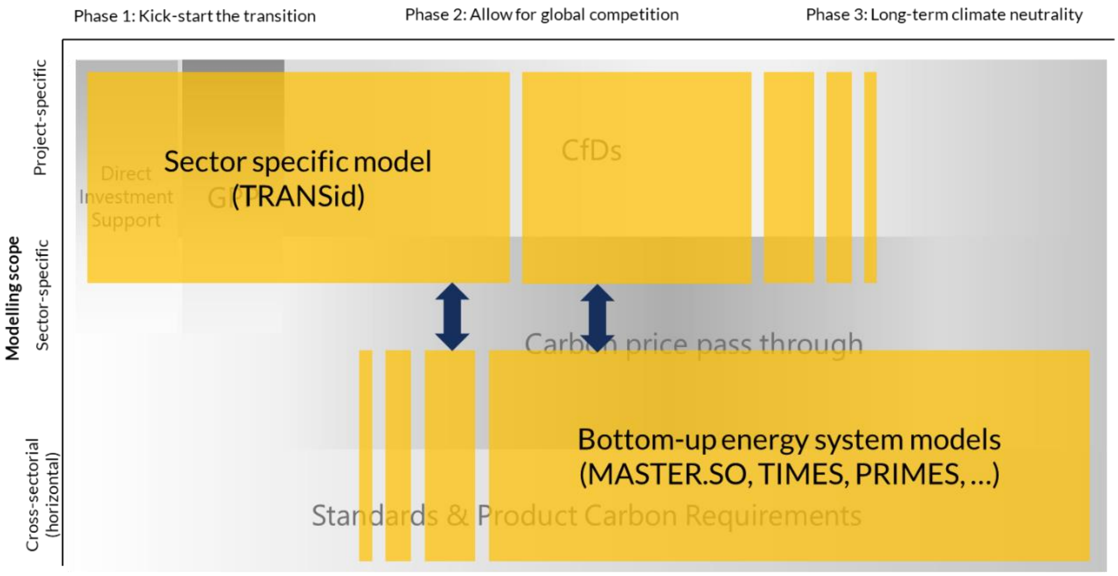

Figure 6-2: The interplay of a sector-specific (TRANSid) and bottom-up energy system models to study industrial decarbonisation pathways[193]

[193] See, Figure 5-11 for the policy pathway along the modelling scope and the temporal phases.

6.3. Conceptual Model Design

The focus of the modelling framework is on the industry- and sector-specific transition given changing policy scenarios. In the following, I develop the conceptual model in two steps. First, I show how the modelling gaps to be addressed by TRANSid overlap with the introduction of technology options categorised with the decarbonisation option framework in Chapter 3. Then, I highlight how my work on energy market dynamics and policy options can be used within this modelling scope (section 6.3.1). In section 6.3.2, I draw up a conceptual framework.

6.3.1. The modelling scope

The TRANSid model shall allow for a more detailed study of industry and sector transition by exploring technological pathways to a greater detail than system models to study industrial policies. Its scope should cover the emission abatement areas categorised in section 3.2.

Reorganising these different abatement areas, one can distinguish between those that primarily involve timely changes and modification at an industrial plant´s production steps and process level and those that affect the sector or system level (Figure 6-3). Here, "Improved Process Technologies" is split into three different subcategories, namely "Improved Production Processes" at plant level, "New Process Technologies", and "Improving Process Technologies". This differentiation shows that current processes could be maintained, only changing or modifying some process steps or replacing the plant level entirely.

The categorization of the other abatement areas corresponds to the framework presented in section 3.2. They have been assigned to either production step, plant level process, sector, or system changes.

"Recycling & Reuse" can take place at the plant, sector, and system level. Rejects from production can be directly reutilised as feed within the production process or by other basic material industries, such as steel-slag use for cement making. However, circularity, the availability and purity of post-consumer waste stream as feedstock for industrial processes depend on system-level changes on how products are designed, collected and recycled. Energy recovery and use have a similar scope, covering the use of off-heat within a plant, provision to other basic materials via local heat networks or, for example, the production of electricity from off-heat gases, depending on energy system dynamics.

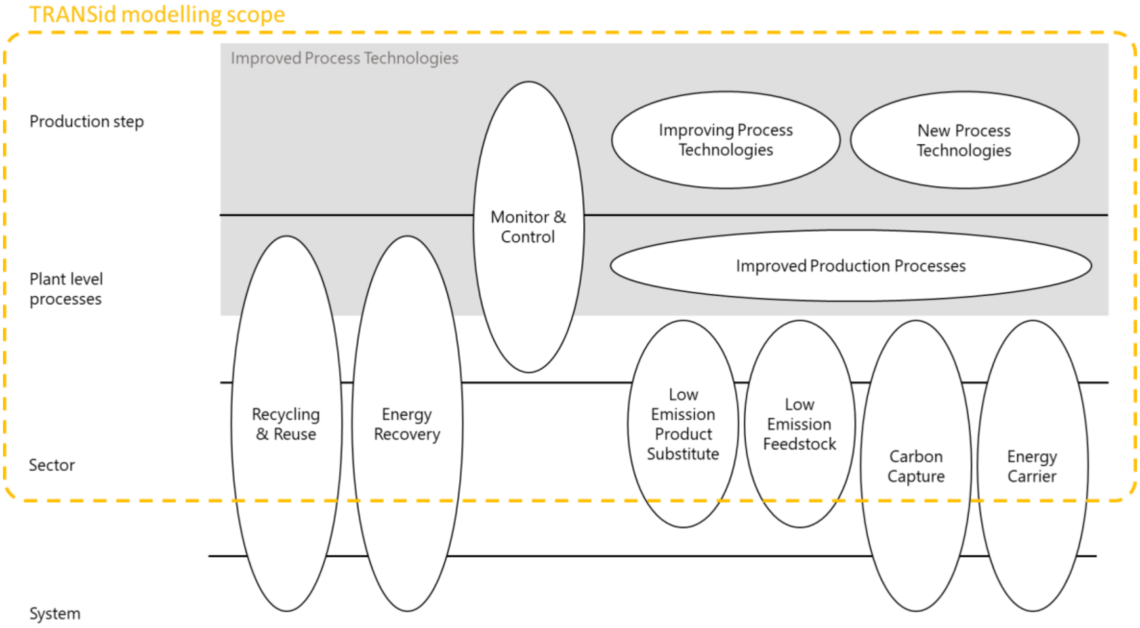

Figure 6-3: The TRANSid modelling scope based on the framework of decarbonisation option presented in section 3.2

The efficiency of technologies can be improved by better monitoring and controlling. "Monitor & Control" is closely linked to "Improved Process Technologies". Therefore, the two abatement areas are partially overlapping for production steps and plant-level processes.

Changing process inputs to "Low Emission Feedstock" and outputs "Low Emission Product Substitutes" is subject to its competition with conventional processes and potential displacement effects on the sector-level that might require changes to the production process.

"Carbon Capture" and alternative "Energy Carrier" have in common that they might imply plant-level changes, but their economics depend on system-level dynamics. CCS needs CO_2 consumers, a transport infrastructure and economically viable storage options. Similarly, switching to another energy carrier implies that the alternative is adequately available at a competitive cost on the system level, as analysed in section 4.3.

This overview is open to debate. I do not want to deny that, for example, new process technologies can imply changing energy carriers, such as hydrogen-based steel making with DRI-EAF technology instead of using carbon-based blast furnaces. I demonstrate, though, that competing and complementary abatement areas identified in Chapter 3 determine the transition of the basic materials sector for the industry and sector level, mainly within the scope of the TRANSid model. However, clear linkages to the system level exist for abatement areas that imply, among others, changes to energy and recycling streams or carbon capture.

The techno-economic feasibility of decarbonisation options covered by the different abatement areas is subject to market dynamics, especially for energy sources and emission allowance prices. As highlighted in section 6.2.3, the industrial transition itself will have negligible effects on the market dynamics during the early phases of the transition. Among others, findings on electricity and energy market dynamics from Chapter 4 can serve as a basis for developing consistent energy and emission allowance price scenarios by using models such as SPLODER for electricity and MASTER.SO for the energy system. However, these system scenarios will be secondary to the implications of energy, emission allowance prices, and final demand for climate-friendly products due to industry-specific or sector-specific policies (section 5.2).

The TRANSid model explores policy designs by making the transition, for example, subject to industry or sector emission allowance prices. Alternatively, it might be used to study how policy-backed changes to operational and investment costs can trigger the implementation of new technology options in line with intermediate and final decarbonisation targets. The resulting sector scenarios would therefore show how different assumptions about industrial policies and their effect on market signals change the investment decisions in new technology options over time (Figure 6-4)

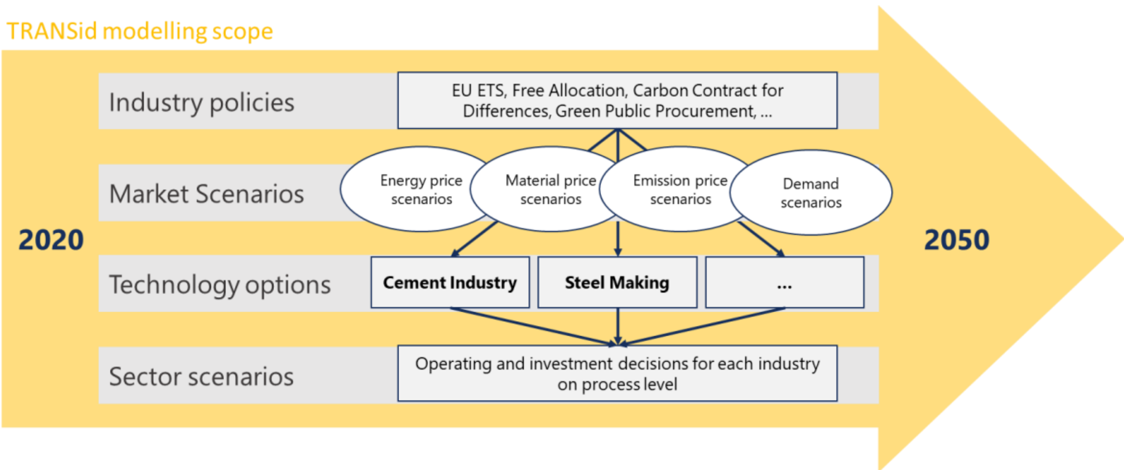

Figure 6-4: The TRANSid modelling scope addressing the technology, economics, and policy gap

6.3.2. The conceptual framework

The work presented in Chapter 3 on categorising and framing different decarbonisation options across the basic-material sector corresponds to a great extent with the scope of the proposed TRANSid model. In the following, I propose a conceptual framework that can translate my findings on the general characteristics of decarbonisation options into a model design.

In parallel to the framework presented in section 3.2, I use the categorisation of manufacturing processes by Groover (2010) as a point of departure. By breaking down the different operations, such as shaping, property enhancing and surface operations into black box diagrams with potential input and output flows, one can reduce any industrial process step to one of the following operations:

1. **Mix**
   Multiple homogenous material streams are added into one heterogeneous material stream
2. **Mill**
   One homogenous material is divided into one homogenous material stream
3. **Separate**
   One heterogeneous material is divided into multiple homogenous material streams
4. **Transform**
   Two homogenous materials are added to obtain one new homogenous material
5. **Form**
   One homogenous material stream is added into one homogenous material
6. **Crack**
   One homogenous material stream is divided into multiple homogenous material streams

Each of these operations is not spontaneous and requires input energy. Following the laws of thermodynamics, energy use is never 100% efficient and results in heat losses as output to the operation. Additionally, to waste (heat) energy, processes can cause emissions, either linked to the energy use or caused by the chemical transformation process. Using the denominators A, B and C for different materials, all industrial processes can be modelled as a set of these six operations, as visualised in Figure 6-5.

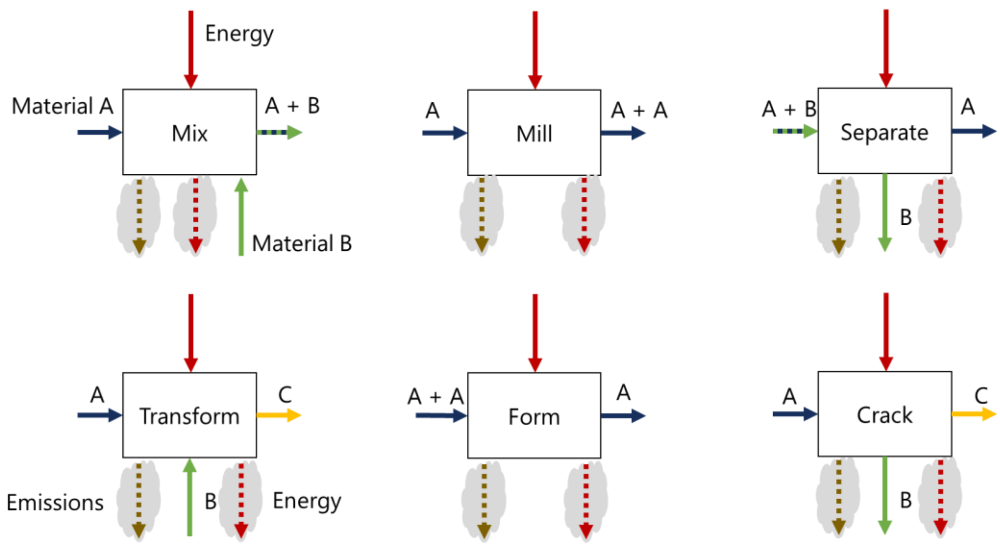

Figure 6-5: The six basic operations defining all production processes

Using cement clinker making with its linear production process as an example, one can show how a combination of these six operations can represent each of the different steps of the production process. In Figure 6-6, the production process is segregated into four production steps.[194] All material preparations are mixing operations of feed such as clay and limestone. The blended feed is then heated in the cement kiln to transform limestone to cement clinker. The cooling process can be considered a forming operation before the clinker is ground with mills to obtain fine clinker, then mixed with additives to obtain cement. In its entirety, clinker making is a transformation process with clay and limestone as feed and clinker as process output. Nevertheless, a more detailed representation of cement clinker making permits us to study investment decisions for alternative technologies for each production step.

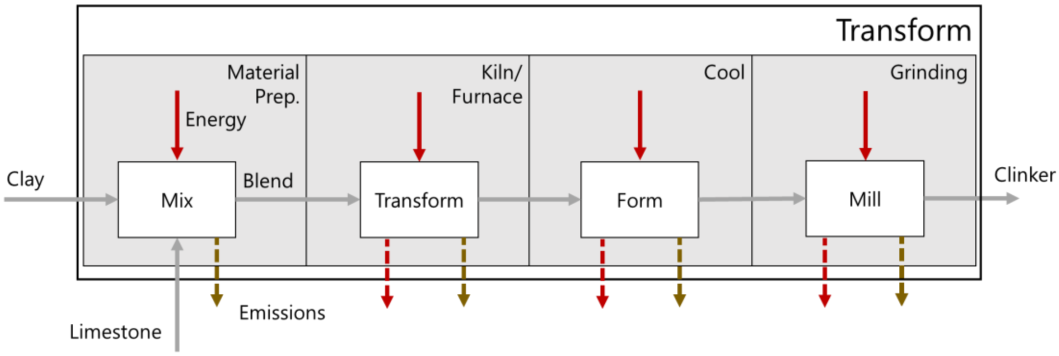

Figure 6-6: Conceptual design of the cement-making process

Considering various alternatives for each production step creates a solution space for potential process designs of cement plants. Here, brownfield retrofit of existing plants should consider the remaining design life of installed production steps. Figure 6-7 draws up such a solution space, differentiating between current processes with remaining design life and no installation costs (CAPEX = 0€) and production step alternatives with an associated installation cost greater than zero. Combining current and production steps alternatives can produce the same basic material.

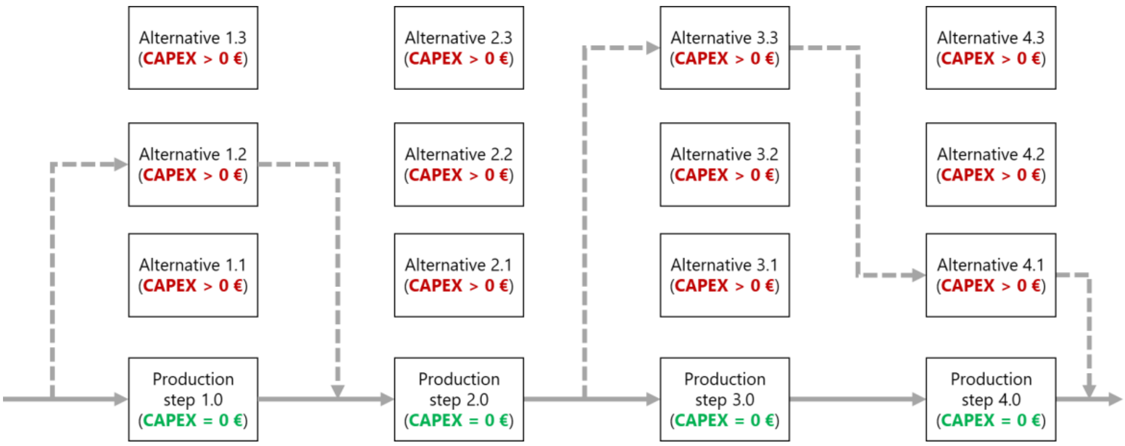

Figure 6-7: Conceptual representation of current and alternative production steps[195]

[194] Note, this is a highly simplified exemplary representation that leaves out some of the operations within a cement plant.
[195] The dotted line represents an alternative production route that could be cost-competitive to the currently use process design with production step 1.0 to 4.0.

The choice for installing product step alternatives depends on its installation and operational costs, compared to currently installed processes or, if installed processes reach the end of their design life, compared to other alternatives. The investment decision is driven by economic considerations so that the cost-optimal option is always the preferred option.

While investment costs are fixed at the moment of the investment decision, expected operational costs depend on the future prices for all operational cost positions. One can differentiate between three main operational cost positions for the basic material industry: energy, material, and emissions. Therefore, investment decisions are based on expected future price scenarios over the entire design life of current and alternative production step technologies. Together with demand scenarios that define the need for production capacities, price scenarios drive the transition. Like those reviewed in Chapter 5, industrial policies can change demand and price scenarios and impact investment decisions. As such, basic material sector scenarios result from demand and price scenarios, shaped by industrial policies that define investment and operational decisions for new and existing plants (Figure 6-8). These investment and operational decisions can be evaluated by detailing industrial plants in each basic material industry using the six basic operations for industrial production steps, as shown in Figure 6-6. Here, industrial policies can have a very different impact on transitioning the production steps of each studied plant in the basic material sector. Investment incentives might vary depending on the industry-specific or sector-specific demand and price scenarios subject to industrial policies. Understanding the effects of such policy scenarios is one of the main goals of the TRANSid model.

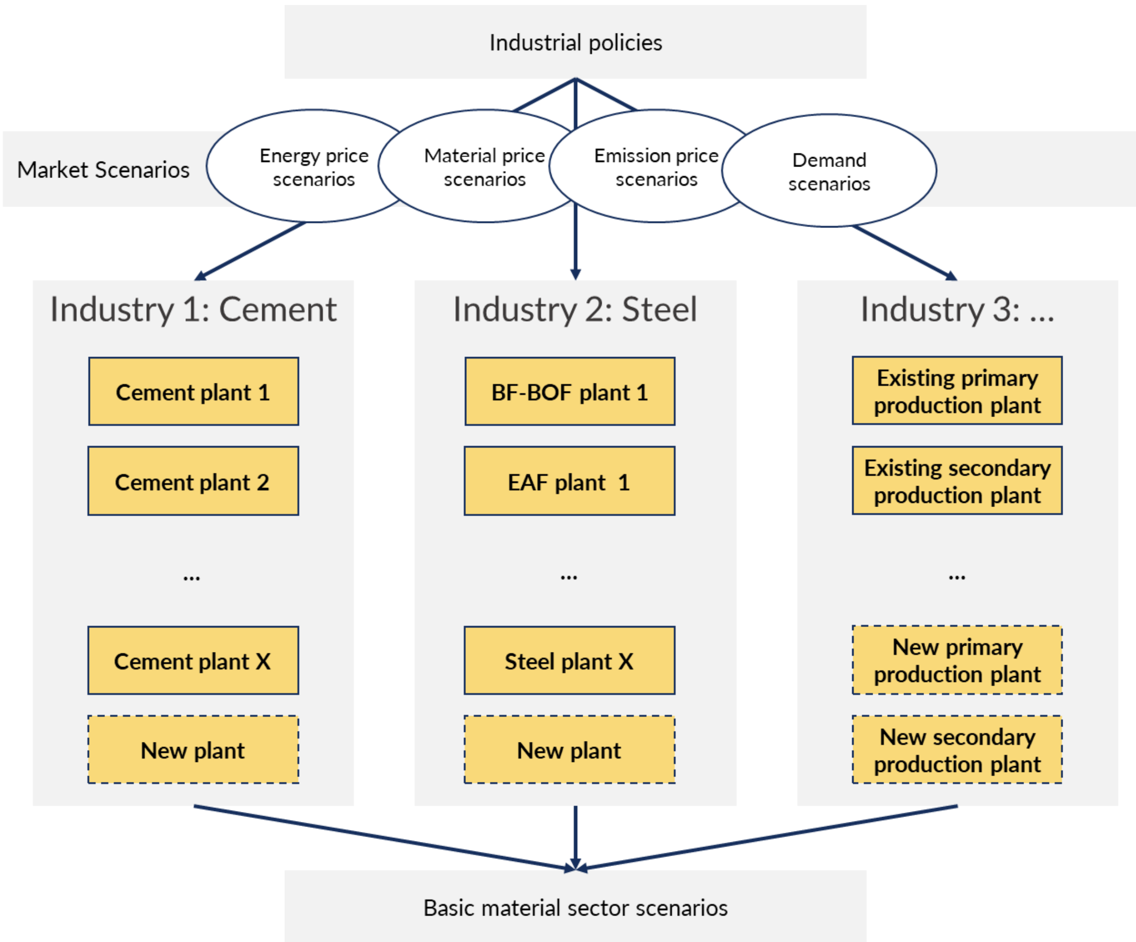

Figure 6-8: Sector transformation within the scope of the TRANSid model

6.4. Mathematical Model Formulation

For translating the conceptual design into a mathematical model, I present an exemplary linear programming (LP) approach that minimises the total costs over the entire scenario landscape. The model output is the cost-optimal operation and investment of the considered basic material sectors given the model constraints and underlying assumptions for demand and cost scenarios. In the following, I introduce a possible mathematical formulation by first specifying the main objective function (section 6.4.2) and the equations that determine the installation (section 6.4.3) and operational cost (section 6.4.4). Then I dive into the constraints that detail the different model functions of how available production capacity is defined (section 6.4.5), material (sections 6.4.6 & 6.4.7), energy (section 6.4.8), and emission flows (section 6.4.9). In section 6.4.10, I comment on how this mathematical model reflects the conceptual model scope and would have to be extended.

The following mathematical formulation covers the basic functionalities of the model and shall serve as an example of how TRANSid can be implemented.

6.4.1. Sets, Variables and Parameters

For the mathematical formulation, I differentiate between multiple variables, parameters and sets. Sets are expressed with small letters that are listed together with their respective alias in

Table 6-B. The material type set (i) can be further differentiated between materials used for production (i_M) and emission streams (i_E). Mathematically, there is no differentiation between the sets i_M and i_E since both represent a flow of matter. For a better understanding, I differentiate between both for the mathematical model formulation to highlight variables and parameters that are limited to the materials used for production (i_M), emission streams (i_E), or both (i). I also do not use separate sets for off-heat, depicted as energy type (e), production steps (p), and alternatives. The production steps and production step alternatives are shown in Figure 6-5, Figure 6-6 and Figure 6-7 are represented mathematically by considering them as two different production steps (p) that are interchangeable. Though not detailed for the basic model formulation, off-heat can be an energy outflow (e) for each product step (Figure 6-9).

Variables are denoted with a "vName" format and parameters with a "Name" format and respective units indicated within brackets.

Table 6-C lists all variables, and

Table 6-D all parameters with their corresponding units. All variables are strictly positive.

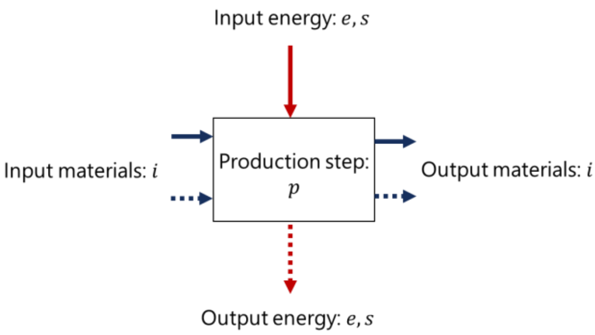

Figure 6-9: Production step represented by sets with a dotted line as secondary flows

Table 6-B: Sets and their alias

Set and alias	Description	Examples from the cement sector
i, ii, iii	material type	[limestone, clay, gypsum, clinker, CO_2e, …]
e, ee	energy type	[electric energy, thermal energy]
s, ss	energy source	[electricity, natural gas, oil, coal, wood, …]
p, pp	production step	[1,2, …,N_p]
f	plant (factory) level process	[1,2, …,N_f]
t, tt, ttt	time step in years	[1,2, …,N_t]

Table 6-C: Variables

	Description	Unit
$vCost$	Total costs over all production steps in all plants (factories) to meet material demand in all time steps.	[€]
$vCostInstall_{p,f,t}$	Cost for installing production step (p) in plant (f) at time step (t).	[€]
$vCostMaterials_{p,f,t}$	Cost of materials in production step (p) in plant (f) at time step (t).	[€]
$vCostEnergy_{p,f,t}$	Cost of energy needed to realise the operation of production step (p) in plant (f) at time step (t).	[€]
$vCostOperationalFix_{p,f,t}$	Additional operational costs to realise the operation of production step (p) in plant (f) at time step (t).	[€]
$vCostEmissions_{f,t}$	Cost of linked to atmospheric emissions on plant level (f) at time step (t).	[€]
$vCapacity_{i,p,f,t}$	Available capacity to produce material (i) with production step (p) in plant (f) at time step (t).	$[ton_{M/E}]$
$vNewCapacity_{i,p,f,t}$	New capacity added to the previous capacity for producing material (i) with production step (p) in plant (f) at time step (t).	$[ton_{M/E}]$
$vRetiredCapacity_{i,p,f,t}$	Retired capacity removed from the previous capacity for producing material (i) with production step (p) in plant (f) at time step (t).	$[ton_{M/E}]$
$vMaterial_{i,p,pp,f,t}$	Material flow (i_M) from production step (p) to production step (pp) in plant (f) at time step (t).	$[ton_M]$
$vMaterialProd_{i,p,f,t}$	Material (i_M) produced by production step (pp) in plant (f) at time step (t).	$[ton_M]$
$vLegacyMaterialProd_{i,p,f,t,tt}$	Material (i_M) produced by production step (p) in plant (f) at time step (t) that has been installed previously in time step (tt).	$[ton_M]$
$vEnergy_{e,s,p,f,t}$	Energy flow of type (e) to production step (p) in plant (f) at time step (t).	$[MJ]$
$vEnergyNeeded_{e,p,f,t}$	Energy (e) needed to operate production step (p) in plant (f) at time step (t).	$[MJ]$
$vEnergyRecovered_{e,p,f,t}$	Energy (e) recovered from production step (p) in plant (f) at time step (t).	$[MJ]$
$vEmissions_{i,p,pp,f,t}$	Emission flow of type (i_E) from production step (p) to production step (pp) in plant (f) at time step (t).	$[ton_E]$
$vEmissionProcess_{i,p,pp,f,t}$	Process emissions flow of type (i_E) from production step (p) to production step (pp) in plant (f) at time step (t).	$[ton_E]$
$vEmissionsFuel_{s,i,p,pp,f,t}$	Fuel emissions flow of type (i_E) from production step (p) to production step (pp) in plant (f) at time step (t).	$[ton_E]$
$vCapturedEmissions_{i,p,f,t}$	Emissions (i_E) captured by production step (p) to production step (pp) in plant (f) at time step (t).	$[ton_E]$
$vCapturedBioEmissions_{i,p,f,t}$	Biogenic emissions (i_E) captured by production step (p) to production step (pp) in plant (f) at time step (t).	$[ton_E]$
$vLegacyCapEmission_{i,p,f,t,tt}$	Emissions (i_E) captured by production step (p) in plant (f) at time step (t) that has been installed previously in time step (tt).	$[ton_E]$

Table 6-D: Parameters

	Description	Unit
$InstallationCost_{p,f,t}$	Cost of installing production capacity in tons for production step (p) in plant level (f) at time step (t)	$\left[\frac{€}{ton_{M/E}}\right]$
$MaterialCost_{i,t}$	Cost of purchasing material (i) per ton at time step (t)	$\left[\frac{€}{ton_{M}}\right]$
$EnergyCost_{s,t}$	Cost of purchasing energy in MJ of source (s) at time step (t)	$\left[\frac{€}{MJ}\right]$
$OperationsCost_{p,t}$	Operating cost of production step (p) for producing/treating one ton of material/emissions at time step (t)	$\left[\frac{€}{ton_{M/E}}\right]$
$EmissionCost_{i,t}$	Cost for emitting one ton of emissions (i) at time step (t)	$\left[\frac{€}{ton_{E}}\right]$
$DiscountRate$	Discount rate for calculating the NPV of costs	[%]
$DesignLife_{p,f}$	Maximum design life of production step (p) equipment in plant level (f).	$[years]$
$PlantCapacity_{i,f,t}$	Maximum capacity to produce material (i) with plant (f) at time step (t). Parameter used to represent existing plant capacities.	$[ton_{M}]$
$MaterialDemand_{i,t}$	Total material demand of type (i) to be satisfied at time step (t)	$[ton_{M}]$
$MaterialNeed_{i,ii,p,t}$	Material of type (i) needed to produce material of type (ii) by production step (p) at time step (t)	$\left[\frac{ton_{M}}{ton_{M}}\right]$
$EnergyNeed_{e,p,t}$	Energy of type (e) needed to operate production step (p) at time step (t).	$\left[\frac{MJ}{ton_{M/E}}\right]$
$EnergyExcess_{e,p,t}$	Off-heat (e) resulting from operating production step (p) at time step (t).	$\left[\frac{MJ}{ton_{M/E}}\right]$
$EnergyMaxRestrict_{e,s,p,t}$	Technical restriction of certain energy sources (s), mostly biomass, to be used for production step (p) at time step (t).	$\left[\frac{MJ}{MJ}\right]$
$MaxEnergyAltShare_{e,p,t}$	Highest share of combined restricted energy sources, mostly biomass, to be used for production step (p) at time step (t).	$\left[\frac{MJ}{MJ}\right]$
$EmissionProcess_{i,p}$	Emissions (i_E) caused per ton of output by operating the process in production step (p).	$\left[\frac{ton_{E}}{ton_{M}}\right]$
$EmissionFuel_{s,i}$	Emissions (i_E) caused per MJ of energy source (s) used.	$\left[\frac{ton_{E}}{MJ}\right]$
$BioEmissionFuel_{s,i,t}$	Share of biobased emissions (i_E) when using energy source (s) at time step (t).	$\left[\frac{ton_{E}}{ton_{E}}\right]$
$CaptureRate_{i,p}$	Share of emissions captured from input emission stream (i_E) by production step (p).	$\left[\frac{ton_{E}}{ton_{E}}\right]$
$CaptureRange_{i,p,pp}$	Ability of production step (p) to capture emission (i_E) from production step (pp).	[0/1]

6.4.2. Objective Function

The main objective function of the model minimises both installation and operational costs ($vCost$) over the entire time horizon (N_t) for all plant level processes (N_f). Installation costs ($vCostInstall_{p,f,t}$) for the different production steps is a variable that depends on the different production steps to be installed to produce the required material output. Operational costs have four components: $vCostEnergy_{p,f,t}$,$vCostMaterials_{p,f,t}$,$vCostOperations_{p,a,f,t}$,$vCostEmissions_{f,t}$. All of them must reflect the operational expenditures of the active production step equipment (p) at each time step (t) and are further detailed in the following. In case of $vCostEmissions_{f,t}$ these costs are calculated for the entire plant level process (f) to account for captured emissions from all production steps (p) in case that carbon capture technology has been installed (sections 6.4.7 & 6.4.8). Since installation and operational costs are expected future costs, they need to be brought to the net present value (NPV) by adjusting them with the expected discount rate.

$$min\,vCost[€] = \sum_{t}^{N_t} \frac{1}{(1 + DiscountRate[\%])^t} * \left[\sum_{f}^{N_f} \left[\sum_{p}^{N_p} vCostInstall_{p,f,t}[€] + vCostMaterials_{p,f,t}[€] + vCostEnergy_{p,f,t}[€] + vCostOperationalFix_{p,f,t}[€]\right] + vCostEmissions_{f,t}\,[€]\right] \quad 6.4.2.1$$

In the following, I introduce the main equations to calculate both installation and operational costs over the entire time horizon (N_t) of each model run. The plant-level set (N_f) is mainly used for equipment replacement and renewals operations on existing installations (section 6.4.5). It plays a minor role in most of the following equations.

6.4.3. Installation Costs

In this model, I represent installation costs in the form of annualised production step equipment costs over the entire design life of the installed alternatives. Total installation costs at a given time step (t) have to reflect the annualised cost of process equipment installed in this time step and the annuities of all equipment installed in previous time steps but that has not reached the end of its design life.

The total installation cost for production step equipment for each time step (t) is the sum of all annuities of newly installed equipment in the present time step (t) and all previously installed equipment up to the time step the equipment had been installed (tt). The design life of each equipment alternative ($DesignLife_{p,f,tt}$) defines the number and duration of annuity payments. New equipment capacity ($vNewCapacity_{i,p,f,tt}$) installed in time step $tt = t - 10$, will not result in annuity payments for time step t if the design life ($pDesignLife_{p,f,tt}$) is < 10 time steps, or simply said when it has reached the end of its design life and has to retire. Installed production step capacity is expressed in tons of material $[ton_M]$. Constant annual annuities are calculated based on the total cost of an installation according to the NPV approach.

$$vCostInstall_{p,f,t}[€] = \sum_{i}^{N_{ii}} \sum_{tt}^{N_{tt}} vNewCapacity_{i,p,f,tt}[ton_{M/E}] * InstallationCost_{p,f,tt}\left[\frac{€}{ton_{M/E}}\right] * \frac{(1 + DiscountRate[\%])^{DesignLife_{p,f}[years]}}{\sum_{a=1}^{DesignLife_{p,f}[years]} \frac{1}{(1 + DiscountRate[\%])^a}}, \quad \forall tt: t \leq t, \forall tt: t > t - DesignLife_{p,f}[years] \quad 6.4.3.1$$

6.4.4. Operational Costs

This model differentiates between four different types of operational costs, which characterise the various production step equipment alternatives (p) available; the cost of material feedstock, energy, operation and emissions.

All material obtained from external sources for the production process has a material cost associated with it. The first production step ($p = 1$) is always representing the external material stock, and all flows of material feedstock (i) have an associated cost when they originate from the first production step ($p = 1$) to any other production step (pp) of the production route. For a detailed explanation of the material flow annotation, see section 6.4.6.

$$vCostMaterials_{p,f,s}[€] = \sum_{i}^{N_i} \sum_{pp}^{N_{pp}} vMaterial_{i,p,pp,f,t}[ton_M] * MaterialCost_{i,t}\left[\frac{€}{ton_M}\right], \quad \forall p: p = 1 \quad 6.4.4.1$$

Almost all production steps (p) require external energy, which may be of different energy types (e) and stem from various types of energy sources (s). The total energy cost is the price per unit for energy source (s) $\left[\frac{€}{MJ}\right]$ multiplied by consumption $[MJ]$ from active and installed production step equipment alternatives (p) for a given time step (t).

$$vCostEnergy_{p,f,t}[€] = \sum_{s}^{N_s}\sum_{e}^{N_e} vEnergy_{e,s,p,f,t}[MJ] * EnergyCost_{s,t}\left[\frac{€}{MJ}\right] \quad 6.4.4.2$$

Production step equipment has additional operational costs, for example, related to wear and tear. Since the throughput and process operation cause these costs over time, they can be associated with each ton of produced material.

$$vCostOperations_{p,f,t}[€] = \sum_{i}^{N_i} vMaterialProd_{i,p,f,t}\ [ton_M] * OperationsCost_{p,t}\left[\frac{€}{ton_{M/E}}\right] \quad 6.4.4.3$$

Only those emissions must be paid for that are not captured by optionally installed carbon capture production steps. For each emitter (i = CO_2e emissions), the associated emission allowance cost is multiplied by the difference between initially emitted and captured emissions. Biobased emissions can also result in emission allowance cost profits since non-fossil emissions are captured and not emitted to the atmosphere.

$$\begin{aligned} &vCostEmissions_{f,t}[€] \\ &= \sum_{i}^{N_i}\sum_{p}^{N_p}\sum_{pp}^{N_{pp}} (vEmissions_{i,p,pp,f,t}[ton_E] \\ &- vCapturedEmissions_{i,pp,f,t}[ton_E] - vCapturedBioEmissions_{i,pp,f,t}[ton_{BE}]) \\ &* EmissionCost_{i,t}\left[\frac{€}{ton_E}\right] \end{aligned} \quad 6.4.4.4$$

6.4.5. Capacity additions

The prerequisite for the representation of production flows is the characterisation of the different production processes. This section introduces the equations and constraints that create the model´s industrial park, setting up the initial brownfield capacity, replacing existing equipment with new equipment alternatives, and setting up novel process routes. As such, the purpose of the following equations is to determine the capacity for each production step alternative (p) at each time step (t). Defining capacities bottom-up allows for the representation of plant-level processes (f). Figure 6-10 visualises exemplary how such capacity changes can occur between three different time steps. Flow colours represent changes to the material flow in the first step.

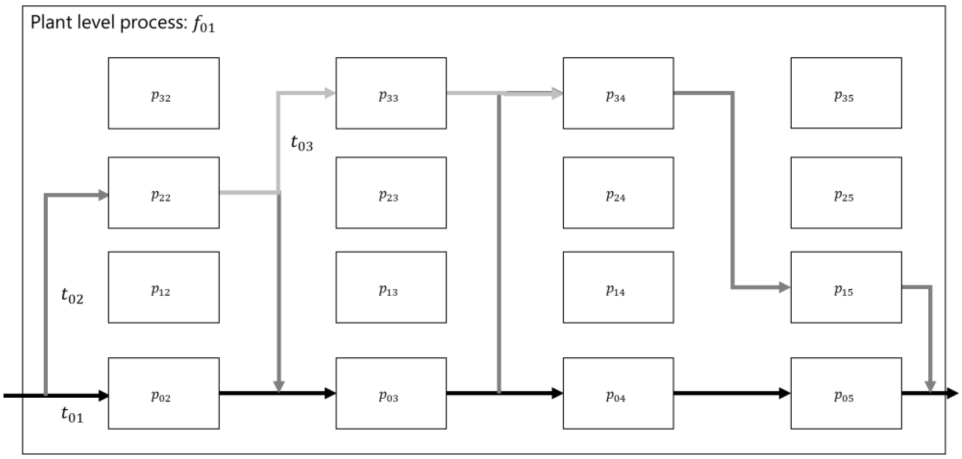

Figure 6-10: Interrelations of sets to represent capacity changes for production steps[196]

[196] Grey lines and their corresponding time steps (t) represent changes from the original installed production steps to production steps alternatives.

The basic premise for all equipment alternatives (a) is that the production activity ($vMaterialProd_{I,p,f,t}$) for a certain material (i) does not exceed the active capacity ($vCapacity_{i,p,f,t}$). Material production can only take place when capacity has been installed beforehand. As for all the following capacity change operations, the first production step (p=1) is excluded from this premises since it represents the raw material supply which is not subject to capacity installations.

$$vCapacity_{i,p,f,t}[ton_{M/E}] \geq vMaterialProd_{i,p,f,t}[ton_{M/E}], \quad \forall p: p > 1 \qquad 6.4.5.1$$

Capacity availability is temporary. Newly installed capacity for production step equipment cannot be operated longer than the predetermined equipment design life. Subsequently, it must be retired and replaced latest when reaching the end of its design life (equation 6.4.5.3). The total active capacity in time step (t) ($vCapacity_{i,p,f,t}$) is the sum of capacity that had been active in the previous time step (tt = t-1) and new capacity editions in time step (t) subtracted by retired capacity in time step (t).

$$\begin{aligned} vCapacity_{i,p,f,t}[ton_{M/E}] &= vCapacity_{i,p,f,tt}[ton_{M/E}] + vNewCapacity_{i,p,f,t}[ton_{M/E}] \\ &- vRetiredCapacity_{i,p,f,t}[ton_{M/E}], \\ &\forall p: p > 1, \forall tt: t = t - 1 \end{aligned} \qquad 6.4.5.2$$

As previously mentioned, the equipment alternatives (p) have to be retired until the end of their design life ($DesignLife_{p,f}$). Since the design life for each production step is a constant for each equipment (p), the new capacity in time step (t) needs to retire at time step (tt) when having reached the end of its design life. Note, new equipment that is installed at a time step (t) that is close to the final time step N_t has no equivalent retirement point since the retirement point lies beyond the final time step. Mathematically, this formulation does not allow for the early retirement of equipment. Nevertheless, the model is not enforcing installed capacity to be operated (constraint 6.4.5.1) so that any capacity without material flow can be considered hibernated or retired.

$$\begin{aligned} vNewCapacity_{i,p,f,t}[ton_{M/E}] &= vRetiredCapacity_{i,p,f,tt}[ton_{M/E}], \\ &\forall p: p > 1, \forall t: t \leq N_t - DesignLife_{p,f}[years], \\ &\forall tt: t = \ t + \ DesignLife_{p,f}[years] \end{aligned} \qquad 6.4.5.3$$

To account for existing facilities, the maximum production capacity ($PlantCapacity_{i,f,t}$) for plant-level processes (f) can be limited for the final product (i = final product) of some plant-level processes (f). Note that this constraint is only active for those final materials (i) which are used to characterise the final capacity of a plant or factory and not intermediate materials (i ≠ final product). The first production step (p=1) is excluded since it represents the external material stock.

$$PlantCapacity_{i,f,t}\ [ton_M] \geq \sum_{p>1}^{N_p} vMaterialProd_{i,p,f,t}\ [ton_M], PlantCapacity_{i,f,t} > 0 \qquad 6.4.5.4$$

Existing facilities are introduced as new capacity in the first-time step (t=1). To reflect existing facilities´ age and remaining design life, operational characteristics are only defined for the production step equipment that reflects old existing installations in time step (t). Existing plants are set up based on the plant capacity set with constraint 6.4.5.4.

$$vCapacity_{i,p,f,t}[ton_M] = vNewCapacity_{i,p,f,t}[ton_M], \forall t: t = 1 \qquad 6.4.5.5$$

6.4.6. Material flows

The model´s objective function represents the total costs of one or several basic material sectors, though cost shall be minimised while ensuring that demand scenarios are met. The total material production needs to be equal to or exceed the material consumption, provided as an external demand scenario ($MaterialDemand_{i,t}$) for different final materials (i) for each time step (t). While the demand vector allows for demand to be defined for all materials (i), in practice, the demand is only greater than zero for those materials, which are final products of the production step that meets the material demand.

$$MaterialDemand_{i,t}\ [ton_M] \leq \sum_{f=1}^{N_f} \sum_{p=1}^{N_p} vMaterialProd_{i,p,f,t}\ [ton_M], \quad MaterialDemand_{i,t}[ton_M] > 0 \qquad 6.4.6.1$$

Each production step equipment (pp) requires a different set of feedstock materials (i), which make up the ingredients for producing the output material (ii) ($vMaterialProd_{ii,pp,,f,t}$). The transformation ratios from material (i) to material (ii) are defined externally for each process equipment alternative (i). Material flows must meet material needs. As shown in Figure 6-11, material flows ($vMaterial_{i,p,pp,f,t}$) therefore always link different production steps (p and pp) for one specific material type (i). Note that all materials, which other processes cannot provide, need to be obtained from the external material stock (p=1), while the receiver production step (pp) and departing production step (p) cannot be the same to avoid looping.

$$vMaterialProd_{ii,pp,f,t}[ton_M] \ \leq \sum_{p=1}^{N_p} vMaterial_{i,p,pp,f,t}[ton_M] * MaterialNeed_{i,ii,pp,t}\left[\frac{ton_M}{ton_M}\right], \quad MaterialNeed_{i,ii,pp,t}\left[\frac{ton_M}{ton_M}\right] > 0, \forall pp: p > 1, \forall pp: p <> p \qquad 6.4.6.2$$

The sum of material flows departing from a production step (p) to another one (pp) cannot exceed the actual production ($vMaterialProd_{i,p,f,t}$). Whereas the purpose of constraint 6.4.6.3 is mainly to avoid positive material flows if no material production is given, constraint 6.4.6.4 is a safeguard mechanism to ensure that any material not produced in another production step has to be conceived from the external processes.

$$vMaterialProd_{i,p,f,t}[ton_M] \geq \ vMaterial_{i,p,pp,f,t}[ton_M], \quad \forall p: p > 1, \forall pp: p <> p \qquad 6.4.6.3$$

$$vMaterialProd_{i,p,f,t}[ton_M] \geq \sum_{pp<>p}^{N_{pp}} vMaterial_{i,p,pp,f,t}[ton_M] \qquad 6.4.6.4$$

Material production can only occur in production equipment alternatives (p), for which a material need is defined. The motivation for this constraint is to avoid phantom material production by activating undefined equipment alternatives without associated operational characteristics.[197]

$$vMaterialProd_{ii,p,f,t}[ton_M] \leq MaterialNeed_{i,ii,p,t}\left[\frac{ton_M}{ton_M}\right] * \infty[ton_M], \quad \forall p: p > 1 \qquad 6.4.6.5$$

[197] Constraint 6.4.6.5 is modelled differently when translated into an executable program to avoid big M constraints.

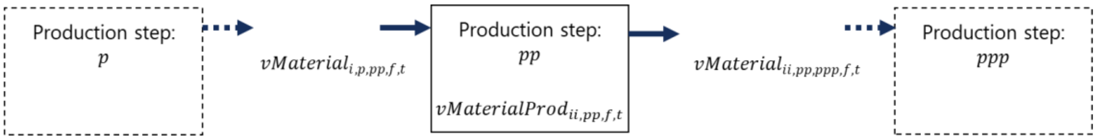

Figure 6-11: Material flows arriving at and departing from production step pp

For the material stock (p=1), $vMaterialProd_{ii,p,f,t}$ shall not exceed the sum of all departing material flows to other production steps (pp).

$$vMaterialProd_{ii,p,f,t}[ton_M] \leq \sum_{pp}^{N_{pp}} vMaterial_{i,p,pp,f,t}[ton_M], \quad \forall p: p = 1 \qquad 6.4.6.6$$

As an additional measure to avoid internal looping of material flows and any backflows to the material stock (p=1), the following equation ensures that non-feasible flows do not take any value.

$$vMaterial_{i,p,pp,f,t}[ton_M] = \begin{cases} 0, \forall pp: p = 1 \\ 0, \forall pp: p = p \\ 0, \forall p: p = 1, MaterialCost_{i,t} = 0 \end{cases} \qquad 6.4.6.7$$

6.4.7. Differentiation between material and emission flows

As stated at the beginning of section 6.4.1, the material set (i) reflects both material and emission flows. Therefore, one needs to differentiate between both for realising the introduction of carbon capture options, further detailed in section 6.4.9.

At any time, step (t) material production for any material type (i) is the sum of materials produced with newly and previously installed equipment in the current and previous time steps (tt). In the following, I refer to the material production across all newly and previously installed equipment as $vLegacyMaterialProd_{I,p,f,t,tt}$.

$$vMaterialProd_{i,p,f,t}[ton_M] = \sum_{tt \leq t}^{N_{tt}} vLegacyMaterialProd_{i,p,f,t,tt}[ton_M], \quad \forall p: p > 1 \qquad 6.4.7.1$$

Legacy material production cannot surpass the available legacy capacity that has been installed for each production step. Here, though, one needs to differentiate between capacity that has only been installed to treat emission streams (i), namely $vLegacyCapEmission_{I,p,f,t,tt}$ and capacity that serves for material production $vLegacyMaterialProd_{i,p,f,t,tt}$.

$$vCapturedEmission_{i,p,f,t}[ton_E] = \sum_{tt \leq t}^{N_{tt}} vLegacyCapEmission_{i,p,f,t,tt}[ton_E], \quad \forall p: p > 1 \qquad 6.4.7.2$$

Capacity installed to treat emissions (CCS and CCU) should not have material streams associated with it that are part of the production process and shall be dimensioned according to the emissions that need to be captured.

$$vNewCapacity_{i,p,f,tt}[ton_M] \geq vLegacyMaterialProd_{i,p,f,t,tt}[ton_M] + vLegacyCapEmission_{i,p,f,t,tt}[ton_E], \forall p: p > 1 \qquad 6.4.7.3$$

Lastly, the following equation ensures that neither legacy material production nor emission treatment can occur with equipment not yet installed.

$$vLegacyMaterialProd_{i,p,f,t,tt}[ton_M] + vLegacyCapEmission_{i,p,f,t,tt}[ton_M] = 0, \quad \forall tt: t \leq t - DesignLife_{p,f}[years] \tag{6.4.7.4}$$

6.4.8. Energy flows

Almost all production steps need external energy flows for material production or carbon capture ($vEnergyNeeded_{e,p,f,t}$). The magnitude of these external energy flows is defined with a relative consumption parameter ($EnergyNeed_{e,p,tt}$) $\left[\frac{MJ}{ton_{M/E}}\right]$ for production step (p) and its corresponding time step of the installation (tt).

$$vEnergyNeeded_{e,p,f,t}[MJ] = \sum_{i=1}^{N_i} \sum_{tt}^{N_{tt}} EnergyNeed_{e,p,tt}\left[\frac{MJ}{ton_{M/E}}\right] * \left(vLegacyMaterialProd_{i,p,f,t,tt}[ton_M] + vLegacyCapEmission_{i,p,f,t,tt}[ton_E]\right), \forall tt: t \leq t \tag{6.4.8.1}$$

Given the available production step equipment, some energy can be recovered as off-heat and used as input energy stream for other production steps. How much excess energy can be recovered by equipment installed in the current and previous time steps (tt) is given as a parameter that expresses the recovery ratio based on the throughput of materials ($EnergyExcess_{e,p,tt}$) $\left[\frac{MJ}{ton_{M/E}}\right]$.

$$vEnergyRecovered_{e,p,f,t}[MJ] = \sum_{i=1}^{N_i} \sum_{tt}^{N_{tt}} EnergyExcess_{e,p,tt}\left[\frac{MJ}{ton_M}\right] * \left(vLegacyMaterialProd_{i,p,f,t,tt}[ton_M] + vLegacyCapEmission_{i,p,f,t,tt}[ton_E]\right), \forall tt: t \leq t \tag{6.4.8.2}$$

Several energy sources are available to satisfy thermal or electrical energy demand. The sum of final energy flows from external sources equal the difference between the energy needed and the energy recovered and reused in a process at the plant level (f).

$$\sum_{s}^{N_s} \sum_{p}^{N_p} vEnergy_{e,s,p,f,t}[MJ] = \sum_{p}^{N_p} vEnergyNeeded_{e,p,f,t}[MJ] - vEnergyRecovered_{e,p,f,t}[MJ] \tag{6.4.8.3}$$

Each external energy flow of source (s) cannot exceed the total energy needed for each production step (p) but must be met with the available energy sources for the required energy type.

$$vEnergy_{e,s,p,f,t}[MJ] \leq vEnergyNeeded_{e,p,f,t}[MJ] * EnergyRestrict_{e,s}\left[\frac{MJ}{MJ}\right] \tag{6.4.8.4}$$

The technical characteristics restrict the usage of some energy sources. For example, a production step that needs liquid fuels may not operate with gaseous alternatives. The parameter ($EnergyMaxRestrict_{e,s,p,tt}$ [MJ/MJ]), sets the maximum possible share of energy carriers for specific equipment. If this parameter has a value of 50%, then only half of the energy demand of type (e) can be satisfied with energy source (s).

$$
\begin{aligned}
&vEnergy_{e,s,p,f,t}[MJ] \\
&\qquad \leq \sum\nolimits_{i}^{N_i} \sum\nolimits_{t}^{N_{tt}} EnergyNeed_{e,p,tt} \left[\frac{MJ}{ton_M}\right] * EnergyMaxRestrict_{e,s,p,tt} \left[\frac{MJ}{MJ}\right] \\
&\qquad * \left(vLegacyMaterialProd_{i,p,f,t,tt}[ton_M]\right. \\
&\qquad \left. + vLegacyCapEmission_{i,p,f,t,tt}[ton_E]\right), \\
&\qquad\quad \forall tt\colon t \leq t,\ EnergyMaxRestrict_{e,s,p,tt} \left[\frac{MJ}{MJ}\right] > 0
\end{aligned}
\tag{6.4.8.5}
$$

Additionally, the maximum use of a certain group of energy sources might be restricted for some production steps. Different biobased resources such as timber or household waste are available, though, combined these heterogeneous resources might only cover a certain percentage of final energy demand ($MaxEnergyAltShare_{e,p,t}[MJ/MJ]$), for example, in cement kilns.

$$
\begin{aligned}
&\sum\nolimits_{s}^{N_s} vEnergy_{e,s,p,f,t}[MJ] \\
&\qquad \leq MaxEnergyAltShare_{e,p,t} \left[\frac{MJ}{MJ}\right] \\
&\qquad * \sum\nolimits_{s}^{N_s} vEnergy_{e,s,p,f,t}[MJ] * EnergyRestrict_{e,s} \left[\frac{MJ}{MJ}\right], \\
&\qquad EnergyMaxRestrict_{e,s,p,t} \left[\frac{MJ}{MJ}\right] > 0
\end{aligned}
\tag{6.4.8.6}
$$

6.4.9. Emission flows

Direct emissions (i) caused by each production step alternative (p) is the sum of those emissions related to fuel consumption ($vEmissionsFuel_{s,i,p,pp,f,t}$) across all different energy sources (s) and therefore energy consumption, and those caused by the chemical transformation within a production process ($vEmissionProcess_{i,p,pp,f,t}$), which is linked to the actual material flows of the process.

$$
\begin{aligned}
&vEmissions_{i,p,pp,f,t}[ton_E] \\
&\qquad = vEmissionProcess_{i,p,pp,f,t}[ton_E] + \sum\nolimits_{s}^{N_s} vEmissionsFuel_{s,i,p,pp,f,t}\,[ton_E]
\end{aligned}
\tag{6.4.9.1}
$$

Process-based emissions are linked to the production throughput in a specific production step with each marginal unit of material production causing process-related emissions as a ratio of the material flow ($EmissionProcess_{i,p}$).

$$
\begin{aligned}
&\sum\nolimits_{pp}^{N_{pp}} vEmissionsProcess_{s,i,p,pp,f,t}\,[ton_E] \\
&\qquad = \sum\nolimits_{ii}^{N_{ii}} vMaterialProd_{ii,p,f,t}[ton_E] * EmissionProcess_{i,p} \left[\frac{ton_E}{ton_M}\right]
\end{aligned}
\tag{6.4.9.2}
$$

Fuel based emissions are directly linked to the consumption of a specific energy type, with each fuel being characterised by an emission factor ($EmissionFuel_{s,i}$).

$$
\sum\nolimits_{pp}^{N_{pp}} vEmissionsFuel_{s,i,p,pp,f,t}\,[ton_E] = \sum\nolimits_{e}^{N_e} vEnergy_{e,s,p,f,t}[MJ] * EmissionFuel_{s,i} \left[\frac{ton_E}{MJ}\right]
\tag{6.4.9.3}
$$

Since many industries consider carbon capture (CCS and CCU) as one feasible option for decarbonisation, the following equations and constraints introduce a mechanism to implement carbon capture. In mathematical terms, emissions captured are subtracted from the process emissions being priced by the emission trading system (see Equation 6.4.4.4). Capturing emissions

(i) depends on the existence of carbon capture capacity ($\mathrm{vCapacity}_{i,p,f,t}$) that must be equal or bigger than captured emission streams ($\mathrm{vCapturedEmissions}_{i,p,f,t}$).

$$vCapturedEmissions_{i,p,f,t}[ton_E] \leq vCapacity_{i,p,f,t}[ton_E] \qquad 6.4.9.4$$

The capture capacity needs to be big enough to account for all emission flows leading from different production steps (p) towards the installed capture facility (pp).

$$\sum_{p}^{N_p} vEmissions_{i,p,pp,f,t}[ton_E] \leq vCapacity_{i,pp,f,t}[ton_E] \qquad 6.4.9.5$$

Since only production steps with carbon capture processes could reduce the total plant-level emissions, the variable $\mathrm{vCapturedEmissions}_{i,p,f,t}$ can only take positive values for equipment alternative (pp) with a capture functionality ($\mathrm{CaptureRate}_{i,pp} > 0$). Depending on the carbon capture technology installed, processes either capture emissions of the entire plant ($\mathrm{CaptureRange}_{i,pp,pp} = 1$) or only of an individual production step (p), ($\mathrm{CaptureRange}_{i,pp,p} = 1$). In case of capturing emissions across the entire plant level, $\mathrm{CaptureRate}_{i,pp}$ sets the percentage value of emissions captured across all production steps.

$$vCapturedEmissions_{i,pp,f,t}[ton_E] \leq \sum_{p}^{N_p} vEmissions_{i,p,pp,f,t}[ton_E] * CaptureRate_{i,pp} \left[\frac{ton_E}{ton_E}\right], \quad CaptureRange_{i,pp,pp}[0/1] = 1 \qquad 6.4.9.6$$

In case of capturing emissions for only one production step, $\mathrm{CaptureRate}_{i,pp}$ sets the capture efficiency for emissions linked to the individual production step (p) only.

$$vCapturedEmissions_{i,pp,f,t}[ton_E] \leq \begin{cases} vEmissions_{i,p,pp,f,t}[ton_E] * CaptureRate_{i,pp}\left[\frac{ton_E}{ton_E}\right], \\ \quad CaptureRange_{i,pp,p}[0/1] = 1, \forall pp: p <> p \\ 0, CaptureRange_{i,pp,p}[0/1] = 0, \forall pp: p <> p \end{cases} \qquad 6.4.9.7$$

Carbon capture equipment allows for capturing biobased emissions if capturing emissions streams originating from the combustion of biofuels. Capturing and storing these emissions, though, can result in a negative carbon footprint. The parameter $\mathrm{BioEmissionFuel}_{s,i,t}$ sets the biobased emission share $[\mathrm{ton_{BE}}/\mathrm{ton_E}]$ for the different fuel types for each time step to account for the reduced carbon intensity of biofuel provision over time. Biobased emissions can be captured across all production steps on the plant level.

$$\begin{aligned} &vCapturedBioEmissions_{i,pp,f,t}[ton_E] \\ &\leq \sum_{s}^{N_s}\sum_{p}^{N_p} vEmissionsFuel_{s,i,p,pp,f,t}[ton_E] * CaptureRate_{i,pp} \left[\frac{ton_E}{ton_E}\right] \\ &* BioEmissionFuel_{s,i,t}\left[\frac{ton_E}{ton_E}\right], CaptureRange_{i,pp,pp}[0/1] = 1 \end{aligned} \qquad 6.4.9.8$$

Accordingly, only partial capture of biobased emissions for specific production steps is also feasible.

$$\begin{aligned} &vCapturedBioEmissions_{i,pp,f,t}[ton_E] \\ &\leq \begin{cases} \sum_{s}^{N_s} vEmissions_{i,p,pp,f,t}[ton_E] * CaptureRate_{i,pp}\left[\frac{ton_E}{ton_E}\right] * BioEmissionFuel_{s,i,t}\left[\frac{ton_E}{ton_E}\right], \\ \quad CaptureRange_{i,pp,p}[0/1] = 1, \forall pp: p <> p \\ \quad 0, CaptureRange_{i,pp,p}[0/1] = 0, \forall pp: p <> p \end{cases} \end{aligned} \qquad 6.4.9.9$$

Capturing biobased emissions does not require different equipment since carbon dioxide-equivalent emissions from fossil fuel and biobased sources are the same on the molecular level. Biobased emission capture refers to a fraction of all captured emissions that can, at maximum, correspond to all captured emissions.

$$vCapturedBioEmissions_{i,pp,f,t}[ton_E] \leq vCapturedEmissions_{i,p,f,t}[ton_E] \qquad 6.4.9.10$$

6.4.10. Remarks about the conceptual model scope

The scope of the conceptual model, as introduced in section 6.3, aims at three domains that have been studied in depth for this thesis, namely technologies, economics and policies. In the following, I briefly reflect on the design elements of the conceptual TRANSid model and show how they are represented in the mathematical formulation. For testing combinations of different industrial policies, the presented mathematical formulation is insufficient, though I identify minor extensions that would enable me to fully reflect the impact of various policies on investment and operational decisions over the studied period (N_t).

Technology options

The mathematical model shall consider prospective alternative technology options for the different industrial processes used in various basic material industries while considering the evolution of the existing industrial park and future technology adoption rates.

The mathematical model allows designing various industrial processes that operate in parallel to meet different material demands for various basic material industries. The model opts for a set of production steps (p), ensuring that the final material demand (i) ($MaterialDemand_{i,t}$) is met for each time step (t) (constraint 6.4.6.1). In case of different material demands such as cement, steel or petrochemical products, the model chooses a set of production steps (p) that enables the provision of these final materials at the lowest cost with different industrial plants (f).

For the mathematical model, existing plants with conventional technologies are defined as production steps (p), though their design life ($DesignLife_{p,f}$) is limited to reflect the remaining years before replacement. If no reinvestment in conventional technologies is feasible when reaching the end of their design life, the installation cost parameter ($InstallationCost_{p,f,t}$) corresponds to values that equal a very high penalty fee to enforce investments in alternative technologies. Alternative technology options are also production steps (p) that can perform the same material transformation from material (i) to material (ii) as the conventional process ($MaterialNeed_{i,ii,p,t}$), though using the installation cost parameter are only made available at their time step of expected technological maturity (t). Alternatively, they may also face reduced installation costs over time to reflect potential learning rates for different technologies.

Economics

The mathematical formulation presented relies on static market scenarios using parameters for installation cost ($InstallationCost_{p,f,t}$), energy ($EnergyCost_{s,t}$), material ($MaterialCost_{i,t}$) and emission ($EmissionCost_{i,t}$) pricing for each time step (t). By running the model for various combinations of price scenarios, the sensitivities for both installation and operational costs can be studied.

As stated in detail for the conceptual model, TRANSid shall especially be used to study industry-specific policies. Industry and basic material sector-specific market policies, such as emission pricing, can be studied by slightly modifying the objective function (equation 6.4.2.1) by excluding, for example, emission pricing ($vCostEmissions_{f,t}$). Instead, an additional constraint would need to be introduced that sets final target emissions for specific time steps (t). The dual variable of the constraint can be used to determine the corresponding emission prices across the studied basic material sectors to reach set emission reduction targets.

The mathematical formulation includes a provision to calculate the net present value (NPV) of future investments and operational costs. Depending on the discount rate, modelling results might differ substantially. If 2021 Euro area bond yields for 30 years are used as a reference, a discount rate of 0.34% would have to be applied. Government bond rates as a reference for the NPV have been applied in studies as by McKane et al. (2017). However, benchmark studies for the IEAGHG apply discount rates as high as 8% (IEAGHG, 2013a, 2013b).

Policies

Scenarios that reflect the different policies could be studied by adjusting existing parameters and extending additional sets.

Green public procurement creates a demand for materials with climate-friendly production characteristics. The resulting climate-friendly demand could be introduced as an additional material demand (ii), such as green steel for public use, as a subset of steel´s overall material demand (i).

CfDs correspond to pricing scenarios for which the cost of energy, emissions or materials are stabilised for certain quantities over a given time horizon. Only studying individual plants (f), CfDs replace market-oriented price scenarios for energy ($\mathsf{EnergyCost}_{s,t}$), material ($\mathsf{MaterialCost}_{i,t}$) and emission ($\mathsf{EmissionCost}_{i,t}$) over a certain number of time steps (t). Their effect can be studied by contrasting results from various model runs with different pricing scenarios. With minor modifications, the current model formulation, namely equations 6.4.4.1, 6.4.4.2 and 6.4.4.4, CfD pricing scenarios could be defined only for specific plants (f). If limited to a specific new production plant (f) with a certain production capacity ($\mathsf{PlantCapacity}_{i,f,t}$) the interplay between plants operating under CfD regimes and those without CfDs can be studied with one model run.

While the impact of CBAMs with or without free allocation can be investigated by varying emission price scenarios ($\mathsf{vCostEmissions}_{f,t}$) for all time steps N_t, a more thorough distinction of the effects from different CBAM design options would require an extension of the current modelling formulation. An additional parameter could characterise free allowance allocations with different allocation scenarios to reflect CBAM design alternatives.

Product carbon requirements correspond to emission limits that approach net-zero. Studying them requires similar modifications to the mathematical model as sector-specific emission pricing described above. Limits on emissions would need to be set for time steps across different sectors.

6.5. A case study for the cement sector

Limitations of the mathematical model formulation imply that it cannot fully reflect the desired functionalities identified as part of the conceptual design for the TRANSid model in section 6.3. Therefore, the following case study aims to demonstrate the current capabilities of the proposed mathematical formulation. I present the underlying modelling assumptions along the three dimensions of the model, first specifying the parameters used to model the current industrial park and technology options, then detailing market assumptions and briefly reflecting on the corresponding industrial policy of this case study (section 6.5.1). In section 6.5.2, I then present and interpret the results of this case study and various scenario runs.

6.5.1. Introducing the case study

Aiming to demonstrate the basic functionalities of TRANSid, the case study is based on the cement industry with its linear production process. It builds upon the exemplary description of the cement sector for the development of a conceptual model in section 6.3. The case study is kept as simple as possible to demonstrate the functioning of different aspects of the proposed linear programming (LP) model. The case study mainly focuses on the model´s ability to adequately account for legacy equipment replacement and introduce new technology options, namely carbon capture and storage technologies. Results of different scenarios can demonstrate functionalities like adding new plants and using high purity biomass streams throughout 30 yearly time steps, corresponding to the transition period between 2020 and 2050.

Technologies

The case study encompasses two legacy cement production plants with a distinct remaining plant lifetime for their equipment to show how re-investments replace production steps over time. These two plants entered into service 10 (f01) and 20 (f02) years ago, each with a standard plant capacity of 1 Mt/year (Voldsund et al., 2019). For simplicity reasons, it is assumed that both cement plants operate with the best available technology (BAT). Operational characteristics were obtained by contrasting, crosschecking and combining BAT data obtained from multiple sources.

Cement production requires various materials for obtaining intermediate products such as raw meal or cement clinker. Table 6-E lists the material flow ratios that reflect the transformations from input material (i) to output material (ii) across different production steps in the BAT process.

Table 6-E: Material need characteristics for main material streams in BAT cement marking process

$\mathbf{MaterialNeed}_{i,ii,p,t}$	(i to ii)	Sources
Clinker to cement	0.737	(Voldsund et al., 2019)
Gypsum to cement	0.050	(Schorcht et al., 2013)
Mineral additions to cement	0.213	(Schorcht et al., 2013)
Raw meal to clinker	1.600	(Voldsund et al., 2019)
Limestone ($CaCO_3$) to raw meal	0.770	(Voldsund et al., 2019)
Silica (SiO_2) to raw meal	0.140	(Voldsund et al., 2019)
Al_2O_3, Fe_2O_3, $MgCO_3$ to raw meal	0.090	(Voldsund et al., 2019)

Material transformation takes place across multiple production steps, though not all transform materials, but also perform other operations such as forming or preparing material flows. The electric and thermal energy required to operate the different production steps listed in

For this case study, equipment that reached the end of its design life can be replaced with improved BAT technologies. An efficiency improvement factor of 0.5% p.a. is assumed for new equipment so that a production step (p) replaced by its equivalent in time step (t=t04) requires 1.49 % less energy than an equivalent installation in time step (t=t01). Equally, new equipment can manage higher biomass shares ($\mathrm{EnergyMaxRestrict}_{e,s,p,t}$) reaching 100% in t=t10.

Table 6-F corresponds to values obtained by combining BAT operational characteristics from various sources. Note that the production step (p = p01) is undefined since it represents the material stock (section 6.4.6).

One peculiarity of the cement industry is that burning limestone causes process emissions (section 2.1). These process emissions originate in the kiln (0.06 tCO_2/t clinker) and the precalciner (0.51 tCO_2/t clinker) (Hills et al., 2017), represented by the parameter $\mathrm{EmissionProcess}_{i,p}$.

Installation costs are expressed in annuities for each different production step. Annuities have been calculated based on investment cost data published by the European Cement Research Academy (2017) and Gardarsdottir et al. (2019) and design life according to Erumban (2008) and Gardarsdottir et al. (2019) (

Existing (f01, f02) or novel factory-level plants (f03, ...) can also be equipped with new production steps that enable carbon capture and storage (CCS). Two different carbon capture technologies are available, each with different capture rates and years of commercial availability. Both technologies can be installed as brownfield solutions in existing facilities and can even be combined to maximise carbon capture rates. Characteristics of these technologies are summarised in Table 6-H and investment costs, design life and availability in

Table 6-I.

Table 6-G). A discount rate of 0% has been assumed when calculating the NPV of investments. Note that for both BAT plants (f01 and f02), the remaining lifetime of installed equipment is significantly lower than the design life since the plants entered service 10 and 20 years ago and partially replaced their initial production steps already. Different equipment age, however, has no impact on annuities. Process related operational costs are benchmarked with data published in Gardarsdottir et al. (2019) and distributed across the various production steps (p02 to p10, p48) based on their electricity consumption. The underlying assumption is that operational expenditures are primarily linked to mechanical equipment consuming electricity.

For this case study, equipment that reached the end of its design life can be replaced with improved BAT technologies. An efficiency improvement factor of 0.5% p.a. is assumed for new equipment so that a production step (p) replaced by its equivalent in time step (t=t04) requires 1.49 % less energy than an equivalent installation in time step (t=t01). Equally, new equipment can manage higher biomass shares ($\mathrm{EnergyMaxRestrict}_{e,s,p,t}$) reaching 100% in t=t10.

Table 6-F: Production steps, energy need and output materials

Production step		$\mathbf{EnergyNeed}_{e,p,t}$ (MJ/ton(i))		Output (i)		Sources
		e = electric	e = thermal			
p02	Raw material handling	15	20	i04	Raw meal loose	(Afkhami et al., 2015; Voldsund et al., 2019)
p03	Raw Mill	83		i05	Raw meal grinded	(Afkhami et al., 2015; Voldsund et al., 2019)
p04	Preheater		-600	i06	Clinker (preheated)	(European Cement Research Academy, 2017; Hills et al., 2017)
p05	Precalciner		2219	i07	Clinker (precalcined)	(European Cement Research Academy, 2017; Hills et al., 2017)
p06	Kiln	119	1479	i08	Clinker (hot)	(Afkhami et al., 2015; Schorcht et al., 2013; Voldsund et al., 2019)
p07	Cooler			i09	Clinker (cold)	(European Cement Research Academy, 2017)
p09	Cement Mill	112		i13	Cement mixed	(Afkhami et al., 2015; European Cement Research Academy, 2017; Voldsund et al., 2019)
p10	Finishing/Auxiliaries	35		i14	Cement final	(Afkhami et al., 2015; Voldsund et al., 2019)

Existing (f01, f02) or novel factory-level plants (f03, ...) can also be equipped with new production steps that enable carbon capture and storage (CCS). Two different carbon capture technologies are available, each with different capture rates and years of commercial availability. Both technologies can be installed as brownfield solutions in existing facilities and can even be combined to maximise carbon capture rates.[198] Characteristics of these technologies are summarised in Table 6-H and investment costs, design life and availability in

Table 6-I.

Table 6-G: Investment cost, design life and annuities of production step equipment

Production step		$\mathbf{DesignLife}_{p,f}$ (years)			$\mathbf{InstallationCost}_{p,f,t}$ (€/ton(i))		Sources
		As new	f01	f02	Total (capacity)	Annuity (f01/f02)	
p02	Raw material handling	12	2	4	26.26	3.48	(European Cement Research Academy, 2017; Gardarsdottir et al., 2019)
p03	Raw Mill	12	2	4	8.48	1.13	(European Cement Research Academy, 2017; Gardarsdottir et al., 2019)
p04	Preheater	25	15	5	6.78	0.64	(European Cement Research Academy, 2017; Gardarsdottir et al., 2019)
p05	Precalciner	25	15	5	64.44	6.04	(European Cement Research Academy, 2017; Gardarsdottir et al., 2019)
p06	Kiln	25	15	5	176.39	16.52	(European Cement Research Academy, 2017; Gardarsdottir et al., 2019)
p07	Cooler	25	15	5	13.57	1.27	(European Cement Research Academy, 2017; Gardarsdottir et al., 2019)
p09	Cement Mill	12	2	4	15.00	1.99	(European Cement Research Academy, 2017; Gardarsdottir et al., 2019)
p10	Finishing/Auxiliaries	12	2	4	28.34	3.76	(European Cement Research Academy, 2017; Gardarsdottir et al., 2019)

Table 6-H: CCS production steps, energy need and capture rate

Production step		$\mathbf{EnergyNeed}_{e,p,t}$ (MJ/ tonCO_2e)		$\mathbf{CaptureRate}_{i,p}$	$\mathbf{CaptureRange}_{i,p,pp}$	Sources
		e = electric	e = thermal			
p45	LEILAC CCS	[199]		95%	only precalciner	(Hills et al., 2017)
p48	MEA CCS	887	3073	94%	all processes	(Gardarsdottir et al., 2019)

Table 6-I: Investment cost, design life and annuities of CCS equipment

Production step		$\mathbf{DesignLife}_{p,f}$ (years)	Availability (t)	$\mathbf{InstallationCost}_{p,f,t}$ (€/tonCO_2e)		Sources
				Total (capacity)	Annuity (f01/f02)	
p45	LEILAC CCS	25	t20	100.00	9.34	(Hills et al., 2017)
p48	MEA CCS	25	t05	76.00	7.12	(Gardarsdottir et al., 2019)

[198] The LEILAC design can be combined with other CCS options to maximize carbon capture rates (Hills et al., 2017).
[199] LEILAC may operate without significant additional energy demand.

Markets

Given that basic materials are commodities with homogenous product characteristics (section 2.3), the business case for conventional and novel production technologies is primarily defined by investment and operational cost positions. Here, operational costs depend on the market scenarios for energy, material prices and emissions. For this case study, the focus is on energy and emission price scenarios. Since proposed technological changes do not imply a significant shift in feedstock consumption, changing material prices would have little influence on the case study results.[200] Constant market prices for feedstock have been selected to reproduce the share of material costs in the final cost scenarios for different cement production routes, as presented in Gardarsdottir et al. (2019).

Only one constant electricity price of 50 €/MWh (13.9 €/GJ) is used for this case study. Based on our analysis in section 4.2, hourly electricity price volatility is set to increase in the future. For the LP, though, we assume time steps with an annual granularity. Therefore, a flat electricity price scenario for all time steps reflects our conclusions from 4.2.7. To benefit from low electricity prices, consumers need to reduce and increase their demand and adjust it to electricity market fluctuations. We assume that electricity demand for cement making is inelastic to such price signals for this case study.

Coal, biomass, natural gas and hydrogen are the available resources for meeting the thermal energy demand of cement making. Given the long term price uncertainties of fossil fuels, flat price scenarios for coal (3.0 €/GJ) and natural gas (6.0 €/GJ) are based on Gardarsdottir et al. (2019). With reference to section 4.3.5, it is difficult to frame current cost and emission reduction estimates for biomass. For this case study, we assume that biomass has the same emission intensity as coal. No emission allowance cost is associated with biomass emissions. A medium price scenario (8.9 €/GJ) within the range of prices determined for the Swedish case study published in Agar et al. (2020) serves as a cost estimate. Low or zero-emission hydrogen can also be used as fuel in cement kilns. The price scenario for green hydrogen, shown in Figure 6-12, is based on very optimistic installation costs and operating characteristics for 2020 with a production cost decline that would require additional incentives during the first years, given the findings presented in section 4.3.4. It is designed to show whether hydrogen could be competitive to other fuel sources in a scenario aligned with a potential reference price for green hydrogen in Spain by 2050, as stated by the IEA in 2019 (IEA, 2019a). The respective energy cost in 2020 is 27.1 €/GJ (3.28 €/KgH_2) and 16.5 €/GJ (2.00 €/KgH_2) in 2050.

Table 6-J: Emissions and energy cost for different energy sources

Energy source		$\mathbf{EmissionFuel_{s,i}}$		$\mathbf{EnergyCost_{s,t}}$	
		gCO_2/MJ	Sources	€/GJ	Sources
s01	Electricity	[201]		13.9	-
s02	Natural Gas	56.1	(Umweltbundesamt, 2016)	6.0	(Gardarsdottir et al., 2019)
s03	Coal	81.1	(Umweltbundesamt, 2016)	3.0	(Gardarsdottir et al., 2019)
s04	Biomass	81.1	[202]	8.9	(Agar et al., 2020)
S05	Hydrogen	[201]		27.1 (2020) / 16.5 (2050)	(IEA, 2019a) (long term)

[200] Different market scenarios for material feedstock would have to be considered when including production processes for cement with lower clinker ratios and a higher share of alternative climate-friendly feedstock, thereby reducing the role of limestone for cement making (section 3.3.3).
[201] Electricity and hydrogen cause no direct emissions when consumed.
[202] For simplicity biomass emissions are considered equal to coal emissions.

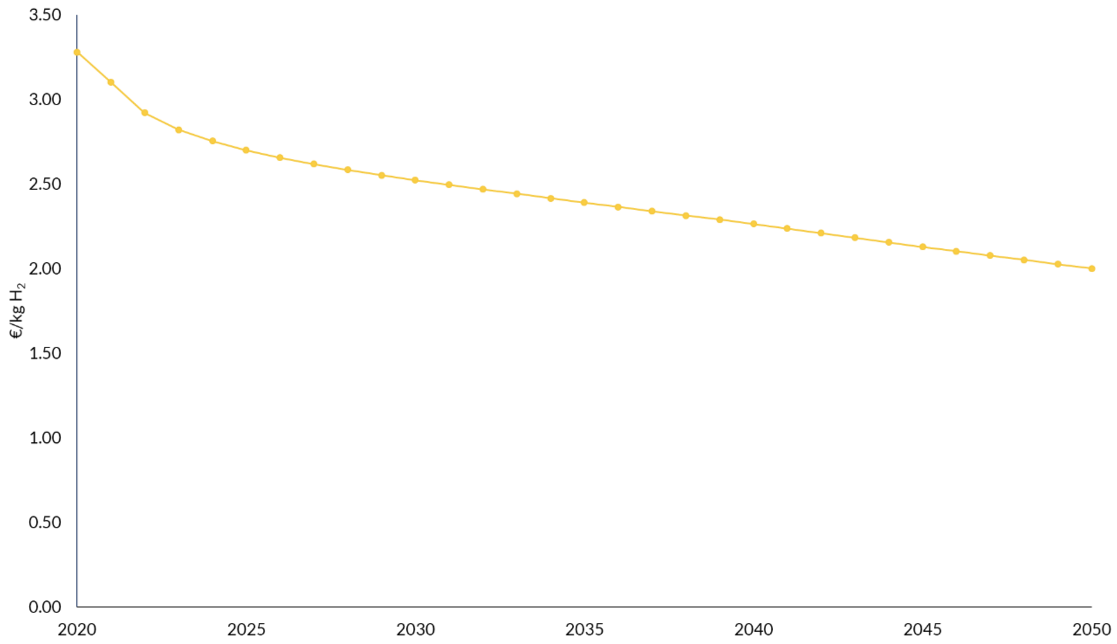

Figure 6-12: Exemplary long-term hydrogen cost scenario until 2050 used for the case study

The cost of emission allowance determines the competitiveness of biomass, hydrogen and zero-emission electricity supply with fossil fuel sources. As described in section 5.3.4, free allowances for the basic material sector used to cover most of the emissions from their operations during the early phases of the EU ETS. In phase 4, from 2021 onwards, free allowances shall be gradually reduced and phased out. As a departure point for the case study, the resulting emission price for the cement industry after utilising free allowances for BAT is assumed to be zero in 2020. It gradually increases to 250 €/tCO_2e in 2050 (Figure 6-13).

Material demand scenarios ($MaterialDemand_{i,t}$) are adjusted to the available production facilities of the two legacy plants (2 Mt/year). The role of global competition to meet the demand with imports is not part of the case study, assuming a fully functioning carbon border adjustment mechanism and disregarding its design challenges, as discussed in section 5.3.4.

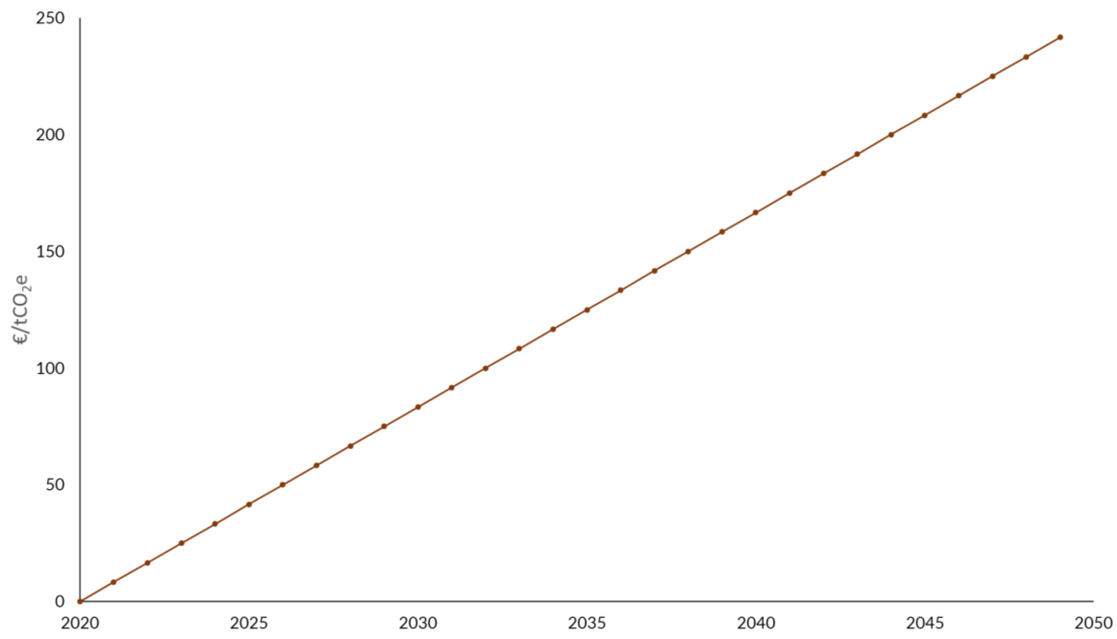

Figure 6-13: An emission allowance cost scenario with gradually decreasing free emission allowances

Policies

As commented about the limitations of mathematical formulation concerning the conceptual modelling scope in section 6.4.10, the ability to design a case study with the presented LP that reflects different industrial policies is very limited. As described in the previous section, the case study describes an emission allowance market with free allowances being gradually phased out and an active CBAM. Several of the scenarios presented in the following diverge from this assumption and include scenarios without free allowance allocations and/or stable emission allowance prices. However, these scenarios do not present specific policies and are mainly applied to demonstrate the model´s capabilities.

6.5.2. Results for different case study scenarios

The case study provides insights into the potential investment and operating decisions for the two legacy cement plants for a single scenario. As such, I deviate from the initial case study assumptions by introducing various scenario variations to demonstrate the functionalities of the LP formulation. Table 6-K names and highlights the different scenarios, pointing out the changing assumptions about available energy sources, available technologies, material demand and emission allowance prices.

BASE Scenario

The base scenario estimates the cost-optimal replacement schedule for the two legacy cement plants (f01, f02), assuming a gradual phase-out of free allowances and rising allowances prices until 2050 (Figure 6-13). For the first time step, resulting emission allowances costs are 0 €/tCO_2e, allowing for a comparison to the cost structure of the reference cement plant studied by (Gardarsdottir et al., 2019) with a final production cost of 62.6 €/t of cement clinker. At the first time step of this scenario, the final cost per ton of cement is 59.3 €/t, corresponding to 80.5 €/t of cement clinker. This difference is rooted entirely in the higher equipment costs for the case study compared to the figures published in (Gardarsdottir et al., 2019). In (Gardarsdottir et al., 2019), equipment costs account for 20.4 €/t of cement clinker while the equivalent of the case study result is 29.2 €/t of cement (equivalent to 39.6 €/t of cement clinker) (Figure 6-14). This difference could be explained by the cost of financing assumed to be 8% for the case study[203], while (Gardarsdottir et al., 2019) states no assumptions about the financing costs.

Table 6-K: Assumptions for case study scenarios

Scenario	Energy sources	CCS	**MaterialDemand$_{i,t}$**	**EmissionCost$_{i,t}$**
BASE	no biomass	all	2 Mt/year constant	Free allowance phase-out (Figure 6-13)
BASEBIO	all	all	2 Mt/year constant	Free allowance phase-out (Figure 6-13)
MEA	no biomass	MEA	2 Mt/year constant	85 €/tCO_2e constant
HYDROGEN	no biomass	none	2 Mt/year constant	Free allowance phase-out (Figure 6-13)
NEWDEMAND	no biomass	all	2 Mt/year until 2029, then 2.5 Mt/year	85 €/tCO_2e constant

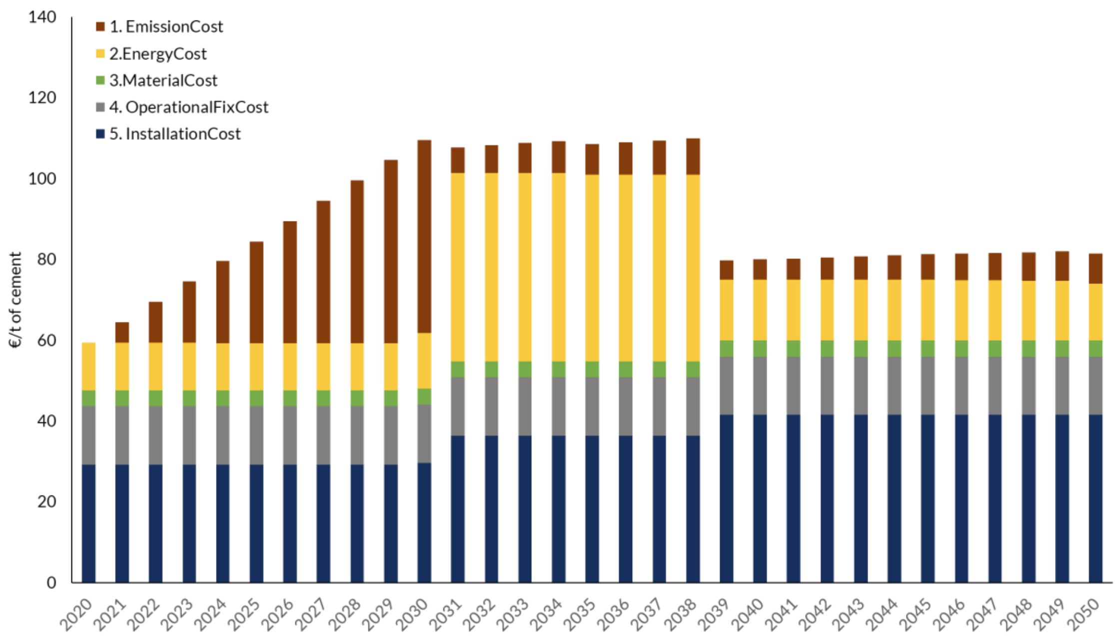

Figure 6-14: Break-down of relative costs of cement from operating both plants f01 and f02 for the BASE scenario

The breakdown of the relative costs per ton of cement in Figure 6-14 also shows the cost-optimal investment decisions given an expected emission price scenario, as shown in Figure 6-13. Note that even though available in the year 2024 in time step 5, MEA CCS is only first installed in the year 2031 (time step 12) at an emission allowance price of 91.7 €/tCO_2e. This cost is slightly higher than the 80 €/tCO_2e estimated by Gardarsdottir et al. (2019) and could also be justified by the higher installation costs of MEA CCS due to the cost of financing considered for this caste study. Both factories are being equipped with MEA CCS in the same year. As shown in Figure 6-15, the brownfield investment in MEA CCS is unaffected by the replacement schedule for the existing production step equipment. Since LEILAC CCS is available and installed in 2039 (time step 20), emission and energy costs drop significantly while relative investment costs increase.

[203] For this simplified case study the discount rate (DiscountRate) to calculate the net present value is assumed to be 0%. However, an annual premium of 8% was applied externally when setting the external ($InstallationCost_{p,f,t}$) parameter for the annuity of new equipment. This approach limits the validty of model results since it only reflects very high financing costs, but not the NPV of other cash flows (section 6.6.2).

Additional to the annuities of the installed non-CCS production step equipment, aggregated annuities also include payments for non-utilised MEA CCS and novel LEILAC CCS equipment.

Figure 6-15 shows the percentage of the total production step equipment installed, renewed and retired in both plants for each time step. From the modelling perspective, all production step equipment of f01 and f02 enters operation in time step 1 with a remaining design life corresponding to the age of the two facilities. With reference to the design life of production step equipment for f01 and f02 summarised in

Existing (f01, f02) or novel factory-level plants (f03, ...) can also be equipped with new production steps that enable carbon capture and storage (CCS). Two different carbon capture technologies are available, each with different capture rates and years of commercial availability. Both technologies can be installed as brownfield solutions in existing facilities and can even be combined to maximise carbon capture rates. Characteristics of these technologies are summarised in Table 6-H and investment costs, design life and availability in

Table 6-I.

Table 6-G, production step equipment with a remaining design life of 2 (f01), respective 4 (f02) years is renewed in 2022 (f01) and 2024 (f02), while the kiln and precalciner are renewed for the first time in 2035 (f01) and 2025 (f02). Note that the relative capacity additions for the MEA CCS in 2031 are relatively small since they are sized according to the resulting emission flows. LEILAC CCS is installed as soon as available in time step 20 (2039). Note that MEA CCS would be operated together with LEILAC CCS until the end of its design life, but about 90% of its capacity is phased out in time step 25 (2044). Only 10% of the MEA CCS capacity remains to capture those emissions that LEILAC CCS does not capture since LEILAC CCS only captures precalciner emissions. While not a practical solution, the results show that the model optimises production step equipment and retires equipment that is not needed anymore.

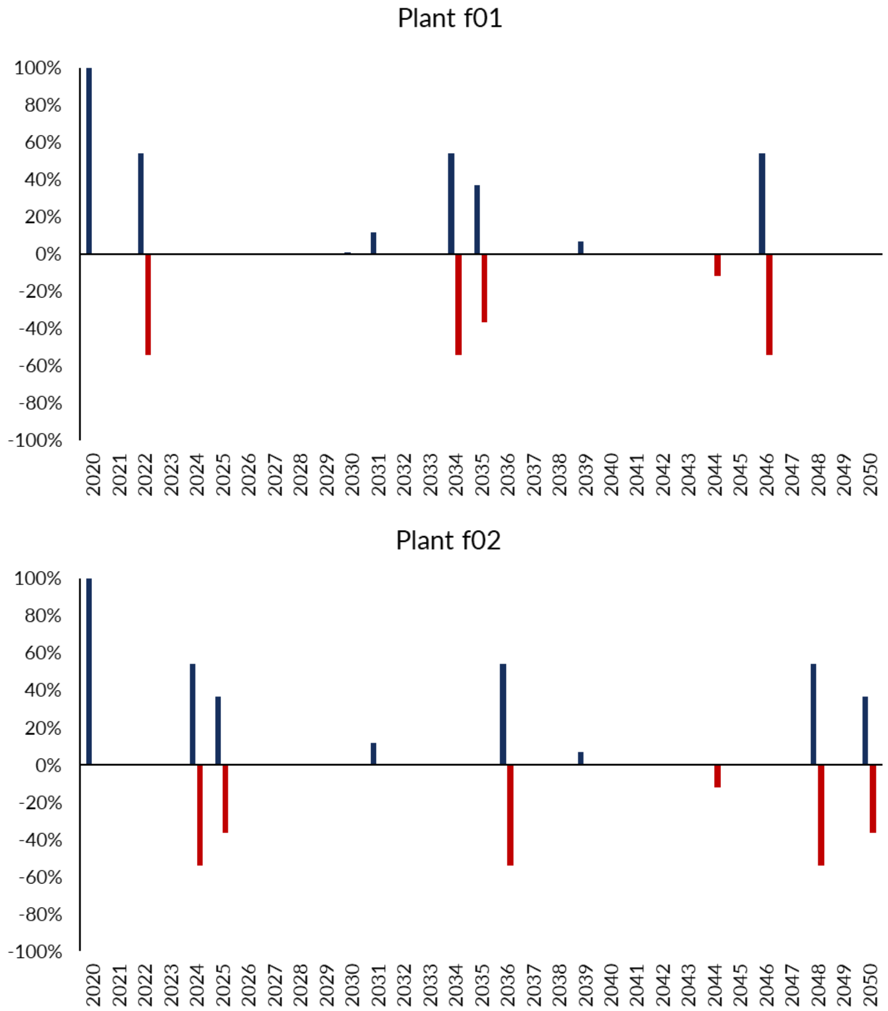

Figure 6-15: Scope of refurbishing operations, including additions (blue) and retirements (red) of production step equipment for the BASE scenario[204]

[204] 100% indicates the full replacement of all factory production equipment.

The interplay with the two different CCS technologies is also reflected in the energy consumption balance in Figure 6-15. Since BAT technology is installed, total consumption in time step 1 corresponds to 2305 MJ of thermal energy per ton of cement, equivalent to thermal 3128 MJ per ton of clinker. These figures are at the lower end of the specific thermal energy demand identified by BAT technologies in the EC JRC reference report for the cement sector (3000 – 4000 MJ/t of clinker) (Schorcht et al., 2013). Coal is the cheapest but also most emission-intensive energy source to meet thermal energy demand. As such, coal continues to be used when installing MEA CCS since the energy cost outweighs the potential benefits of capturing emissions from natural gas instead. Note that operations switch towards covering part of the demand with natural gas as soon as LEILAC CCS is installed. Natural gas is only used in the precalciner from which emissions are captured via the LEILAC technology. LEILAC has significantly higher installation costs and no additional energy consumption, thereby favouring the installation of a unit that handles less carbon-intensive exhaust streams. These observations confirm the functioning of the model but also demonstrate its limitations. In practice, kiln and precalciner are fuelled jointly but have two different emission outlets.

Combined, Figure 6-15 and Figure 6-16 also demonstrate the effect of expected future efficiency improvements for available technologies. Plant f02 has its last retrofitting campaign in the year 2050 (time step 31). By replacing old production step equipment with more efficient new plant equipment, the relative energy demand per ton of cement decreases slightly compared to time step 30.

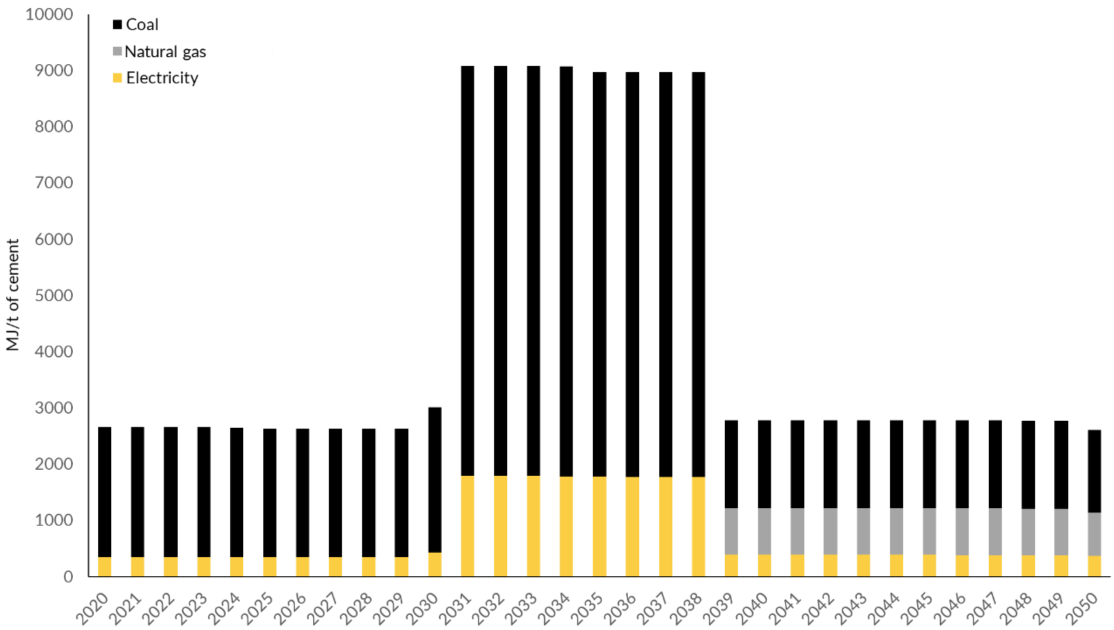

Figure 6-16: Relative energy intensity of cement for the BASE scenario

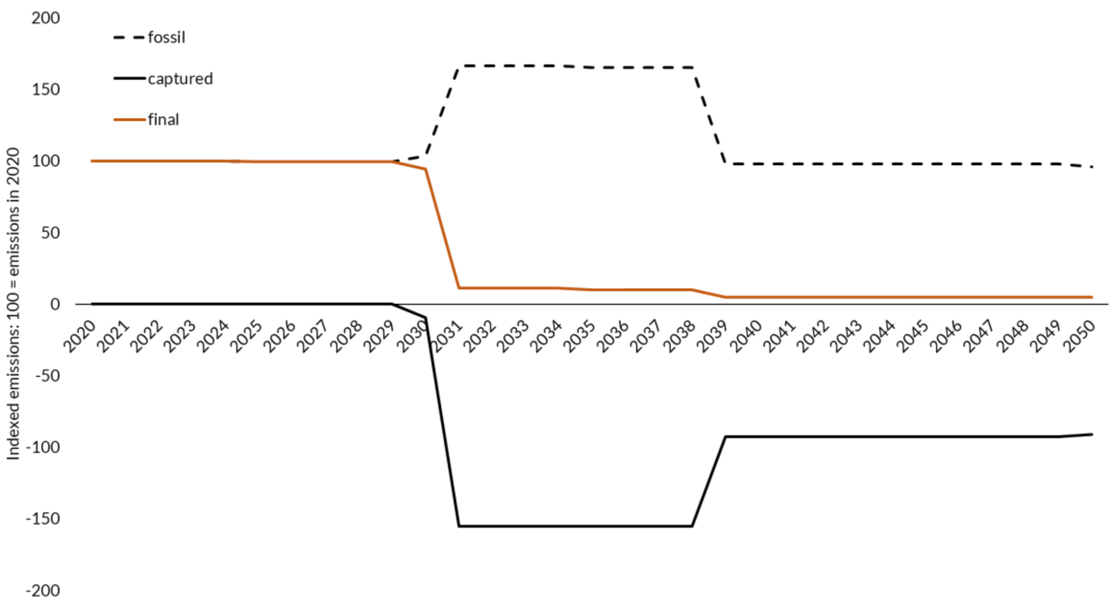

Figure 6-17: Fossil emissions, captured and final atmospheric emissions for the BASE scenario

Figure 6-17 shows the resulting fossil emissions trajectory for operating both plants jointly. Emissions only start to decrease notably after CCS equipment is installed in both plants by 2031 (time step 12). Note that the amount of occurring and captured emissions is significantly higher while operating only MEA CCS, which relies on additional external fossil consumption to meet the thermal energy demand requirements of the process. After installing LEILAC CCS, the amount of released and captured emissions decreases, reducing the final emissions to a minimum equivalent to 4.86 % of the emissions released per ton of cement in 2020.

BASEBIO Scenario

This scenario uses the same assumptions as the BASE scenario but allows for biomass as an energy carrier. Using the cost-breakdown (Figure 6-18) relative energy intensity balance (Figure 6-19), the BASEBIO scenario highlights the benefits of using biomass in the modelled case study. It demonstrates the limitations of the proposed mathematical formulation.

Biomass is used as soon as MEA CCS equipment is installed in 2030 (time step 11), one year earlier than the BASE scenario. While there is no cost associated with biobased carbon dioxide-equivalent emissions, the model includes provisions for reimbursing the capture and use of biobased carbon dioxide-equivalent emissions (Equation 6.4.4.4). In practice, free allowances obtained by capturing renewable carbon dioxide-equivalent emissions translate into profits for selling these free allowances. In its current formulation, the model only operates with positive variables. Therefore it is only feasible to compensate payments of non-abatable process emissions and not possible to generate profits. This limitation of the current model formulation explains why relative costs for emission avoidance disappear after introducing MEA CCS (Figure 6-18). Using biobased emissions to offset fossil emissions, the relative cost of cement when operating MEA CCS in f01 and f02 for the BASEBIO scenario is lower (105 €/t of cement in 2038) than in the BASE scenario (100 €/t cement in 2038).

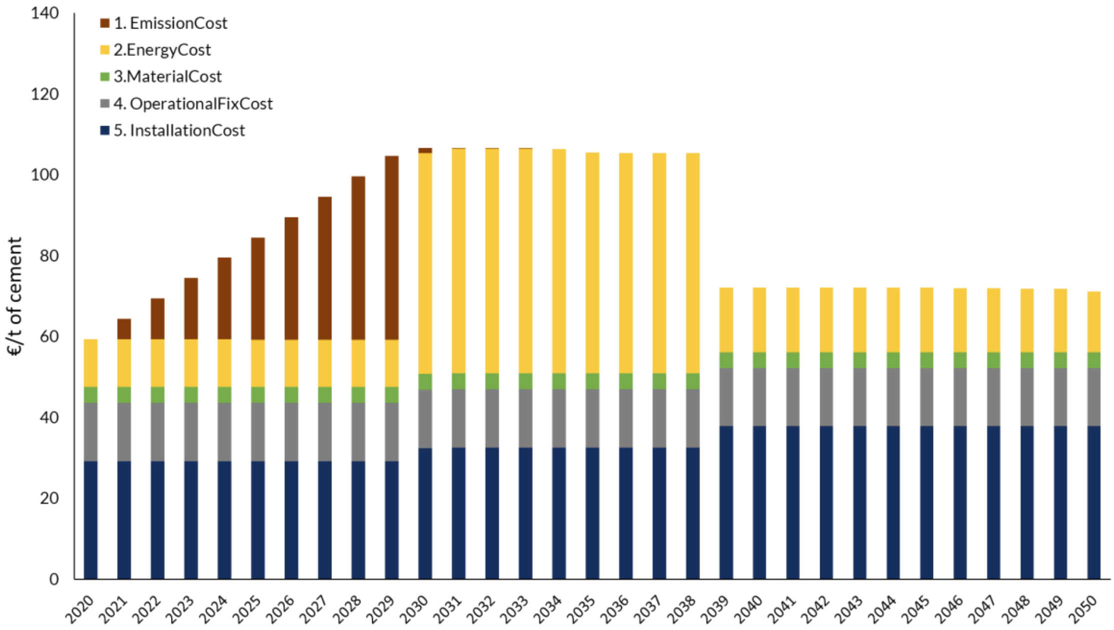

Figure 6-18: Break-down of relative costs of cement from operating both plants f01 and f02 for the BASEBIO scenario

By only capturing those biobased emissions necessary to compensate payments for non-abatable emissions, the MEA CCS is sized significantly smaller than in the BASE scenario. In the BASEBIO scenario, total energy demand never exceeds 5568 MJ/t of cement compared to a maximum consumption of 9078 MJ/t in the BASE scenario. Biomass is used as the only thermal energy carrier when operating the MEA CCS. After additionally installing LEILAC CCS in 2039, the main share of thermal demand is met with coal again (Figure 6-19). Biomass is a more expensive energy carrier than coal, and LEILAC CCS can be operated without additional energy demand. Therefore, the LEILAC CCS is sized to capture only emissions equivalent for compensating potential fossil emission payments.

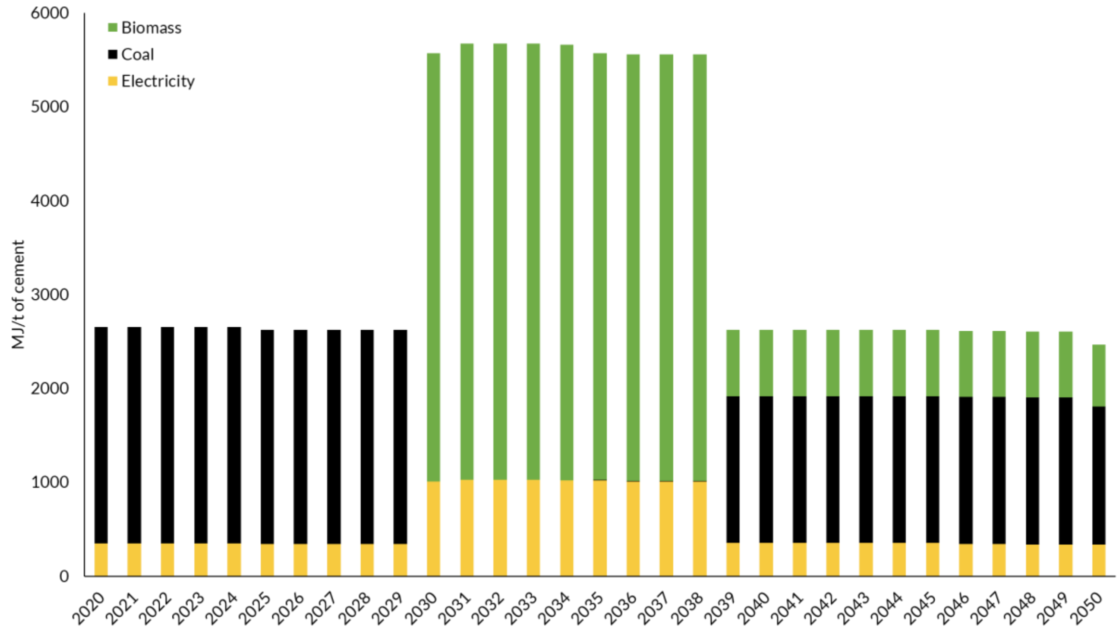

Figure 6-19: Relative energy intensity of cement for the BASEBIO scenario

MEA Scenario

Carbon capture by using MEA CCS is available from time step 5 (year 2024) onwards. Even though a relatively mature technology (section 3.3.3), the model only opts to introduce MEA CCS in the years 2031 (scenario BASE) and 2030 (scenario BASEBIO) when the carbon pricing reaches a level that makes MEA CCS economically viable. Since the TRANSid model optimises investments over the entire time horizon, it takes investment decisions based on expected future costs of carbon dioxide-equivalent emissions. The MEA scenario is designed to study the economic viability of MEA CCS with a flat emission price of 85 €/t, slightly below the technology threshold for introducing the technology in the BASE scenario (91.7 €/tCO_2e). LEILAC CCS is not available in this scenario.

As shown in Figure 6-20, MEA CCS is installed in 2036, significantly later than in the BASE and BASEBIO scenario. This delay in installing MEA CCS can be explained by the improved performance of MEA CCS installed in 2036 compared to MEA CCS installed in 2031. As such, this scenario shows the model´s capability to reflect expected annual efficiency improvements at a rate of 0.5 % per year. In Table 6-L, the cost structure for MEA CCS for the BASE scenario is compared to the cost structure in the MEA scenario. The prospective of higher penalty payments for fossil-based carbon dioxide-equivalent emissions in the BASE scenario makes it economically feasible to install MEA CCS, increasing the relative cost per ton of cement for emissions, energy, and the installation itself. Even though the model only accounts for efficiency improvements, higher efficiencies mean that MEA CCS needs fewer fossil fuels to operate, thereby slightly reducing the required equipment size for capturing emissions caused by using the MEA CCS process.

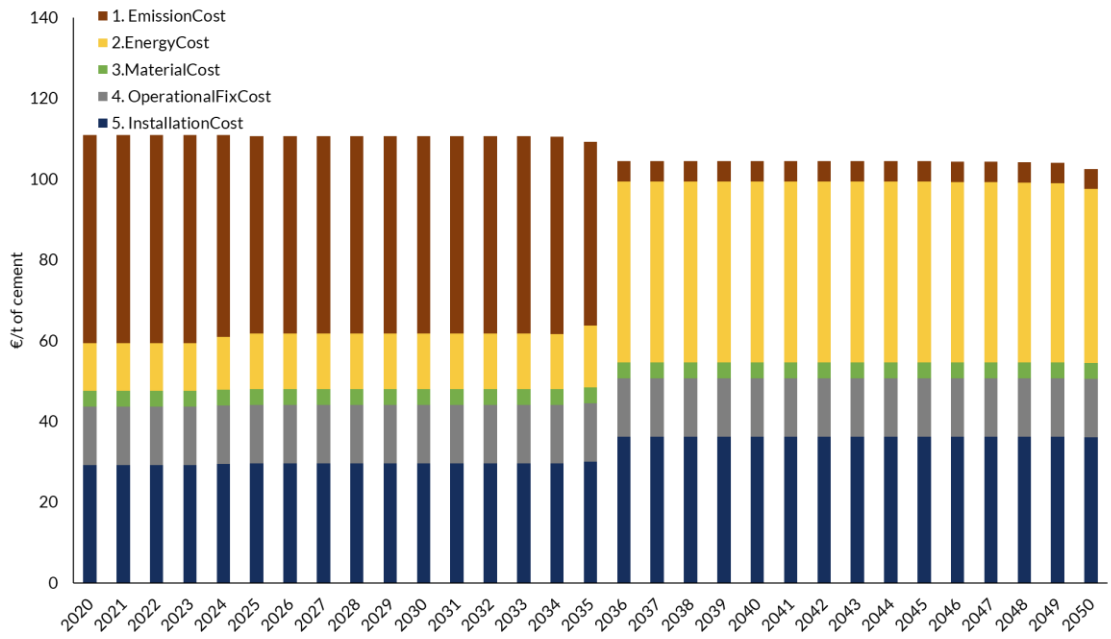

Figure 6-20: Break-down of relative costs of cement from operating both plants f01 and f02 for the MEA scenario

Table 6-L: Cost increase per ton of cement in the BASE Scenario compared to MEA CCS after installing MEA CCS

			Relative cost per ton of cement (€/t)				
	time step	$\mathbf{EmissionCost_{i,t}}$	Emissions	Energy	Materials	Operational	Installation
BASE Scenario	2031 (t12)	91.63 €/tCO_2e	6.217	46.739	3.938	14.376	36.367
MEA Scenario	2036 (t17)	85.00 €/tCO_2e	5.038	44.790	3.938	14.376	36.251
			+23.40 %	+4.35%	-	-	+0.32%

HYDROGEN Scenario

Along with natural gas and coal, hydrogen is a low-emission thermal energy carrier available in all previous scenarios. However, in none of these scenarios, hydrogen is used. The HYDROGEN scenario demonstrates the capability of the model to opt for the most economical energy carrier given varying emission allowance costs by disabling CCS options.

Assuming linearly increasing carbon dioxide-equivalent emission prices such as in the BASE scenario, the model opts for switching from the most emission-intensive energy carrier, coal, first to natural gas in 2035 (125.0 €/tCO_2e) and finally to hydrogen in 2045 (208.3 €/tCO_2e). Given its expected price decline (Figure 6-12), hydrogen serves as an energy carrier starting at 2.13 €/kgH_2. For this scenario, the model can only reinvest in more efficient equipment at the end of its design life, which explains the stepwise reduction of total energy intensity, as observed in Figure 6-21.

Switching fuel carriers cannot reduce cement industry emissions to an absolute minimum since about two-thirds of BAT emissions originate from the chemical reaction of limestone within the kiln (section 2.1). Consequently, the final emission caused by cement production, declining stepwise with every fuel switch, stabilised from 2045 onwards at a level that is only 30.75 % lower than with the operation of BAT technology in 2020 (Figure 6-22).

Due to increasing carbon dioxide-equivalent emissions costs, the price of cement increases almost in parallel with the emission allowance price, though slight mitigating effects for using less emission-intensive energy carriers slightly flatten the curve. Figure 6-23 shows the impact of continuously decreasing hydrogen prices so that the peak energy cost per ton of cement is reached in 2045 and slightly decreases in the years after. However, the reduced energy costs are marginal compared to cost increase due to higher emission allowance prices. Departing from production costs of 59.3 €/t of cement in 2020, costs double by 2032, reach 178.2 €/t of cement in 2045 when using hydrogen for the first time and peak at 190.6 €/t of cement when the emission allowance price peaks at 250 €/tCO_2e in 2050. Cement production costs per ton in 2050 that are almost four times today´s cost and mainly linked to purchasing emission allowances to cover process-related emissions is a highly unrealistic scenario. As shown in the BASE scenario, carbon capture alternatives only increase production costs by about 30% in the long run while actually limiting the carbon footprint of cement production.

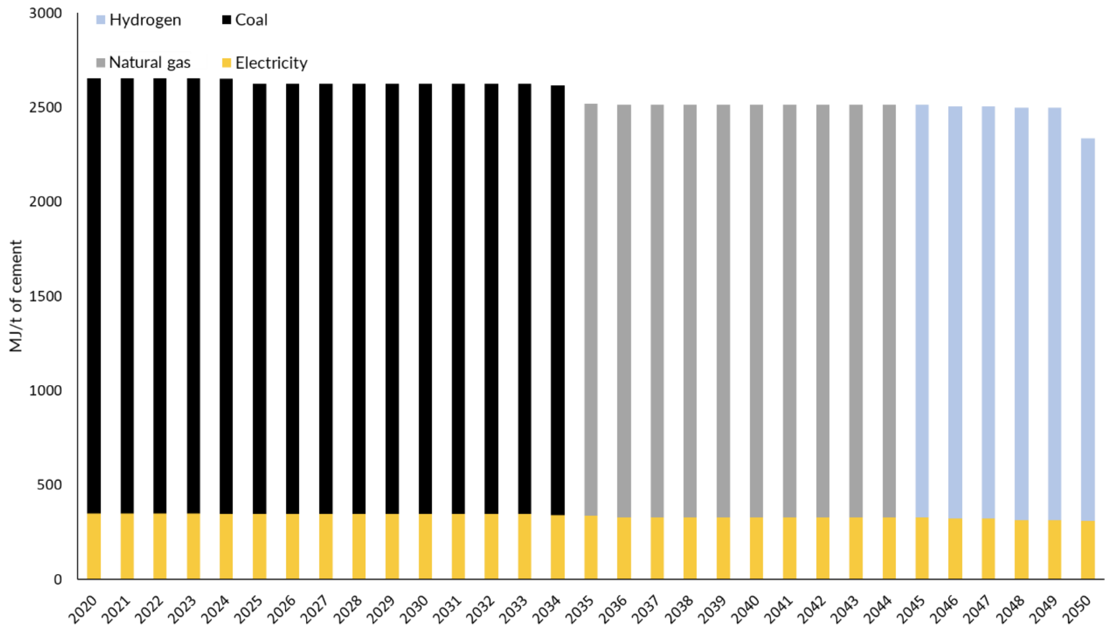

Figure 6-21: Relative energy intensity of cement for the HYDROGEN scenario

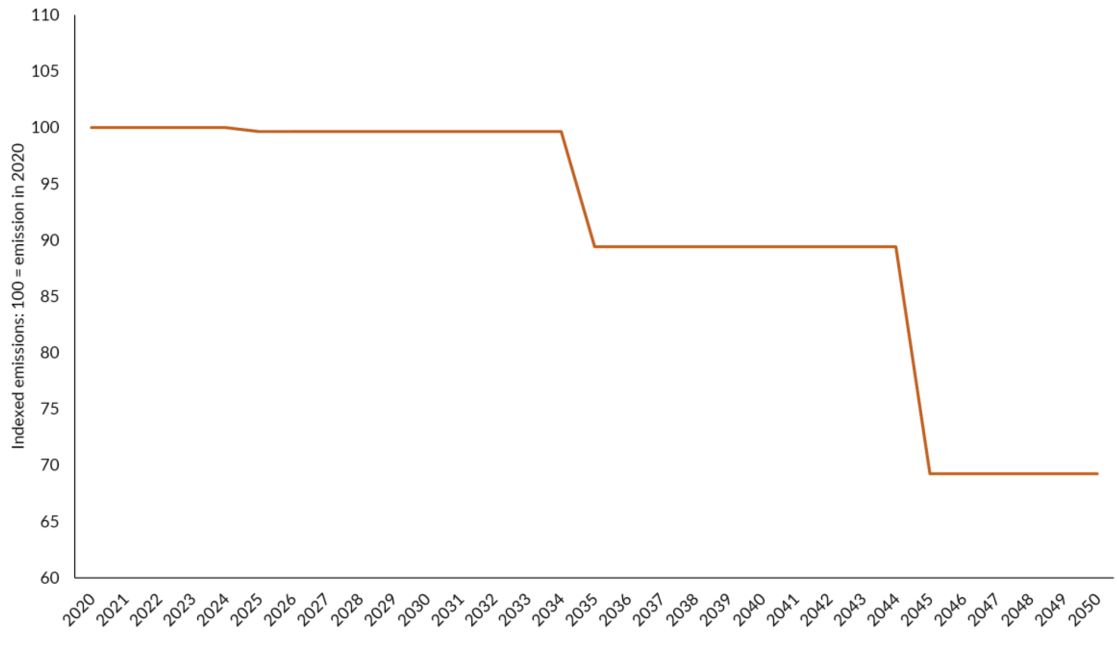

Figure 6-22: Final fossil emissions for the HYDROGEN scenario

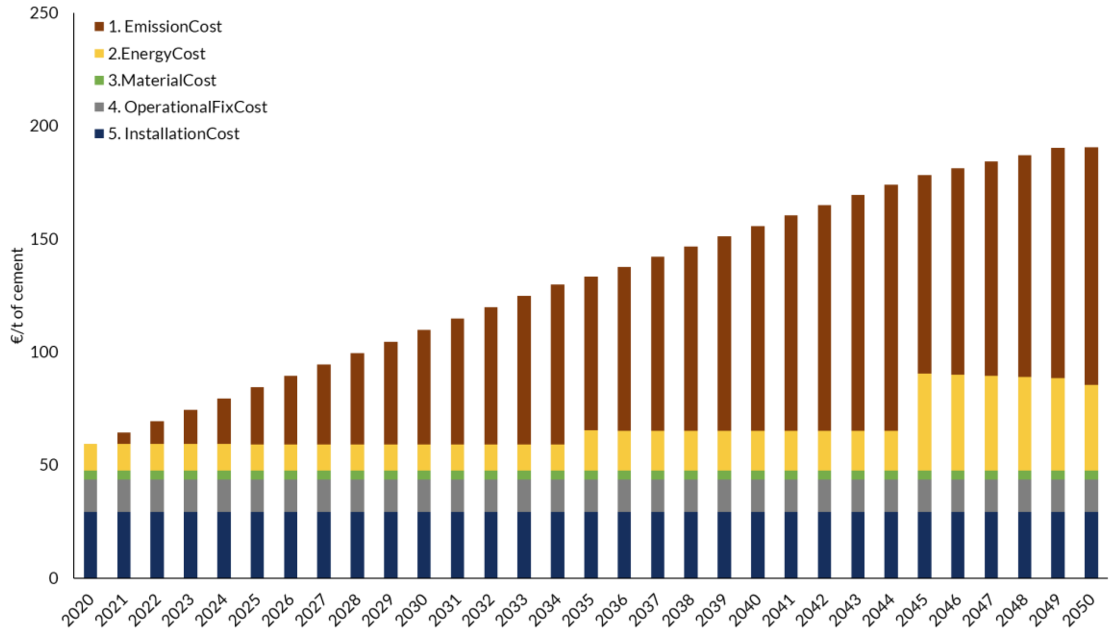

Figure 6-23: Break-down of relative costs of cement from operating both plants f01 and f02 for the HYDROGEN scenario

NEWDEMAND Scenario

All scenarios presented up to this point only cover existing legacy plants and their transition under varying energy, emission, and technology scenarios. The NEWDEMAND scenario demonstrates that the current LP can cope with changing demand patterns and add new plant-level factories (f03, ….) to meet additional material demand. To limit the impact of the expected emissions allowance price fluctuations on the investment scenarios, a flat price of 85 €/tCO_2e is assumed, equal to the MEA scenario.

As shown in Figure 6-24, a new plant is being installed in 2030 (time step 11). This plant (f03) has a capacity that corresponds to 50% of f01 and f02. Since the current LP has no minimum limit for sizing new cement plants, it allows for installing and refurbishing plants with marginally sized production step equipment without differentiating between its relative functional characteristics. Though the model formulation gives a reasonable result for stepwise demand changes that correspond to a new production facility of feasible size (0.5 Mt/a), the validity of results for marginal demand changes is limited since the model would respond with marginal investment or retirement of production step equipment.

Comparing the results of the NEWDEMAND with the MEA scenario, both assuming the same flat emission allowance price, is the different deployment of CCS technology. In the MEA scenario, LEILAC CCS is not an available investment option, so that the model installs MEA CCS from 2036 onwards (Figure 6-20). With the prospective availability of LEILAC CCS in the year 2039 (time step 20), none of the plants invests in MEA CCS, and all opt for adding LEILAC CCS capacity in 2039, as indicated in Figure 6-24.

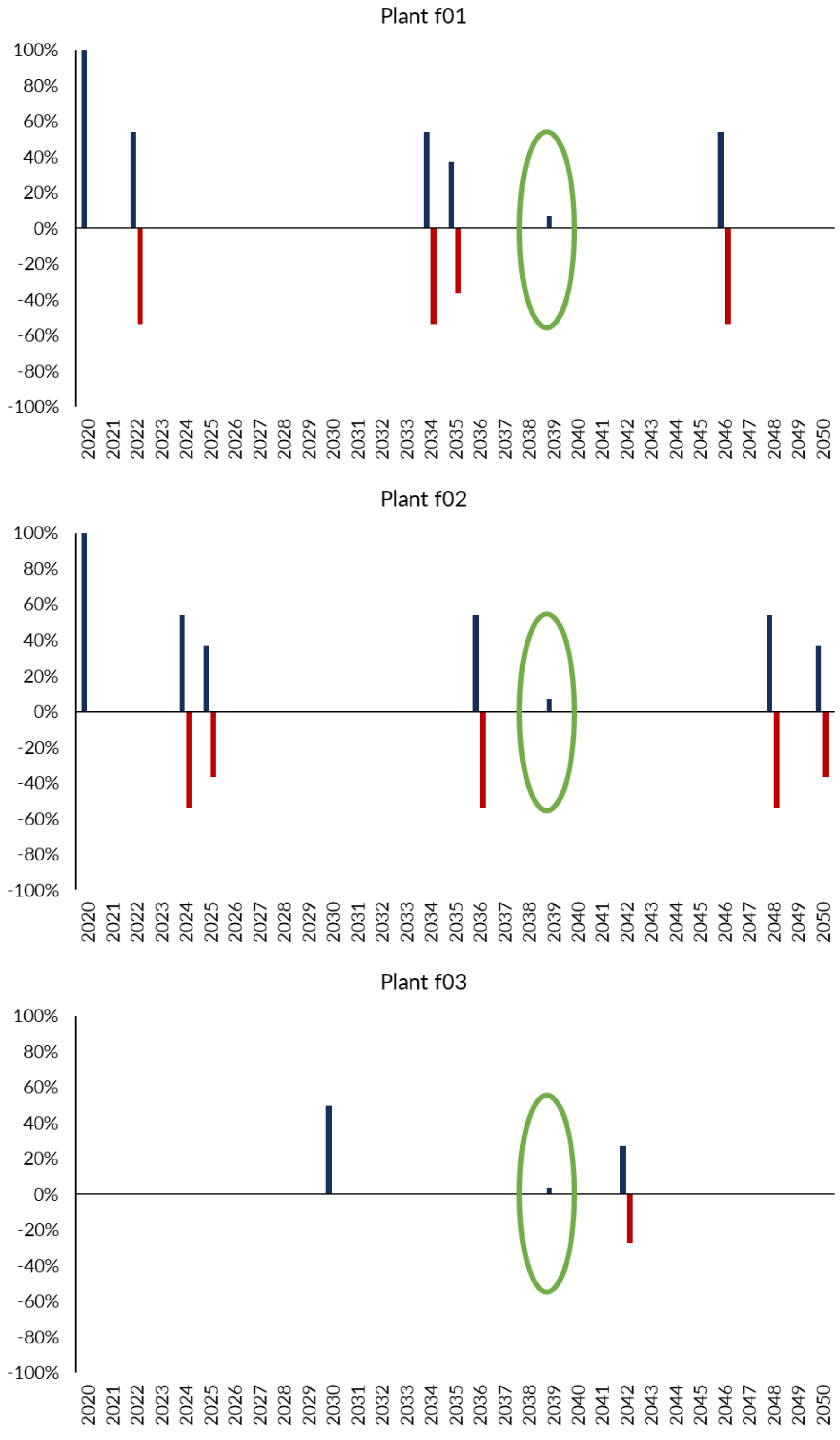

Figure 6-24: Scope of refurbishing operations, including additions (blue) and retirements (red) of production step equipment for the NEWDEMAND scenario[205]

[205] 100% indicates the full replacement of all factory production equipment. A green circle is used to highlight the introduction of LEILAC CCS in 2039.

6.6. Discussion

The mathematical model in section 6.4 is one approach to translate the conceptual model into a fully operational version of the TRANSid modelling framework previously proposed in section 6.3. I use the case study introduced in section 6.5 to show that the basic concept of the mathematical approach works. It allows studying how investment decisions can be subject to changing assumptions about future material, energy and emission allowance cost scenarios. However, the case study is of simplified complexity by analysing the business case of two isolated cement plants without considering potential market dynamics with other novel technologies and materials, recycling options and other economic activities.

In the following, I reflect on the insights obtained from the case study (section 6.6.1) and its limitations (section 6.6.2). Based on the limitation, I then identify modelling gaps that need to be addressed to create a mathematical model that meets the design requirements of the conceptual model and fully addresses the modelling gaps identified (section 6.6.3).

6.6.1. Insights from the case study

Multiple observations based on the five case study scenarios presented in section 6.5 can be summarised under one of the following four insights. These insights are not novel, though they represent some of the challenges the basic material industry faces on its road towards decarbonisation and confirm the ability of the case study to at least partially reflect them.

Technological availability does not imply technology adoption. For all except the HYDROGEN scenario, MEA CCS is available from 2024 onwards. This assumption reflects the technological availability of the technology that has already been implemented on an industrial scale. However, in none of the scenarios MEA CCS is implemented earlier than the year 2030 (BASEBIO scenario). Improved technological characteristics, better energy efficiency in the case study, and primarily the functioning and level of emission pricing determine if, when and how CCS is adopted under purely economic considerations.

Expectations about tomorrows technology impact today´s investment decision. The interplay between MEA CCS and LEILAC CCS across the different scenarios shows how technology expectations might withhold investments in the current state of the art technologies. Though only capturing precalciner emissions and facing higher investment costs, LEILAC CCS is the superior technology option for CCS in this case study since no additional energy is needed to realise carbon separation and capture. The MEA and NEWDEMAND scenarios operate under the same energy, emission allowance and material cost assumptions, though LEILAC CCS is only available in the NEW DEMAND scenario. By anticipating the future availability of LEILAC CCS in 2039, the model opts for not investing in MEA CCS in the NEWDEMAND scenario and waits until the technologically superior carbon capture option is available. In the MEA scenario, both plants will be equipped with MEA CCS technology by 2036.

The economics of renewable fuels for combustion is subject to emission allowance pricing. Cement production is one of the most fuel price-sensitive industries. Its requirements for different fuel sources are relatively low, allowing for the combustion of various fuel types or combinations. The HYDROGEN scenario highlights the high emission allowance prices or equivalent support mechanisms needed to switch to less carbon-intensive energy sources. The BASEBIO scenario, on the other hand, points to the economics of biomass if CCS is installed. Suppose biomass receives full emission allowances for capturing non-fossil carbon dioxide-equivalent emissions, then rising emission allowance prices would have a multiplier effect on the profitability of biomass. Higher emission allowance prices represent a higher cost for fossil-fuel use, improving the economics of biomass. However, selling emission allowances from capturing biobased carbon dioxide-equivalent emissions would double the discount on biomass compared to fossil fuels without CCS in the cement industry.

With high emission allowance prices, the cost of limestone-based cement without CCS multiplies. Today, no alternative to limestone-based cement has emerged that could be commercially competitive to the conventional methods. In parallel to the results published by

(Gardarsdottir et al., 2019), carbon capture solutions for the cement sector that can potentially limit the premium for climate-friendly cement production to 30% - 50% of today´s production cost, such as in the BASE, BASE BIO and MEA scenarios. However, these costs disregard additional premiums that might have to be paid for installing, operating, and maintaining storage infrastructure. Without CCS capabilities, cement production has to pass on at least two-thirds of the carbon price onto the final product even if climate-friendly fuels are used. Disregarding potential carbon leakage concerns, doubling production costs with an emission allowance price below 120 €/tCO_2e and tripling at a price around 170 €/tCO_2e (HYDROGEN scenario) would not only significantly increase the material costs for construction projects but also open up opportunities for alternative materials. If scientific and societal arguments speak against the practical feasibility of CCS, emission allowance pricing will create cost incentives for developing alternative binders and construction without limestone-based cement.

6.6.2. Limitations of case study results

Besides demonstrating the basic functionality of the mathematical model, the case study presented in section 6.5 foremost helps to point out the limitations of the proposed mathematical formulation. I describe some of these limitations in the following.

As mentioned when discussing the case study results of the BASEBIO scenario, the cement plant operator cannot generate profits from selling more emissions allowances than required to offset its fossil-based carbon dioxide-equivalent emissions. As such, the validity of the model for studying the role of CCS to offset carbon dioxide-equivalent emissions is highly compromised.

In its current state, the mathematical formulation limits the maximum size of factory level plants (Equation 6.4.5.4) but does not set limits on marginal investments into new equipment. As mentioned in the discussion of results for the NEWDEMAND scenario, modelling results for non-linear emission allowance, material, energy price or demand scenario result in marginal adjustments to currently used equipment. While the validity of model results is influenced by this limitation to a lesser degree if studying the macro-transition of cement making on a European or global scale, it falsifies results when studying the transitional dynamics in scenarios with a reduced set of available plants and production capacities.

As pointed out for the BASE scenario, the case study does not reflect the level of technical detail that is necessary to account for the correct flow of energy and emissions streams to integrated equipment, such as the precalciner and kiln. Therefore, the case study and potentially the mathematical formulation must be revised to reflect the technical details at a level that allows for valid model results. The case study also fails to reflect how material, energy and emissions streams could benefit from synergies between different industries, such as residual heat, hydrogen and CO_2 networks. In the latter case, the cost of carbon capture only includes capturing, but not the handling, transport and potentially long-term storage of CO_2.

By focussing on the introduction of CCS technologies that can be installed as brownfield installations in retrofit campaigns, the case study did not differentiate between the potential benefits of coordinating the renewal of the critical production steps with the introduction of technological changes. While for the different scenario runs, CCS implementation and renewal of precalciner always lie at least five years apart, the economics of scale and efficiency improvements for integrated and combined renewal of equipment is not reflected in this case study. Additionally, major renewal campaigns often imply months-long plant closures that potentially reduce the annual output and incentivises plant operators to reduce the frequency of plant overhauls, which is neither reflected by the case study nor foreseen in the mathematical formulation.

The validity of the model results concerning the interplay of retrofits and greenfield investments is also limited by not using a discount rate for calculating the NPV. As mentioned in section 6.4.10, the cost of finance is currently very low, which could partially justify a discount rate of 0%. However, the case study inflates equipment costs by adding an 8% financing premium. This premium has been responsible for the difference in installation cost-share compared to reference studies (section 6.5.2). It also impacted model results for this case study since higher investment costs favour the continued operation of existing equipment. Additional model runs are needed to explore the effect of varying discount rates on the NPV and its influence on investment decisions. Installation cost parameters need to be revised to reduce the cost of finance since it should at least partially be fully reflected in the discount rate applied when calculating the NPV.

All scenarios are just minor variations to the BASE scenario in this case study. They only describe one limited combination of technical, material, energy, emission allowance and demand assumption. As already pointed out in section 6.5.1, its limited scope reduces the validity of the case study and its significance for understanding the transition of the basic material sector. Studying different industry or sector-specific policies and their impact on the transition within one or several basic material industries, as intended with the conceptual TRANSid modelling framework, is not possible at this point. Furthermore, the case study does not fully validate nor verify the functionality of the mathematical formulation. However, the case study does show that model results can be explained given the mathematical provisions made in section 6.4.

6.6.3. To-Does for addressing the modelling gap

Most of the areas of improvement mentioned above can be addressed by a thorough revision of the mathematical formulation presented in section 6.4. The ability to generate profits from emissions allowance offsets requires introducing an additional variable to the objective function that subtracts such revenue streams from the installation and operational cost positions. Extra constraints can set minimum capacity limits for new or renewed equipment, address the identified inaccuracies to reflect technologies such as CCS and penalise scattered equipment renewal on existing plants, and incentivise coordinated refurbishing campaigns. Even though such revision of the mathematical formulation is time-consuming and requires a careful validation and verification of the model´s functionalities, these modifications could be implemented into the LP introduced in section 6.4.

The more significant challenge lies in adjusting the LP in such a way that it addresses all the modelling gaps identified in section 6.2.3:

1. **Study industry and sector transition**
2. **Explore technology pathways**
3. **Greenfield installations vs brownfield extension**
4. **Avoiding the carbon lock-in**
5. **The temporal dimension of transition policies**

Based on the results presented in section 6.5.2 and their discussion in sections 6.6.1 and 6.6.2, the case study can explore technology pathways, potentially evaluate the role of greenfield and brownfield extensions and based on the scenario results, might also be used to identify market scenarios that lead towards a carbon lock-in. However, the case study fails to demonstrate how industry and sector transitions are interlinked by only looking at the transition of the cement sector. The case study captures the temporal dimension of emission allowance pricing policies. Still, by design, it fails to encompass other policy design choices that have been analysed in Chapter 5 and motivated the conceptual model design introduced in section 6.3. Potential modifications to reflect various policy options were already identified in section 6.4.10 but require a more sophisticated case study design.

The main challenge I faced when extending the case study to cover more sectors, processes and scenarios was the increasing numbers of variables to be solved by the model. The higher the number of variables, the more difficult it was to find the optimal solution with available commercial solvers. The case study encompasses six different sets with a total of 77 set elements. Multidimensional variables, such as $vMaterial_{i,p,pp,f,t}$ consist of up to 615,195 (15(i)*21(p)*21(pp)*3(f)*31(t)) individual values for the case study and presolving operations with commercial solvers such as CPLEX can only reduce the solution space to 16,219,444 non-zero variables. Adding, for example, all five additional carbon capture alternatives presented by (Gardarsdottir et al., 2019) increases the number to 17,545,324 non-zero variables. A study encompassing two other legacy cement plants with varying equipment ages almost doubles the number of non-zero variables compared to the BASE scenario (29,220,116). These considerations do not even include the additions of factory-level plants that produce other materials than cement, requiring an additional unique set of production steps to satisfy, for example, steel demand. Note that additional constraints to detail the technical complexity of production steps, as described at the beginning of this section, might require additional variables and increase the solution space.

Another challenge to overcome the modelling gaps is the wide range of parameters needed to describe industrial processes, energy, material and emission streams. Running the BASE scenario of the case study, the condition number of $1.1*10^8$ is achieved by meeting a material demand of 2 kg per time step, instead of 2 Mt/year, using kg as the unit for masses, MJ for energy and euro cents as the monetary unit, rescaling model results after obtaining an optimal solution. Though the LP can be considered ill-conditioned already ($>10^8$), the principal difficulty in reducing the parameter range is the variety of parameters used to describe the industrial equipment´s operational characteristics that are set to increase if including further details. The bigger the parameter range, the more difficult for the solver algorithm to find a unique solution with a solution sensitivity that does not violate constraints crucial to the validity of the model results.

Future research needs to address the challenges concerning the scalability of the model. First, a structured and formalised approach can help to improve the mathematical formulation. Even though the model presents a novel approach, a detailed review of how industrial processes have been modelled for other studies and identifying mathematical problems with a similar structure for other applications can be a good starting point for improving the model. However, it might be necessary also to question the capabilities of the chosen mathematical approach (section 6.4) to fully implement the conceptual model design (section 6.3) by developing another way to address the modelling gaps identified in section 6.2.

6.7. Conclusions

Connecting the dots. This saying describes the role of the last part of this thesis project and the purpose of the conceptual design for the TRANSid model presented in this chapter. After reviewing existing bottom-up modelling approaches and contrasting them with techno-economic studies of the basic material sector, I conclude that we need a novel model to account for the technical, economic and policy dimensions of transforming the basic materials industry (section 6.2). Models help us understand how emission-intensive industries can move towards climate-friendly production processes. However, the model results need to be robust against the propositions about technological readiness (Chapter 3), the economics of energy supply (Chapter 4) and industrial policy options (Chapter 5) that I identified throughout this thesis.

In section 6.3, I introduce the conceptual design of the TRANSid model, which can address the identified modelling gap by identifying policy scenarios to enable industrial decarbonisation. The mathematical formulation of an LP optimisation problem is the first go implementing the conceptual model (section 6.4). Model results of a simplified case study allow me to demonstrate the LP´s capabilities and highlight its limitations to address the modelling gap adequately in section 6.5.

However, exploring the factors that impact the investment decisions for renewal of existing infrastructure and refurbishment with novel CCS technologies with the case study provides first insights on how to address the fourth thesis sub-objective of this thesis:

> *II. Explore how the energy demand and characteristics of the basic material sector can evolve by introducing new process innovations under various premises concerning available technologies, market scenarios and policies.*

The five case study scenarios and resulting investment and operational scenarios for the cement plants (section 6.5.2) show how varying emission allowance price scenarios and changing expectations about available technologies and their energy demand can impact the evolution of the industrial park.

Revising, extending and further validating the proposed model to address the modelling gap better would allow me to explore potential transition scenarios of the basic material sector to a greater extent.

Chapter 7

Conclusions & Contributions

This thesis has been a journey, passing through many fields of science. Departing from an engineering perspective, I study market dynamics and enter into policy design before addressing industrial decarbonisation from a mathematical perspective. Such a multidisciplinary approach for understanding the implications of industrial decarbonisation was not the envisioned scope of this thesis back in 2017 when I started my work on the topic. It was neither planned, not foreseen from the beginning but rather born from the needs, uncertainties, and resultant knowledge gaps I encountered when asking about the role of the industrial sector in future energy systems.

The premise of achieving a net-zero emission society by 2050 in Europe requires us to rethink any energy use case and source of fossil carbon dioxide-equivalent emissions today. One can only grasp how energy systems might look in the future when understanding what it takes to decarbonise the different sectors of our economy. The industry is the backbone of our society and lends its name to the period of industrialisation that led Europe toward the industrialized societies that we live in today. While the economic importance of industrial value creation is in decline with western economies moving towards service-oriented activities, their importance for allowing us to live our daily life remains crucial. We are surrounded by manufactured goods made from a very small group of basic materials, each of them energy and emission-intensive in their making. While about one-third of our energy use and emission intensity in Europe are linked to industrial activities, most energy consumption and emissions are linked to the production of steel, cement, petrochemical products, paper and other non-ferrous metals and non-metallic minerals. For becoming a net-zero emission society by 2050, the way we produce, process, and use these basic materials must change fundamentally.

The gravity of this transition implies that for exploring the role of the industrial sector for future energy systems, one first must understand why, how and when the industrial transition will take place. My thesis has been motivated by the implications of industrial decarbonisation for the energy system but led me towards exploring the various dimensions that will decide whether and how the industry will transform.

In the following, I first summarise my academic contributions for each of the chapters in section 7.1. Then I revisit the main objective of this thesis. Reflecting on the different thesis sub-objectives, I highlight the main contributions in section 7.2. Since my thesis cannot provide a conclusive answer on how industrial decarbonisation will be achieved, I ultimately suggest how my findings can motivate and frame future work in section 7.3.

7.1. Academic contributions

The thesis consists of five main chapters that provide the necessary background and analysis to respond to the main research objective and the different sub-objectives formulated at the beginning (section 1.2).

Chapter 2 introduces the multidisciplinary nature of the transition from conventional processes to climate-friendly basic material production. The high-level review of, among others, physical, energetic and economic aspects of industrial processes motivates the focus of this thesis on the technical, economic and policy dimensions. The framing of the transition challenge in the basic materials sector along these three dimensions is a novel contribution that helps to refocus the way we study and analyse the industry.

Chapter 3 explores the technology dimension. The work presented in this chapter is primarily based on my first journal paper (Gerres et al., 2019b), published in the Journal of Cleaner Production JCR: 7.246 Q1 (2019). My work introduces a novel approach to categorizing emission abatement options across different industrial sectors to make them comparable.[206] The results of my analysis provide quantitative evidence that strengthens various hypotheses about the cross-sectoral implications of industrial transition, thereby contributing to the scientific understanding of the transition.

Chapter 4 looks at the objectives to be met by our energy systems and their implications. It is based on various scientific contributions that enhance our knowledge about future electricity market dynamics. My second journal paper (Gerres et al., 2019c), published in Energy Policy JCR: 5.042 Q1 (2019) and an IEEE conference paper (Gerres et al., 2019d), demonstrate how different system objectives, market mechanisms, and technology assumptions impact the market outcome for future electricity systems. For the fourth chapter of my thesis, I further explore the need to meet emission avoidance, adequacy and affordability objectives and project my findings from the electricity market on the future availability of other energy carriers. The analysis presented in this chapter contributes to the characterisation of future energy markets and their interdependencies for meeting emission avoidance and availability criteria.

Chapter 5 evaluates how different industrial policies can support the transition of the basic materials sector. Among others, it builds upon two scientific publications. My third journal paper, written jointly by the main author Olga Chiapinelly and myself as the second author (Chiappinelli et al., 2021), was published by Climate Policy JCR: 5.085 Q1 (2020).[207] Additionally, my fourth interdisciplinary paper was published in the Review of European, Comparative & International Environmental Law JCR: 2.541 Q1 (2020) with myself as the first author, but written jointly with Alice Pirlot and support of Manuel Haussner and Karsten Neuhoff. My contributions in this thesis chapter go beyond identifying policy needs to kick-start the transition of the basic material sector, as presented in (Chiappinelli et al., 2021). By showing how various policy instruments and design options address specific and horizontal policy needs differently and mapping their relevance during the transition phases, I further contribute to the scientific understanding of why industrial policies need to be aligned to meet their objectives effectively.

Chapter 6 introduces the conceptual TRANSid model and a corresponding mathematical model formulation. By highlighting a modelling gap that needs to be addressed to study de multidimensional nature of the transition, I show that approaches used until now provide insufficient answers. The main contributions of this chapter is the conceptual model demonstrating how this modelling gap can be addressed and the mathematical model that incorporates this multidimensionality. The novel modelling approach presented in this chapter can form the groundwork for future scientific work studying industrial transformation implications.

[206] The framework and method is the basis for work by other research groups, such as Rehfeldt et al. (2020).
[207] 12 additional co-authors supported us in designing the research methodology, conducting interviews, and analysing research findings.

7.2. Concluding the main research objective

The main research objective, as stated in section 1.2.1, is the following:

Identify the implications of decarbonising the energy-intensive basic material sector and frame its role in future energy systems under consideration of technical, economic, and regulatory aspects.

Rather than reflecting on the main research objective, Chapter 3 to 6 each addresses one of the thesis sub-objectives, as stated in section 1.2.2. In the following, I reflect on each sub-objective, highlighting their contributions to the main objective.

Sub-objective I

Evaluate the principal emission abatement options for the basic material sector, their cross-sector applicability and decarbonisation potential for the European industrial sector.

To ***identify the implications of decarbonising the energy-intensive basic material sector***, one must first analyse the technical dimension of decarbonising the different industrial processes. Chapter 3 introduces a framework for categorizing different decarbonisation options across various energy-intensive sectors, quantifies their abatement potential and provides technology cost ranges. Based on these findings, I present five different propositions about the technical dimension of the transition in section 3.5:

III.I: Conventional processes should be incentivised for industries that can reach deep decarbonisation by gradual optimisation. In contrast, optimisation of current process designs shall not define the transition in the emission-intensive basic materials sector.

III.II: Specific technologies with high emission reduction potential offer alternative pathways to reduce emissions, but deep decarbonisation may imply the joint implementation of various specific technology solutions simultaneously.

III.III A transition of the basic materials sector until 2050 can only be achieved if current industrial renewal rates are accelerated compared to current and past investment cycles within the industry.

III.IV: Underlying assumptions for future industrial transition scenarios need to correctly reflect the cost and emission reduction potential of market-ready and near market-ready technologies while balancing the uncertainties and prospects of future technology options.

III.V: The transition of a particular basic material industry and its emission reductions are subject to the cross-sectoral interdependencies with other basic material sectors, the entire value-chain of basic material use and the energy system.

Sub-objective II

Analyse the interplay of the energy system evolution and industrial transformation, emphasising the role of the electricity markets and a potential hydrogen economy.

Changes to how industry consumes energy would have a significant impact beyond the industrial sector but ***framing its role in future energy systems*** requires an understanding of the economics of low-emission energy carriers. Chapter 4 does not focus on industrial energy demand but addresses thesis sub-objective II by first analysing future electricity markets. I then show that energy markets for other low-emission energy carriers need to comply with emission avoidance, adequacy, and affordability criteria. The five propositions about future energy markets that I state in section 4.4 reflect on how future energy markets are key for future industrial energy demand:

IV.I: The policy design should acknowledge the clear interdependency among the three objectives: affordability, adequacy, and emission avoidance.

IV.II: Alternative policies aiming to achieve the same objective may have a different impact on other objectives.

IV.III: Policy designs that are not fully aligned with the system objectives may lead to undesirable outcomes.

IV.IV: Policy design should be as technology-neutral as possible to reach any of the system objectives.

IV.V: When pricing different services (energy, adequacy, emissions), policy designs impact consumption and thereby the need for additional services.

Sub-objective III

Contrast long-term policy options that can foster desirable transitions of the industrial park to reach decarbonisation targets without jeopardising the economic viability of all stakeholders.

Both Chapter 3 and Chapter 4 present industrial decarbonisation as a techno-economic challenge routed in the difficulty of meeting basic material demand with climate-friendly technologies that are competitive to today´s emission-intensive conventional processes. Chapter 5 aims at presenting solutions for this challenge. ***Under consideration of technical, economic, and regulatory aspects,*** I analyse different policy options to kick-start the transition, create competitive markets and ensure the long-term climate-neutrality of basic material consumption. Reflecting on the main objective of this thesis, the contributions to thesis sub-objective III address more the importance of novel policy instruments for industrial decarbonisation rather than the implications of industrial decarbonisation. However, the four propositions summarised in section 5.5 show that industrial decarbonisation would only occur if supported and guided by a new approach towards industrial policy:

V.I: For kick-starting the transition, a horizontal policy framework needs to detail how governments can design sector- and project-specific policies that strengthen the business case for first industrial-scale installation, serving the domestic basic materials market.

V.II: Ensuring compliance with sector-specific intermediate emission reduction targets implies a level playing field for domestic producers and importers. Policies shall foster climate-friendly basic material consumption without favouring domestic producers nor distorting competition with imports.

V.III: Product carbon requirements for all basic materials, resulting in a de facto ban of carbon-intensive basic material production, is the only policy in a global decarbonised basic materials market. Horizontal emission-pricing policies shall only define the cost for offsetting non-abatable emissions with available carbon sink options.

V.IV: The effectiveness of horizontal and specific industrial policies for climate-friendly basic material market needs to be evaluated based on their impact on the cross-sectoral interdependencies of emissions, energy and material use in basic material industries and other emission-intensive sectors.

Based on the findings from Chapter 5, the decarbonisation of the energy-intensive basic material sector will only have an implication for energy systems if policy needs are thoroughly addressed across all phases of the transition. Without additional policies, the decarbonisation of these sectors will not happen.

Sub-objective IV

Explore how the energy demand and characteristics of the basic material sector can evolve by introducing new process innovations under various premises concerning available technologies, market scenarios and policies.

Chapter 6 bridges the analysis presented across Chapter 3 to Chapter 4 by using the propositions made at the end of each chapter to argue that we need a novel approach to study ***the implications of industrial decarbonisation***. As such, thesis sub-objective IV translates the main objective into a clear task. One needs to study the transition of the energy-intensive basic material sector under consideration of available technologies, market scenarios and policies to ***frame its role in future energy systems***. Chapter 6 showcases a possible approach towards studying the transition by introducing the conceptual framework of the TRANSid model. The model addresses the following modelling gaps that derived from the 14 propositions of this thesis (section 6.2.3):

1. **Study industry and sector transition**
2. **Explore technology pathways**
3. **Differentiate between greenfield installations vs brownfield extension**
4. **Avoid the carbon lock-in**
5. **Account for the temporal dimension of transition policies**

However, my analysis of the proposed mathematical formulation for such a model and the presented case study highlights additional steps to address the identified modelling gap. I, therefore, conclude in section 6.7 that the proposed TRANSid model might be a feasible approach to address thesis sub-objective IV. The TRANSid model might also be a valuable tool to continue my work addressing the main research objective and supporting the analysis presented in this thesis with quantitative model results.

7.3. Future Work

Research is never conclusive and always raises new questions. In the case of my work presented over the seven chapters of this thesis, none of the chapters is conclusive, raises further research questions and highlights how little industrial decarbonisation and its implications are understood yet. In the following, I summarise the main challenges to be addressed by future work based on the three dimensions of technology options, energy markets and policy options. I then reflect on implications for modelling the transition of the basic material sector.

Technology options

The framework for categorizing abatement options and reviewing low-emission alternatives for the energy-intensive basic material sector includes primary production routes and acknowledges the importance of recycling streams and secondary production routes. Nevertheless, departing from a framework based on the input-output structure of industrial processes falls short of capturing the entire product life cycle of basic materials, their use cases, potential alternatives, and recovery options. As such, it does not fully value the potential of circularity and alternatives that can potentially meet the demand for steel, cement or plastics "services" with other means. Reducing the potential of recycling options to the limited availability of virgin waste streams does not capture how much and at what cost emission abatement is possible by rethinking how we use basic materials. Future work shall therefore address the following research objective:

Contrast the techno-economic potential and limitations of alternatives to the decarbonisation of primary production processes to meet the demand for services offered by basic materials.

Energy markets

The technology review demonstrates that three main routes towards industrial decarbonisation include direct electrification, hydrogen use or carbon capture technologies. My analysis in Chapter 4 highlights how these three options are interlinked with each other. Green hydrogen is produced from electricity, therefore relying on the same energy source as electrification options. Blue hydrogen implies carbon capture. As such, using blue hydrogen in industry implies that the processes equally rely on carbon capture as if carbon capture technologies were directly installed in industrial furnaces, kilns, or other point sources for carbon dioxide-equivalent emissions. Therefore, the economics of these main industrial decarbonisation options depend on the interplay of electricity markets with green hydrogen and carbon capture options on the energy market. Research objectives for future work should address this interplay:

Evaluate the economics of hydrogen markets under consideration of different technology options to decarbonise energy consumption, such as direct electrification and carbon capture.

Policies

The policy package analysed in Chapter 5 includes many policy instruments that have not been implemented today. My analysis of these different options highlights that various design elements of these policies need to be understood better. The different impact policies might have on each other and the role of specific policy design choices within a protentional industrial policy package remains little understood. However, my research points to the need for an adequate modelling framework to study the design elements of the policy package.

Therefore, future research concerning policies itself shall primarily focus on another aspect that has received little attention in my thesis. Industrial decarbonisation comes at a price that certainly increases the cost of basic materials, material use, and alternatives. Little work has been done to evaluate the social aspect of these policies. I have referred to a publication by Stede et al. (2021) in section 5.3 that quantifies the effect of emission allowance prices for various consumer groups. However, emission pricing is only one of the policy instruments discussed in this thesis. Future research can therefore have the design of socially just financing mechanisms as the main objective:

Identify how industrial policies can ensure that the cost burden for transforming the basic material sector can be allocated in a just way, acknowledging, among others, social, demographic, and regional factors.

Industrial transition models

This thesis identifies a need for understanding industrial decarbonisation better and proposes the TRANSid model framework to address this need. The attempt to address this need with the mathematical formulation presented in section 6.4 remains inconclusive. As such, I have identified multiple to-Does for improving and rethinking how the modelling gap can be addressed in section 6.6. Future research shall address these needs and the main objective of this thesis by providing quantitative results that can support the design and revaluation of industrial policies on the road towards climate-friendly basic material markets. The objective for such research can be formulated as follows:

Validate and verify how the conceptual TRANSid model can be implemented to evaluate industrial policies and their interdependencies across the energy-intensive basic material sector.

7.4. Main publications and working papers

Journal publications:

Gerres, T., Chaves, J.P., Linares, P., Gómez, T., 2019. A review of cross-sector decarbonisation potentials in the European energy-intensive industry. Journal of Cleaner Production. 210, 585–601. 10.1016/j.jclepro.2018.11.036

Gerres, T., Chaves, J.P., Martín, F., Rivier, M., Cossent, R., Sánchez, Á., Gómez, T., 2019. Rethinking the electricity market design: Remuneration mechanisms to reach high RES shares. Results from a Spanish case study. Energy Policy. 129, 1320-1330. 10.1016/j.enpol.2019.03.034

Chiappinelli, O., Gerres, T., Neuhoff, K., Lettow, F., de Coninck, H., Felsmann, B., Joltreau, E., Khandekar, G., Linares, P., Richstein, J.C., Sniegocki, A., Stede, J., Wyns, T., Zandt, C., 2021. A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions. Climate Policy. 10.1080/14693062.2021.1922340.

Gerres, T., Haussner, M., Neuhoff, K., Pirlot, A., 2021. To Ban or Not to Ban Carbon-intensive Materials: A Legal and Administrative Assessment of Product Carbon Requirements. Review of European, Comparative & International Environmental Law. 10.1111/reel.12395

Conference paper:

T. Gerres, Chaves, J.P., Martín, F., Rivier, M, Gómez, T.,2019. The Role of Nuclear Power Plants in Electricity Systems with High RES Share. *2019 IEEE Milan PowerTech*, Milan, Italy. 10.1109/PTC.2019.8810545

Working paper:

Cosbey, A., Das, K., Fischer, C., Gerres, T., Ismer, R., Linares, P., Mehling, M., Neuhoff, K., Pirlot, P., Sato, M., Sniegocki, A., 2020. Designing Border Carbon Adjustments and Alternative Measures: An Overview.

Reports and other publications:

Rivier, M., Gómez, T., Chaves, J.P., Cossent, R., Sánchez, Á., Martin, F., Gerres, T., 2018. Análisis de escenarios futuros para el sector eléctrico en España para el período 2025-2050. IIT, UP Comillas.

Gómez, T., Rivier, M., Chaves, J.P., Martín, F., Gerres T., 2018. Señales de precio a la inversión en un mercado eléctrico con elevada penetración de renovables. Papeles de Energía.

Gerres, T., Chaves, J.P., Linares, P., 2019. The transformation of the Spanish basic materials sector towards a low carbon economy. Papeles de Energía.

Gerres, T., Linares, P., Chaves, J.P., Gómez, T., 2019. Tecnologías para la descarbonización de la industria del uso intensivo de energía. IIT, UP Comillas.

Chiappinelli, O., Bartek-Lesi, M., Błocka, M., Chaves Ávila, J.P., Felsmann, B., Gerres, T., Linares, P., Neuhoff, K., Śniegocki, A., Szajkó, G., Wetmańska, Z., 2019. Inclusive Transformation of the European Materials Sector. EUKI.

Neuhoff, K., Chiappinelli, O., Gerres, T., Haussner, M., Ismer, R., May, N., Pirlot, A., Richstein, J., 2019. Building blocks for a climate-neutral European industrial sector. Climate Strategies.

Gerres, T., Linares, P., 2020. Carbon Contracts for Differences: their role in European industrial decarbonisation. Climate Strategies.

Neuhoff, K., Chiappinelli, O., Richstein, J.C., de Coninck, H., Linares, P., Gerres, T., Khandekar, G., Wyns, T., Zetterberg, L., Felsmann, B., Sniegocki, A., 2021. Closing the Green Deal for Industry. Climate Strategies.

References

Abad, A.V., Dodds, P.E., 2017. Production of Hydrogen, in: Abraham, M.A. (Ed.), Encyclopedia of Sustainable Technologies. Elsevier, Oxford, pp. 293–304. https://doi.org/10.1016/B978-0-12-409548-9.10117-4

ACER, 2020. ACER Market Monitoring Report 2019 – Electricity Wholesale Markets Volume. European Union Agency for the Cooperation of Energy Regulators and the Council of European Energy Regulator.

ACER/CEER, 2019. Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2018. ACER/CEER, Brussel, Ljublijana.

Achternbosch, M., Dewald, U., Nieke, E., Sardemann, G., 2016. New calcium hydrosilicate-based cements: Celitement-a Technology Assessment. ZKG INTERNATIONAL 69, 48–57.

ADIB, P., SCHUBERT, E., OREN, S., 2008. Chapter 9 - Resource Adequacy: Alternate Perspectives and Divergent Paths, in: Sioshansi, F.P. (Ed.), Competitive Electricity Markets, Elsevier Global Energy Policy and Economics Series. Elsevier, Oxford, pp. 327–362. https://doi.org/10.1016/B978-008047172-3.50013-1

Adomeit, H., 2016. Germany, the EU, and Russia: The Conflict over Nord Stream 2. Centre for European Studies, CES Policy Brief (April 2016).

Afkhami, B., Akbarian, B., Beheshti A., N., Kakaee, A.H., Shabani, B., 2015. Energy consumption assessment in a cement production plant. Sustainable Energy Technologies and Assessments 10, 84–89. https://doi.org/10.1016/j.seta.2015.03.003

Agar, D.A., Svanberg, M., Lindh, I., Athanassiadis, D., 2020. Surplus forest biomass – The cost of utilisation through optimised logistics and fuel upgrading in northern Sweden. Journal of Cleaner Production 275, 123151. https://doi.org/10.1016/j.jclepro.2020.123151

Agora Energiewende, Wuppertal Institut, 2019. Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement.

Agora Energiewende, Wuppertal Institute, 2021. Breakthrough Strategies for Climate-Neutral Industry in Europe.

Agrawala, S., Dellink, R., Chateau, J., Bibas, R., Lanzi, E., Benkovic, M., 2019. Global Material Resources Outlook to 2060. OECD Publishing, Paris.

Agriculture & Food Insights and Sector Profile 2018 - MaltaProfile.info [WWW Document], 2018. URL https://maltaprofile.info/article/agriculture-and-food-sector-profile-2018 (accessed 3.31.20).

Åhman, M., Nilsson, L.J., 2015. Decarbonizing Industry in the EU: Climate, Trade and Industrial Policy Strategies, in: Dupont, C., Oberthür, S. (Eds.), Decarbonization in the European Union: Internal Policies and External Strategies. Palgrave Macmillan UK, London, pp. 92–114.

Alcoa, 2021. ELYSIS [WWW Document]. URL https://www.alcoa.com/sustainability/en/elysis (accessed 5.6.21).

Allevi, E., Oggioni, G., Riccardi, R., Rocco, M., 2017. Evaluating the carbon leakage effect on cement sector under different climate policies. Journal of Cleaner Production 163, 320–337. https://doi.org/10.1016/j.jclepro.2015.12.072

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2013. Material efficiency: providing material services with less material production. Phil. Trans. R. Soc. A. 371, 20120496. https://doi.org/10.1098/rsta.2012.0496

Amato, I., 2013. Green cement: concrete solutions. Nature news 494.

Ambec, S., Cohen, M.A., Elgie, S., Lanoie, P., 2013. The Porter hypothesis at 20: can environmental regulation enhance innovation and competitiveness? Review of environmental economics and policy 7, 2–22.

Andreola, F., Barbieri, L., Lancellotti, I., Leonelli, C., Manfredini, T., 2016. Recycling of industrial wastes in ceramic manufacturing: State of art and glass case studies. Ceramics International 42, 13333–13338. https://doi.org/10.1016/j.ceramint.2016.05.205

ANFAC, 2019. Informe Anual 2018. Asociación Española de Fabricantes de Automóviles y Camione, Madrid.

AOP, 2019. El refino en España y Portugal. Cuadernos de Energía de ENERCLUB 18, 93–100.

AQPER, 2021. How long does it take to build a hydroelectric power station? [WWW Document]. URL https://www.aqper.com/en/how-long-does-it-take-to-build-a-hydroelectric-power-station (accessed 7.8.21).
Arbeitsagentur, 2021. Statistik der Bundesagentur für Arbeit [WWW Document]. URL https://statistik.arbeitsagentur.de/Auswahl/raeumlicher-Geltungsbereich/Politische-Gebietsstruktur/Kreise/Brandenburg/12066-Oberspreewald-Lausitz.html (accessed 7.5.21).
Arnold, M., 2021. Construction sector warns rising costs will eat into EU recovery plan. Financial Times.
Arns, D., 2018. Chemical raw materials in Europe –Trends & Challenges.
ARUP, 2018. Cost of Capital Benefits of Revenue Stabilisation via a Contract for Difference. ARUP, ScottishPower Renewables.
Asayama, S., Ishii, A., 2017. Selling stories of techno-optimism? The role of narratives on discursive construction of carbon capture and storage in the Japanese media. Energy Research & Social Science 31, 50–59. https://doi.org/10.1016/j.erss.2017.06.010
ASCER, 2021. Encuentra tu cerámica [WWW Document]. URL https://www.tileofspain.com/dir/default.aspx (accessed 5.17.21).
ASPAPEL, 2021. El sector: Centros de producción: [WWW Document]. URL http://www.aspapel.es/el-sector/centros-produccion (accessed 5.11.21).
Atuonwu, J., Tassou, S., 2021. Decarbonisation of food manufacturing by the electrification of heat: A review of developments, technology options and future directions. Trends in Food Science & Technology 107, 168–182. https://doi.org/10.1016/j.tifs.2020.10.011
Baines, S., Wrubell, S., Kennedy, J., Bohn, C., Richards, C., 2019. #HowToPPA: An Examination of the Regulatory and Commercial Challenges and Opportunities Arising in the Context of Private Power Purchase Agreements for Renewable Energy. ALR 389. https://doi.org/10.29173/alr2580
Baldino, C., Pavlenko, N., Searle, S., Christensen, A., 2018. The potential for low-carbon renewable methane as a transport fuel in France, Italy, and Spain. ICCT Working Paper 2018–28.
Baruya, P., 2007. Supply costs for internationally traded coal. IEA. https://doi.org/10.13140/RG.2.2.25536.43521
Batlle, C., Pérez-Arriaga, I.J., Zambrano-Barragán, P., 2012. Regulatory design for RES-E support mechanisms: Learning curves, market structure, and burden-sharing. Energy Policy 41, 212–220. https://doi.org/10.1016/j.enpol.2011.10.039
Batlle, C., Rodilla, P., 2010. A critical assessment of the different approaches aimed to secure electricity generation supply. ENERGY POLICY 38, 7169–7179. https://doi.org/10.1016/j.enpol.2010.07.039
Batool, M., Wetzels, W., 2019. Decarbonisation options for the Dutch fertiliser industry. PBL Netherlands Environmental Assessment Agency.
Beck, F.J., Jotzo, F., Longden, T., 2019. For hydrogen to be truly “clean” it must be made with renewables, not coal [WWW Document]. The Conversation. URL http://theconversation.com/for-hydrogen-to-be-truly-clean-it-must-be-made-with-renewables-not-coal-128053 (accessed 8.4.21).
Bekkers, E., Schroeter, S., 2020. An economic analysis of the US-China trade conflict (WTO Working Papers No. ERSD-2020-04). World Trade Organization (WTO).
Benchaita, T., 2013. Greenhouse Gas Emissions from New Petrochemical Plants (No. IDB-TN-562). Inter-American Development Bank (IDB).
Benna Fresh Milk Products [WWW Document], 2019. URL http://www.benna.com.mt/ (accessed 3.31.20).
Berenschot, 2017. Electrification in the Dutch process industry. Berenschot, Utrecht.
Bhaskar, A., Assadi, M., Somehsaraei, H.N., 2021. Can methane pyrolysis based hydrogen production lead to the decarbonisation of iron and steel industry? Energy Conversion and Management: X 10, 100079. https://doi.org/10.1016/j.ecmx.2021.100079
Blazquez, J., Fuentes-Bracamontes, R., Bollino, C.A., Nezamuddin, N., 2018. The renewable energy policy Paradox. Renewable and Sustainable Energy Reviews 82, 1–5. https://doi.org/10.1016/j.rser.2017.09.002
Bloomberg Finance, 2017. Bloomberg: Energy Outlook 2017. Bloomberg.

BMWi, 2020. Die Nationale Wasserstoffstrategie. Bundesministerium für Wirtschaft und Energie, Berlin.

Böhringer, C., Behrens, M., 2015. Interactions of emission caps and renewable electricity support schemes. J Regul Econ 48, 74–96. https://doi.org/10.1007/s11149-015-9279-x

Boiral, O., Allur, E., 2018. Three Decades of Dissemination of ISO 9001 and Two of ISO 14001: Looking Back and Ahead, in: Heras-Saizarbitoria, I. (Ed.), ISO 9001, ISO 14001, and New Management Standards, Measuring Operations Performance. Springer International Publishing, Cham, pp. 1–15. https://doi.org/10.1007/978-3-319-65675-5_1

Bonhomme, D., Burignat, D., Miquel, P., Engoian, A., Aubry, C., 2013. Competition: pipeline gas vs LNG in Europe. GDF Suez.

Boonekamp, P.G.M., 2013. A new policy tool for the Netherlands 44.

Boulamanti, A., Moya, J.A., 2017a. Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry. Publications Office of the European Union.

Boulamanti, A., Moya, J.A., 2017b. Production costs of the chemical industry in the EU and other countries: Ammonia, methanol and light olefins. Renewable and Sustainable Energy Reviews 68, 1205–1212. https://doi.org/10.1016/j.rser.2016.02.021

Brändle, G., Schönfisch, M., Schulte, S., 2020. Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen 72.

Brolin, M., Fahnestock, J., Rootzen, J., 2017. Industry's Electrification and Role in the Future Electricity System: A Strategic Innovation Agenda. SP Technical Research Institute of Sweden, Chalmers University of Technology.

Brown, D.P., 2018. Capacity payment mechanisms and investment incentives in restructured electricity markets. Energy Economics 74, 131–142. https://doi.org/10.1016/j.eneco.2018.05.033

Brown, T., Hörsch, J., Schlachtberger, D., 2018. PyPSA: Python for Power System Analysis. Journal of Open Research Software 6. https://doi.org/10.5334/jors.188

Brzeziński, K., Śniegocki, A., 2020. Climate Contribution and its role in European industrial decarbonisation. Climate Strategies.

Burns, P., Hope, D., Roorda, J., 1999. Managing infrastructure for the next generation. Automation in Construction 8, 689–703. https://doi.org/10.1016/S0926-5805(98)00115-0

Burton, M., Biesheuvel, T., 2020. Green Aluminum Maker Sees Opportunity in Green Hydrogen. Bloomberg.com.

Buttler, A., Spliethoff, H., 2018. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Renewable and Sustainable Energy Reviews 82, 2440–2454. https://doi.org/10.1016/j.rser.2017.09.003

Büttner, S.M., Schneider, C., Piccolroaz, C., Sauer, A., König, W., 2020. How does the German manufacturing industry react to the calls to decarbonise?, in: Industrial Efficiency 2020: Decarbonise Industry!, Panel 6. Deep Decarbonisation of Industry. Presented at the Industrial Efficiency 2020: Decarbonise industry!, eceee, online.

Byers, C., Levin, T., Botterud, A., 2018. Capacity market design and renewable energy: Performance incentives, qualifying capacity, and demand curves. The Electricity Journal 31, 65–74. https://doi.org/10.1016/j.tej.2018.01.006

Byrnes, L., Brown, C., Foster, J., Wagner, L.D., 2013. Australian renewable energy policy: Barriers and challenges. Renewable Energy 60, 711–721. https://doi.org/10.1016/j.renene.2013.06.024

Caldecott, B., McDaniels, J., 2014. Stranded generation assets: Implications for European capacity mechanisms, energy markets and climate policy.

Calel, R., Dechezleprêtre, A., 2016. Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. Review of Economics and Statistics 98, 173–191. https://doi.org/10.1162/REST_a_00470

Camia, A., Robert, N., Jonsson, R., Pilli, R., García-Condado, S., López-Lozano, R., Van der Velde, M., Ronzon, T., Gurría, P., M'barek, R., 2018. Biomass production, supply, uses

and flows in the European Union. First results from an integrated assessment. JRC, European Commission.
Capros, P., Höglund-Isaksson, L., Frank, S., Witzke, H., 2017. EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050. European Commission, E3M - Lab.
Carbon4PUR, 2017. Carbon4PUR [WWW Document]. Carbon4PUR. URL https://www.carbon4pur.eu/ (accessed 9.30.20).
Carruth, M.A., Allwood, J.M., Moynihan, M.C., 2011. The technical potential for reducing metal requirements through lightweight product design. Resources, Conservation and Recycling 57, 48–60.
CEFIC, 2020a. 2020 - fact & figures of the European chemical industry. European Chemical Industry Council, Brussels.
CEFIC, 2020b. Chemical industry overview in EU countries [WWW Document]. URL https://www.chemlandscape.cefic.org/country/spain/ (accessed 5.17.21).
CEFIC, 2019. A journey into the Future of Europe with the European Chemical Industry. European Chemical Industry Council - Cefic aisbl, Brussels.
CEFIC, 2013. European chemistry for growth - Unlocking a competitive, low carbon and energy efficient future. European Chemical Industry Council.
CEMBUREAU, 2013. The role of Cement in the 2050 Low Carbon Economy. The European Cement Association.
CEPI, 2020. Key Statistics 2019: European pulp and paper industry. Brussels.
Cerame-Unie, 2012. Paving the way to 2050 - the Ceramic Industry Roadmap. The European Ceramic Industry Association.
CESCE, 2019. Textil: Informe Anual de la Economía Española. Madrid.
Chan, Y., Kantamaneni, R., 2015. Study on energy Efficiency and Energy Saving Potential in Industry and on Possible Policy Mechanisms. ICF Consulting Limited.
Chattopadhyay, D., Alpcan, T., 2016. Capacity and Energy-Only Markets Under High Renewable Penetration. IEEE Trans. Power Syst. 31, 1692–1702. https://doi.org/10.1109/TPWRS.2015.2461675
ChemicalPark.eu, 2020. Chemmed Cluster Tarragona - Chemical park - Spain [WWW Document]. URL https://chemicalparks.eu/parks/chemmed-cluster-tarragona (accessed 3.17.20).
Chevrier, V., 2020. Transitioning to the Hydrogen Economy. Direct from Midrex 1st Quarter 2020.
Chiappinelli, O., Bartek-Lesi, M., Błocka, M., Chaves Ávila, J.P., Felsmann, B., Gerres, T., Linares, P., Neuhoff, K., Śniegocki, A., Szajkó, G., Wetmańska, Z., 2019a. Inclusive Transformation of the European Materials Sector. EUKI.
Chiappinelli, O., Gerres, T., Neuhoff, K., Lettow, F., de Coninck, H., Felsmann, B., Joltreau, E., Khandekar, G., Linares, P., Richstein, J., Śniegocki, A., Stede, J., Wyns, T., Zandt, C., Zetterberg, L., 2021. A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions. Climate Policy 1–19. https://doi.org/10.1080/14693062.2021.1922340
Chiappinelli, O., Gerres, T., Neuhoff, K., Lettow, F., de Coninck, H., Felsmann, B., Joltreau, E., Linares, P., Richstein, J., Śniegocki, A., Wyns, T., Zandt, C., Zetterberg, L., 2020. A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions.
Chiappinelli, O., Gruner, F., Weber, G., 2019b. Green Public Procurement: Climate provisions in public tenders can help reduce German carbon emissions. DIW Weekly Report 9, 433–441.
Chiarini, A., 2012. Designing an environmental sustainable supply chain through ISO 14001 standard. Management of Environmental Quality: An International Journal 24, 16–33. https://doi.org/10.1108/14777831311291113
Cludius, J., de Bruyn, S., Schumacher, K., Vergeer, R., 2020. Ex-post investigation of cost pass-through in the EU ETS - an analysis for six industry sectors. Energy Economics 91, 104883. https://doi.org/10.1016/j.eneco.2020.104883

Colli, A., Mariotti, S., Piscitello, L., 2014. Governments as strategists in designing global players: the case of European utilities. Journal of European Public Policy 21, 487–508. https://doi.org/10.1080/13501763.2013.861764
Collodi, G., Azzaro, G., Ferrari, N., Santos, S., 2017. Techno-economic Evaluation of Deploying CCS in SMR Based Merchant H2 Production with NG as Feedstock and Fuel. Energy Procedia 114, 2690–2712. https://doi.org/10.1016/j.egypro.2017.03.1533
Consoli, C., 2019. Bioenergy and Carbon Capture and Storage. Global CCS Institute.
Cosbey, A., 2008. Border carbon adjustment, in: IISD Background Paper for the Trade and Climate Change Seminar, June. pp. 18–20.
Cosbey, A., Das, K., Fischer, C., Gerres, T., Ismer, R., Linares, P., Mehling, M., Neuhoff, K., Pirlot, P., Sato, M., Sniegocki, A., 2020. Designing Border Carbon Adjustments and Alternative Measures: An Overview.
Croezen, H., Korteland, M., 2010. A long-term view of CO2 efficient manufacturing in the European region. CE Delft.
Daniëls, B.W., Van Dril, A.W.N., 2007. Save production: A bottom-up energy model for Dutch industry and agriculture. Energy Economics 29, 847–867. https://doi.org/10.1016/j.eneco.2007.02.001
de Santoli, L., Paiolo, R., Lo Basso, G., 2017. An overview on safety issues related to hydrogen and methane blend applications in domestic and industrial use. Energy Procedia 126, 297–304. https://doi.org/10.1016/j.egypro.2017.08.224
de Vries, L., Heijnen, P., 2008. The impact of electricity market design upon investment under uncertainty: The effectiveness of capacity mechanisms. Utilities Policy 16, 215–227. https://doi.org/10.1016/j.jup.2007.12.002
DECHEMA, 2017. Low carbon energy and feedstock for the European chemical industry. Frankfurt a.M.
DEEDS, 2020. Industry - Iron and Steel. Dialogue on European Decarbonisation Strategies.
Deerberg, G., Oles, M., Schlögl, R., 2018. The Project Carbon2Chem®. Chemie Ingenieur Technik 90, 1365–1368. https://doi.org/10.1002/cite.201800060
del Río González, P., 2007. The interaction between emissions trading and renewable electricity support schemes. An overview of the literature. Mitig Adapt Strat Glob Change 12, 1363–1390. https://doi.org/10.1007/s11027-006-9069-y
del Río, P., Klessmann, C., Thomas Wink, Malte Gephart, 2013. Interactions between EU GHG and Renewable Energy Policies–how can they be coordinated (No. D6.1b). IEE project: beyond2020, Design and impact of a harmonised policy for renewable electricity in Europe.
Demirbas, A., 2005. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Progress in Energy and Combustion Science 31, 171–192. https://doi.org/10.1016/j.pecs.2005.02.002
Desertec Foundation, 2009. Desertec Red Paper: An Overview of the Dsertec Concept.
Dickel, R., 2020. Blue hydrogen as an enabler of green hydrogen: the case of Germany. Oxford Institute for Energy Studies Paper 159. https://doi.org/10.26889/9781784671594
Djørup, S., Thellufsen, J.Z., Sorknæs, P., 2018. The electricity market in a renewable energy system. Energy 162, 148–157. https://doi.org/10.1016/j.energy.2018.07.100
Dorn, C., Behrend, R., Uhlig, V., Trimis, D., Krause, H., 2017. A technology comparison concerning scale dependencies of industrial furnaces. A case study of glass production. Energy Procedia 120, 388–394. https://doi.org/10.1016/j.egypro.2017.07.230
Duclos, J., Guerrini, O., Marchand, B., Buchet, P., Perrin, M., 2014. Towards green gases solutions for industry, in: International Gas Union Research Conference (IGRC), Copenhagen, Denmark.
Dukan, M., Kitzing, L., Brückmann, R., Jimeno, M., Wigand, F., Kielichowska, I., Klessmann, C., Breitschopf, B., 2019. Effects of auctions on financing conditions for renewable energy: A mapping of auction designs and their effects on financing (No. Report D5.1). AURES II (AUctions for Renewable Energy Support II).
E3MLab, 2016. PRIMES model, Version 6, 2016-2017, Detailed model description. National Technical University of Athens.

EA, 2020. Circular Aluminium Action Plan: a strategy for achieving alumium's full potential for circular economy by 2030. Euopean Aluminium.
EC, 2021a. Towards competitive and clean European steel (Commission Staff Working Document No. SWD(2021) 353 final). European Commission, Brussel.
EC, 2021b. "Fit for 55": delivering the EU's 2030 Climate Target on the way to climate neutrality (No. COM(2021) 550 final). European Commission.
EC, 2020a. Stepping up Europe's 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people (No. COM(2020) 562 final).
EC, 2020b. Weekly Oil Bulletin: Duties and Taxes. European Commission.
EC, 2020c. A hydrogen strategy for a climate-neutral Europe (No. COM(2020) 301 final). European Commission.
EC, 2020d. Commission decision on the financing in the field of Energy for 2020 of the extension of the Preparatory Action Establishing comprehensive support for coal and carbon intensive regions in transition (No. C(2020) 5455 final). European Commission.
EC, 2019a. The European Green Deal. COM (2019) 640 final.
EC, 2019b. Clean Energy for all Europeans. Publications Office of the European Union, Luxembourg.
EC, 2019c. Brief on biomass for energy in the European Union. European Commission's Knowledge Centre for Bioeconomy.
EC, 2019d. Case M.8713 - TATA STEEL / THYSSENKRUPP / JV (No. C(2019) 4228 final). European Commission.
EC, 2019e. Public Procurement Indicators 2017. European Commission Directorate-General for Growth.
EC, 2018a. In-Depth analysis in support of the commission communication COM(2018) 773. European Commission.
EC, 2018b. In-Depth analysis in support of the commission communication COM(2018) 773 (No. COM(2018) 773 final). European Commission, Brussels.
EC, 2018c. A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM(2018) 773 final.
EC, 2018d. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A European Strategy for Plastics in a Circular Economy. COM/2018/028.
EC, 2018e. Competitiveness of the European cement and lime sectors: final report. European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs.
EC, 2017a. Cumulative cost assessment (CCA) of the EU ceramics industry: final report. Publications Office, LU.
EC, 2017b. Cumulative cost assessment (CCA) of the EU glass industry: final report. Publications Office, LU.
EC, 2016a. Revision for phase 4 (2021-2030) [WWW Document]. Climate Action - European Commission. URL https://ec.europa.eu/clima/policies/ets/revision_en (accessed 7.7.21).
EC, 2016b. The "Blue Guide" on the implementation of EU product rules 2016. Official Journal of the European Union 59.
EC, 2016c. Buying green! A handbook on green public procurement, 3rd ed. Publications Office of the European Union, Luxembourg.
EC, 2011. A Roadmap for moving to a competitive low carbon economy in 2050. COM(2011) 112 final.
Ecofys, 2009. Methodology for the free allocation of emission allowances in the EU ETS post 2012: Sector report for the ceramics industry (No. 07.0307/2008/515770/ETU/C2). Ecofys, Fraunhofer Institute for Systems and Innovation Research, Öko-Institut.
Edh Hasselgård, P., 2017. The Use of Tender Procedures to Exclude State Aid: The Situation under the EU 2014 Public Procurement Directives. European Procurement & Public Private Partnership Law Review 12, 16–28. https://doi.org/10.21552/epppl/2017/1/5
EEA, 2021a. Progress on energy efficiency in Europe [WWW Document]. European Environment Agency. URL https://www.eea.europa.eu/data-and-

maps/indicators/progress-on-energy-efficiency-in-europe-3/assessment (accessed 4.28.21).
EEA, 2021b. Waste recycling — European Environment Agency [WWW Document]. URL https://www.eea.europa.eu/data-and-maps/indicators/waste-recycling-1/assessment-1 (accessed 5.14.21).
EEA, 2019. Greenhouse gas emissions by aggregated sector [WWW Document]. URL https://www.eea.europa.eu/data-and-maps/daviz/ghg-emissions-by-aggregated-sector-5#tab-dashboard-02 (accessed 4.21.21).
EEA, 2018. Total EU greenhouse gas emissions, 1990-2016 [WWW Document]. European Environment Agency. URL https://www.eea.europa.eu/data-and-maps/daviz/total-ghg-emissions-1#tab-chart_1 (accessed 7.7.21).
EFET, 2019. Individual Power Purchase Agreement for Corporates and Utilities.
EIA, 2021a. Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021. US Energy Information Administration.
EIA, 2021b. Annual Energy Outlook 2021. U.S. Energy Information Administration.
EIA, D., 2018. Model Documentation Report: Industrial Demand Module of the National Energy Modeling System. US DOE Energy Information Administration. https://www.eia.gov/outlooks/aeo/nems/documentation/industrial/pdf/m064(2016).pdf.
El Independiente, 2021. ORANGE.BAT: la iniciativa de ACS para impulsar el hidrógeno verde en Europa.
El periódico de la energía, 2021. La demanda eléctrica nacional desciende un 1,8 % en octubre. URL https://elperiodicodelaenergia.com/la-demanda-electrica-nacional-desciende-un-18-en-octubre/ (accessed 11.15.21).
electrive, 2019. VW: Erster MEB-Stromer wird wohl offiziell ID.3 getauft [WWW Document]. electrive.net. URL https://www.electrive.net/2019/02/15/vws-kompaktstromer-id-wird-wohl-offiziell-id-3-getauft/ (accessed 2.19.19).
ELYSIS, 2020. Carbon-free Aluminium: A new era for the aluminium industry [WWW Document]. ELYSIS. URL https://www.elysis.com/en/elysis (accessed 9.28.20).
EP ITRE, 2020. Energy-intensive industries: Challenges and opportunities in energy transition. European Parliament's committee on Industry, Research and Energy (ITRE).
EPRC, 2020. Monitoring Report 2019: European Declaration on Paper Recycling 2016-2020. European Paper Recycling Council.
Erumban, A.A., 2008. Lifetimes of machinery and equipment: evidence from Dutch manufacturing. Review of Income and Wealth 54, 237–268.
Euractiv, 2013. Desertec abandons Sahara solar power export dream. www.euractiv.com. URL https://www.euractiv.com/section/trade-society/news/desertec-abandons-sahara-solar-power-export-dream/ (accessed 2.25.21).
Euractiv, Reuters, 2020. Investors caution cement, steel firms on EU climate lobbying [WWW Document]. www.euractiv.com. URL https://www.euractiv.com/section/emissions-trading-scheme/news/investors-caution-cement-steel-firms-on-eu-climate-lobbying/ (accessed 7.20.21).
EUROFER, 2018. European Steel in Figures (2008-2017). EUROFER, Brussels.
EUROFER, 2013. A Steel Roadmap for a Low Carbon Europe 2050. The European Steel Association.
European Cement Research Academy, 2017. Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead, CSI/ECRA - Technology Papers 2017. European Cement Research Academy, Cement Sustainability Initiative, Düsseldof, Geneva.
European Court of Auditors, 2016. The EU system for the certification of sustainable biofuels. Special Report No 18, 2016. Special Report No 18, 2016. Publications Office, Luxembourg.
EUROSTAT, 2021a. Simplified energy balances [WWW Document]. URL https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_s/default/table?lang=en (accessed 4.22.21).

EUROSTAT, 2021b. Energy Balances [WWW Document]. URL https://ec.europa.eu/eurostat/databrowser/view/enps_nrg_bal_c/default/table?lang=en (accessed 5.12.21).
EUROSTAT, 2020. Electricity market indicators.
Evans, S., Mehling, M., Ritz, R., Sammon, P., 2020. Border Carbon Adjustments and Industrial Competitiveness in a European Green Deal.
Falk, R., 2009. Wood as a Sustainable Building Material. FOREST PRODUCTS JOURNAL 59, 8.
Farfan, J., Breyer, C., 2017. Aging of European power plant infrastructure as an opportunity to evolve towards sustainability. International Journal of Hydrogen Energy 42, 18081–18091. https://doi.org/10.1016/j.ijhydene.2016.12.138
Fasihi, M., Efimova, O., Breyer, C., 2019. Techno-economic assessment of CO2 direct air capture plants. Journal of Cleaner Production 224, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086
Ferreira, E.T. de F., Balestieri, J.A.P., 2015. Black liquor gasification combined cycle with CO2 capture – Technical and economic analysis. Applied Thermal Engineering 75, 371–383. https://doi.org/10.1016/j.applthermaleng.2014.09.026
FEVE, 2020. Latest Glass Packaging Recycling Rate Steady at 76% [WWW Document]. The European Container Glass Federation. URL https://feve.org/glass_recycling_stats_2018/ (accessed 3.4.21).
Fleiter, T., Fehrenbach, D., Worrell, E., Eichhammer, W., 2012. Energy efficiency in the German pulp and paper industry – A model-based assessment of saving potentials. Energy 40, 84–99. https://doi.org/10.1016/j.energy.2012.02.025
Fleiter, T., Herbst, A., Rehfeldt, M., Arens, M., 2019. Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation. Fraunhofer Institute for Systems and Innovation Research (ISI), ICF Consulting Services Limited, Karlsruhe.
Fleiter, T., Schlomann, B., Eichhammer, W. (Eds.), 2013. Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien: Einsparpotenziale, Hemmnisse und Instrumente, ISI-Schriftenreihe "Innovationspotenziale." Fraunhofer-Institut für Systemtechnik und Innovationsforschung, Stuttgart.
Fleiter, T., Worrell, E., Eichhammer, W., 2011. Barriers to energy efficiency in industrial bottom-up energy demand models—A review. Renewable and Sustainable Energy Reviews 15, 3099–3111. https://doi.org/10.1016/j.rser.2011.03.025
Fletcher, K., Marshall, M., 1995. Forecasting Regional Industrial Energy Demand: The ENUSIM End-Use Model. Regional Studies 29, 801–811. https://doi.org/10.1080/00343409512331349423
Frangoul, A., 2021. Cement giants turn to green hydrogen and carbon capture in efforts to curb emissions [WWW Document]. CNBC. URL https://www.cnbc.com/2021/02/15/cement-giants-turn-to-green-hydrogen-carbon-capture-to-curb-emissions.html (accessed 5.7.21).
Frassine, C., Rohde, C., Hirzel, S., 2016. Energy saving options for industrial furnaces – the example of the glass industry, in: ECEEE Industrial Summer Study Proceedings 2016. Fraunhofer ISI.
Fritsche, U.R., Sims, R.E.H., Monti, A., 2010. Direct and indirect land-use competition issues for energy crops and their sustainable production - an overview. Biofuels, Bioprod. Bioref. 4, 692–704. https://doi.org/10.1002/bbb.258
GALTCO, 2021. Línea de tiempo [WWW Document]. Complejo Verde de Transformación de Aluminio para Colombia. URL https://neocolombia.com/vision (accessed 7.24.21).
García-Segura, T., Yepes, V., Alcalá, J., 2014. Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. Int J Life Cycle Assess 19, 3–12. https://doi.org/10.1007/s11367-013-0614-0
Gardarsdottir, S., De Lena, E., Romano, M., Roussanaly, S., Voldsund, M., Pérez-Calvo, J.-F., Berstad, D., Fu, C., Anantharaman, R., Sutter, D., Gazzani, M., Mazzotti, M., Cinti, G., 2019. Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis. Energies 12, 542. https://doi.org/10.3390/en12030542

Gas for Climate, 2020. European Hydrogen Backbone: How a dedicated infrastructure can be created.
Gellings, C., 2009. Program on Technology Innovation: Industrial Electrotechnology Development Opportunities. Electric Power Research Institute (EPRI).
Georges, P., Nietvelt, K., de Taisne, B., Stenqvist, A., Schiavo, M., 2018. European Integrated Utilities In 2017: Rebenchmarking The Sector. S & P Global.
Gerbaulet, C., von Hirschhausen, C., Kemfert, C., Lorenz, C., Oei, P.-Y., 2019. European electricity sector decarbonization under different levels of foresight. Renewable Energy 141, 973–987. https://doi.org/10.1016/j.renene.2019.02.099
Gerres, T., Chaves Ávila, J.P., Linares Llamas, P., Gómez San Román, T., 2020. Overcoming the carbon lock-in: a techno-economic analysis of the Spanish cement sector, in: Industrial Efficiency 2020: Decarbonise Industry! Eceee Industrial Summer Study Proceedings. Presented at the European Council for an Energy Efficient Economy Summer Study on Energy Efficiency - ECEEE 2020.
Gerres, T., Chaves Ávila, J.P., Linares, P., 2019a. The transformation of the Spanish basic materials sector towards a low carbon economy. Papeles de Energía 7, 61–84.
Gerres, T., Chaves Avila, J.P., Linares, P., Gómez San Roman, T., 2019b. A review of cross-sector decarbonisation potentials in the European energy intensive industry. JOURNAL OF CLEANER PRODUCTION 210, 585–601. https://doi.org/10.1016/j.jclepro.2018.11.036
Gerres, T., Chaves Ávila, J.P., Martín Martínez, F., Rivier Abbad, M., Cossent Arín, R., Sánchez Miralles, Á., Gómez San Román, T., 2019c. Rethinking the electricity market design: Remuneration mechanisms to reach high RES shares. Results from a Spanish case study. Energy Policy 11.
Gerres, T., Chaves Ávila, J.P., Martin Martínez, F., Rivier Abbad, M., Gómez San Roman, T., 2019d. The Role of Nuclear Power Plants in Electricity Systems with High RES Share. Presented at the 2019 IEEE Milan PowerTech, Milan, Italy, pp. 1–6. https://doi.org/10.1109/PTC.2019.8810545
Gerres, T., Haussner, M., Neuhoff, K., Pirlot, A., 2021. To ban or not to ban carbon-intensive materials: A legal and administrative assessment of product carbon requirements. Review of European, Comparative & International Environmental Law 14. https://doi.org/10.1111/reel.12395
Gerres, T., Linares, P., 2020. Carbon Contracts for Differences: their role in European industrial decarbonization. Climate Friendly Materials Platform, Climate Strategies.
Gerres, T., Linares, P., Chaves Ávila, J.P., Gómez San Román, T., 2019e. El futuro de las materias primas en España. IIT Comillas, Madrid.
Gerres, T., Linares, P., Chaves Ávila, J.P., Gómez San Román, T., 2019f. Tecnologías para la descarbonización de la industria del uso intensivo de energía. IIT Comillas, Madrid.
Ghanta, M., Fahey, D., Subramaniam, B., 2014. Environmental impacts of ethylene production from diverse feedstocks and energy sources. Appl Petrochem Res 4, 167–179. https://doi.org/10.1007/s13203-013-0029-7
Glenk, G., Reichelstein, S., 2019. Economics of converting renewable power to hydrogen. Nature Energy 4, 216–222. https://doi.org/10.1038/s41560-019-0326-1
Global Cement, 2019. ENCI Maastricht plant closure to make 50 jobless - Cement industry news from Global Cement [WWW Document]. URL https://www.globalcement.com/news/item/10200-enci-maastricht-plant-closure-to-make-50-jobless (accessed 3.24.20).
Goldman Sachs, 2018. Solar to transform Europe´s energy mix, Equity Research.
Gómez, T., Rivier, M., Chaves, J.P., Martín Martínez, F., Gerres, T., 2018. Señales de precio a la inversión en un mercado eléctrico con elevada penetración de renovables. Papeles de Energía 9–38.
Gouardères, F., 2021. General principles of EU industrial policy. European Parlaiment.
Government of Sweden, 2021. The Swedish climate policy framework. Ministry of the Environment and Energy.
Groover, M.P., 2010. Fundamentals of Modern Manufacturing - Materials, Processes, and Systems, 4th ed. John Wiley & Sons, Inc., Hoboken, NJ.

Grubb, M., 2014. Planetary Economics: Energy, climate change and the three domains of sustainable development, 1st ed. Routledge. https://doi.org/10.4324/9781315857688
Gutenberg, E., 1951. Grundlagen der Betriebswirtschaftslehre - Band 1: Die Produktion. Springer-Verlag.
Habert, G., Billard, C., Rossi, P., Chen, C., Roussel, N., 2010. Cement production technology improvement compared to factor 4 objectives. Cement and Concrete Research 40, 820–826. https://doi.org/10.1016/j.cemconres.2009.09.031
Haley, U.C.V., Schuler, D.A., 2011. Government Policy and Firm Strategy in the Solar Photovoltaic Industry. California Management Review 54, 17–38. https://doi.org/10.1525/cmr.2011.54.1.17
Hall, L.M.H., Buckley, A.R., 2016. A review of energy systems models in the UK: Prevalent usage and categorisation. Applied Energy 169, 607–628. https://doi.org/10.1016/j.apenergy.2016.02.044
Hanaoka, T., Fujiwara, K., Motoki, Y., Oshiro, K., Hibino, G., Masui, T., Matsuoka, Y., 2015. AIM/Enduse Model Manual AIM Interim Report. National Institute for Environmental Studies: Tsukuba, Japan.
Harrington, J.E., Hüschelrath, K., Laitenberger, U., Smuda, F., 2014. The Discontent Cartel Member and Cartel Collapse: The Case of the German Cement Cartel.
Hartigan, J.A., Wong, M.A., 1979. Algorithm AS 136: A k-means clustering algorithm. Journal of the Royal Statistical Society. Series C (Applied Statistics) 28, 100–108.
Hasanbeigi, A., Nilsson, A., Mete, G., Fontenit, G., Shi, D., 2021. Fostering industry transition through green public procurement.
Hausmann, R., Rodrik, D., 2006. Doomed to choose: industrial policy as predicament. John F. Kennedy School of Government, Harvard University 9.
Hawker, G., Bell, K., Gill, S., 2017. Electricity security in the European Union—The conflict between national Capacity Mechanisms and the Single Market. Energy Research & Social Science 24, 51–58. https://doi.org/10.1016/j.erss.2016.12.009
Haydock, H., Napp, T., 2013. Decarbonisation of heat in industry - a review of research evidence (No. Ricardo-AEA/R/ED58571). Department of Energy & Climate Change (UK), Ricardo-AEA.
Heaton, C., 2014. Modelling Low-Carbon Energy System Designs with the ETI ESME Model.
Hepburn, C., Teytelboym, A., Parry, I., Pittel, K., Vollebergh, H., 2017. Reforming the EU ETS–where are we now? Energy Tax and Regulatory Policy in Europe: Reform Priorities 29–62.
Herbst, A., Elsland, R., Reiter, U., Fleiter, T., Rehfeldt, M., n.d. Benchmarking the EU reference scenario 2016: An alternative bottom-up analysis of long-term energy consumption in Europe.
Hertwich, E.G., Wood, R., 2018. The growing importance of scope 3 greenhouse gas emissions from industry. Environ. Res. Lett. 13, 104013. https://doi.org/10.1088/1748-9326/aae19a
Hills, T.P., Sceats, M., Rennie, D., Fennell, P., 2017. LEILAC: Low Cost CO2 Capture for the Cement and Lime Industries. Energy Procedia 114, 6166–6170. https://doi.org/10.1016/j.egypro.2017.03.1753
Hilpert, S., Kaldemeyer, C., Krien, U., Günther, S., Wingenbach, C., Plessmann, G., 2017. The Open Energy Modelling Framework (oemof)-A novel approach in energy system modelling. Preprints.
Hirth, L., 2017. The European Electricity Market Model EMMA Model documentation. Neon Neue Energieökonomik GmbH, Potsdam.
Hirth, L., 2013. The market value of variable renewables. Energy Economics 38, 218–236. https://doi.org/10.1016/j.eneco.2013.02.004
Hirth, L., Ueckerdt, F., 2013. Redistribution effects of energy and climate policy: The electricity market. Energy Policy 62, 934–947. https://doi.org/10.1016/j.enpol.2013.07.055
Hita, A., Seck, G., Djemaa, A., Guerassimoff, G., 2011. Assessment of the potential of heat recovery in food and drink industry by the use of TIMES model, in: ECEEE 2011. pp. 735–743.
Hogan, W.W., 2005. On an “energy only” electricity market design for resource adequacy.
How governments spurred the rise of solar power, 2021. . The Economist.

Howard, B.C., 2018. 5 recycling myths busted. National Geographic.
Hydrogen Council, 2021. Hydrogen Insights: A perspectiv on hydrogen investment, market developement and cost competitiveness.
HyNet, 2020. HyNet Industrial Fuel Switching - Feasibility Study.
ICAP, 2021. EU Emissions Trading System (EU ETS). International Carbon Action Partnership.
ICF, 2015. Utility-Scale Solar Photovoltaic Power Plants: A projects developer´s guide.
IDAE, 2020. Balance del Consumo de energía final [WWW Document]. URL http://sieeweb.idae.es/consumofinal/bal.asp?txt=2019&tipbal=t (accessed 2.23.21).
IDAE, 2019. Informe de Precios de la Biomasa para Usos Térmicos (No. 15). IDAE, MITECO, Madrid.
IDAE, 2009. Guía técnica: Instalaciones de biomasa térmica en edificios. IDAE, Madrid.
IDEPA, 2021. Mercado de trabajo [WWW Document]. URL https://www.idepa.es/conocimiento/asturias-en-cifras/mercado-de-trabajo (accessed 7.5.21).
IEA, 2021a. Indicative hard coking coal FOB supply curve 2019 and average FOB marker prices.
IEA, 2021b. Net Zero by 2050 - A Roadmap for the Global Energy Sector.
IEA, 2020a. Global CO2 emissions in 2019 – Analysis [WWW Document]. URL https://www.iea.org/articles/global-co2-emissions-in-2019 (accessed 4.21.21).
IEA, 2020b. Global CO2 emissions by sector, 2018 – Charts – Data & Statistics [WWW Document]. URL https://www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2018 (accessed 4.21.21).
IEA, 2020c. World Energy Outlook 2020.
IEA, 2020d. World Energy Balances – Analysis [WWW Document]. URL https://www.iea.org/reports/world-energy-balances-overview (accessed 6.19.21).
IEA, 2020e. Average annual gas prices in the United States and Europe, 2010-2020.
IEA, 2020f. Cost curve of potential global biomethane supply by region, 2040.
IEA, 2019a. The Future of Hydrogen. International Energy Agency, Paris.
IEA, 2019b. The Role of Gas in Today's Energy Transitions. International Energy Agency.
IEA, 2018a. The Future of Petrochemicals - Methodological Annex. International Energy Agency.
IEA, 2018b. Technology Roadmap Low-Carbon Transition in the Cement Industry. World Business Council for Sustainable Development and International Energy ….
IEA ESTAP, 2012. Aluminium Production. IEA Energy Technology System Analysis Programme.
IEAGHG, 2013a. Deployment of CCS in the Cement Industry. International Energy Agency (IEA).
IEAGHG, 2013b. Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill). International Energy Agency (IEA).
Ihnat, V., Lübke, H., Balbercak, J., Kuňa, V., 2020. Size reduction downcycling of waste wood. Review. Wood Res 65, 205–220.
IIASA, 2016. Overview — MESSAGE-GLOBIOM 1.0 documentation [WWW Document]. URL http://data.ene.iiasa.ac.at/message-globiom/overview/index.html (accessed 3.11.18).
Intraw, 2019. The world of raw materials 2050. URL https://intraw.eu/the-world-of-raw-materials-2050/ (accessed 4.1.19).
IPCC, 2006. Chapter 2: Mineral Industry Emissions, in: 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
IRENA, 2020. Renewable Power Generation Costs 2020.
IRENA, 2019. Renewable Power Generations Costs in 2018. International Renewable Energy Agency, Abu Dhabi.
Islam, R., Nazifa, T.H., Yuniarto, A., Shanawaz Uddin, A.S.M., Salmiati, S., Shahid, S., 2019. An empirical study of construction and demolition waste generation and implication of recycling. Waste Management 95, 10–21. https://doi.org/10.1016/j.wasman.2019.05.049

Ismer, R., Neuhoff, K., Pirlot, A., 2020. Border Carbon Adjustments and Alternative Measures for the EU ETS An Evaluation. DIW iscussion Papers 1855.
ISO, 2020. The ISO Survey 2019 [WWW Document]. International Organization for Standardization. URL https://www.iso.org/the-iso-survey.html (accessed 7.22.21).
Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., Creutzig, F., 2020. Quantifying the potential for climate change mitigation of consumption options. Environ. Res. Lett. 15, 093001. https://doi.org/10.1088/1748-9326/ab8589
Jaccard, M., 2015. Energy-economy modeling and behavioral realism: How much is useful?
Jacobsson, S., Johnson, A., 2000. The diffusion of renewable energy technology: an analytical framework and key issues for research. Energy policy 28, 625–640.
Jakob, M., Steckel, J.C., Edenhofer, O., 2014. Consumption- Versus Production-Based Emission Policies. Annual Review of Resource Economics 6, 297–318. https://doi.org/10.1146/annurev-resource-100913-012342
Jepsen, M., Serrano Pascual, A., 2005. The European Social Model: an exercise in deconstruction. Journal of European Social Policy 15, 231–245. https://doi.org/10.1177/0958928705054087
Jermann, C., Koutchma, T., Margas, E., Leadley, C., Ros-Polski, V., 2015. Mapping trends in novel and emerging food processing technologies around the world. Innovative Food Science & Emerging Technologies 31, 14–27. https://doi.org/10.1016/j.ifset.2015.06.007
Jiang, P., Van Fan, Y., Klemeš, J.J., 2021. Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. Applied energy 285, 116441.
JRC, 2007. Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry. Publications Office of the European Union.
JSW Steel, 2019. Integrated Report 2018-2019.
Kadefors, A., Lingegård, S., Uppenberg, S., Alkan-Olsson, J., Balian, D., 2021. Designing and implementing procurement requirements for carbon reduction in infrastructure construction – international overview and experiences. Journal of Environmental Planning and Management 64, 611–634. https://doi.org/10.1080/09640568.2020.1778453
Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., Jäger-Waldau, A., 2021. Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. Energy Conversion and Management 228, 113649. https://doi.org/10.1016/j.enconman.2020.113649
Karlsson, I., Rootzén, J., Toktarova, A., Odenberger, M., Johnsson, F., Göransson, L., 2020. Roadmap for Decarbonization of the Building and Construction Industry—A Supply Chain Analysis Including Primary Production of Steel and Cement. Energies 13, 4136.
Karneyeva, Y., Wüstenhagen, R., 2017. Solar feed-in tariffs in a post-grid parity world: The role of risk, investor diversity and business models. Energy Policy 106, 445–456. https://doi.org/10.1016/j.enpol.2017.04.005
Kätelhön, A., Meys, R., Deutz, S., Suh, S., Bardow, A., 2019. Climate change mitigation potential of carbon capture and utilization in the chemical industry. Proc Natl Acad Sci USA 116, 11187–11194. https://doi.org/10.1073/pnas.1821029116
Keay, M., Robinson, D., 2019. The limits of auctions: reflections on the role of central purchaser auctions for long-term commitments in electricity systems. The Oxford Institute for Energy Studies Paper.
Kennedy, S., Johnson, C.K., 2016. Perfecting China, Inc: the 13th Five-Year Plan, A report of the CSIS Freeman Chair in China Studies. Rowman & Littlefield, Lanham, MD Boulder New York London.
Keramidas, K., Kitous, A., Despres, J., Schmitz, A., Vazquez, A.D., Mima, S., Russ, P., Wiesenthal, T., 2017. POLES-JRC model documentation. Joint Research Centre (Seville site).
Khan, A.S.M., Verzijlbergh, R.A., Sakinci, O.C., De Vries, L.J., 2018. How do demand response and electrical energy storage affect (the need for) a capacity market? Applied Energy 214, 39–62. https://doi.org/10.1016/j.apenergy.2018.01.057

Kosmadakis, G., 2019. Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. Applied Thermal Engineering 12.
Kujanpää, L., Arasto, A., Ranta, T., 2018. Finland – 2018 update: Bioenergy policies and status of implementation. IEA, Paris.
La Vanguardia, 2021. Factura de la luz: Octubre cierra con el recibo más caro de la historia.
Lane, N., 2020. The New Empirics of Industrial Policy. Journal of Industry, Competition and Trade 20, 209–234. https://doi.org/10.1007/s10842-019-00323-2
Lechtenböhmer, S., Nilsson, L.J., Åhman, M., Schneider, C., 2016. Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. Energy 115, 1623–1631. https://doi.org/10.1016/j.energy.2016.07.110
Leeson, D., Mac Dowell, N., Shah, N., Petit, C., Fennell, P.S., 2017. A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. International Journal of Greenhouse Gas Control 61, 71–84. https://doi.org/10.1016/j.ijggc.2017.03.020
LevelTen Energy, 2021. Energy PPA Price Index: Q2 2021 Europe.
Lewis, W.A., 1954. Economic development with unlimited supplies of labour.
Liemberger, W., Groß, M., Miltner, M., Harasek, M., 2017. Experimental analysis of membrane and pressure swing adsorption (PSA) for the hydrogen separation from natural gas. Journal of Cleaner Production 167, 896–907. https://doi.org/10.1016/j.jclepro.2017.08.012
Linares, P., Declercq, D., 2017. Escenarios para el sector energético en España 2030-2050. economics for energy.
Linares, P., Santos, F.J., Ventosa, M., 2008. Coordination of carbon reduction and renewable energy support policies. Climate Policy 8, 377–394. https://doi.org/10.3763/cpol.2007.0361
Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2016. Documentation for the TIMES Model: Energy Technology Systems Analysis Programme. International Energy Agency Paris.
Lund, H., Münster, E., Tambjerg, L.H., 2014. EnergyPLAN. Computer model for energy system analysis version 6.
Margarit i Roset, J., 2011. Evaluación del Potencial de Energía de la Biomasa - Estudio Técnico per 2011-2020. Instituto para la Diversificación y Ahorro de la Energía (IDAE).
Marsh, G.P., 1864. Man and Nature or, Physical Geography as Modified by Human Action. Charles Scribner, New York.
Martín-Martínez, F., Sánchez-Miralles, A., Rivier, M., Calvillo, C.F., 2017. Centralized vs distributed generation. A model to assess the relevance of some thermal and electric factors. Application to the Spanish case study. Energy 134, 850–863. https://doi.org/10.1016/j.energy.2017.06.055
Mastropietro, P., Rodilla, P., Batlle, C., 2019. De-rating of wind and solar resources in capacity mechanisms: A review of international experiences. Renewable and Sustainable Energy Reviews 112, 253–262. https://doi.org/10.1016/j.rser.2019.05.053
Material Economics, 2021. EU biomass use in a net-zero economy.
Material Economics, 2018. The Circular Economy - A powerful force for climate mitigation. Material Economics, Stockholm, Sweden.
McAllister, S., Chen, J.-Y., Fernandez-Pello, A.C., 2011. Fundamentals of Combustion Processes, Mechanical Engineering Series. Springer New York, New York, NY. https://doi.org/10.1007/978-1-4419-7943-8
McBrien, M., Serrenho, A.C., Allwood, J.M., 2016. Potential for energy savings by heat recovery in an integrated steel supply chain. Applied Thermal Engineering 103, 592–606. https://doi.org/10.1016/j.applthermaleng.2016.04.099
McCarten, M., Bayaraa, M., Caldecott, B., Christiaen, C., Foster, P., Hickey, C., Kampmann, D., Layman, C., Rossi, C., Scott, K., Tang, K., Tkachenko, N., Yoken, D., 2021a. Global Database of Cement Production Assets. Spatial Finance Initiative.

McCarten, M., Bayaraa, M., Caldecott, B., Christiaen, C., Foster, P., Hickey, C., Kampmann, D., Layman, C., Rossi, C., Scott, K., Tang, K., Tkachenko, N., Yoken, D., 2021b. Global Database of Iron and Steel Production Assets. Spatial Finance Initiative.
McGee, P., Campbell, P., 2019. Fiat Chrysler pools fleet with Tesla to avoid EU emissions fines. Financial Times.
McKane, A., Therkelsen, P., Scodel, A., Rao, P., Aghajanzadeh, A., Hirzel, S., Zhang, R., Prem, R., Fossa, A., Lazarevska, A.M., Matteini, M., Schreck, B., Allard, F., Villegal Alcántar, N., Steyn, K., Hürdoğan, E., Björkman, T., O'Sullivan, J., 2017. Predicting the quantifiable impacts of ISO 50001 on climate change mitigation. Energy Policy 107, 278–288. https://doi.org/10.1016/j.enpol.2017.04.049
Meadows, D.H., Randers, J., Meadows, D.L., 1972. The Limits to Growth. Yale University Press.
Mearns, E., 2016. CO2 Emissions Variations in CCGTs Used to Balance Wind in Ireland. Energy Matters. URL http://euanmearns.com/co2-emissions-variations-in-ccgts-used-to-balance-wind-in-ireland/ (accessed 6.21.21).
Medarac, H., Moya, J.A., Somers, J., European Commission, Joint Research Centre, 2020. Production costs from iron and steel industry in the EU and third countries.
Mehling, M.A., van Asselt, H., Das, K., Droege, S., Verkuijl, C., 2019. Designing Border Carbon Adjustments for Enhanced Climate Action. Am. j. int. law 113, 433–481. https://doi.org/10.1017/ajil.2019.22
Minenergía, 2021. Colombia's hydrogen roadmap.
Mineral Products Association, Cinar, VDZ, 2019. Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility (Summary report). UK Department for Business Energy and Industrial Strategy, London.
MINETUR, 2016. Planificación energética. Plan de desarrollo de la red de transporte de energía eléctrica 2015-2020. Ministerio de Industria, Energía y Turismo, Madrid.
Ministry of Steel, 2021. Energy and Environment Management in Iron & Steel sector [WWW Document]. URL https://steel.gov.in/technicalwing/energy-and-environment-management-iron-steel-sector (accessed 7.22.21).
MITECO, 2021. RESOLUCIÓN DE LA DIRECCIÓN GENERAL DE POLÍTICA ENERGÉTICA Y MINAS POR LA QUE SE RESUELVE LA PRIMERA SUBASTA CELEBRADA PARA EL OTORGAMIENTO DEL RÉGIMEN ECONÓMICO DE ENERGÍAS RENOVABLES AL AMPARO DE LO DISPUESTO EN LA ORDEN TED/1161/2020, DE 4 DE DICIEMBRE.
MITECO, 2020a. Plan nacional integrado de energía y clima 2021-2030.
MITECO, 2020b. Hoja de Ruta del Hidrógeno: una apuesta por el hidrógeno renovable.
MITECO, 2019. Fabricación de Aluminio (Emisiones de Proceso). Ministerio para la Transición Ecológica, Madrid.
Mofijur, M., Fattah, I.M.R., Alam, M.A., Islam, A.B.M.S., Ong, H.C., Rahman, S.M.A., Najafi, G., Ahmed, S.F., Uddin, Md.A., Mahlia, T.M.I., 2021. Impact of COVID-19 on the social, economic, environmental and energy domains: Lessons learnt from a global pandemic. Sustainable Production and Consumption 26, 343–359. https://doi.org/10.1016/j.spc.2020.10.016
Moksnes, N., Welsch, M., Gardumi, F., Shivakumar, A., Broad, O., Howells, M., Taliotis, C., Sridharan, V., 2015. 2015 OSeMOSYS User Manual.
Monforte, C., 2018. Los cierres de Alcoa coinciden con una rebaja del 40% del incentivo eléctrico a la industria [WWW Document]. Cinco Días. URL https://cincodias.elpais.com/cincodias/2018/10/18/companias/1539886969_674557.html (accessed 2.17.20).
Mora, J.A., Pavel, C.C., 2018. Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry. Publications Office of the European Union, JRC, Luxembourg.
Morfeldt, J., Silveira, S., 2014. Capturing energy efficiency in European iron and steel production—comparing specific energy consumption and Malmquist productivity index. Energy Efficiency 7, 955–972. https://doi.org/10.1007/s12053-014-9264-8

Morfeldt, J., Silveira, S., Hirsch, T., Lindqvist, S., Nordqvist, A., Pettersson, J., Pettersson, M., 2015. Improving energy and climate indicators for the steel industry – the case of Sweden. Journal of Cleaner Production 107, 581–592. https://doi.org/10.1016/j.jclepro.2015.05.031
Moshkelani, M., Marinova, M., Perrier, M., Paris, J., 2013. The forest biorefinery and its implementation in the pulp and paper industry: Energy overview. Applied Thermal Engineering 50, 1427–1436. https://doi.org/10.1016/j.applthermaleng.2011.12.038
Mosovsky, B., Titus, L., 2018. Lifting the Veil on Hidden Risk in Renewable Power Purchase Agreements. Global Commodity Applied Research Digest 3.
Möst, D., Fichtner, W., 2010. Renewable energy sources in European energy supply and interactions with emission trading. Energy Policy 38, 2898–2910. https://doi.org/10.1016/j.enpol.2010.01.023
Moya, J.A., Boulamanti, A., Singerland, S., van der Veen, R., Gancheva, M., Rademaekers, K., Kuenen, J., Visschedijk, A., 2015. Energy efficiency and GHG emissions: prospective scenarios for the aluminium industry. EU Joint Research Center.
Murphy, R., Rivers, N., Jaccard, M., 2007. Hybrid modeling of industrial energy consumption and greenhouse gas emissions with an application to Canada. Energy Economics 29, 826–846. https://doi.org/10.1016/j.eneco.2007.01.006
Naumann, A., 2018. The German cement cartel – a landmark decision for private damages actions. Lexxion Competition Blogs. URL https://www.lexxion.eu/en/coreblogpost/the-german-cement-cartel-a-landmark-decision-for-private-damages-actions/ (accessed 7.15.21).
Neelis, M., Patel, M., Blok, K., Haije, W., Bach, P., 2007. Approximation of theoretical energy-saving potentials for the petrochemical industry using energy balances for 68 key processes. Energy 32, 1104–1123. https://doi.org/10.1016/j.energy.2006.08.005
Nemet, G.F., Zipperer, V., Kraus, M., 2018. The valley of death, the technology pork barrel, and public support for large demonstration projects. Energy Policy 119, 154–167. https://doi.org/10.1016/j.enpol.2018.04.008
Neuhoff, K., Chiappinelli, O., Gerres, T., Haussner, M., Ismer, R., May, N., Pirlot, A., Richstein, J., 2019. Building blocks for a climate-neutral European industrial sector. Climate Strategies, London.
Neuhoff, K., Chiappinelli, O., Richstein, J.C., de Coninck, H., Linares, P., Gerres, T., Khandekar, G., Wyns, T., Zetterberg, L., Felsmann, B., Sniegocki, A., 2021. Closing the Green Deal for Industry. Climate Friendly Materials Platform, Climate Strategies.
Neuhoff, K., May, N., Richstein, J.C., 2018. Renewable energy policy in the age of falling technology costs. DIW Discussion Papers 1746.
Newbery, D., 2016. Missing money and missing markets: Reliability, capacity auctions and interconnectors. Energy Policy 94, 401–410. https://doi.org/10.1016/j.enpol.2015.10.028
Newbery, D.M., 1997. Privatisation and liberalisation of network utilities. European Economic Review 41, 357–383. https://doi.org/10.1016/S0014-2921(97)00010-X
NGET, 2017. Duration Limited Storage De-Rating Factor Assessment. National Grid (NGET), London.
Nies, S., 2008. Oil and Gas Delivery to Europe: An Overview of Existing and Planned Infrastructures. European Governance and the Geopolitics of Energy. French Institute for International Relations (Ifri).
O'Brien, K.L., 2001. Do values subjectively define the limits to climate change adaptation?, in: Adger, W.N., Lorenzoni, I., O'Brien, K.L. (Eds.), Adapting to Climate Change. Cambridge University Press, pp. 164–180. https://doi.org/10.1017/CBO9780511596667.011
ODYSSEE-MURE, 2015. Energy Efficiency Trends and Policies In Industry.
OECD, 2020. Economic analysis in merger investigation - contribution from Spain, in: Session III. Presented at the Global Forum on Competition, OECD.
OECD, 2014. Going green: best practices for green procurement - Netherlands.
OECD, 2006. The Political Economy of Environmentally Related Taxes.
OED Online, 2021. industry, n. Oxford English Dictionary.

OFICEMEN, 2021. Fábricas de cemento en España | Oficemen, formamos parte del territorio. Oficemen. URL https://www.oficemen.com/el-cemento/fabricas-cemento-espana/ (accessed 5.17.21).
OFICEMEN, 2020. Hoja de ruta de la industria cementera española para alcanzar la neutralidad climática en 2050.
OFICEMEN, 2016. Anuario del sector cementero español 2015. Agrupación de Fabricantes de Cemento de España.
Olivier, J.G.J., 2002. On the quality of global emission inventories: Approaches, methodologies, input data and uncertainties (PhD Thesis). Utrecht University.
Olsson, O., Nykvist, B., 2020. Bigger is sometimes better: demonstrating hydrogen steelmaking at scale. SEI.
O'Rourke, K.H., Williamson, J.G., 2002. When did globalisation begin? European Review of Economic History 6, 23–50.
Outlook for natural gas, 2017. , in: World Energy Outlook 2017. International Atomic Energy Agency, pp. 333–365. https://doi.org/10.1787/weo-2017-10-en
Pawłowski, A., 2008. How many dimensions does sustainable development have? Sustainable development 16, 81–90.
Pelkmans, J., Renda, A., 2014. How Can EU Legislation Enable and/or Disable Innovation. Report for the European Commission DG Research and Innovation, Available at this link.
Peña Fernández, Á.L., 2014. Evaluation and design of sustainable energy policies: an application to the case of Spain (Dissertation (Phd)). Universidad Pontificia Comillas, Madrid.
Pérez-Fortes, M., Schöneberger, J.C., Boulamanti, A., Tzimas, E., 2016. Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. Applied Energy 161, 718–732. https://doi.org/10.1016/j.apenergy.2015.07.067
Pettersson, K., Harvey, S., 2012. Comparison of black liquor gasification with other pulping biorefinery concepts – Systems analysis of economic performance and CO2 emissions. Energy 37, 136–153. https://doi.org/10.1016/j.energy.2011.10.020
Pfenninger, S., 2018. Calliope Documentation - Release 0.5.5. ETH Zurich.
Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews 33, 74–86. https://doi.org/10.1016/j.rser.2014.02.003
Pfenninger, S., Keirstead, J., 2015. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. Applied Energy 152, 83–93. https://doi.org/10.1016/j.apenergy.2015.04.102
Pierce, C.E., Huynh, N.N., Guimaraes, P., 2012. Cost indexing and unit price adjustments for construction materials. University of South Carolina. Dept. of Civil & Environmental Engineering.
Polzin, F., Egli, F., Steffen, B., Schmidt, T.S., 2019. How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. Applied Energy 236, 1249–1268. https://doi.org/10.1016/j.apenergy.2018.11.098
Portwain, V., 2018. How Long Does it Take to Build a Wind Farm? [WWW Document]. Energy Central. URL https://energycentral.com/c/ec/how-long-does-it-take-build-wind-farm (accessed 7.8.21).
POSCO, 2019. Corporate Citizenship Report 2019.
Poterba, J., 1991. Tax Policy to Combat Global Warming: On Designing a Carbon Tax (No. w3649). National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w3649
Prol, J.L., O, S., 2020. Impact of COVID-19 measures on short-term electricity consumption in the most affected EU countries and USA states. iScience. https://doi.org/10.1016/j.isci.2020.101639
Prosperi, P., Kirwan, J., Maye, D., Bartolini, F., Vergamini, D., Brunori, G., 2019. Adaptation strategies of small-scale fisheries within changing market and regulatory conditions in the EU. Marine Policy 100, 316–323. https://doi.org/10.1016/j.marpol.2018.12.006
Pye, S., Anandarajah, G., Fais, B., McGlade, C., Strachan, N., 2015. Pathways to Deep Decarbonization in the United Kingdom. IDDRI, SDSN, UCL Energy Institute.

Quoilin, S., 2017. DispaSET Documentation - Release v2.2-35-gefcdfdb. University of Liège, Joint Research Centre, European Commission.
Radetzki, M., 2008. 4. Price formation and price trends in commodities, in: A Handbook of Primary Commodities in the Global Economy. Cambridge University Press, Cambridge, p. 245.
Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and chemical recycling of solid plastic waste. Waste Management 69, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044
Rahimpour, M.R., Jafari, M., Iranshahi, D., 2013. Progress in catalytic naphtha reforming process: A review. Applied Energy 109, 79–93. https://doi.org/10.1016/j.apenergy.2013.03.080
Redl, C., Hein, F., Buck, M., Graichen, P., Jones, D., 2020. The European Power Sector in 2019: Up-to-Date Analysis on the Electricity Transition. Agora Energiewende, Sandbag.
REE, 2019. El sistema eléctrico español 2018. Red Eléctrica de España, Madrid.
REE, 2016. El sistema Eléctrico Español: Informe 2015 Producción de energía eléctrica. Red Eléctrica de España.
Rehfeld, M., Fleiter, T. (Eds.), 2017. Integration Erneuerbarer Energieträger in industrielle Hochtemperaturprozesse: Technische Grenzen des Energieträgerwechsels. Fraunhofer ISI, Vienna.
Rehfeldt, M., 2020. A review of the emission reduction potential of fuel switch towards biomass and electricity in European basic materials industry until 2030. Renewable and Sustainable Energy Reviews 16.
Rehfeldt, M., Fleiter, T., Toro, F., 2016. A bottom-up estimation of the heating and cooling demand in European industry. Energy Efficiency 1–26.
REN21, 2020. Renewables 2020 Global Status Report. REN21 Secretariat.
Reus, L., Munoz, F.D., Moreno, R., 2018. Retail consumers and risk in centralized energy auctions for indexed long-term contracts in Chile. Energy Policy 114, 566–577. https://doi.org/10.1016/j.enpol.2017.12.028
Richstein, J.C., 2017. Project-Based Carbon Contracts: A Way to Finance Innovative Low-Carbon Investments. DIW Discussion Papers 1714. https://doi.org/10.2139/ssrn.3109302
Riesz, J., MacGill, I., 2013. 100% Renewables in Australia. Working Paper.
Ritchie, H., Roser, M., 2017. Fossil Fuels. Our World in Data.
RITE, 2008. Overview of the DNE21+ Model. RITE, Kyoto, Japan.
Rivier, M., Gómez, T., Chaves Ávila, J.P., Cossent Arín, R., Sánchez, Á., Martín-Martínez, F., Gerres, T., 2018. Análisis de escenarios futuros para el sector eléctrico en España para el perído 2025-2050. Universidad Pontificia Comillas, IIT, Madrid.
Robinson, D., Keay, M., Hammes, K., 2017. Fiscal policy for decarbonisation of energy in Europe. The Oxford Institute for Energy Studies Paper 22.
Rocchi, P., Serrano, M., Roca, J., Arto, I., 2018. Border Carbon Adjustments Based on Avoided Emissions: Addressing the Challenge of Its Design. Ecological Economics 145, 126–136. https://doi.org/10.1016/j.ecolecon.2017.08.003
Rodrik, D., 2014. Green industrial policy. Oxford Review of Economic Policy 30, 469–491. https://doi.org/10.1093/oxrep/gru025
Rodrik, D., 2008. Normalizing industrial policy (Working Paper No. No. 3). World Bank.
Rootzén, J., 2015. Pathways to deep decarbonisation of carbon-intensive industry in the European Union: techno-economic assessments of key technologies and measures, Doktorsavhandlingar vid Chalmers Tekniska Högskola. Chalmers Univ. of Technology, Göteborg.
Rootzén, J., Johnsson, F., 2016. Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry. Energy Policy 98, 459–469. https://doi.org/10.1016/j.enpol.2016.09.021
Ross, M.H., Thimmapuram, P., Fisher, R.E., Maciorowski, W., 1993. Long-term industrial energy forecasting (lief) model (18-sector version). Argonne National Lab., IL (United States).
Saevarsdottir, G., Kvande, H., Welch, B.J., 2020. Aluminum Production in the Times of Climate Change: The Global Challenge to Reduce the Carbon Footprint and Prevent Carbon Leakage. JOM 72, 296–308. https://doi.org/10.1007/s11837-019-03918-6

Sandin, G., Peters, G.M., Svanström, M., 2014. Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. Int J Life Cycle Assess 19, 723–731. https://doi.org/10.1007/s11367-013-0686-x
Sartor, O., Bataille, C., 2019. Decarbonising basic materials in Europe: How Carbon Contracts-for-Difference could help bring breakthrough technologies to market (Study No. 06/19), IDDRI. IDDRI, Paris.
Sastre, C.M., Gonzalez-Arechavala, Y., Santos, A.M., 2015. Global warming and energy yield evaluation of Spanish wheat straw electricity generation - A LCA that takes into account parameter uncertainty and variability. APPLIED ENERGY 154, 900–911. https://doi.org/10.1016/j.apenergy.2015.05.108
Sato, M., Singer, G., Dussaux, D., Lovo, S., 2019. International and sectoral variation in industrial energy prices 1995–2015. Energy Economics 78, 235–258. https://doi.org/10.1016/j.eneco.2018.11.008
Scalet, B.M., Garcia Muñoz, M., Sissa, A.Q., Roudier, S., Delgado Sancho, L., 2013. Best available techniques (BAT) reference document for the manufacture of glass: industrial emissions Directive 2010/75/EU: integrated pollution prevention and control. Publications Office of the European Union, Luxembourg.
Schaper, R., 2017. Projektsteckbrief Salzgitter Flachstahl GmbH: Leuchtturm energieeffiziente Abwärmenutzung [WWW Document]. Deutsche Energie-Agentur (dena) - Initiative EnergieEffizienz Private Haushalte. URL http://www.abwaerme-leuchtturm.de/leuchttuerme/salzgitter-flachstahl-gmbh/ (accessed 4.9.18).
Scheer, H., 2012. Der energethische Imperativ. Antje Kunstmann.
Schill, W.-P., Zerrahn, A., 2018. Long-run power storage requirements for high shares of renewables: Results and sensitivities. Renewable and Sustainable Energy Reviews 83, 156–171. https://doi.org/10.1016/j.rser.2017.05.205
Schittekatte, T., Meeus, L., Jamasb, T., Llorca, M., 2021. Regulatory experimentation in energy: Three pioneer countries and lessons for the green transition. Energy Policy 156, 112382.
Schlosser, F., Jesper, M., Vogelsang, J., Walmsley, T.G., Arpagaus, C., Hesselbach, J., 2020. Large-scale heat pumps: Applications, performance, economic feasibility and industrial integration. Renewable and Sustainable Energy Reviews 133, 110219. https://doi.org/10.1016/j.rser.2020.110219
Schmid, S., Grosche, P., 2008. Managing the International Value Chain in the Automotive Industry. Bertelsmann Stiftung.
Schmitt, T.M., 2018. (Why) did Desertec fail? An interim analysis of a large-scale renewable energy infrastructure project from a Social Studies of Technology perspective. Local Environment 23, 747–776. https://doi.org/10.1080/13549839.2018.1469119
Schmitz, A., Kamiński, J., Maria Scalet, B., Soria, A., 2011. Energy consumption and CO2 emissions of the European glass industry. Energy Policy 39, 142–155. https://doi.org/10.1016/j.enpol.2010.09.022
Schorcht, F., Kourti, I., Scalet, B.M., Roudier, S., Delgado-Sancho, L., 2013. Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). Publications Office of the European Union, JRC, Luxembourg.
Scott, T., 2013. Closure of the Queensland Gas Scheme.
Sholl, D.S., Lively, R.P., 2016. Seven chemical separations: to change the world: purifying mixtures without using heat would lower global energy use, emissions and pollution--and open up new routes to resources. Nature 532, 435–438.
Shoreh, M.H., Siano, P., Shafie-khah, M., Loia, V., Catalão, J.P., 2016. A survey of industrial applications of Demand Response. Electric Power Systems Research 141, 31–49.
Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel, C., Peteves, S., European Commission, Joint Research Centre, Institute for Energy and Transport, 2013. The JRC-EU-TIMES model: assessing the long-term role of the SET plan energy technologies. Publications Office, Luxembourg.

Simon, F., 2019. European coal power output sees “unprecedented” decline. www.euractiv.com. URL https://www.euractiv.com/section/emissions-trading-scheme/news/european-coal-power-output-saw-unprecedented-drop-in-2019/ (accessed 3.16.21).
SmartCrusher, 2013. Smart Crusher: Results lab crusher and pilot installation.
Smith, C., Hill, A.K., Torrente-Murciano, L., 2020. Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape. Environmental Science 14.
Söder, L., Tómasson, E., Estanqueiro, A., Flynn, D., Hodge, B.-M., Kiviluoma, J., Korpås, M., Neau, E., Couto, A., Pudjianto, D., Strbac, G., Burke, D., Gómez, T., Das, K., Cutululis, N.A., Hertem, D.V., Höschle, H., Matevosyan, J., Roon, S. von, Carlini, E.M., Caprabianca, M., Vries, L. de, 2020. Review of wind generation within adequacy calculations and capacity markets for different power systems. Renewable and Sustainable Energy Reviews 119, 109540. https://doi.org/10.1016/j.rser.2019.109540
Solis, M., Silveira, S., 2020. Technologies for chemical recycling of household plastics – A technical review and TRL assessment. Waste Management 105, 128–138. https://doi.org/10.1016/j.wasman.2020.01.038
SSAB, 2020. Annual Report 2019.
Stede, J., Pauliuk, S., Hardadi, G., Neuhoff, K., 2021. Carbon pricing of basic materials: Incentives and risks for the value chain and consumers. Ecological Economics 189, 107168. https://doi.org/10.1016/j.ecolecon.2021.107168
Ştefãnuţ, L., 2018. Brexit Blues for Romania’s Embattled Garment Industry. Balkan Insight. URL https://balkaninsight.com/2018/07/02/brexit-blues-for-romania-s-embattled-garment-industry-06-11-2018/ (accessed 7.2.21).
Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge.
Street Finance, 2019. Top 10 commodity exchanges in the world - Commodities. Street Finance. URL https://street-finance.com/top-10-commodity-exchanges-of-the-world/ (accessed 2.22.21).
Swalec, C., Shearer, C., 2021. Pedal to the Metal. Global Energy Monitor.
Szabó, L., Bartek-Lesi, M., Dézsi, B., Diallo, A., Mezősi, A., Wigand, F., Anatolitis, V., 2020. Auctions for the support of renewable energy: Lessons learnt from international experiences – Synthesis report of the AURES II case studies (No. Report D2.3). AURES II (AUctions for Renewable Energy Support II).
Taibi, E., Blanco, H., Miranda, R., Carmo, M., 2020. Green Hydrogen Cost Reduction. IRENA.
TATA Steel, 2017. HIsarna: game changer in the steel industry. Tata Steel.
Terwel, B.W., ter Mors, E., 2015. Host community compensation in a carbon dioxide capture and storage (CCS) context: Comparing the preferences of Dutch citizens and local government authorities. Environmental Science & Policy 50, 15–23. https://doi.org/10.1016/j.envsci.2015.01.015
Thomas, S., 2003. The Seven Brothers. Energy Policy 31, 393–403. https://doi.org/10.1016/S0301-4215(02)00135-0
Toktarova, A., Karlsson, I., Rootzén, J., Odenberger, M., 2020. Technical Roadmap Steel Industry. Chalmers University of Technology; University of Gothenburg; Mistra Carbon Exit, Gothenburg.
Tollefson, J., 2018. Sucking carbon dioxide from air is cheaper than scientists thought. Nature 558, 173–173. https://doi.org/10.1038/d41586-018-05357-w
Tollefson, J., 2010. Hydrogen vehicles: fuel of the future? Nature News 464, 1262–1264.
Tsafos, N., 2020. When Natural Gas Prices Converge [WWW Document]. CSIC (Center for Strategic & Internationnal Studies). URL https://www.csis.org/analysis/when-natural-gas-prices-converge (accessed 6.19.21).
Umweltbundesamt, 2016. CO2 Emission Factors for Fossil Fuels.
Umweltbundesamt, 2014. Germany in 2050 – a greenhouse gas-neutral country. Umweltbundesamt, Berlin.
UN, 2015. The 17 goals [WWW Document]. United Nations. URL https://sdgs.un.org/es/goals (accessed 2.25.21).
UNECE, 2019. Working Party on Pollution and Energy (GRPE) [WWW Document]. URL http://www.unece.org/trans/main/wp29/meeting_docs_grpe.html (accessed 7.17.19).

UNEP, KEITI, 2019. Green Public Procurement in the Republic of Korea: A Decade of Progress and Lessons Learne. United Nations Environ- ment Programme (UNEP); Korea Environmental Industry & Technology Institute (KEITI).
UNESID, 2021. Mapa siderúrgico nacional 2021 [WWW Document]. URL https://unesid.org/el-sector-mapa.php (accessed 5.17.21).
Upham, P., Roberts, T., 2011. Public perceptions of CCS in context: Results of NearCO2 focus groups in the UK, Belgium, the Netherlands, Germany, Spain and Poland. Energy Procedia 4, 6338–6344. https://doi.org/10.1016/j.egypro.2011.02.650
UPME, 2021. Balance energetico colmbiano (BECO) [WWW Document]. URL https://www1.upme.gov.co/InformacionCifras/Paginas/BECOCONSULTA.aspx (accessed 5.13.21).
Vaillancourt, K., Giannakidis, G., 2013. Policy Analysis Tools for Global Sustainability (PAT-SUS): E4 systems tools and joint studies. International Energy Agency (IEA).
van der Reijden, R., de Coninck, H., Khandekar, G., Wyns, T., 2021. Transforming industrial clusters to implement the European Green Deal. Climate Friendly Materials Platform, Climate Strategies.
van Ewijk, S., Stegemann, J.A., Ekins, P., 2021. Limited climate benefits of global recycling of pulp and paper. Nat Sustain 4, 180–187. https://doi.org/10.1038/s41893-020-00624-z
Van Kooten, G.C., Eagle, A.J., Manley, J., Smolak, T., 2004. How costly are carbon offsets? A meta-analysis of carbon forest sinks. Environmental science & policy 7, 239–251.
van Laar, R., Corus, D., 2016. Modern blast furnace design. Millenium Steel 2016 35–40.
van Lieshout, M.M., 2015. Update Prioritering handelings-perspectieven verduurzaming betonketen 2015. CE Delft.
van Renssen, S., 2020. The hydrogen solution? Nat. Clim. Chang. 10, 799–801. https://doi.org/10.1038/s41558-020-0891-0
Vazquez, C., Rivier, M., Perez-Arriaga, I., 2002. A market approach to long-term security of supply. IEEE TRANSACTIONS ON POWER SYSTEMS 17, 349–357. https://doi.org/10.1109/TPWRS.2002.1007903
VCI, 2019. Roadmap Chemie 2050 auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland: eine Studie von DECHEMA und FutureCamp für den VCI.
Vellinga, P., 1999. Industrial transformation project, IT: science plan. IHDP.
Vogl, V., Åhman, M., Nilsson, L.J., 2018. Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production 203, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279
Vogl, V., Sanchez, F., Gerres, T., Lettow, F., Bhaskar, A., Swalec, C., Mete, G., Åhman, M., Lehne, J., Schenk, S., 2021. Green Steel Tracker.
Voldsund, M., Gardarsdottir, S., De Lena, E., Pérez-Calvo, J.-F., Jamali, A., Berstad, D., Fu, C., Romano, M., Roussanaly, S., Anantharaman, R., Hoppe, H., Sutter, D., Mazzotti, M., Gazzani, M., Cinti, G., Jordal, K., 2019. Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation. Energies 12, 559. https://doi.org/10.3390/en12030559
Wei, M., McMillan, C.A., de la Rue du Can, S., 2019. Electrification of Industry: Potential, Challenges and Outlook. Curr Sustainable Renewable Energy Rep 6, 140–148. https://doi.org/10.1007/s40518-019-00136-1
Weiss, O., Bogdanov, D., Salovaara, K., Honkapuro, S., 2017. Market designs for a 100% renewable energy system: Case isolated power system of Israel. Energy 119, 266–277. https://doi.org/10.1016/j.energy.2016.12.055
Wiertzema, H., Svensson, E., Harvey, S., 2020. Bottom–Up Assessment Framework for Electrification Options in Energy-Intensive Process Industries. Front. Energy Res. 8, 192. https://doi.org/10.3389/fenrg.2020.00192
Wiese, F., Bramstoft, R., Koduvere, H., Pizarro Alonso, A., Balyk, O., Kirkerud, J.G., Tveten, Å.G., Bolkesjø, T.F., Münster, M., Ravn, H., 2018. Balmorel open source energy system model. Energy Strategy Reviews 20, 26–34. https://doi.org/10.1016/j.esr.2018.01.003
Williams, J., Haley, B., Jones, R., 2015. Policy Implication sof Deep Decarbonization in the United States. Deep Decarbonization Pathways Project, Energy and Environmental Economics, Inc.

Williams, J.H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W.R., Price, S., Torn, M.S., 2012. The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. Science 335, 53–59. https://doi.org/10.1126/science.1208365

Wilson, A., Dobreva, A., 2019. Energy Supply and Security. European Parliamentary Research Service.

World Bank, 2021. Up-to-date overview of carbon pricing initiatives [WWW Document]. Carbon Pricing Dashboard. URL https://carbonpricingdashboard.worldbank.org/map_data (accessed 3.18.21).

World Steel, 2020. Steel Statistical Yearbook 2020. World Steel Association, Brussels.

World Steel, 2019. Steel Statistical Yearbook 2019. World Steel Association, Brussels.

WSP, DNV GL, 2015. Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050. Department of Energy and Climate Change (DECC).

Zeller, T., 2009. Europe Looks to Africa for Solar Power. The New York Times.

Zhao, Q., 2019. Technical and Economic Impact of the Deployment of a VSC-MTDC Supergrid with Large-scale Penetration of Offshore Wind. Universidad Pontificia Comillas, Madrid.

Zheng, J., Suh, S., 2019. Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Chang. 9, 374–378. https://doi.org/10.1038/s41558-019-0459-z

Zhu, Q., 2011. CO2 abatement in the cement industry. IEA Clean Coal Centre.