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A methodological model for assessing Renewable Fuels pathways.

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List of acronyms

1G	First generation
2G	Second generation
3G	Third generation
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
ASTM	American Society for Testing and Materials
AtJ	Alcohol to jet
BEV	Battery electric vehicle
BtB	Biomass to bioenergy
BtB	Biowaste to bioenergy
BtL	Biomass to liquids
C	Carbon
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CH4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO2	Carbon dioxide
CSR	Cellulosic solid residue
DAC	Direct atmospheric carbon capture
DME	Dimethyl ether
E2E	End to end
EBTP	European Biofuels Technology Platform
EEA	European Environment Agency
Efuels	Electrofuels
EJ	Exajoule
ER	Equivalent ratio

ETBE	Ethyl tert-butyl ether
EUAs	EU emission allowances
EUETS	EU Emissions Trading Scheme
FAME	Fatty acid methyl ester
FFA	Free fatty acid
FFV	Flex Fuel Vehicles
FOGS	Fats, oils and greases
FP	Feedstock platform
FPU	Fuel platform
FT	Fischer-Tropsch
G+FT	Gasification + Fischer-Tropsch
G+ME	Gasification + Synthesis of methanol
GHG	Greenhouse gas
GJ	Gigajoules
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
H_2SO_4	Sulfuric acid
HDV	Heavy duty vehicle
HEFA	Hydroprocessed esters and fatty acids
HFO	Heavy fuel oil
HV	Heavy vehicle
HVO	Hydrotreated Vegetable Oil
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
ICCT	International Council on Clean Transportation
IDAE	Instituto para la Diversificación y Ahorro de la Energía
IEA	International Energy Agency

ILUC	Indirect land use change
IMF	International Monetary Fund
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
IRR	Internal rate of return
ITF	International Transport Forum
KWh	Kilowatt hour
LCOE	Levelized cost of electricity
LCOH	Levelized cost of hydrogen
LDV	Light duty vehicle
LPG	Liquefied petroleum gas
MeOH	Methanol
MGO	Marine gasoil
MITECO	Ministerio para la Transición Energética y el Reto Demográfico
MJ	Megajoules
MSP	Minimum selling price
MSW	Municipal solid waste
MTBE	Methyl tert-butyl ether
MtJ	Methanol to jet
MWh	Megawatt Hour
N2	Nitrogen
NaCl	Sodium chloride
NH3	Ammonia
NZE	Net Zero Emissions by 2050 Scenario
OEM	Original Equipment Manufacturer
OPEX	Operational expenditure
P2C	Power to Chemicals
P2G	Power to Gas
P2H	Power to Heat

P2H2	Power to Hydrogen
PtChe	Power to Chemicals
PtG	Power to Gas
PtL	Power to liquids
PtX	Power to X
PV	Photovoltaic
RDF	Refuse-derived fuel
RE	Renewable energy
RWGS	Gasification and reverse water gas-shift
SAF	Sustainable air fuel
SO2	Sulfur dioxide
SPK	Synthetic paraffinic kerosene
SPK/A	Synthetic paraffinic kerosene with aromatics
SRF	Solid recovered fuel
STEPS	Stated Policies Scenario
TEA	Techno-economic analysis
TP	Technology platform
TRL	Technology readiness level
TW	Terawatt
UCO	Used cooking oil
USD	United States dollar
VOCs	Volatile organic compounds
WCO	Wasted cooking oil
WGS	Water-gas-shift
WtL	Waste to Liquids

Abstract

Achieving a global net-zero energy system is imperative to reaching the goals in the Paris roadmap. The transport sector requires complementary measures to electrification by producing carbon-neutral fuels to replace the current industry of liquid fuels. The most straightforward option to achieve this is building up a new renewable fuel industry that will focus on producing electrolytic H_2 and shifting C streams to non-fossil sources.

This research focuses on the economic variables that impact capturing biogenic CO_2, linking the three main factors that should be considered: the biogenic carbon source (feedstock), the conversion technology, and the fuel to be produced. These three factors are interrelated and constitute the so-called renewable fuel pathway.

This research aims to propose a global framework for the economic analysis of the production pathways of these renewable fuels by defining platforms for the three categories (feedstocks, technologies, fuels) grouped because they share common variables.

In addition to its detailed description of these platforms and the dynamics between them in this research, we have conducted two analyses explicitly designed to measure and analyze the impact of various variables on the outcome. The first is a sensitivity exercise for two intermediate fuel pathways where we evaluate the breakeven production cost and other variables. The second exercise includes a techno-economic analysis (TEA) for three Sustainable Air Fuels (SAF) production routes.

The proposed framework simplifies each pathway's economic viability analysis by grouping similar factors that impact its profitability by platform. From the practical application of this framework in both sensitivity cases, the main conclusion emerges that it is a helpful tool for identifying the main variables impacting economic viability; for example, as one of the specific conclusions from the sensitivity exercise, we can infer that long-term challenges to the availability and cost of feedstock supplies are crucial when evaluating a potential investment.

Chapter 1. Introduction

Under the Paris commitments, the journey towards zero energy systems is crucial to a net zero future. Among these energy systems, the transport sector is one of the most challenging to decarbonize because absolute electrification is not viable in key mobility segments like aviation or maritime transport and solutions such as liquid renewable fuels will be needed.

To achieve a net zero transportation system, it is critical to produce carbon-neutral fuels by replacing the current industry of fossil liquid fuels, which cracks crude oil to transform hydrocarbon chains into different products (gasoline, diesel, jet fuel), with an industry that produces liquid renewable fuels synthesizing electrolytic H_2 and non-fossil C (Neves, 2020). This new industry will focus on producing a competitive electrolytic H_2 and shifting C streams to non-fossil sources.

Regarding electrolytic H_2, massive hydrogen production is needed since three moles of H_2 are required to synthesize one mole of CO_2 in a hydrocarbon chain. Also, producing electrolytic H_2 requires significant support from renewable generation (e.g., to produce 1GW of H_2, approx. 5GW solar power will be needed). Thus, competitive production of electrolytic H_2 is closely linked to generating near-zero-cost renewable electricity to decrease the Levelized Cost of Hydrogen (LOCH)[1].

The critical variable in shifting C streams to non-fossil sources will be the cost of capturing biogenic carbon. The three primary cost drivers are the biogenic carbon source (feedstock), the conversion technology, and the fuels to be produced.

These three elements constitute a renewable fuel production pathway. They are interrelated, and the final production cost depends on the specific characteristics of the feedstock chosen, the conversion technology selected, the final fuel being sought, and the relationships mentioned above between the three factors, which differ depending on the chosen route. The main difficulty in assessing the feasibility of a path is precisely the uniqueness of each route.

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[1] We have excluded the technological challenges of producing electrolytic hydrogen from the scope of this work. However, the LOCH will be considered an input in the sensitivity analyses in Chapter 6.

A renewable fuel pathway combines a range of feedstocks and conversion technologies that produce one or more fuels. There are over thirty potential renewable fuel pathways with over nine feedstock categories, twelve conversion technologies, and more than ten different fuels.

This wide range of options in the different routes makes an economic feasibility analysis of any investment project in this area challenging. The limitations, constraints, and relationships between feedstocks, technologies, and fuels must be considered in a full-cycle production approach, from the feedstock origin until the final fuel delivery. An analysis between categories or platforms with common characteristics (feedstocks, technologies, and fuels) and not between individual routes greatly facilitates economic sensitivity exercises.

Considering an investor's point of view, a methodology for approaching investments and their sensitivity exercises that consider the relationships between analogous packages of feedstocks, similar classes of technologies, and equivalent fuels instead of analyzing routes one by one will be critical.

For instance, some renewable fuels (e.g., biodiesel and ethanol) must be blended with fossil fuels to achieve the specifications for fossil fuels. These fuels can be grouped into a platform called substitute. Another category of renewable fuels (e.g., HVO) can completely replace fossil fuels, does not need blending, and can be grouped under the same platform tag drop-in.

Suppose we conduct an investment analysis to select some of the two pathways and produce substitutes or drop-ins. This platform approach will significantly facilitate this exercise instead of examining fuel by fuel route.

Both categories share common elements (in the delivery, there is no need to change internal combustion engine technology in the vehicles, and can use the same logistics and distribution systems as existing systems). However, they also have significant differences. The conversion technologies for producing substitute fuels are well known (grouped in a common platform called catalytic). They have been producing on an industrial scale for a long time and represent a barrier to new investors in developing new technologies, as their implementation costs have already been amortized. In the case of drop-in fuels, the technologies are still under development and need to be scaled up. The advantage of conversion technologies to produce drop-in fuels is that they can treat a wide range of feedstocks considered marginal so far (grouped in a platform called waste) with a consequent impact on lower production costs. In the case of substitute fuels, the natural source of their feedstocks (food crops) will be threatened by regulation, with a consequent increase in production costs. Therefore, platform identification will facilitate the rapid identification of constraints, opportunities, and risks in each pathway without having to go into a detailed analysis of each production route with a specific feedstock for a particular technology with a certain fuel.

When analyzing feedstock platforms, not all variables are equally important in the different platforms. For example, if we refer to all feedstocks that can be categorized as waste, the key variables to be analyzed will be availability (that the feedstock is available in sufficient quantity, reliability and consistency in its supply, and of the required quality), the logistics and sorting needed for the different feedstocks, and how the trading market for these feedstocks is set up (where they can be traded). These variables are different in the case of the platform food crops, for example.

One of the fundamental restrictions between platforms in a pathway is that not all technologies can transform all feedstocks, limiting the options to produce certain types of fuels. Grouping the technologies into categories where they may share common characteristics facilitates their feasibility analysis.

The three technology platforms (biological platform, catalytic platform, and thermochemical platform) grouped technologies under development with commercial technologies but have specific variables to consider that are critical when analyzing the viability of a given investment. For example, in the case of catalytic technologies, the economics of degradation of the catalysts needed for the reactions is a critical variable; on the other hand, in the thermochemical platform, energy efficiency, yield, and selectivity of the process will be the critical variables.

A policymaker will also be interested in this platform approach, allowing him to analyze the impacts of the regulatory tools he can deploy to support the rapid deployment of the renewable fuels industry more quickly and easily. For example, suppose the regulator establishes a system of mandatory quotas to generate demand in a specific sector for the insertion of a particular renewable fuel in the fuel mix of that sector. In that case, this will affect the final fuel market (i.e., as is the case for Sustainability Air Fuel (SAF), a drop-in fuel in air transport) and the technology and feedstock market, stressing the whole cycle.

The policymaker will also want to know how to subsidize undeveloped technologies in the most efficient way to overcome the funding gap, i.e., which technology platform will be the one that, with the minor public funds, manages to reach commercial scale first, alternatively, how to support certain raw materials to build logistics and pre-treatment processes that make them competitive. A global approach to the renewable pathway's end-to-end cycle will help achieve this aim.

Existing research on renewable fuels can be categorized into four main areas: feedstock characteristics of specific biomass sources, specific conversion technologies for converting biomass into renewable fuels, development of renewable fuel specifications, and techno-economic or life cycle analysis of pathways.

The first chapter of this research describes the difficulties of decarbonizing the transport sector and how the massive increase in renewables dramatically reduces power production costs, enables the use of electrolytic hydrogen, and creates an integrated system Biomass to Liquids (BtL) scheme to supply the CO_2 required for making renewable fuels. The second chapter presents a conceptual proposal for a global framework of renewable fuel pathways. The third chapter focuses on the first component of renewable fuel, the feedstock platforms, and explains the three of them and their development challenges. The fourth chapter outlines the second platform of the framework, technologies, comparing the three technology platforms for renewable fuel production. The fifth chapter explains the final platform of the framework, fuels and zooms in on SAF production as an exhaustive example. The sixth chapter details an economic sensitivity analysis applied to two intermediate fuels through two technological routes (within the same platform) with two feedstocks (within the same platform). The seventh chapter evaluates the factors that most affect the production economics of the three SAF production pathways, including a comparison of minimum selling prices among them. The eighth chapter presents the main conclusions of the thesis.

The research makes two principal contributions:

i) A tool of an applicable global framework for analyzing investments related to renewable fuels and assessing the feasibility of a completely renewable fuel pathway considering all elements along the value chain. The paper comprehensively describes the three leading platforms (feedstocks, technologies, fuels) that form the basis of the production pathways, the interrelationship between these platforms and the building blocks that constitute them, and the main factors that influence each. The proposal of this framework is novel in that it provides a highly useful tool for evaluating investments by considering risks at the aggregate pathway level rather than individually.

ii) Two economic sensitivity analyses are practical examples of the global framework's application. The first evaluates several different economic scenarios. It is a comparative economic sensitivity analysis, which applies the framework to two pathways where the technology is fixed (gasification) and the final conversion technology is modified (Fisher Tropsch or Methanol); therefore, the final fuel (syncrude/methanol), and how the feedstocks (MSW and lignocellulose) affect.

In the second exercise, we run a techno-economic analysis (TEA) in which we set the final fuel (SAF) and reach it through three production routes.

The proposed framework's main conclusion is that it simplifies each pathway's economic viability analysis by clustering the equal factors that impact its economic viability by platform (Feedstocks, Technologies, Fuels).

On the other hand, the main conclusions from the application of the sensitivity exercise in Chapter 6 and the TEA in Chapter 7 can be summarized as follows:

-When a specific investment pathway is considered, the challenges to the availability and cost of feedstock supplies in the long term need to be assessed. For example, in the sensitivity case shown in Chapter 6, the most cost-effective production pathways involve using Municipal Solid Waste (MSW) as a feedstock due to its low (even negative) cost. In Chapter 7, the case of the technical and economic analysis (TEA) applied for the three SAF pathways, the Hydroprocessed Esters and Fatty Acids (HEFA) route fed by UCO would be the most competitive SAF production route, given its lower Minimum Selling Price (MSP). In both cases, the feedstock's long-term sustainability must be carefully considered.

-Due to their impact, some inputs to specific processes need to be carefully evaluated in terms of cost. For example, the cost of hydrogen significantly impacts some specific routes, such as Gasification with Methanol, and variations could risk the profitability of this route.

-Not all pathways are equally sensitive to the different levels of public support provided regarding subsidy. Applying the TEA to the three SAF pathways shows a significant difference in the Minimum selling prices of the three cases compared to the Jet A1. The policymaker could extract a conclusion from these data on where to use public support in the most efficient way to bridge this gap.

1.1 Literature Review

This section first describes the challenge of building a net zero energy system for the transport sector (Heavy Duty Vehicles (HVD), aviation, and shipping). It then reviews how the evolution of PtX systems could help to achieve this aim driven by the extension of renewable power and how the subsets driven by this extension, such as Power to Liquids (PtL) and Integrated Power and Biomass to Liquids (BtL), are defined within them. Based on this, we propose a framework for evaluating investments in a renewable fuel pathway based on the three platforms (feedstocks, technology, and products) and their relationships.

1.1.1 Net- zero emissions energy system.

To meet international climate targets, such as limiting the average global temperature increase to no more than 2°C (Davis, 2018), a net-zero emissions energy system is required by the end of this century.

According to its definition, "net-zero emissions systems" are energy systems that do not emit any net CO_2 or greenhouse gases. These systems are expected to be significantly different from current energy systems and will require changes in demand, behavior, and operations, as well as the development of new technological options. Innovative fuel and technology pathways and different policy emphases, such as distributional impacts, will also be necessary. (International Energy Agency, 2023; Azevedo, 2021).

CO_2 emissions from fossil fuels must be neutralized to achieve net zero energy systems. This can be achieved through two methods: (i) capturing CO_2 emissions before or after the combustion process of these fossil fuels and geologically storing the carbon (CCS). (ii) replacing the carbon contained in fossil fuels with a biological source. Fossil fuel usage will depend on costs relative to biofuels, hydrogen, and electricity, as well as the scope and cost of CCS and CDR in the energy system. Given their high energy density and feedstock utility, oil and gas will likely dominate residual fossil fuel demand. (Davis,2018).

Many studies on deep decarbonization modeling emphasize the significance of extensive electrification as a vital decarbonization approach (Williams, 2012). However, having a single electricity solution for some energy system components is only sometimes feasible.

Net-zero emissions systems may rely on hydrogen and renewable fuels for transport, such as long-distance freight transportation, long-haul aviation, and shipping. Segments that rely on energy-dense fuels that cannot be replaced by electricity (Nimmas, 2024; IEA, 2023; Azevedo, 2021; de Blas, 2020; Douglas,2024). These solutions aim to replace fossil fuels carbon with a biological source to produce renewable fuels.

1.1.2 Challenges of achieving net zero in the transport sector.

More than half of global transport CO_2 emissions come from hard-to-abate applications, like Heavy- Duty Vehicles (HDV), Aviation, and Maritime. (Arthur D Little, 2022; Millinger., 2022; Gray, 2021). Since 1970, CO_2 emissions from the transport sector have tripled, accounting for nearly 30% of global final energy demand and 23% of total direct energy sector CO_2 emissions in 2019. (IEA, 2020). This proportion rose to 26% in 2022 and is projected to increase further in the coming decades. Under the current ambitious scenario, passenger demand is expected to grow by 79% by 2050, while freight demand is projected to double. Under a high decarbonization ambition scenario, these increases would be 65% and 59% respectively (IEA, 2024). Due to the increase in CO_2 emissions from transportation, it rose by 28% in 2020 compared to 2000. Furthermore, emissions are projected to increase by 11% by 2050 compared to 2020 (ITF, 2024).

1.1.2.1 Heavy Duty Vehicle (HDV)

Although light-duty vehicles (LDVs) are rapidly moving towards electrification as the preferred technological solution to decarbonization, heavy-duty vehicles (HVD) face specific challenges.

According to a McKinsey report, road freight was responsible for 53% of CO_2 emissions related to global trade in 2021. This percentage is predicted to rise to 56% by 2050. In Europe, road freight contributes 15% of CO_2 emissions, with medium—and heavy-duty trucks accounting for 70% (World Economic Forum, 2021).

Furthermore, global CO_2 emissions from heavy trucks have increased by 5% since 2020. In Europe, if the current growth trajectory of the transport sector continues, CO_2 emissions are expected to increase by approximately 15% by 2030 (Transport & Environment, 2021).

Energy demand by trucks corresponds to 31.7% of the Energy dedicated to road transport, or approximately 636 Mtoe HV transport has limitations in terms of cargo space and payload, which require the use of fuels with high energy density (MJ/m^3) and specific Energy (MJ/kg) for cost-effective operation. It is crucial to use fuels that meet these requirements for economical operation. Many initiatives are underway to improve the efficiency of road transport (i.e., the improvement of the energy efficiency of internal combustion engines (ICE) and the introduction of fuel-saving technologies in all auxiliary units (ignition, air conditioning) (Gray, 2021). To significantly reduce carbon emissions in the sector, it is necessary to implement a combination of measures. More than these measures are needed to achieve deep decarbonization. The industry could be fueled by a variety of sources, including hydrogen in a fuel cell (101 Mtm), hydrogen in an internal combustion engine (ICE) (138.7 Mt), renewable methane (532.3 Mtm), methanol (1475 Mtm), DME (927.7 Mtm), or ammonia (1427.6 Mtm) in an ICE (Candelaresi, & Spazzafumo,2021)

1.1.2.2 Aviation

Depending on the region, air transport is projected to grow by up to 4% annually until 2050. (IATA, 2023). Given the lengthy life cycles of infrastructure investments in this sector, mainly related to engines and aircraft, and the limited range of options such as hydrogen or electrification (Scheelhaase, 2019), the use of renewable fuels appears to be the most viable short-term alternative (Wei, 2019) for decarbonization in the aviation sector.

The aviation industry has been exploring decarbonization options for a while now. However, at present, only short-haul flights can be electrified. For long-haul flights, liquid fuels will continue dominating the industry beyond 2030.

Sustainable Aviation Fuels (SAFs). These can be of the “drop-in” type, kerosene-like fuels, which can be distributed with the same infrastructure and burned in the identical aviation turbines already in use without any adaptation while reducing emissions. Drop-in SAFs represent a quick substitute for conventional jet fuel, are wholly interchangeable or mixable, and can be used 'as is' on currently flying aircraft. Within this category of SAF, biojet is a promising alternative for the aviation industry, especially Hydroprocessed Esters and Fatty Acids (HEFA) derived from vegetable oils, waste lipids, and animal fats. However, this jet fuel must be blended with fossil kerosene to comply with the stringent IATA regulations.

Over 200,000 flights have used various blends of aviation biofuels, but the current proportion of jet kerosene is less than 0.1%. Another critical option the drop-in SAF gives is synfuel, which uses power combined with the Fischer-Tropsch process to produce a liquid drop-in SAF similar to kerosene (De Blasio,2019).

The industry requires Sustainable Aviation Fuels (SAF) that meet high safety standards and are compatible with aircraft fleets and refueling infrastructure. Only with excellent performance in jet engines that meet ASTM D7566 are approved. (Panoutsou, 2021; (Candelaresi, & Spazzafumo,2021)

1.1.2.3 Shipping

Maritime freight transport accounts for approximately 3% of global anthropogenic greenhouse gas (GHG) emissions but is not covered by the Paris Agreement targets. In 2012-18, emissions from shipping increased by 9.6%, from 977 million tons to 1071 million tons of CO_2, driven by growth in global seaborne trade (Daniel & Lee, 2022).

Nearly 90% of global seaborne trade is carried by ships, making international shipping a significant sector of the global economy. Most of the existing fleet runs on conventional fuels, such as heavy fuel oil (HFO) and marine gas (MGO).

In early 2023, the International Maritime Organization (IMO) revised the 2050 Roadmap to achieve zero greenhouse gas emissions from international shipping by 2050, with interim milestones in 2030: - 20- 30% compared to 2008 and - 70%- 80% by 2040.

In addition, in 2024, shipping emissions will be included in the EU cap-and-trade system: the EU Emissions Trading Scheme (EUETS). As a result, shipping companies using European ports will have to monitor and report their emissions and purchase and surrender EU emission allowances (EUAs) for each ton of emissions.

Biofuels are a promising option for decarbonizing deep-sea shipping. They can be used as a drop-in or blended with existing fuels without requiring significant modifications to engines or storage systems (Watanabe et al., 2022; Ghi,, Kansabanik & Gu, 2023).

1.2 Power to X schemes

Power to X" (PtX) refers to a range of technologies that convert electrical power (often from renewable sources like wind or solar) into other forms of energy, fuels, and chemical products (Burre, 2022; de Vasconcelos & Lavoie, 2019; Perner, 2018).The "X" can represent various outputs, such as hydrogen (Power to Hydrogen), synthetic fuels (Power to Fuel), chemicals (Power to Chemicals), or heat (Power to Heat) (see fig1.1).

i)Power to Hydrogen (P2H2): This process uses electrolysis to split water into hydrogen and oxygen using electricity. The hydrogen produced can be used directly as a fuel, in fuel cells, or as a feedstock for chemical processes.

ii) Power to Gas (P2G) This involves converting electricity into gaseous fuels. Typically, it starts with producing hydrogen via electrolysis (P2H2) and then may involve a further step to convert hydrogen and carbon dioxide into methane, creating synthetic natural gas;

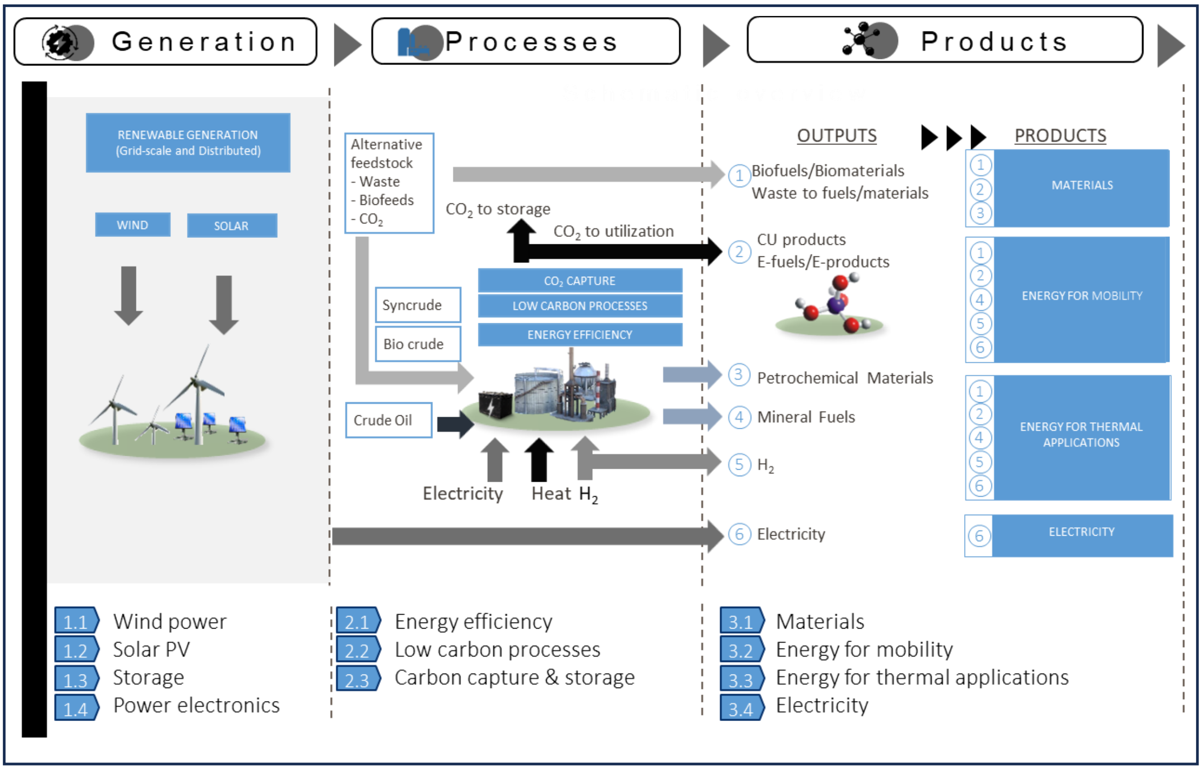
iii) Power to Liquids (P2L): In this process, electricity is used to produce liquid fuels, such as synthetic diesel or jet fuel. This usually involves producing hydrogen first and then combining it with carbon dioxide through chemical processes like Fischer-Tropsch synthesis.

iv)Power to Chemicals (P2C): This involves using electricity to produce essential chemicals like ammonia, methanol, or other industrial chemicals, which can be used as raw materials for various industrial processes.

v) Power to Heat (P2H): This refers to converting electrical energy into thermal energy, which can be used for heating buildings or industrial processes. Technologies like electric boilers, heat pumps, and resistance heaters are commonly used.

The overarching goal of Power to X technologies is to store and utilize renewable energy more efficiently, helping to balance supply and demand, reduce greenhouse gas emissions, and facilitate the transition to a low-carbon economy. These technologies can play a crucial role in sectors that are difficult to decarbonize, such as heavy industry, aviation, and shipping. An example of PtX can be seen in Figure 1.1.

Fig 1.1 A conceptual PtX description



Source: Repsol internal report

One essential condition for building a net-zero energy system is having a substantial and inexpensive supply of electricity that does not emit CO_2. By 2050, renewables are expected to contribute between 30-76% of the global energy mix under different scenarios, such as a continuation of current policies (STEPS), compliance with current countries' voluntary commitments (APS), and a net-zero scenario (NZE). This would double or even triple the current contribution of around 30% in 2022 (IEA, 2021).

Electricity demand is forecasted to increase by 80% to 150% in 2050. This growth will be accompanied by significant development of renewable energy sources, such as solar, offshore, and onshore wind and hydro, in various STEPS, APS, and NZE scenarios. (IEA, 2023).

Over the last two decades, installed renewable energy (RE) capacity growth has highlighted the need to store excess electricity, a critical issue in facilitating the large-scale integration of intermittent renewable technologies into energy systems (Eveloy, 2021).

In addition, the increased installed capacity has coincided with a decrease in the levelized cost of electricity (LCOE). When considering the LCOE calculation methodology on a global scale, the cost of different energy sources has reduced between 2010 and 2022 (IRENA, 2022): solar photovoltaic (-89%), concentrated solar power (-69%), offshore wind (-59%), and onshore wind (-69%).

In 2022, the weighted levelized average cost of electricity (LCOE) of new solar PV, onshore wind, solar thermal, bioenergy, and geothermal projects decreased despite higher material and equipment costs. For greenfield onshore wind projects, the overall weighted average LCOE decreased by 5% between 2021 and 2022, from USD 0.035/kWh to USD 0.033/kWh, while for large-scale solar PV projects, it decreased by 3% to USD 0.049/kWh in 2022 compared to the previous year. For offshore wind, the levelized cost of electricity for new projects increases by 2% compared to 2021, from USD 0.079/kWh to USD 0.081/kWh in 2022 (IRENA, 2023). In 2010, the global weighted average LCOE of onshore wind was 95% higher than the lowest cost fossil fuel-fired power; in 2022, the global weighted average LCOE of new onshore wind projects is 52% lower than the cheapest fossil fuel-fired solutions.

The combination of these three factors: the prominent role of renewables in the energy mix, the need for excess electricity storage capacity, and a significant reduction in LCOE has led to Power to X (PtX) systems gaining traction as an alternative for decarbonization in sectors where alternative solutions are challenging to find. (Burre, 2022; de Vasconcelos & Lavoie, 2019; Perner, 2018)

Several routes exist for the conversion of renewable energy resources into X options: per power-to-gas (PtG), Power- to- chemicals (PtChe), and Power- to- liquids (PtL) (Monitor Deloitte, 2022; The Royal Society, 2019; Brynolf,2018; Perner, 2018); e.g., liquid, gas, fuels, chemicals) through the utilization of climate-neutral CO_2 captured from different sources. A conventional PtX pathway has four main subsystems: power production (RES), hydrogen production (H_2), CO_2 capture and utilization, and fuel upgrading (Trinca, 2023).

1.2.1 Power to Liquids

The power-to-liquids (PtL) concept is based on converting renewable Energy (RE) to liquid fuels and chemicals. These liquids offer the high energy density required for aircraft, ships, and other applications with a high power demand and the need to serve long distances.

The fundamental elements of a Power-to-Liquid (PtL) system consist of green hydrogen, which is needed for the hydrogenation of CO_2 to generate hydrocarbons (Zhang et al., 2019), and carbon derived from climate-neutral CO_2. This climate- neutral CO_2 can be acquired from three distinct sources: the capture of CO_2 from spent fossil fuels, creating so-called recycled carbon fuels; the capture of CO_2 from the atmosphere through Direct Atmospheric Carbon Capture (DAC), allowing for electro-fuels (efuels) (Ababneh, 2022), and the capture of CO_2 from biomass, enabling the creation of renewable fuels (Sheldon, 2014). These two final options produce what are named synthetic fuels.

This research focuses on the third option.

1.2.2 Integrated Power & Biomass to Liquids (BtL)

Biomass to Liquids (BtL) applies to systems that do not require H_2, such as gasification without external H_2, where only the energy contained in the biomass itself is converted. However, to establish a renewable fuel industry, the product resulting from such gasification must be synthesized with electrolytic H_2 to build the corresponding C-H chain.

Therefore, the economic scale for Integrated Power and BtL systems is determined by the LCOE, the LOCH, and the cost of capturing renewable carbon.

Considering both LCOE and LOCH as exogenous variables, the economic scale of Integrated Power and BtL systems depends on the cost of producing renewable carbon and, thus, on the feedstocks, the technologies for their conversion, and the final renewable fuels produced. (Khanal, 2020; Rego de Vasconcelos and Perner, 2019).

Biomass is widely regarded as a carbon-neutral energy source because the CO_2 emitted during combustion is offset by the CO_2 absorbed by trees and plants throughout their lifespan. (Roder and Welfle, 2019). Research indicates that biomass energy production could reach between 200 and 700 EJ per year (Knápek, 2020; Alatzas, 2019), with projections suggesting an increase to between 50 and 1000 EJ by 2050. Currently, biomass contributes approximately 10% of the global energy supply, providing 50 EJ of Energy annually, with its potential for energy generation estimated between 140 and 270 EJ. If this non-used potential were used to produce BTL, this potential could be transformed into 215-415 EJ of BtL fuels.

For example, a promising biomass type could be lipid in energy crops. These lipids are interesting because their composition is close to hydrocarbon composition, and their energy density is much higher than average. Lipids are conventionally a mix of triglycerides and free fatty acids (FFAs) that can be transformed into fuels by hydrogenating oxygenates or transesterification. The raw material used determines the structure of the fatty acid. The different structures of fatty acids in the oil can impact the degree of saturation and unsaturation, which can affect the length of the carbon chain. Renewable fuel is composed of long-chain fatty acids, which means that the fatty acid profile of the biomass source is one of the most critical factors that influence the formation of efficient carbon-hydrogen chains in producing renewable fuels. As a result, it is one of the most extensively studied factors in the upstream chain of renewable fuels (Singh and Dipti, 2010).

Chapter 2. Building Renewable Fuels Pathways

The following chapter presents a conceptual proposal for a global framework of renewable fuel pathways. Subsequent chapters 3, 5, and 6 describe these pathways' three fundamental components.

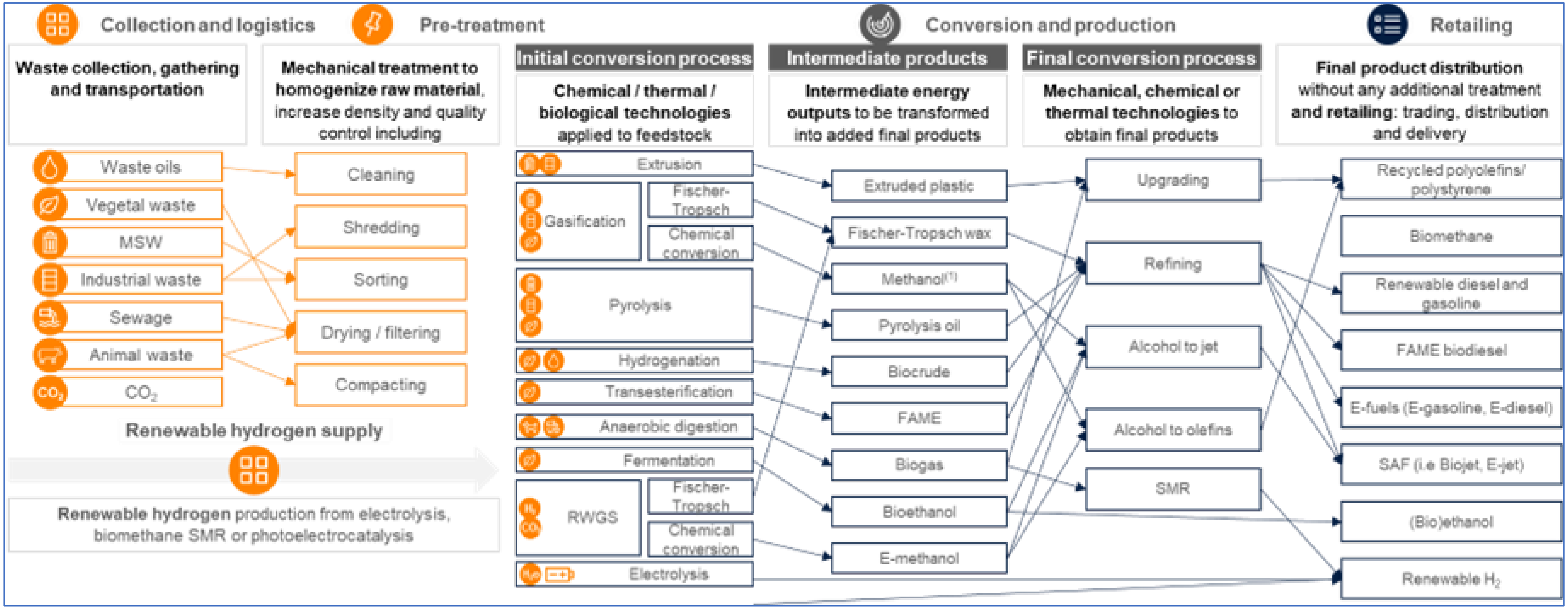
When investing in a renewable fuels development project, it is essential to consider the profitability variables associated with the specific technology and the investment potential of the different complete pathway alternatives, considering the feedstocks, technologies, and resulting products.

In recent decades, the renewable fuels industry has undergone significant evolution. It started with producing biofuels such as ethanol or biodiesel (FAME), but now it incorporates numerous feedstocks and technologies to produce different types of fuels. The final product's labeling depends on the origin of the biofuel feedstock utilized, which highlights the potential fuel pathways that can result from combining different feedstocks and technologies. This gives rise to the concept of fuel pathway, which involves examining three factors: the feedstock, the technology, and the final product, to determine the feasibility of producing a specific renewable fuel.

There are over thirty potential renewable fuel pathways, nine feedstock categories, twelve conversion technologies (grouped into three platforms), and more than ten different fuels (see Figure 2.1).

The challenge is performing standardized investment analysis for different pathways without revealing too much specific detail about the feedstock, technology, or fuel involved.

Figure 2.1: Classic Renewable Fuels Pathways description



Source: Repsol Internal document; Monitor Deloitte (2020)

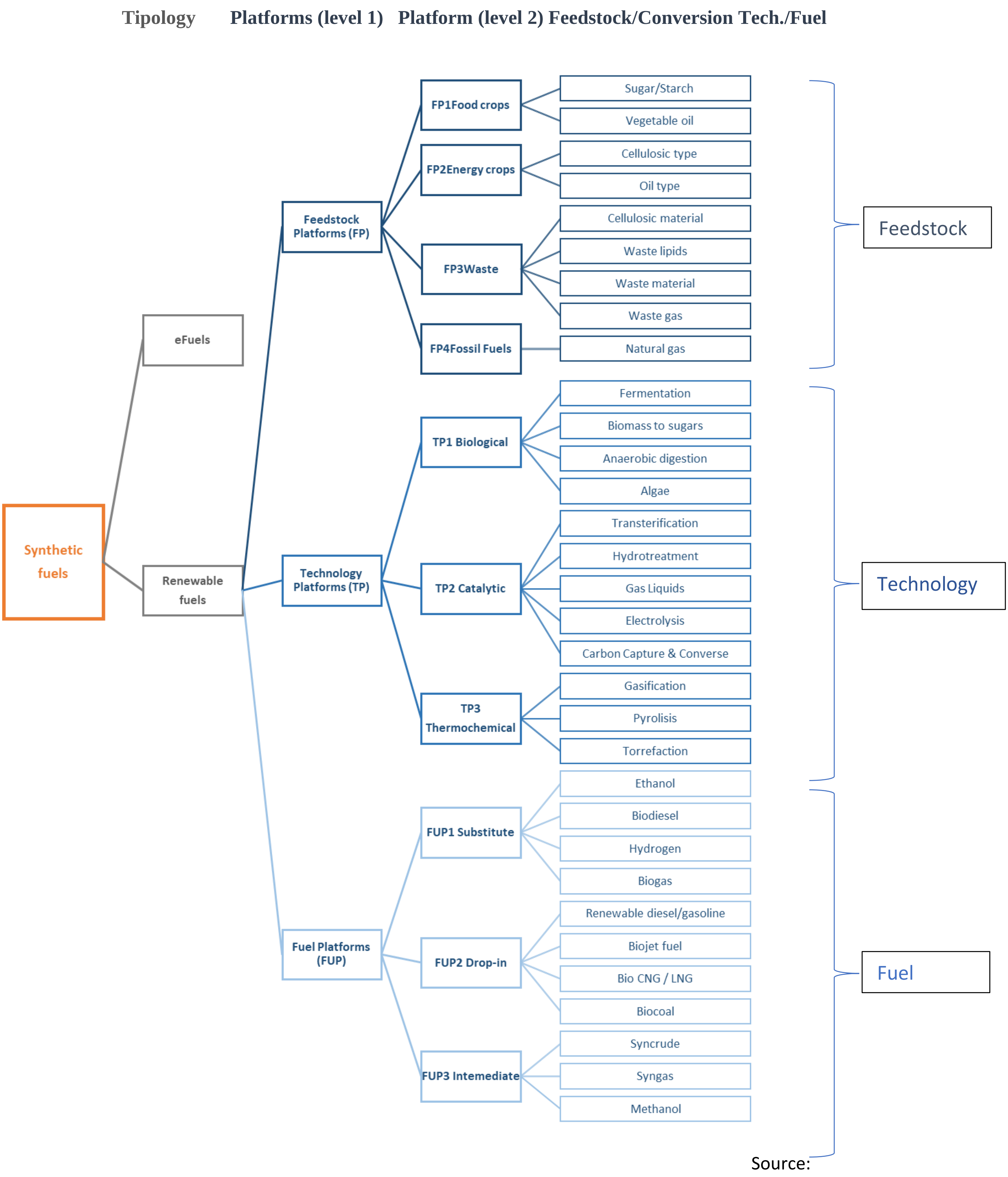
Figure 2.1 shows a classic description of the different possible pathways for producing renewable fuels in great detail. This very granular description makes a standard application of criteria to be considered in an investment analysis difficult. In general, the feedstocks part starts from the singular origin of the individual feedstocks (sources) without grouping them according to shared characteristics or similar problems. This implies that the corresponding discussion of the pathway is too specific to a particular feedstock and the technologies that can convert it (e.g., waste oils can go through gasification (in both versions with and without RWGS), pyrolysis, hydrogenation, and transesterification. Each of these linkages produces a specific pathway). Considering the final products as the third variable in a pathway, several production methods converge in the same final product with different analyses closely associated with the corresponding technology. It complicates the analysis for intermediate products such as syncrude or syngas, which can already play a relevant role in adopting different pathways (e.g., liquid fuels or materials) without going through the final conversion step. In the technology segment, the description shown in Figure 1. 2 makes it difficult to understand the similarities and differences between the proposed technologies (e.g., Gasification and Reverse Water Gas-Shift (RWGS), technology is a chemical process that converts carbon dioxide (CO_2) and hydrogen (H_2) into carbon monoxide (CO) and water (H_2O) through a process, a catalyst, typically containing metals such as iron, copper, or nickel, facilitates the reaction at high temperatures (ranging from 500 to 1000°C) are shown as two different technologies where RWGS is a variant of the first.) (RWGS). Additionally, the openness of the final conversion technologies complicates the analysis of the individual pathways.

The proposed framework (see Fig. 2.2) could contribute to renewable fuel production. It groups the three components of the pathways into platforms with similar characteristics, simplifying the analysis of the relationships between the different platforms. This standardization allows the framework to be applied universally for other routes. For instance, in the case of Feedstocks, there are three platforms: food crops, energy crops, and waste, each with unique characteristics (see Chapter 3). Similarly, the Technologies are grouped into three platforms: biological, catalytic, and thermochemical, each with distinct conversion capacities, various feedstock pre-treatment needs, diverse operating conditions, different final product production capacities, and dissimilar states of maturity.

In this research, although we briefly describe the technologies within the biological platform, we have focused more on the detailed description of the catalytic and thermochemical platform and specifically on the transesterification and gasification technologies, respectively, as they are currently the most promising in the development of renewable fuel production projects (see Chapter 4). Finally, in the case of final Fuels, we grouped them into three platforms: substitutes, drop-ins, and intermediates. In the case of substitute products, they share the characteristic that they need to be blended with fossil fuel fractions for consumption. In the case of drop-in products, they can be used directly in today's engines in their pure form without the need for blending. We have proposed to put the platform of intermediates at the same level as products because it clarifies the analysis of the different routes to choose from (see Chapter 5). We have focused on liquid renewable fuels. Gaseous fuels and hydrogen are beyond the scope of this paper.

This approach using platforms that group feedstocks, technologies, and fuels also allows a more aggregated analysis of life cycle environmental impacts, visualization of developments in the regulatory framework that may apply to complete blocks of any of the three building blocks, and easier detection of competition for resources or speeds of the evolution of the associated technologies.

Figure 2.2. A renewable fuels pathways framework based on platforms.



Source: Daliah (2017) and self-elaboration.

We will briefly describe, as an example, the four main variables impacting the pathway analysis triggered by the proposed framework.

Feedstock Platform FP1 Food crops
Feedstock: Sugar/starch
Technology Platform TP1 Biological
Conversion technology Fermentation
Fuel Platform FUP1 Substitute
Fuel: Ethanol

This is the most common and developed way to make alternative fuels. Ethanol made from sugar/starch crops is called 1G ethanol. It has a capacity of about 132.475 m3 annually, mainly in the USA and Brazil. The way to make it is well-established, with few chances for significant changes in production methods. The crops cost 60% of the total production cost. It is not as cheap as gasoline when oil is $50 per barrel, but it is strongly supported by subsidized volume limits, which have made it a big part of gasoline markets with different mixing levels. 1G ethanol emits the most carbon of all biofuels at 80gCO_2/MJ. The 1G ethanol way has little competition along the value chain. However, it may face challenges from the food vs. fuel debate and places like China or India regulating against it. This is the only way that uses the same crops. From a technology perspective, its main competitor, biomass to sugars, is still new and scaling up. It is not a commercial threat in the short term.

Feedstock Platform FP1 Food crops/FP2 Waste material
Feedstock: Sugar/starch/Waste liquids
Technology Platform TP2 Catalytic
Conversion technology Transesterification
Fuel Platform FUP1 Substitute
Fuel: Biodiesel

Biodiesel production is the second most crucial biofuel pathway. Initially, it used vegetable oils from food crops, but now it primarily uses Waste/FOGS. This method is widely utilized in the EU and ASEAN regions. The biodiesel sector has made significant advancements, with worldwide demand for FAME reaching 12M m3 and installed capacity concentrated mainly in the USA, Argentina, and ASEAN (IEA, 2024). Biodiesel is cheaper than diesel and has entered the market through quotas, subsidies, and tax breaks. In terms of reducing CO_2 emissions, biodiesel has an impressive impact because its carbon intensity ranges from 25gCO_2/MJ with waste FOGS to 55gCO_2/MJ with vegetable oils.

This pathway competes with others for feedstock availability. Similar to the sugar/starch pathway, the availability of vegetable oil feedstock depends on the food vs. fuel issue, and waste feedstock collection is complex. Furthermore, from a technological standpoint, hydrotreatment can produce a better product (HVO) using the same waste feedstock, causing transesterification to lose out in the entire value chain. The regulatory outlook for biodiesel could be improved since the increase in blending percentages is being challenged.

Feedstock Platform: FP2 Waste material
Feedstock: Waste solids/Waste liquids
Technology Platform: TP2 Catalytic
Conversion technology: Hydrotreating
Fuel Platform: FUP2 Drop-in
Fuel: HVO

This is the first commercial-scale process to make a drop-in. The production is large-scale but only for some companies and technology developers. The global capacity for hydrotreated drop-in fuels is 3.785 m3 per year. Like FAME or biodiesel, HVO's feedstock cost is 60% of the total cost. The H_2 also adds more cost. The CO_2e reductions range from 20 to 50 gCO_2/MJ, depending on the feedstock. As a drop-in, it does not need any vehicle infrastructure change. It has a strong value proposition across the value chain. HVO is better than FAME and may take some of its market share. In terms of technology, gasification will be a competitor in the next decade. The regulations support the drop-in scenario, making this pathway the leader for the others. Worldwide, the current demand for HVO is 10,000 Dm3 (for 2017-22) and will rise to over 18,000 Dm3 (adding HVO and biojet) by 2028. (IEA, 2024)

Feedstock Platform: FP2 Waste material
Feedstock: Waste solids/Waste liquids
Technology Platform: TP3 Thermochemical
Conversion technology: Gasification
Fuel Platform: FUP3 Intermediate
Fuel: Syngas

This thermochemical process is crucial as it produces drop-in fuels. Traditionally used for generating power, gasification can convert syngas into Sustainable Aviation Fuel (SAF) through catalytic processes like Fischer-Tropsch (FT). Despite being well-developed, these technologies still require further industrial integration. Large-scale production plants are anticipated to be operational by the end of the decade. One of its key benefits is the ability to process a wide range of waste, making it a superior alternative to waste incineration.

Chapter 3. Feedstock Platforms

In this chapter, we describe the evolution of the naming of feedstocks closely associated with creating the pathway concept. Subsequently, we detail the characteristics of the FP3 Waste material platform and illustrate the resource's availability and each source's defining characteristics.

Regarding feedstocks, a substantial corpus of research describes macro routes to CO_2-neutral energy systems. These systems share certain characteristics but differ in their specific applications. The literature on this topic includes descriptions of the low-carbon advanced fuel processes Power to Gas (PtG), Power to Liquids (PtL), Biomass to Liquids (BtL), and Waste to Liquids (WtL). However, research has yet to develop a connection between these processes or describe their differences. Furthermore, there are a large number of similar terms that do not refer to the same thing and often have overlapping areas of work. These include Biomass to Bioenergy (BtB), Biowaste to Bioenergy (BtB), Bioconversion process and circular bioeconomy, and so on (Ahmed, 2023).

Paradoxically, it is necessary to start with the end products (fuels) to describe how the classification of feedstocks has evolved. Historically, the concept of a pathway as a construction of different related but independent elements has yet to be explicit from the beginning, and the name of a biofuel also included the origin of the feedstock and the technology used (see tables 3.1, 3.2). Therefore, before delving into renewable fuel production methods, it is crucial to understand the evolution of the definition of biofuels, as this can lead to confusion in describing these methods.

3.1 Biofuels Classification Evolution

Academic literature extensively discusses biofuel classification. Typically, biofuels are classified based on three main criteria: the origin of the feedstock, the conversion or production technologies used, and the characteristics of the final product. The final biofuels are produced using specific technologies that depend on the feedstock source.

A schematic classification of biofuels can be divided into conventional and advanced categories (Table 3.1) based on technology maturity as a criterion for defining conventional or advanced.

Table 3.1: Classification of Biofuels

	Conventional biofuels	Advanced Biofuels		
Tech Stage	Commercial	Early commercial	Demonstration	Research
Bioethanol	Sugar and starch			
Biodiesel	Transesterification	HVO	BtL	Microalgae
Biomethane	Biogas		syngas	

Source: Pandey A. (2019)

However, the most common classification uses the origin of the raw material as a criterion to decide what is advanced and what is not. For example, in Pandey's table, HVO is considered advanced. However, when considering the origin, we have first-generation HVO if we use palm or soya oil as the raw material and advanced oil if we use residual lipids.

However, Table 3.1's classification must be revised as it combines conversion technologies and biomass origin with end products. Additionally, identifying the feedstock's origin is crucial in determining its impact on the food chain.

The need for classification schemes for biofuels that consider feedstock origin, conversion technologies, and results was identified early on. This has resulted in schemes that categorize biofuels into generations based on feedstock origin and competition with the food value chain, ranging from 1G to 3G or defined as first to fourth generation (Table 3.2).

Table 3.2: Biofuels Alternative Classification

Source	Subgroup		Specific	Generation
Plantation	Crops	Food	Corn, wheat	1G
		Non food	Cassava	1.5G
	Oil bearing crops		Jatropha	
	Cellulosic crops		Fast growing grass	2G
Nonplantation	Agricultural residues		Corn, cob, straw	
	Forestry residues		Forest residues	
	Waste oil		Waste cooking oil	
Algae			Algae	3G

Source: Pandey A. (2019)

This classification does not associate feedstocks with end products. Alternative proposals have been made to name biofuels based on the link between feedstock and the final product.

Therefore, the above classification systems must be improved to establish renewable fuel pathways and deployment roadmaps. One of the main issues is that the technology required to manufacture the end products needs to be explicitly visualized. Although the technological variable is implicit in this definition, it is not explicit, complicating the economic appraisal of the different production routes. Another must explicitly mention intermediate products that can pivot between final products, such as syngas (Panoutsou, 2021).

Chapter 1 underlined the importance of considering the pathways. Therefore, the proposed Table 3.3, contrary to the previous classifications, only attempts to group some things in the classification (raw material, conversion technology, and end product). It is the first piece to assess the feasibility of deploying a given pathway of renewable fuel production.

Table 3.3: Feedstock Platforms

Feedstock Platforms	Feedstock	
FP1 Food Crops	Sugar starch	Corn, Sugarcane, Wheat, and Rice
	Vegetable oil	Soybean, Canola, Palm, Camelina and Rapeseed
FP2 Energy Crops	Cellulosic type	Switchgrass, Miscanthus, Sorghum, and Poplar
	Oil- tape	Pongamia, Jatropha, Castor and Carinata
FP3 Waste	Waste lipids	Waste oils, fats, and greases (FOGS) come from domestic, commercial, and industrial sources. Examples include cooking oil (UCOs), animal fats, and corn oil.
	Waste materials	Municipal solid waste (MSW), food waste, industrial waste, and plastic waste
	Cellulosic material	Forestry and agricultural residue. Forestry residues are wood chips and sawdust, and agricultural residues are corn stover, sugarcane bagasse, wheat straw, rice straw, rice hull, palm kernel, and empty fruit bunches.

Source: Kumar (2019; Daliah (2017); Doliente(2020) and self-elaboration.

The choice of a particular feedstock for the production of renewable fuels will depend on several factors, such as availability, recurrence of source generation, cost of production, competition with other production chains such as food, need and cost of pretreatment prior to conversion, conversion efficiency profile, creation of fatty acid profile, and competitiveness of logistics for collection and disposal at the conversion sites (Prussi, 2022; Kumar & Verma, 2021; Panoutsou, 2019; Zwart, 2006)

3.2 Feedstock Platform FP3 Waste

Nevertheless, the development of renewable fuels requires the utilization of wastes as feedstock to provide the carbon required for the reaction. The three principal categories of waste employed are lipid waste, solid waste, and cellulosic waste. See table 2.4. (Das and Tiwari, 2018; Kassargy, 2018; Galadima and Muraza, 2015)

The transformation of these wastes into renewable fuels is a complex process. To achieve this, it is necessary to consider the specific characteristics of the waste in question. For instance, while lipidic waste can be converted into renewable fuels (such as HVO) with commercial or near-commercial technologies, solid waste is not the case. It is necessary to scale up solutions such as gasification to achieve economies of scale. In the case of lignocellulosic waste, it is essential to extend technology development efforts over several years, as conversion technologies such as pyrolysis are not yet available for efficient production from this feedstock. Conversely, the availability of waste at a competitive cost would be in the following order: waste lipids, solid waste, and cellulosic waste.

As previously discussed, securing a sufficient supply of suitable waste feedstocks is a crucial hurdle in the widespread implementation of renewable fuels (Yazdanparast, 2022; Panoutsou, 2020; Zwart, 2006).

In this regard, several studies try to address this question:

- In Europe, up to 465 million tonnes of waste could be available for collection between 2030 and 2050, including 3 million tonnes of lipid waste, 112 million tonnes of municipal solid waste, and up to 161 million tonnes of lignocellulosic residues from agricultural waste, and 190 million tonnes from forests (Manfred, 2023; EEA, 2020; Eurostat; Kichner, 2024).

- In 2018, 22.3 million tonnes of MSW were generated annually. Of this, 4 Mta were recycled, 3.8 Mta were dedicated to compost, and 2.6 Mta were destined for incineration. Additionally, 11.9 Mta were sent to landfill after being rejected by the plant (source: MITECO).

- In Spain, more than 18.7 Mt of biomass (forest, agricultural (herbaceous, and woody) is available annually out of a total estimated potential of 46.8 Mt. (IDAE, 2021; Karras, 2022).

- Forest residue is abundant in Spain (up to 6.6Mtpa). Spain is a significant producer of biomass resources, ranking third in the E.U. in terms of absolute woodland area. However, its use of biomass is lower than the European average, at 35% compared to 61% (Camia,2021; EEA, 2023) ~57% of Spain's surface is covered by forests, which positions Spain as the second country in the E.U. with the most significant area covered by forests and potential forest residue 6.6Mtpa (Estrategia Española para el desarrollo del uso energético de la biomasa forestal residual, Ministerio de Medio Ambiente y Medio Rural y Marino, 2010).

3.2.1 Waste Lipids

Waste oils can be categorized into the following types:

- Used cooking oils produced by households and restaurants.
- Animal fats
- Waste lipids produced as byproducts of agrifood or other industries such as paper.
- Oils from energy crops produced in degraded land or as a cover crop.

Utilizing these waste oils requires additional processing to handle the high-temperature-acquired acid and eliminate any residues.

Greases can be obtained from animal fats: i) Yellow grease is derived from cooking oil used in commercial and industrial cooking operations. It may also contain rendered animal fat; ii) Brown grease: Waste grease recovered from traps installed in the sewage lines of restaurants/food processing plants and wastewater treatment plants (Tao, 2017).

Raw feedstocks typically require pretreatment to meet fuel specifications by reducing total metals, phosphorus, moisture, and impurities. Pretreatment processes include general degumming to reduce phosphorus and some metals and bleaching to adsorb contaminants and refine the feedstock. Filtering, centrifuging, and decanting are also done to remove impurities, soil, and moisture (Cárdenas, 2021).

3.2.1.1 Used Cooking Oils (UCOs)/Wasted Cooking Oils (WCO)

Used Cooking Oil (UCO) is a category that deserves special attention in the lipid residues. UCOs are derived from oils used for frying and cooking in households, restaurants, hotels, and other institutions.

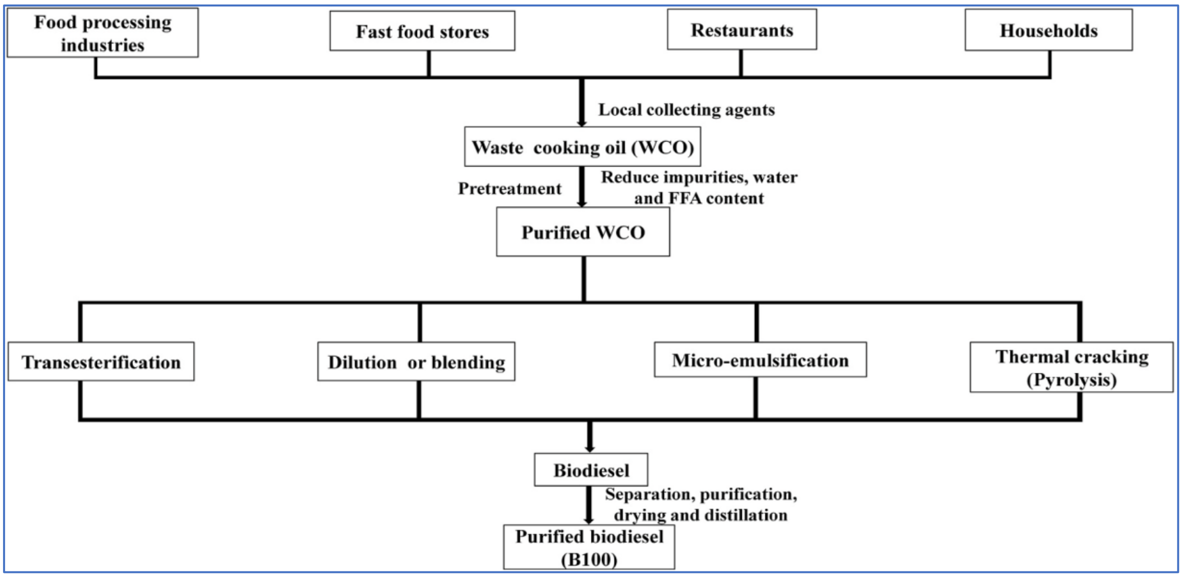
Most Wasted Cooking Oil (WCO) is disposed of improperly, such as thrown into a dustbin, drainage system, or onto soil. This causes a lot of environmental issues. However, instead of disposing of WCO, it can be used as a feedstock for producing biodiesel, which is economical due to its low cost. Unlike edible oils, using WCO as a feedstock does not create a food vs fuel crisis. WCO is also readily available and does not cause any environmental issues. However, WCO has a high FFA (free fatty acid) and water content, which makes its transesterification reaction (a process used to produce biodiesel) very difficult. Therefore, UCO (used cooking oil) must be pretreated or esterified with acid before its transesterification reaction (Monika, 2023).

In 2019, 1100 kt of used cooking oil (UCO) were produced in the E.U., of which 166 kt were produced in Spain and 106 kt were collected (Transport & Environment, 2021; Van Grinsven, 2020).

Depending on their origin, UCOs are composed of different types of oil, such as rapeseed, sunflower, or olive oil. They comprise triglycerides (>95%) with unsaturated chains between 14 and 22 carbon atoms. The level of unsaturation and the distribution of single, double, and triple bonds vary considerably between oils. This variation affects the amount of hydrogen consumed and the associated exothermicity for each oil.

UCOs require pretreatment before conversion. This is due to the presence of impurities and the degradation of oils during the frying process. Pretreating aims to remove solid impurities (for example, UCO can have high levels of sodium and inorganic chlorine due to the presence of NaCl from the addition of common salt during frying), remove moisture, and neutralize FFA. (which can react with alcohol (methanol) to form soaps instead of biodiesel and hinder the separation process) before transesterification (Chanphavong, 2023; Tan, 2023; Adhikesavan, 2022; Awogbemi, 2021). As an example of a UCO or WCO route, Figure 3.1. shows the different pathways to obtain a B100 biodiesel (drop in fuel).

Figure 3.1. Purified biodiesel B100 route from WCO



Source: Digambar (2021)

3.2.2 Waste Materials

3.2.2.1 Municipal Solid Waste (MSW)

Although Municipal Solid Waste (MSW) can be utilized as a substrate for creating valuable products and energy, managing it presents numerous challenges. One of the primary obstacles is the high variability in both regional and seasonal composition and volumes, which can impact the emissions generated during incineration. The high moisture content also increases the weight and volume of MSW., necessitating drying before transportation. This process is both energy and cost- demanding, increasing the total process cost. However, MSW is generated in almost every residual area, and introducing a decentralized system where low-volume facilities locally use MSW can help avoid the need for drying and long-distance transportation (Matsakas, 2017).

Mechanical biological treatment plants produce biogas, commonly used to generate electricity. The waste stream can also be upgraded to recover materials such as plastic, paper, cardboard, aluminum, and metal (Hameed, Z, 2021; Grande, L., 2021).

Compost is produced through the selective collection of organic waste, followed by anaerobic digestion in digesters and treatment in tunnels. Refining rejection is produced when unsuitable materials are removed from the compost. This stream typically consists of fines, such as small broken glass and olive pits.

After maturing in tunnels, the all-in-one collection produces a pseudo-compost known as digestate. This can be applied to the field as waste but not as fertilizer. The waste that goes to landfills consists mainly of plant rejection, known as Solid Recovered Fuel (SRF), which typically accounts for over 50% of the input. The fraction of Municipal Solid Waste (MSW) that cannot be recycled can be combusted or converted to syngas and then used for energy or processed into renewable biofuels.

3.3 Lignocellulosic Material

3.3.1 Forestry and Agricultural Residue

Forest biomass residue is the waste from forest treatment and exploitation for protection and improvement. To further utilize this residue, it is mainly transformed into pellets, which serve as biofuel for heat or power production. The wood biomass can also be obtained from the Wood Products Industry, mainly furniture manufacturers. However, many companies reuse their waste in their production process, and the amount of wood available is limited (Alalwan, 2019).

The cell wall of lignocellulosic biomass is a complex mixture of components. It is composed of two carbohydrate polymers, cellulose (40%–50%) and hemicellulose (20%–30%), as well as one non-carbohydrate phenolic polymer, lignin (10%–25%). Cellulose is a crystalline polymer of glucose (C6), while hemicellulose is composed of both hexose (glucose, galactose, and mannose) and pentose (xylose and arabinose) sugars. Lignin is a three-dimensional network composed of three phenylpropane units: coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol.

To produce fuel or chemicals from lignocellulose, the polymers must be separated.

This can be achieved through two technology platforms: biological or thermochemical conversion processes (Zhongyang, 2023; Naz, 2020). Biotechnological conversion, on the other hand, converts sugars into biofuels such as ethanol or butanol through fermentation using enzymes and microbial cells. This route requires pretreatment (physical, chemical, biological, or thermal) before entering the enzymatic hydrolysis reactor to convert cellulose and hemicellulose into fermentable sugars (Singhania, 2017). Thermochemical conversion methods, such as pyrolysis and gasification, involve breaking down lignocellulose directly at high temperatures.

The primary challenge in producing cellulosic ethanol via biological means is the high dosage of cellulase required, which accounts for a significant portion of the technology's cost. Enzyme costs have been a significant barrier to industrial second-generation ethanol production. However, since 2005, they have decreased by 80% (VTT, 2023).

Cellulases are currently the third-largest industrial enzyme worldwide in terms of dollar volume. They are used in various industries, including cotton processing, paper recycling, juice extraction, and animal feed additives.

Cellulases will play a crucial role if enzymatic ethanol production from lignocellulosic biomass becomes a primary mode of transportation.

3.3.2 Agricultural residue

Agricultural waste is produced during crop cultivation, including unused parts of agricultural produce and waste generated during land preparation for the next season.

Agricultural waste originates in two ways: (i) through regular agricultural activity, which extracts the plant parts needed for production and leaves behind stalks and leaves, and (ii) through primary processing of the product, which contains seeds, roots, and husks.

Agricultural residues are usually starchy or cellulosic, and few are nitrogen-rich. Most residues contain approximately 40% cellulose, 30% hemicelluloses, and 25% lignin. The composition may vary depending on the nature of the biomass (Singhania, 2017).

In 2018, Spain generated 23.7Mt, making it the second-largest agricultural producer in Europe. (MITECO on waste generated by crop per ha and MITECO2018 data for cultivated land per crop in Spain).

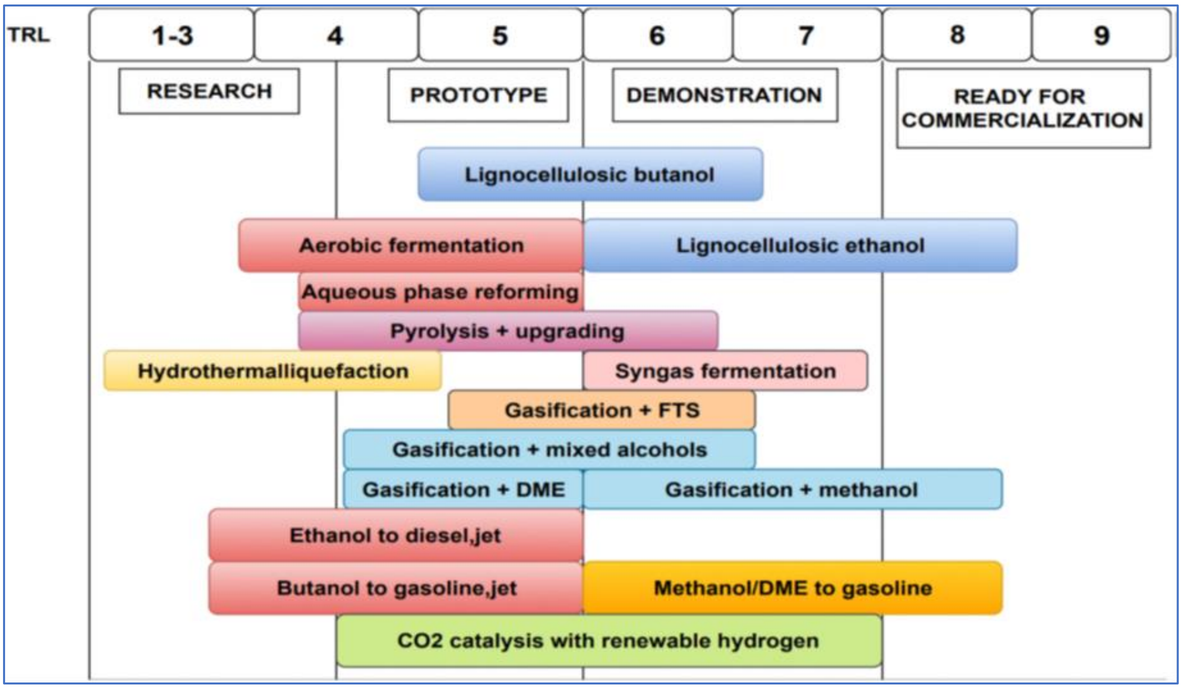
Chapter 4. Technology Platforms (TP)

Regarding conversion technologies, numerous papers (Shahbaz, 2021; Shivananda & Dasappa, 2016; Ullaha, 2018; Meurer & Kern, 2021) delve into specific technologies and their developmental stages. However, these discussions often occur in isolation, failing to connect them to the entire cycle of feedstocks and end products. For example, a significant body of research defines biorefineries as the heart of the new molecule synthesis industry. Unlike traditional refineries, biorefineries stand out as they use biomass as feedstock instead of fossil oil feedstock. There is an academic approach where, in the context of net zero systems, the biorefinery itself is considered the fundamental building block of the net zero systems instead of the renewable pathways. This concept, while related, goes beyond the scope of this research (Vogt & Weckhuysen, 2024; Pyrgakis & Kokossis, 2019; Serna, García-Velásquez & Cardona, 2018; Sammons, 2008).

In Chapter 2, we learned that to analyze renewable fuel production processes, we must examine the technologies being used. These technologies can be grouped into three platforms: biological, catalytic, and thermochemical, each with various technologies at different stages of development. Table 4.1 shows an example of the TRLs of several of these conversion technologies.

Before choosing the best process to optimize the final product's yield, it is essential to understand how all the reaction conditions or parameters affect the efficiency of the biomass conversion process. The investment choice in specific technologies depends on their level of development, modularity, CAPEX, OPEX, size, and other factors. As shown in Figure 4.1, each conversion technology is at different stages of technological development (TRL).

Figure 4.1 TRLs of several conversion technologies



Source: Kargbo, Stuart & Anh (2021)

This chapter will describe the catalytic technology platform, particularly in transesterification, and the thermochemical technology platform, particularly in gasification. The first example refers to a commercial technology with several production plants. The second example is one of the most promising technologies due to its versatility in treating a wide range of feedstocks. Additionally, it could create syngas as an intermediate product.

Tabla 4.1 Technology platforms

Technology Platform	Conversion Technology	Description
TP1Biological Platform	Fermentation	Yeast conversion of sugar/starch feedstock into alcohols is the most mature alternative fuel technology primarily used to produce ethanol. These conversions occur at low rates of reaction and temperature.
	Biomass to sugar	Physical or chemical pretreatment followed by enzymatic hydrolysis to convert food crops, energy crops, and waste cellulosic material into sugars. Sugars are converted via fermentation to produce cellulosic ethanol. These conversions occur at low rates of reaction and temperature.
	Anaerobic digestion	Methanogenic bacterial conversion of organic waste into biogas, a mixture of methane and carbon dioxide
	Algae	Photosynthetic conversion of carbon dioxide for algae growth. Algae is then harvested for algal oil and biomass for further processing into end products.

TP2Catalytic Platform	Transesterification	Low- temperature conversion of oil-based feedstock (i.e., waste lipids) into biodiesel using an acid or base catalyst.
	Hydrotreatment	Hydrogen and solid catalysts convert oil-based feedstock into (HVO), naphtha, and LPG at high temperatures.
	Gas to liquids	Low- temperature conversion of oil-based feedstock into biodiesel using an acid or base catalyst.
TP3Thermochemical Platform	Gasification	Cellulosic materials and waste solids can be converted into syngas by adding an oxidizing agent (e.g., oxygen) and heating to 700–900 ◦C. The main product is syngas (synthesis gas).
	Pyrolisis	Cellulosic material and waste solids can be decomposed into a mixture of carbon-rich solids, oil, and gases. This process occurs to 300◦C without oxygen and is endothermic, requiring heat. Pyrolysis can be classified as slow, intermediate, or fast. Pyrolysis oil, or crude, is an intermediate product that can be refined into downstream products. The gases produced are rich in carbon monoxide, hydrogen, and methane and can be used as fuel or feedstock for producing chemicals..
	Torrefaction	A low-temperature variant of pyrolysis is used to produce bio-coal, which can replace conventional coal. Torrefaction technology is often used to thermally pretreatment biomass resources.

Source: Daliah (2017); Osman (2023); Jha (2022) and self-elaboration.

Biological conversion involves the chemical and enzymatic breakdown of biomass residues. After microorganisms degrade them, this process releases fermentable components that can be used to produce valuable products. Catalytic conversion presents various processes, from commercially viable transesterification to academic-scale CCC.

On the other hand, thermochemical conversion processes involve exposing feedstocks to high temperatures, pressures, and catalysts. This leads to the thermal decomposition of organic components, which produces biofuels and biochemical building blocks. Thermochemical processes have faster reaction rates compared to biological conversion processes. This is due to applying high temperatures, pressures, and catalysts. Each platform gathers a set of different technologies at a different TRL, which are most efficient when used with a specific feedstock type (Jha, 2022).

The following sections focus on the Catalytic Platform and Thermochemical Platform.

4.1 Technology Platform TP2Catalytic

4.1.1 Transesterification

Transesterification is a chemical process involving alcohol and a fat or oil to create fatty acid alkyl esters (FAAE), also known as biodiesel (FAME) and glycerol. This reaction usually requires a catalyst to increase the reaction rate and yield. Excess alcohol (Methanol or ethanol) shifts the equilibrium towards the product as the reaction is reversible.

Triglycerides comprise a glycerol backbone and three long-chain fatty acid molecules, each containing 8- 24 carbon atoms. FAME, on the other hand, consists of fatty acid chains that are chemically bonded to a methanol molecule. When the fatty acid chains break away from the triglyceride, they become free fatty acids (FFA). While free fatty acids are also used to create FAME, they must undergo an esterification process before the remaining triglycerides can be converted into biodiesel through transesterification. It is worth noting that the final biodiesel product contains almost no glycerol molecules. (Monika, 2023; Athar, 2020; Singh, 2010).

Methanol is a frequently used alcohol in the transesterification process for creating biodiesel, primarily derived from FAME. Biodiesel made from feedstocks with a high fatty acid content tends to have low viscosity, a lower cetane number, lower heat value, and higher density. If there is an excess of unsaturated fatty acids in biodiesel fuel, it can decrease thermal efficiency while reducing emissions of VOCs, CO, and smoke. However, biodiesel with a high melting point associated with saturated fatty acid composition may present potential issues (Singh, 2024).

Several experimental parameters, such as the catalyst type and quantity, reaction duration, and temperature, influence the quality and quantity of biodiesel formation. The transesterification reaction, which produces biodiesel, can be classified into three primary categories: homogeneous, heterogeneous, and enzyme-catalyzed transesterification. These categories can be further subdivided based on whether the catalyst used is acidic or alkaline (Kumar, 2024; Athar, 2020).

Obtaining biodiesel through an industrial-scale transesterification reaction usually involves using a solid catalytic base for homogeneous catalysis. This method boasts several benefits, such as faster reaction times, higher conversion rates, and the need for only a small amount of catalyst compared to other catalytic techniques. However, FFA and water can cause soap formation, leading to a decrease in yield reaction. In contrast, acid-catalyzed reactions that use sulfuric or hydrochloric acid are impervious to FFA but are sensitive to water and require higher temperatures, resulting in a slower reaction (Ameen, 2022; Fonseca,2019).

There are two methods to produce biodiesel: homogeneous or heterogeneous acid and alkaline catalysts. Homogeneous catalysts are known for their higher activity and are commonly used in chemical reactions. However, the cost of the process may rise due to the challenges in recovering spent homogeneous catalysts. In contrast, heterogeneous catalysts are more accessible for recovery and recycling (Kumar, 2024; Jha, 2022).

4.1.2 Hydrotreatment

Hydrogenation of vegetable oil is a process where unsaturated fats are converted into hydrocarbons in the range of jet and diesel by adding hydrogen. This process typically involves using a catalyst such as Nickel-Molybdenum or Cobalt-Molybdenum Sulfide at higher temperatures (between 250ºC to 375ºC) and moderated pressures (typically between 30 to 80 bar). Diesel produced -conventionally named HVO- has excellent quality properties compared to regular diesel (lower density, higher heat value, and higher cetane). Cold flow properties could be an issue but can be improved if HVO is processed into an isomerization section.

Production costs for HVO are primarily driven by feedstock costs, which can account for 65- 80% of the total cost.

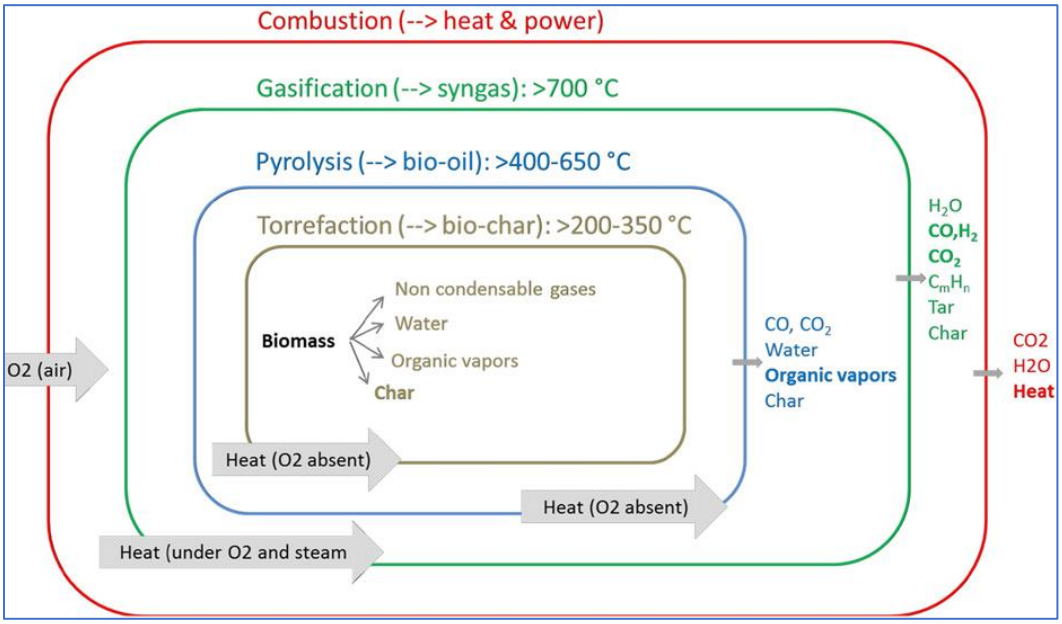
4.2 Technology Platform TP3 Thermochemical

Thermochemical conversion technologies cover a range of processes that efficiently convert biomass into valuable products such as gas, oil, and charcoal. These processes include gasification, pyrolysis, and torrefaction, which operate at high temperatures with limited oxygen supply.

The final products are primarily determined by the conditions of each process - such as temperature, heating rate, and oxygen supply. For example, pyrolysis involves fast heating rates and moderate temperatures, resulting in liquid products. In contrast, torrefaction involves low temperatures and long residence times, resulting in the formation of char. Both pyrolysis and torrefaction imply thermal processing in the absence of oxygen. On the other hand, gasification is a thermal process where feedstock is processed with air or oxygen, which uses high temperatures and heating rates, producing primarily gaseous products, including condensable and non-condensable gases.

Gasification, pyrolysis, and torrefaction are not entirely distinct processes. Pyrolysis can be seen as an incomplete gasification process, while torrefaction can be seen as an initial stage of gasification and pyrolysis, as shown in Figure 4.2

Fig.4.2 Comparison of combustion, gasification, pyrolysis, and torrefaction technologies



Source: Matsakas (2017)

The properties of biomass play a crucial role in the various parameters involved in the thermochemical conversion process, such as reaction rate, yield, and quality of the end products. Its proximate and ultimate composition determines the essential features of biomass. The initial composition is measured based on the amount of moisture, ash, fixed carbon, and volatile matter present in the biomass. On the other hand, the ultimate composition includes carbon, hydrogen, nitrogen, sulfur, and oxygen. Ash constitutes the mineral matter that remains as a residue after combustion.

High ash content in biomass can pose a significant challenge during thermochemical conversion, particularly during combustion, pyrolysis, gasification, and co-firing, as it can lead to the formation of agglomerates, entrapment, and corrosion. Additionally, the high moisture content in biomass necessitates more energy input for drying the feedstock before its conversion and results in a lower heating value of the biofuel product. On the other hand, lower moisture, oxygen, and ash contents can enhance the calorific value of the conversion product. (Jha, 2022)

4.2.1 Gasification

Gasification is a complex process that partially oxidizes a material with reduced oxygen compared to complete stoichiometric combustion. The temperature required for the process varies based on reactor type and feedstock composition, usually ranging from 800 to 1200°C. This process ultimately breaks down the material into a gas mixture primarily composed of H_2, CO, CO_2, CH_4, and N_2. The composition of the mix is influenced by various operating conditions, such as the type of gasifying agent used, gasifier type, and other factors, including temperature, equivalence ratio (ER), feedstock type, feedstock moisture level, fuel particle size, and catalyst. However, it is also important to note that the syngas mixture may contain some unwanted components, such as particulate matter, tar, alkali metals, chlorine, and sulfide.

This process is highly energy-intensive, with energy typically provided by partial combustion of the raw material with oxygen. Consequently, some of the energy contained in the raw material is lost in the form of heat.

There are various gasification options: with/without steam supply, heating at several thermal levels or one thermal level, catalytic reforming of tars or thermal reforming, and gasifier type (Tezer, 2022; Shahbaz, 2021; Matsakas, 2017).

Three types of gasifiers are used in gasification. The fluidized bed gasifier offers several advantages, such as uniform heat transfer and mixing, high conversion of biomass to gas, and suitability for large-scale production. They are characterized by simple construction, low capital investment, and high cold gas efficiency. On the other hand, the fixed bed gasifier is suitable for small-scale production and biomass with low ash and moisture content. Finally, the entrained flow gasifier is unsuitable for biomass use, although it has been widely used for coal gasification. They have been considered a promising alternative for large-scale biomass gasification. They produce synthesis gas with a very low tar and methane content and achieve nearly complete carbon conversion. Disadvantages of entrained flow gasification include higher capital costs, more complex construction, and more intensive pretreatment of the feedstock as smaller particle sizes are required (Zimmer, 2017)

In the gasification agent, steam helps produce higher H_2 content syngas. It favors both small- and large-scale systems, leading to gaseous mixtures dominated by more than 60% H_2 and less CO_2 and methane products. Obtaining tar-free producer gas from biomass gasification is a challenge for its downstream applications like internal combustion engines and catalytic synthesis (Shahabuddin, 2020; Neves, 2020)

Various factors directly affect biomass's gasification process, including its size, shape, porosity, density, and composition. Biomass can consist of hemicellulose, cellulose, lignin, extractives, and ash. Gasification is a process that can work well with low-quality raw materials with a medium—to low humidity level, such as CSR or low-quality biomass. However, it can be capital-intensive and not the best option for medium—to high-quality raw materials or raw materials with high humidity.

Cellulosic materials and waste solids can serve as fuel sources for gasification. However, they contain combustible and non-combustible materials, like municipal solid waste (MSW), which contains paper, plastic, cardboard, wood, textiles, metals, glass, and other materials. These materials in gasification technologies must undergo pretreatment to become a refuse-derived fuel (RDF). Pretreatment typically involves removing non-combustible materials such as steel, concrete, and glass, reducing the moisture content, and homogenizing the waste to minimize operational issues (Shahabuddin, 2020).

A summary of the advantages and disadvantages of the technologies described can be found in Table 4.2.

Table 4.2. SWOT of TP1 Catalytic and TP2 Thermochemical conversion technologies

TP1 Catalytic	
Transesterification	Short reaction times. The cost of the production process is relatively lower. Reaction condition can be regulated. The methanol generated in the process can be recycled. Catalysts usually show sensitivity towards the existence of water in the feedstock. Homogeneous catalysts could present issues with recyclability. Large-scale production is possible. Feedstocks show a high conversion rate. In the case of a high biodiesel blending engine, modification is required.
TP2 Thermochemical	
Torrefaction	This technology can be used as a pretreatment and biomass conversion technology. Presents a high energy content per unit volume. Improves the calorific value of biomass. Pelletizing torrefied biomass makes its transportation easy for long- distances. Reduces moisture content. Low energy input. Shows reduced operating costs. Presents a lower overall efficiency. Optimization of torrefaction reactors is essential to meeting the end-use necessities financially and achieving market product standardization. No catalyst is required.
Pyrolysis	High efficiency. Probable applications of produced compounds (e.g., tar, bio-oil, and char). Requires lower/higher energy input for slow/fast pyrolysis. Complex product stream, difficulty venting out product gases without treatment owing to high concentrations of CO Issues with recyclability of homogeneous and carbon-based catalysts. Development of the market for pyrolysis liquid and char products. Feasibility is established only in large-scale plants High cost.
Gasification	Syngas can be directly utilized as fuel or for value-added products such as synthetic natural gas, chemicals, hydrogen, kerosene, and naphtha. High operating cost. High maintenance cost. Issues with recyclability of homogeneous and carbon-based catalysts. Large-scale operations are possible. High unexploited potential.

Source: Jha (2022) and self elaboration.

Chapter 5. Fuels Platforms (FUP)

In this chapter, we will examine the three fuel platforms in detail. We will also outline biodiesel and ethanol as examples of fuels belonging to the FUP1 platform, HVO and SAF from the FUP2 platform, and Syngas from the FUP3 platform—summary of Renewable Fuel Platform in Table 5.1.3

Related to the renewable fuel specifications, the designations of the final fuels could be more precise. Different names are shared for the same products (e.g., FAME vs. biodiesel). Different names refer to renewable fuels, such as CO_2-derived fuels, liquid solar fuels (Kraan,2019), green fuels, advanced biofuels, synfuels, or electrofuels, and even names such as green diesel vs. renewable diesel vs. biodiesel are used synonymously. In this thesis, the term "renewable fuel" has been selected as the most appropriate designation for a fuel that contributes to constructing net-zero energy systems (Nimmas, 2024; Semmel, 2021; Fukuzumi, 2017). In addition, the regulator introduces bias by creating a regulatory framework prioritizing certain feedstocks and end products (Paris, 2021). This leads to different designations for similar end fuels. In this work, the regulatory analysis of the various jurisdictions has been left out to highlight the essential elements that constitute a pathway. When selecting a particular path, a detailed analysis of existing and potential regulations in the region where the specific investment is to be made will have to be carried out.

Fuels are the last building block necessary to define a renewable fuel production pathway. The ultimate fuel options can be classified into three fuel platforms: FUP 1 substitutes, FUP2 drop-ins, and FUP3 intermediates. Intermediates serve as foundational components that can be utilized as carriers for green hydrogen or transformed into substitute or drop-in fuels. Various competing clean technologies for shipping are being developed in all scenarios, including electricity, hydrogen, and derived fuels such as NH_3, MeOH, and LNG.

Substitute products need to be blended in a portion with fossil fuels. Drop-in fuels are liquid fuels that meet the exact specifications of hydrocarbon fuels derived from petroleum (Kargbo, Harris & Phan, 2021). Intermediate products are raw materials that can be transformed into different types of final products based on market conditions such as regulation, customer demand, and market premium. Intermediate products require a secondary conversion process to be converted into final products. These products are exciting as they allow switching between producing liquid fuels and chemical materials.

Table 5.1 Renewable Fuel Platforms

Renewable Fuel Platform	Renewable Fuel	Description
FUP1Substitute Need to be blended with fossil fuels	Ethanol	Gasoline substitute typically blends from 5% to 15% and can replace up to 100% in FlexFuelVehicules (FFV).
	Biodiesel	Biodiesel substitute that blends between 2% and 5% but with certain vehicle modifications allows up to 20%.
FUP2Drop-in Fossil fuels can substitute it	Renewable diesel/Renewable gasoline	Diesel or gasoline produced from the hydrotreating of oil or the conversion of cellulosic feedstock or solid waste
	Biojet fuel (SAF)	Jet produced from hydrotreating of oil or conversion of cellulosic feedstock or solid waste
	Bio CNG/LNG	Natural gas replacement from upgrading biogas to greater than 95% CH4 and subsequently compressed(bio-CNG) or liquified (Bio-LNG)
FUP3Intermediate It can be used to produce both fuels and materials	Biocrude/syncrude	It is produced from the pyrolysis of cellulosic material or waste solids. It is sometimes called syncrude, produced from the Fischer-Tropsch gas-to-liquid syngas conversion. Biocrude/syncrude can be further upgraded into various hydrocarbons or co-processed with conventional crude oil.
	Syngas	Syngas is produced from gasifying cellulosic material or waste solids. It is often used directly for power production. Syngas can be catalytically converted into ethanol, methanol, diesel, or gasoline. Additionally, it can be upgraded into hydrogen.

Source: Daliah (2017) and self-elaboration.

5.1. Platform FPU1 Substitute

Conventional biofuels primarily derive from food crops, which produce ethanol from grains or sugar-rich plants or biodiesel/FAME from vegetable oils.

5.1.1 Bioethanol, ETBE, MTBE

Common crops for bioethanol production through fermentation include sugarcane, corn, wheat, and sugar beet, rich in sugars or starch. Bioethanol is frequently blended with gasoline to enhance its octane rating. The most common blend is E10, consisting of 10% ethanol and 90% gasoline. Flex-fuel vehicles can use E85, a blend containing up to 85% ethanol. The United States and Brazil are the leading producers and consumers of corn and sugarcane-based bioethanol, respectively, accounting for 95% of global production. In 2019, 110.2 million cubic meters of bioethanol was produced, with the United States contributing 58.5

million cubic meters, Brazil 32 million cubic meters, and the European Union 5.5 million cubic meters (Aresta, 2022; Ullaha, 2018).

5.1.2 Biodiesel, FAME

Biodiesel is a fatty acid methyl ester (FAME) produced by transesterification with methanol from fatty acid esters obtained from some feedstock. This process converts triglycerides in the oils and fats into fatty acid methyl esters (FAME) and glycerol.

Biodiesel's physical and chemical properties are similar to those of petroleum-based diesel. It can be used in existing diesel engines blended with fossil fuel, but the blend percentage is limited to prevent mechanical modifications in the motor.

FAME needs to blend with fossil fuel because of vehicle specifications (unlike HVO, see in next section, which is chemically similar to a hydrocarbon; FAME is an oxygenate. The chemical nature of oxygenates is different, and the energy density is lower). Autoxidation and instability towards long-term storage at room temperature are the foremost concerns of FAME due to the unsaturated fatty acids that make them prone to oxidative degradation.

The blend ranges from B100 (pure biodiesel) to B10 (10% biodiesel). Blends are denoted as BXX., where XX represents the percentage of biodiesel in the mixture (Singh, 2024; Monika, 2023; Nisar, 2021).

In 2019, around 40 million cubic meters of biodiesel were produced globally, with Indonesia, the U.S.A., and Brazil as top producers.

International trade impacts all biofuels; Biofuel imports to the EU have consistently risen since 2014, leading to a biofuel trade deficit of over €2 billion in 2021, primarily from imports from Argentina, China, and Malaysia. The Netherlands and Germany are the largest biofuel exporters in the E.U. and globally. In 2021, the total value of imported biofuels was €3.596 billion, while the exported value was €1.259 billion, reflecting the nascent state of the biofuels industry in Europe (Scarlat, 2022).

The world's leading biodiesel producer is the U.S.A., followed by Brazil, Germany, Indonesia, and Argentina. These countries accounted for more than 80% of the global biodiesel production in 2016, as shown in Table 5.2.

Table 5.2. Top biodiesel producing countries in 2016 Country Biodiesel production (in 10^3 liters)

USA	5.5
Brazil	3.8
Germany	3
Indonesia	3
Argentina	3
France	1,5
Thailand	1,4
Spain	1,1
Belgium	0,5
Colombia	0,5
Canada	0,4
China	0,3

Source: Karmakar (2019)

Currently, most conventional biofuels are produced using food crops. Sugar and starch feedstocks are the primary sources of ethanol fuel globally, while vegetable oils are the primary sources of biodiesel (Athar, 2020). This means that the cost of producing biodiesel is mainly determined by the price of refined vegetable oils, which accounts for over 80% of the total cost. The feedstock will continue to be the most significant factor affecting the price of biodiesel worldwide in the future. (Monika, 2023)

A significant concern in biofuel production is the competition between biomass sources for producing bioethanol and biodiesel and their impact on the food chain, potentially causing inflationary effects (Srinivasulu, 2019; Pour, 2014). Utilizing edible oils as a source of feedstock for biodiesel production challenges the food supply chain. It increases costs, as raw oil represents a significant portion (60- 80%) of the total production cost. For this reason, the use of edible oils for fuel production will be limited in the future.

5.2 Platform FPU2 Drop-In

5.2.1 HVO

HVO is a renewable fuel type that must not be blended with fossil fuel to meet ICE standards. (This could be mentioned, as well as a drop in fuel.)

Hydrotreated Vegetable Oil (HVO) mainly comprises medium to long-chain hydrocarbons, distinguishing it from biodiesel and bioethanol. (Scarlat, 2022; Tao, 2017). It is possible to produce HVO by a process known as hydrotreating. Essentially, this process involves reacting vegetable oils or animal fats with hydrogen in the presence of a catalyst at high temperatures and pressures. The result is the removal of oxygenates, impurities, and the saturation of the double bonds of the fatty acids, ultimately transforming them into

hydrocarbons like diesel fuel. Hydroprocessing conversion technologies, specifically hydrotreating, deoxygenation, isomerization, and hydrocracking, are widely utilized by refineries to generate transportation fuels.
In a forward scenario, the increase for HVO from 2018 to 2024 could exceed 330% (IEA, 2024; Argus, 2022; Energies Nouvelles, 2023). Barclays Research in Europe predicts that the HVO supply will triple from 2019, and imports will be at least four times higher than the supply considered in 2019.

Over the past three decades, the biofuel industry has primarily sourced biomass from food crops (Aresta, 2022; Karatzos, 2017).

Energy crops are considered a promising alternative to food crops due to their high yield and low cost. In the case of energy crops, the four key factors to be considered for biofuel production are the suitability of these plants for local agro-climatic conditions, their low cost, easy accessibility, their high yield compared to other crops, and their lack of competition with food raw materials. Energy crops can be cultivated without impacting food and feed production through crop rotation or low-intensity cropping on marginal lands that farmers no longer use. However, commercial success in this field remains distant despite their potential benefits. The availability of land is being restricted due to the conflict between the production of fuel and food. More than 300 oil-bearing crops, including soybean, rapeseed, and palm, can be used as a source of biodiesel.

However, 70- 75% of biodiesel production costs depend on the feedstock used. Therefore, it is essential to have a cost-effective feedstock that meets the required specifications for wide use. Many factors must be carefully considered when developing renewable fuels, starting from the feedstock piece. Ensuring a reliable supply of feedstocks, promoting a strong economy, and balancing the carbon footprint are all crucial considerations. Equally important is the in-depth analysis of the fatty acid composition of the oil feedstocks being used and the structural composition of the intended biomass feedstocks.

This analysis provides valuable insight into the conversion process and helps to determine whether biofuel can be practically used in real-world applications (Kumar, 2024; Muhammad, 2021; Singh, 2010; Athar, 2020).

5.2.2 Biojet Fuel or Sustainable Air Fuels (SAF)

Jet fuel, commonly called Jet A or Jet A-1, is a type of fuel that does not have a standard chemical formula. Instead, it is identified by specific functional attributes, such as boiling point range, carbon number, and aromatic content. A comprehensive range of aviation fuels and paraffins is available, each tailored to specific specifications, applications, and uses.

Jet fuel (or kerosene) is primarily used to power jet engines. Produced from crude oil, it is a blend of various types composed of hydrocarbon molecules with a carbon atom range of 8 to 16.

Jet fuel is obtained as the middle distillate between diesel and gasoline during the refining process. It is important to note that the boiling point range of jet fuel overlaps with that of diesel, which means refiners can choose to produce only diesel instead of jet fuel, which is typically the case today. However, should there be a decrease in demand for diesel, refiners can shift their production to jet fuel instead (Raniah, 2023).

In a current refinery, jet fuel makes up to 10% of the crude oil fraction. Jet fuel is chosen to power jet engines instead of gasoline because it is denser and less volatile at high temperatures. It is used instead of diesel because it is lighter and less prone to producing low-temperature wax (Doliente,2020). Jet fuel presents high cold stability temperatures of −47 to 40◦C, elevations above 10.000m, and enough energy density to supply long-range flights (Ramos, 1997).

SAF are liquid hydrocarbon fuels produced from biogenic or waste feedstock. They can either work as Substitute (blended) or as Drop-in (referred to as entirely interchangeable for conventional petroleum-derived jet fuel, i.e., Jet A or Jet A-1). The fact that no adaptions are required for the existing fuel systems (i.e., aircraft engines, fuel distribution network) establishes SAFs as dominant alternatives towards the decarbonization of the aviation field. Hydro-processed esters and fatty acids (HEFA) are the most widely used of these pathways and the only one that produces SAF on a large scale. Other pathways, such as ATJ, are in an early commercial stage, and current production is negligible nowadays.

SAFs are categorized based on the technology and feedstock used to produce them. There are eight ASTM-approved technology pathways for SAF, with four more under consideration. (Raniah, 2023; Panoutsou, 2021)

Currently, eight routes are approved for blending with conventional paraffin. Recent approval of A8 ATJ-SKA (Alcohol to Jet with aromatics/Isobutene to Jet). Under evaluation HDO-SAK, Plastic to Jet (OMV), HEFA with aromatics, Methanol to Jet. Starting POtJet process (Pyrolysis Oil to Jet)

SAFs are categorized based on the technology and feedstock used to produce them. There are six ASTM-approved technology pathways for SAF, with two more under consideration. (Raniah, 2023; Panoutsou, 2021)

SAF fuel differs from conventional jet fuel in some characteristics. Jet fuel specifications ensure efficiency, predictability, and safety in use. Changing feedstock and fuel behavior under varying pressure and temperature conditions can pose different risks in aviation compared to maritime or land transport. Therefore, certification of renewable origin and specifications is essential for its expansion and introduction to the market.

Some approved routes by the American Society for Testing and Materials (ASTM) can produce aromatic-free biojet fuel, whereas conventional jet fuel contains aromatic compounds in its composition. Despite being responsible for the emissions of particulates during combustion, aromatic compounds must be present in conventional jet fuel in a defined range to avoid engine leakage and guarantee some properties, such as the density required in the regulation. Biojet fuel must be blended in different amounts with conventional jet fuel to achieve this specification. Besides, biojet fuel does not contain sulfur or nitrogen compounds, thus avoiding the production of SO_2 and $H2_SO_4$, for example, during combustion (Detsios, 2023).

Aviation fuel, which includes Jet A and Jet A-1, needs to comply with international ASTM standards. It is mandatory for all types of jet fuel, including the ones blended with SAF, to get approved through the ASTM specification process before use. Currently, the technical requirements for the primary fuel types used in civil aviation are defined by international standards, namely ASTM D1655 and DEF STAN 91-91 (Meurer & Kern, 2021). The consideration of SAF and the definition of its requirements is regulated by annexes of the ASTM D7566, providing various approved production pathways. The process of ASTM certification for aviation turbine fuel containing synthesized hydrocarbons comprises three significant phases. Firstly, the fuel is subjected to testing, which involves analyzing fuel specifications, evaluating its fit-for-purpose properties, testing its components and rigs, and subjecting it to engine and aircraft unit testing. Once the fuel testing is complete, a research report is generated and submitted for review by original equipment manufacturers. Secondly, the OEM review occurs, with significant aviation companies and Rolls-Royce scrutinizing the research reports. The process moves to the ASTM voting phase if the report is approved. The ASTM voting phase is conducted every six months.

Further tests and evaluations are carried out if the research report is not approved. However, if accepted, the new pathway is integrated into ASTM D7566 (Table 5.3) with a specific blending limit, usually 50%. The entire certification process can take between 3 and 5 years, leading to significant delays in adopting SAF in the aviation industry.

Table 5.3 ASTM D7566 approved SAF Pathways

Technology Pathway	Approved Name	Blending limitation	Feedstock Platform/ Feedstock	Technology Conversion Platform/Conversion Technologies	Technology Readiness Level (TRL)	Year approved
Fisher-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	FTK-SPK ASTM D7566 Annex A1	50%	Syngas from: FP1Food crops Vegetable Oils FP3Waste Waste lipids/waste materials	TP1Thermochemical/ Gasification/Fisher Tropsch	7–8	2009
FTK-SPK with Aromatics	FTK-SPK ASTM D7566 Annex A4	50%			7–8	2015
Hydroprocessing Esters and Fatty Acids (HEFA)	HEFA-SPK ASTM D7566 Annex A2	50%	FP2Energy Crops: Cellulosic type/Oil-tape Waste: FP3Waste lipids/Waste materials/Cellulosic material	TP2Catalytic/Hydrotreatment	9	2011
Hydrocarbon-Hydroprocessing Esters and Fatty Acids (HEFA)	HC-HEFA-SPK, ASTM D7566 Annex A7	10%	FP2Energy Crops/ Oil Type/ Algal oil	TP2Catalytic/Hydrotreatment	9	2020

Synthesized Iso-paraffins from Hydroprocessed fermented sugars	SIP ASTM D7566 Annex A3	10%	FP2Energy Crops Cellulosic biomass Waste	TP1 Biological/ /Fermentation/Hydrotreatment	8	2015
Alcohol to Jet (ATJ) Synthetic Paraffinic Kerosene	ATJ-SPK ASTM D7566 Annex A5	50%	FP2Energy Crops/ Cellulosic biomass FP3Waste Cellulosic material	TP1Biological/ Fermentation/Oligomerization/Hydrotreatment	7–8	2016
Catalytic Hydrothermolysis (CH) Synthesized Kerosene	CH-SK or CHJ, ASTM D7566 Annex A6	50%	FP3Waste Waste lipids/ Fatty acids or fatty acid esters or lipids from fat oil greases	TP2Catalytic/Hydrotreatment	5–7 (depending on the sugar type)	2020

Source: Detsios, (2023); Kim, Dodds, & Butnar, (2021) and self-elaboration.

5.3 Platform FPU3 Intermediate

5.3.1 Syngas

Raw syngas consists of a mixture of CO, H_2, CO_2, CH_4 (primary components) and H_2O, H_2S, NH_3, tar, and other trace species (secondary components), with composition dependent on feedstock type and characteristics, operating conditions (i.e., G.A., gasifier temperature, and pressure, kind of bed materials), and gasification technology (Sethuraman, 2023; Molino, 2018).

It is called syngas once the gasification process is complete (see Chapter 3) and the resulting gas has been cleaned and conditioned. This gas primarily comprises hydrogen (H_2) and carbon monoxide (CO), with a specific H_2/CO molar ratio for various downstream applications. Synthesis gas typically contains between 4- 18 M.J./Nm^3 of volumetric energy content, whereas natural gas, primarily comprised of methane, boasts an energy content of 36 M.J./Nm^3. When synthesizing gas from biomass, a considerable amount of energy content remains in the gas mixture through partial oxidation rather than full oxidation, which would primarily yield thermal energy (Shivananda & Dasappa, 2016; Swanson, 2009).

Gas purification is a crucial step following gasification. Depending on the feedstock, the output stream may contain various contaminants, such as H_2S and NH_3. These contaminants and CO_2 must be removed during the purification and upgrading stage. The gas purification process's complexity depends on the gas's intended use, such as generating electricity and steam, producing hydrogen, or synthesizing chemicals like methanol or FT waxes.

During the process of purifying gas, impurities such as tars and SH_2 are removed. If the gas is going to be used for chemical synthesis, the ratio of carbon monoxide (CO) to hydrogen (H_2) should be adjusted to 2:1. Converting the gas to methanol or FT waxes must be of high purity, and the molar ratio of CO/H_2 should be slightly above 2. Additionally, carbon dioxide (CO_2) must be removed or captured, although in the case of methanol, CO2 could also be converted according to the following reaction:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

Gasification, whether for methanol and FT waxes or methanol alone, requires high purity of the gas fed to the sections (Yuan & Eden, 2015). Once syngas is generated, it opens up a world of possibilities. This versatile gas can be converted into a range of products, including methanol, synthetic fuel, renewable biofuel, low-carbon hydrogen, and various chemicals, depending on the specific needs and goals of the process.

To remove impurities and potential catalyst poisons, the gas must be purified when producing renewable fuels from biomass-derived syngas. This step is vital as it ensures the gas attains the required qualitative composition for biofuel production. The purification and conditioning process involves several steps: tar reforming, syngas cooling and quenching, acid gas removal (CO_2 and H_2S), and sulfur recovery. Conditioning operations may also be necessary to adjust the syngas composition to meet downstream process specifications regarding H_2/CO ratio, H_2/CO_2 ratio, and CO_2 content. The steam reforming step and the WGS reaction are specifically used to convert residual tar, light hydrocarbons, and methane to CO and H_2, achieving the H_2/CO and H_2/CO_2 targets required for fuel production. After purification, the syngas can produce chemicals and liquid fuels using various processing pathways, such as methanol synthesis, methanation plant, and Fischer-Tropsch synthesis **(**Tezer, 2022; Molino,2018; Yuan, 2015).

Chapter 6. Economic sensitivity analysis.

Our primary objective in this chapter was to conduct an economic sensitivity analysis of two intermediate fuel production technologies: syncrude and methanol. This sensitivity exercise guides potential investors in gasification conversion technology, considering which route to choose: syncrude or methanol. This sensitivity analysis allows us to focus on the variables that directly affect production costs, such as plant size, feedstock costs, the difference in the cost of dry vs. wet raw materials, and variable costs.

In particular, we consider the following sensitivity economics production case:

Feedstock Platform FP3 Waste
Feedstock: Waste material (MSW)/Lignocellulosic material (agricultural and forestry residues)
Technology Platform TP3 Thermochemical
Conversion technology Gasification:
Conversion tech.from syngas: Fischer-Tropsch (G+FT)/Methanol Synthesis (G+ME)
Fuel Platform FUP3 intermediate
Fuel: Syncrude/Methanol

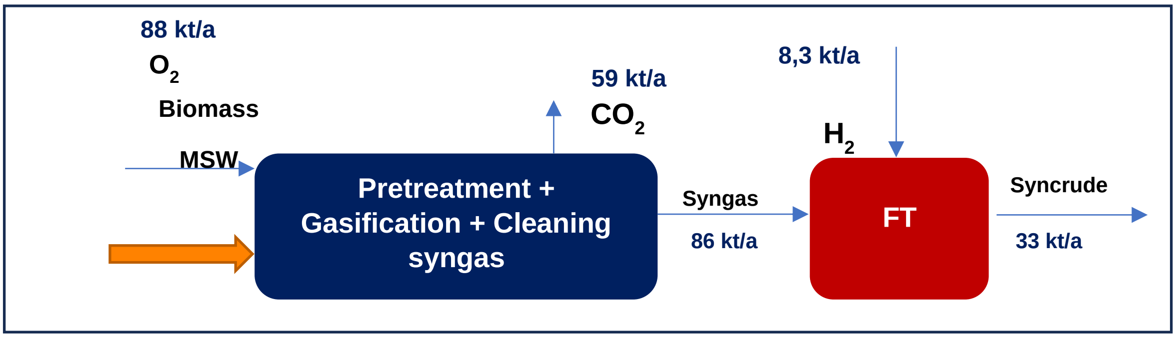
Syncrude is an intermediate product that cannot be directly used as fuel. We need to upgrade this syncrude through distillation, splitting into fractions via hydration and isomerization of the C5 – C6 fraction, reforming of the C7 – C10 fraction to increase the octane number, and cracking with H_2 to convert long-chain fractions into biogasoline and renewable diesel fractions (EBTP, 2024). Methanol is considered an intermediate fuel because it also needs an upgrade for the final fuel (e.g., in maritime transport (de Fournas & Wei, 2022)).

Both routes are based on the same Gasification conversion technology. However, to transform the syngas, a Fisher Tropsch stage is added in the case of Syncrude, while a Methanol synthesis stage is added in the case of methanol. This sensitivity economics production case does not consider the capex and opex required for this last stage.

Additionally, we used waste material (MSW) feedstock and lignocellulosic material (a combination of agricultural and forestry residues) feedstock, resulting in four pathways: $(G+FT)_{MSW/lignocellulosic}$ and $(G+ME)_{MSW/lignocellulosic.}$

The (G+FT) process transforms the clean syngas into alkanes using mostly iron and cobalt catalysts. Figure 6.1 illustrates this process, including a simplified material balance.

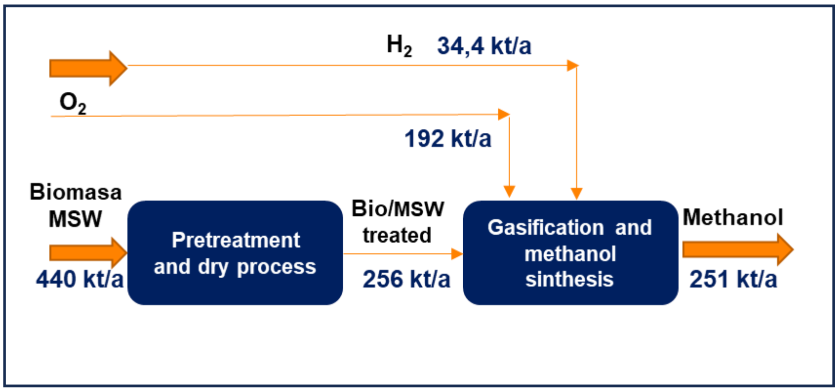
Figure 6.1 Gasification + Fischer-Tropsch (G+FT)



Source: Repsol internal report

In the (G+ME) pathway, syngas is converted to methanol in the presence of a catalyst (usually copper-based) (EBTP, 2024). Figure 6.2 illustrates an example that includes a simplified material balance.

Figure 6.2 Gasification + Methanol(G+ME)



Source: Repsol internal report.

Regarding conversion technology, the requirements of the selected technology (G+FT or G+ME), plant capacity, and capex have been considered. The technologist provides information that affects the process's material and energy balance. When multiple processes are involved, the yields of each process are kept separate.

The investment estimate is based on the information provided by the technologist. This information, adjusted internally to account for aspects not considered by them and scaled to the planned capacity of 400 kt/y on a wet basis, forms the basis of our analysis. The moisture content of the feedstock, a vitally important variable, is also a key consideration in our calculations.

The economic inputs cover all variable and fixed costs (staff, maintenance, insurance), hydrogen price, repayment period, and inflation. In the base case, a repayment period of 25 years and a 10% internal rate of return (IRR) are considered, ensuring a thorough and accurate assessment of the project's economic feasibility.

Initially, the external hydrogen needs in the G+ME process are assumed to be covered with electrolytic hydrogen at 5.9€/kg. However, other hydrogen sources could be considered, and the impact of hydrogen cost on overall production cost is analyzed.

The fixed costs are assumed to be 6% of the capital expenditure (CAPEX), and the utility costs are 3.4 €/MWh. These variable costs encompass energy, chemicals, and additives. For the case analysis, inflation is set at 2%. Biomass (wet basis) has a price range of 50-120 €/t. This price varies depending on the type of biomass and the distance from the production site to the recovery center. However, for sensitivity purposes, we have chosen to use the lower end of the range of €60/t, which has been the most common price on the market in recent months.

The bases assumed in the model for the sensitivity study are shown in Table 6.1.

Table 6.1 Base Parameters Economical sensitivity G+ FT/ G+ ME

Technology Pathway	Gasification + FT		Gasification + Methanol Synthesis	
Feedstock	MSW	Lignocellulose	MSW	Lignocellulose
Moisture content, %w	45%	45%	45%	45%
Price on a wet basis, €/t	-50	60	-50	60
Capacity Plant, kt/y	400	400	400	400
CAPEX, M€	774	604	750	750
Variable Cost, €/MWh	3,4	3,4	3,4	3,4
Hydrogen Price, €/kg	5,9	5,9	5,9	5,9
H2 Consumption, kt/y	0	0	14,5	21,6

i) Breakeven Production Cost Breakdown in €/MWh (see Annex 1. FigsA1 to A8). We have conducted the sensitivity studies impacting on breakeven production cost on feedstock price, variable cost, and capacity plant for these pathways (see Annex1 FigA9 to Fig A12)

In the cost breakdown of base production for (G+FT)$_{\text{MSW}}$, capital expenditure (capex) and capital risk collectively represent 66% of the total production cost, with other opex (without considering feedstock) accounting for 36%. Suppose we transition the feedstock to lignocellulose material. In that case, the base production cost breakdown for (G+FT)$_{\text{lignocellulose}}$ shows a 59% increase compared to the previous scenario, primarily due to higher feedstock costs and reduced yields.

The (G+ME) process with both feedstocks observes a more homogeneous cost distribution. In this technological route, capex contributes 39% (MSW case) and 26% (lignocellulose case) of total production costs, a smaller share compared to the previous route.

ii) Feedstock price (see Annex 1 Figs A13, A17, A21, A26)

How feedstocks weigh the most in the total cost of production is (G+FT)$_{\text{lignocellulose}}$, reaching a value of €45.8/MWh, representing a share of 17% of the total. In the case of (G+ME)$_{\text{lignocellulose}}$, this cost is €20.2/MWh, more than half of the previous case, with a share of the total of 9%. In cases where MSW is used as feed, what in cases with lignocellulose material was a cost now reverses to an income (-€26.8/Mwh and -€16.8/Mwh on the (G+FT)$_{\text{MSW}}$ and (G+ME)$_{\text{MSW}}$ routes, respectively).

On the (G+FT)$_{\text{MSW}}$ and (G+ME)$_{\text{MSW}}$ routes, we conducted the sensitivity analysis by applying increases in the raw material price of +30%, +60%, +100%, and +115%. Both routes have a moderate impact on feedstock prices, with a 115% increase necessary for a significant increase in the breakeven production cost (+18% in the case of (G+FT)$_{\text{MSW}}$ and +12% in the case of (G+ME)$_{\text{MSW}}$).

On the (G+FT)$_{\text{lignocellulose}}$ and (G+ME)$_{\text{lignocellulose}}$ routes, we have applied variations to the price of -40%, -20%, +40% and +60%. Again, as in the MSW cases, using lignocellulose material as feedstock the (G+FT) route presents a greater sensitivity to the feedstock price than the route (G+ME). While increases of +40% and +60% lead to gains in the breakeven cost of production of +7% and +10% in the case of (G+FT), in the case of (G+ME), equal variations would result in increases of +3% and +5%.

iii) Variable Costs Impact (see Annex 1. FigsA14, A18, A22, A27)

When performing a sensitivity analysis of this variable, a significant effect was not identified in any of the routes. In all four cases, variable cost increases have been considered concerning the base case (€3.4/t) of +60%, +80 %, €20/t, and +€50/t.

On routes (G+FT), an increase of + 50€/t in variable costs leads to an increase of only +1% in the case of MSW and + 2% with biomass as feedstock. The impact is somewhat higher on the routes (G+ME), with increases of +5% and +4% for MSW and biomass, respectively, when the same increase in variable costs is applied (+50 €/t).

iv) Capacity Plant Impact (see Annex 1. FigsA15, A19, A23, A28)

Given its relevance when establishing a project's basis, a sensitivity study of the plant's capacity has also been carried out. The variations applied to the base case (400 kt/y) are -30%, -10%, +10%, and -30%.

The most significant impact is observed on the $(G+FT)_{MSW}$ route, in which a 30% reduction in plant capacity implies a 15% increase in production costs, evidencing the competitive advantage of economies of scale in specific costs in this pathway. On the other hand, increases of 10% and 30% result in reductions in production costs of -4% and -10% respectively.

The impact of $(G+FT)_{lignocellulose}$ is slightly lower. A 30% reduction in capacity translates into an 11% increase in production costs. Increases of +10% and +30% in capacity lead to decreases of -3% and -7%, respectively.

With values similar to those of the previous case, when talking about the $(G+ME)_{MSW}$ route, a 30% reduction in capacity translates into an 8% increase in production costs. Increases of +10% and +30% in capacity lead to decreases of -2% and -6% respectively.

The case with the most negligible impact on capacity variation is the $(G+ME)_{lignocellulose}$ case, in which a 30% reduction in capacity translates into a 6% increase in production costs. Increases of +10% and +30% in capacity lead to decreases of -2% and -4%, respectively.

v) Hydrogen price (see Annex 1. Figs A24, A29)

The hydrogen price, a crucial variable, significantly impacts the variable cost in the (G+ME) routes. We have analyzed how different hydrogen prices affect production costs. Specifically, we have considered hydrogen prices of €3/kg and €1.5/kg, compared to the base case price of €5.9/kg, considering the expected cost reduction due to the technological maturity of hydrogen production processes.

For (G+ME)$_{MWS}$, reducing the price to €3.0/kg would mean a 17% reduction in production costs, while with hydrogen valued at €1.5/kg, production costs would fall by 26%. In the case of the (G+ME) biomass, price reductions to €3.0/kg and €1.5/kg lead to production cost improvements of -19% and -28%, respectively. Hydrogen price is the variable with a higher impact on the variable cost in this route. Considering the expected cost reduction due to the more significant technological maturity that hydrogen production processes will acquire, we have analyzed the impact on the production cost by considering hydrogen prices of €3/kg and €1.5/kg.

vi) Impact on CAPEX with subsidies (see Anex1 Figs A16, A20, A25, A30)

Due to the growing increase in subsidies and support programs for renewable projects by governments and public organizations to favor compliance with the increasingly demanding legal requirements, we have analyzed the impact of reducing CAPEX via granting one of these subsidies. To identify the impact of these support programs, we have studied how the cost of production changes in the four technological routes, considering capex subsidies of 10%, 20%, and 30%. The route in which the most significant impact can be seen is the alternative (G+FT)$_{MSW}$ as feedstock, with a reduction of -26 % in the cost of production by including a 30% subsidy.

Each technological route responds differently to the inclusion of a 30% subsidy. The (G+FT)$_{lignocellulose}$ and (G+ME)$_{MSW}$ routes show similar effects, with a reduction in the cost of production of -19% and -17%, respectively. On the other hand, the (G+ME)$_{lignocellulose}$ route is the least affected, with a decrease of -12% when a 30% subsidy is included.

Table 6.2. Cases comparison

Technology Pathway	Gasification + FT		Gasification + Methanol Synthesis	
Feedstock	MSW	lignocelluloses	MSW	lignocellulose
Breakeven Production Cost, €/MWh	167,4	265,4	161,9	226,6
CAPEX	36,6	41,8	22,9	22,9
FEEDSTOCK	-26,1	45,8	-16,8	20,2
HYDROGEN	0,0	0,0	65,1	97,3

OPEX	59,6	68,1	37,8	37,8
TAXES & FINANCIAL INTEREST	24,2	27,7	13,2	12,2
COST AND CAPITAL RISK	73,1	82,1	39,8	36,2

As conclusions of the sensitivity case,

i) From an investor approach

-The most cost-effective production pathways involve using MSW as feedstock, with costs at €161.9/MWh in G+ME synthesis and €167.4/MWh in G+FT. However, assessing this situation's sustainability is essential, particularly with growing competition for this feedstock type.

-Capex on the (G+FT) route nearly doubles that of the (G+ME) route. Moreover, (G+FT) route is sensitive to plant capacity, significantly increasing production costs with capacity reductions. This variable could be a barrier to potential developers.

-In the case of (G+ME) processes, the cost of hydrogen significantly impacts the overall production cost with both feedstocks. Variations in the cost of H_2 production have a significant impact on the profitability of this route.

ii) From a policymaker approach:

To evaluate the range of impacts on cost production by a 30% subsidy on Capex, both feedstock options in the (G+FT) process have the most significant reduction rates in production costs. In the case of (G+ME), the MSW route is also sensible to a 30% subsidy, achieving almost a -17% reduction in production cost. On the other hand, the (G+ME)$_{\text{lignocellulose}}$ route is the least affected. However, in relative terms, recalling that capex on the G+FT route is higher than on the G+ME case, the (G+ME)$_{\text{MSW}}$ route is the one where the most efficient results are achieved in terms of lower subsidy in absolute terms with higher impacts on the reduction of production costs.

Chapter 7. Techno-economic analysis (TEA) for HEFA, FT-SPK and AtJ Pathways.

As seen in previous chapters, there are multiple ways to produce SAF from a wide range of feedstocks. In a competitive market environment, including the wide availability of fossil fuels, SAF competes with other CO_2 mitigation options, such as market-based measures and carbon capture. (Braun, 2024). This makes evaluating each of these possible production routes in economic and technological terms necessary to have objective criteria when assessing each alternative's technical and economic viability and considering all the links in the supply chain. To carry out this analysis, articles by different authors have been reviewed, and the different SAF production routes have been considered from a techno-economic point of view. This chapter presents the sensitivity case for three complete pathways to SAF production.

Techno-economic analysis (TEA) can be instrumental in determining the technical and commercial viability of the different pathways. The techno-economic analysis considers not only economic variables but also technical variables, considering the factors that may impact the profitability of a given route, such as technological readiness level, engineering and operational factors that may affect the profitability of a given pathway (e.g. in the capex variable the plant capacity and size will directly impact due to economies of scale, with a correlation between facility capacity and lower specific production costs (Braun, 2024)).

These studies' vital contribution is in identifying the technical and economic parameters that have the most significant influence on each initiative's performance.

This analysis goes beyond the sensitivity analysis performed in Chapter 6 at several points:

- The sensitivity analysis in Chapter 6 does not consider a complete pathway to obtaining a drop in fuel or a substitute since we stayed at an intermediate fuel. We keep the fuel variable to be obtained open: Syncrude vs. Methanol, two intermediate fuels (FUP3). We left beyond the scope of the sensitivity case the last upgrade stage to obtain a renewable fuel usable in the transport sector.
- The sensitivity analysis in Chapter 6 focuses on describing the break-even breakdown of the syngas and their sensitivity to different variables for the two transformation routes proposed, aiming to raise the main criteria factors to consider when a promoter could face an investment decision.

- The TEA exercise proposed in this chapter starts from a different position. We economically compare three complete pathways aiming at the same fuel obtained: SAF, a drop-in (FUP2).
- TEA results depend on the feedstock type and the conversion technology (Rojas, 2021), including the feedstock cost, capital expenditure, operational expenditure, and other economic variables such as the internal rate of return.
- In the feedstock variable, we compare the main factors impacting the costs of feedstocks (e.g., in energy crops (FP2): cultivation, harvesting, processing, transport, and storage).
- In the Capex variable, we economically compare three conversion technologies at different stages of technological development (FT and AtJ TRL 7-8 and HEFA TRL9; see Table 5.3) and with different downsizing capabilities (to match feedstock production capacity) or the ability to develop brownfield projects (taking advantage of existing assets), all of which are technical factors.
- In the Opex variable, we highlight the economic impact of an operational factor as the SAF yield variable (none of the three routes produces only SAF, and the percentage split between the products produced significantly impacts the profitability of the specific route).

Finally, as the SAF has to be blended in different percentages with the fossil alternative, obtaining the minimum selling prices (MSP) is critical. This will be one of the main results of techno-economic analysis. The MSP allows us to compare the competitiveness of SAF produced from different renewable pathways and provides a vision of the cost parity to fossil fuel Jet A1. The variations in minimum selling price are the long-term average cost resulting from different conversion pathway efficiencies and assumptions on the cost of feedstocks, facility construction, energy, and interest rates, the assumptions performed for co-product revenues. In economic terms, this corresponds to the long-term average cost (Braun, 2024).

Given the increasing demand for sustainable aviation fuels (SAF) necessary to meet carbon reduction targets (Huq, 2024), conducting this analysis is highly useful, equipping policymakers, researchers, and industry professionals with the tools required to evaluate the viability of different SAF production pathways. Many studies compared TEAs on the three prominent technology routes for SAF production: Hydroprocessed Esters and Fatty Acids (HEFA), Fischer–Tropsch Fuels (FT-SPK), and Alcohol-to-Jet (AtJ).

In section 7.1, we illustrate the three pathways where we applied the TEA.

7.1 Description HEFA, FT-SPK, and AtJ Pathways

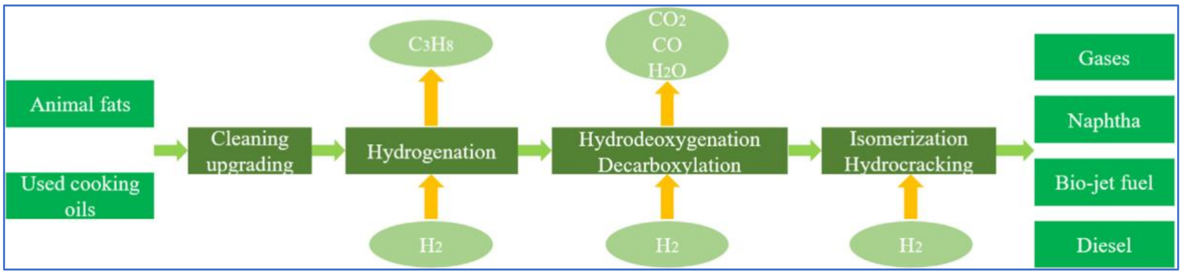
7.1.1 Hydroprocessed Esters and Fatty Acids (HEFA-SPK ASTM D7566 Annex A2/ HC-HEFA-SPK, ASTM D7566 Annex A7)

Feedstock Platform FP2 Energy Crops/FP3 Waste
Feedstock: FP2: Cellulosic material, Oil type
FP3: Waste lipids/waste material/cellulosic material
Technology Platform TP2 Catalytic
Conversion technology Hydrotreatment
Fuel Platform FUP2 drop-in
Fuel: SAF

HEFA-SPK route was approved in 2011 for blend levels of 50% for feedstock, including vegetable oil and waste oils. Hydroprocessed renewable jet fuels (HRJs or HEFA) are produced through the catalytic hydrotreatment process of oil-based feedstock in the presence of hydrogen, removing oxygen and followed by hydrocracking. The process is related to traditional refinery processes, which are being transformed into biorefineries. HRJs are high-energy biofuels used in conventional aircraft engines without further engine modification. Blending HRJs with other conventional fuels overcomes some weaknesses (such as low lubricity). As an aviation fuel, HEFA has already been tested by many airline companies for passenger flights.

HEFA-SPK fuel bears similarities to traditional fossil fuels. However, it boasts several advantages, such as a higher cetane number, lower aromatic content, lower sulfur content, and potentially reduced greenhouse gas emissions. Mature hydroprocessing conversion technologies, like hydrotreating, deoxygenation, isomerization, and hydrocracking, are widely available and commonly used in refineries to produce them (a simplified process diagram can be seen in Figure 7.1). HEFA was the second certified process in July 2011 and is currently the only commercial-scale process for producing aviation biofuel that has undergone extensive testing (Detsios, 2023).

Figure 7.1 HEFA-SPK process.



Source: Wei (2019).

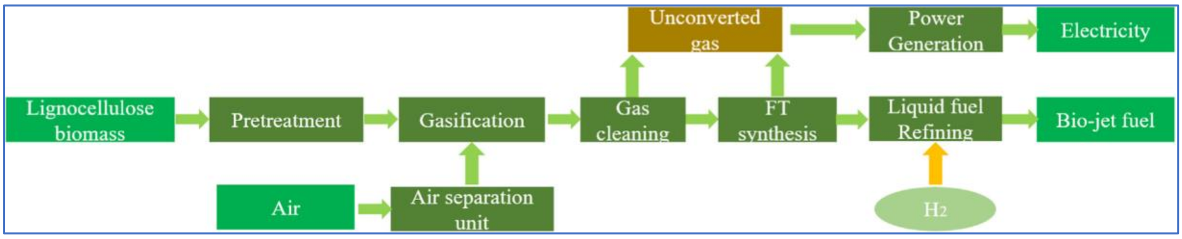
7.1.2 Fisher-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) (FTK-SPK ASTM D7566 Annex A1/ FTK-SPK/A ASTM D7566 Annex A4)

Feedstock Platform FP1 Food Crops/FP3 Waste
Feedstock: FP1 Vegetable oil
FP3 Waste lipids/Waste lipids
Technology Platform TP3 Thermochemical
Conversion technology Gasification
Upgrading process: Fischer-Tropsch (G+FT)
Fuel Platform FUP2 drop-in

FT-SPK was the first pathway approved in 2009 for a blend of up to 50%. The approved feedstocks are lignocellulosic feedstock (including MSW), coal, and natural gas. In the FT-SPK pathway, biomass is converted to syngas using gasification and jet fuel components using the Fischer-Tropsch (FT) synthesis reaction. Fischer-Tropsch synthesized kerosene with aromatics (FT-SPK/A), a variation of the FT process that produces a synthetic alternative aviation fuel containing aromatics. The process is illustrated in Figure 7.2.

Several companies (e.g., Sasol, Shell, Syntroleum) developed the FT process, the first alternative jet fuel pathway approved for regular use in 2009. The FT-SPK pathway produces gasoline, diesel, wax, and jet range fuel. The approved blend limitation for jet fuel the FT-SPK pathway produces is 50%. This blending percentage is linked to the fuel's origin and its use's safety. As experience and implementation lead to further certification, higher concentrations can be achieved (this is general in the industry).

Figure 7.2. A simplified process flow sheet of a possible FT-SPK process



Source: Wei (2019).

The production of Synthetic Aviation Fuel (SAF) using a Fischer-Tropsch (FT) reactor involves three main stages: (I) generating synthesis gas (syngas), which was described in the previous chapter; (II) converting the syngas into synthetic crude (syncrude) using FT-synthesis, and (III) separating, upgrading, and refining the syncrude to produce intermediate or final SAF products. The FT process generates a range of products, from methane to long-chain hydrocarbons (Meurer & Kern,2021).

FT synthesis aims to convert the syngas into synthetic crude (syncrude). This phase is a highly exothermic reaction that produces various alkanes. Higher temperatures (300–350 8C) and iron catalysts are typically adopted for gasoline-range products. Lower temperatures (200–240 ºC) and cobalt catalysts are typically used for diesel-range and wax products in which shorter hydrocarbon chains form as the temperature increases. At high temperatures, selectivity favors methane and light gases. (Douvartzides, 2019; Dimitrioua, 2018; Molino, 2018; van Steen and Claeys, 2008).

The syncrude produced in the previous stage must be separated, upgraded, and refined to produce SAF. FT reactor produces a range of hydrocarbon chains, but only C8 to C16 is helpful for jet fuel. Selectivity favors high-carbon-number wax products at low temperatures, which calls for further hydrocracking/catalytic cracking to the distillate range. These additional downstream units would increase the capital investment but are necessary for liquid fuel production (Meurer & Kern, 2021; Zhao, 2019).

Like HEFA fuels, FT fuels also have low lubricity due to the absence of sulfur. The typical jet fuel fraction in an FT facility is 10%–15%; the academic literature indicates it can be Tuned up to 70%–80%. In comparison to HEFA, FT is more appealing because it offers a greater variety of feedstock options that do not compete with the food supply (Doliente, 2020)

7.1.3 Alcohol-to-Jet (AtJ)
(ATJ-SPK ASTM D7566 Annex A5)

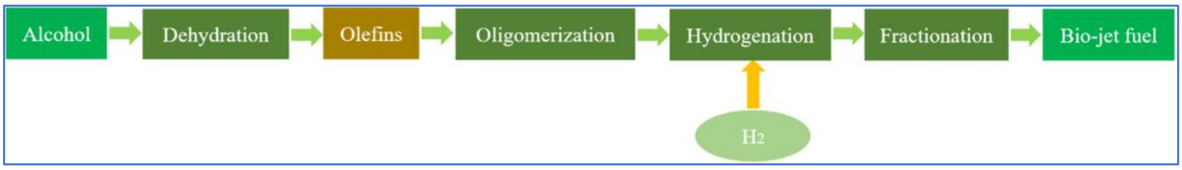
Feedstock Platform FP2 Energy Crops/FP3 Waste
Feedstock: FP2 Cellulosic type
FP3 Cellulosic material
Technology Platform TP1 Biological
Conversion technology Fermentation
Upgrading process: Hydrotreatment
Fuel Platform FUP1 substitute
Fuel: SAF

ATJ was first certified in 2016 for isobutanol at blend levels of 30%; it was since revised to include ethanol and isobutene and increased blend levels of 50%. The ATJ process shown in Figure 7.3 is a sophisticated three-step catalytic conversion technique that efficiently transforms alcohol into jet fuel. In the first step, the alcohol is dehydrated to its alkene form and then oligomerized into long-chain hydrocarbons. Finally, hydrogenation is applied to the hydrocarbons, resulting in the production of jet fuel.

Alcohols can be obtained through conventional methods, such as sugar or starch-rich crop fermentation or hydrolysis from lignocellulosic feedstock (Doliente, 2020). Methanol, ethanol, and isobutanol can also serve as feedstock, but the MTJ route has not yet received approval; however, they have yet received ASTM approval.

When ethanol is used as a feedstock, the intermediate (ethylene, propylene, higher alcohols, and carbonyl) leads the reaction pathway, which requires different technologies and production requirements. Factors such as catalyst cost, process efficiency and complexity, and level of technology maturity must be considered when evaluating each technology.

Figure 7.3. Alcohol-to-Jet route to produce Bio-jet fuel.



Source: Wei (2019).

The oligomerization stage is the crucial step in the ATJ process and the primary factor that sets it apart. ATJ is a rapidly growing approach to sustainable aviation fuel (SAF). While ethanol and isobutanol have already gained ASTM approval, they have a limited supply. Approving methanol as feedstock would be a significant breakthrough, as it can be produced from CO_2 and hydrogen or biomass/MSW gasification.

7.2 Cost of feedstocks.

The first step in conducting a TEA is to review the cost of feedstocks based on production costs, product distribution costs, and processing technology/feedstock for each technology.

The International Civil Aviation Organization (ICAO) guidelines “Rules of Thumb” could be a pragmatic first step toward providing big-picture trends for these delivered feedstock cost comparisons (see Table 7.1) (Brandt, Martinez-Valencia, & Wolcott, 2022). With these rules, ICAO provides a simple, approximate, not detailed, guide to the costs associated with feedstocks. These guidelines are updated regularly.

Table 7.1 ICAO “Rules of Thumb” for feedstocks price.

Processing Technology	Feedstock	Feedstock Price
HEFA	FOGs	580 $/t
HEFA**	Soybean oil	890 $/t
FT*	MSW	30 $/ton
FT*	Forest Residues	125 $/ton
FT*	Agricultural residues	110 $/t
AtJ	ehtanol	0.41 $/L
AtJ	isobutanol-low	0,89 $/L
AtJ	isobutanol-high	1,20 $/L

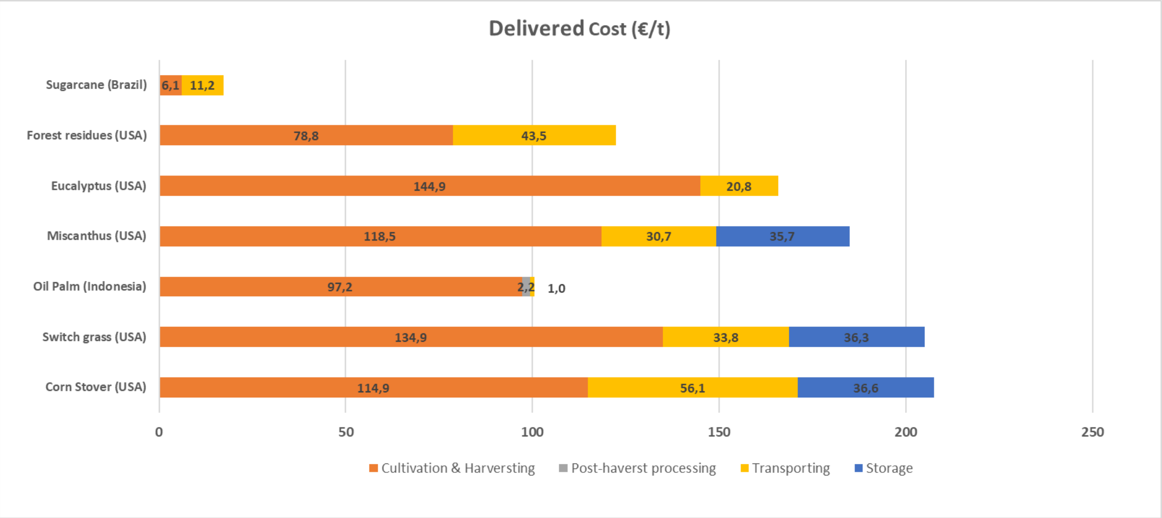
Note: The feedstock price is for pre-processed feedstock **. The 2013-2019 average price of soybean and canola oils.

The breakdown of the delivered cost of feedstocks into the cost of cultivation and harvesting, processing, transport, and storage allows us to see the impact of each of these activities on the total cost. According to this information, in most of the feedstocks represented, the cost of cultivation and harvesting accounts for more than 50%, reaching a value of 97% in the case of Palm Oil (Doliente, 2020).

Corn stover and Switchgrass are the two feedstocks with the highest delivery costs, exceeding €200/t. Most of the total corresponds to cultivation and harvesting activity (114,9

€/t and 134,9 $/t, respectively). Both have very similar storage costs, €36.6 and €36.3/t, respectively, while Corn Stover has higher costs of transport costs, with 56.1 €/t vs 33,8€/t in the case of Switch Grass. Regarding Miscanthus and Eucalyptus, delivery costs are between $150/t and $200/t. While Miscanthus has lower cultivation and harvesting costs (€118.5/t vs €144.9/t), it does have a storage cost of €35.7/t) that eucalyptus does not have. Trasport cost are 30,7 €/t for Miscanthus and 20,8 for Eucalyptus. Between 100 and 150 are the delivered costs of Oil Palm and Forest residue. Oil palm is the only feedstock with a cost associated with post-harvest processing (2,2 €/t). According to Figure 7.4, Sugar cane would be the feedstock Figure 7.4; sugar cane would be the feedstock less penalized by delivery costs (17.3 €/t).

Figure 7.4. Delivered (farm-to-gate) cost.



Source: Doliente (2020) and self-elaboration. Note: The original prices (2019 US $) were adjusted for country inflation in 2023 and converted to € using the IMF consumer prices index and exchange rates.

HEFA is the primary method for producing Sustainable Aviation Fuel (SAF), which relies on vegetable or waste oil feedstock. However, policymakers are encouraged to use vegetable oil for fuel production, limiting the expansion of HEFA. For example, the EU has banned using imported palm oil for fuel production, which has impacted Europe's biodiesel and renewable industry. Furthermore, in Europe, only jets produced with non-edible feedstock are acceptable. That means ATJ cannot use conventional first-generation ethanol or edible vegetal oil HEFA route. However, in other regions such as the USA, SAF produced using food crops is entirely accepted if GHG saving requirements are met.

According to the International Council on Clean Transportation (ICCT) analysis (O'Malley, Pavlenko & Searle, 2021), the EU needs more recoverable waste oil to support the decarbonization of its aviation sector with HEFA. To meet its target of 2.3 Mtonne of SAF by 2030 with HEFA alone, the EU would need 4–6 Mtonne of waste oil. However, according to the ICCT, only 2.4 Mtonne will be available by 2030 for all uses, including non-SAF. HEFA technology is already well-established commercially, so further innovation opportunities are limited. There are efforts to diversify feedstocks to include energy crops and waste to meet the increasing demand for SAF production (Mupondwa, Lia, & Tabil, 2022).

Therefore, the focus is on managing the feedstock supply chain, feedstock cost (see Table 7.2) and optimizing the pretreatment process, as feedstock represents more than 50% of the levelized production costs in every relative techno-economic study of a HEFA facility (Detsios, 2023). Producing HEFA SAF requires additional catalytic cracking and competes with the demand for HEFA diesel by converting long-chain fatty acids into hydrocarbons suitable for jet fuel. However, this process consumes additional hydrogen and reduces fuel yield, making HEFA SAF more expensive than HEFA diesel (Huq, 2021).

Table 7.2 Feedstock Cost for a HEFA process (two-stage hydroprocessing facility)

Feedstocks			Plant Capacity (million l jet fuel)	Feedstock Cost (€/L)
Food crops	Vegetable oil	Camelina oil	225	1,4 (2018)
			219	3,9(2017)
		Soybean oil	116-378	1,2(2013)
Energy crop	Oil- tape	Castor bean oil	193	3,3(2017)
		Jatropha oil	167	0,9(2017)
			113	0,8(2016)
		Palm oil	12	1,0(2019)
		Pennycress oil	153	1,9(2017)
		Pongamia seed	61	0,92 €/kg(2013)
	Cellulosic type	Hybrid poplar wood	64	124,7 €/t(2018)
Waste	Waste Lipids	UCO	257	0,3(2020)
		Yellow grease oil	191	1,3(2017)

Source: Mupondwa (2022), Doliente (2020) and self-elaboration. Note: Original prices (2018 US $) adjusted for US inflation in 2023 and converted to € using the IMF consumer prices index and exchange rates.

The range of feedstocks in the FT-SPK pathway could include various biogenic residues (e.g., forestry, agricultural, and municipal solid waste). The cost of ethanol is primarily the production costs at AtJ. Ethanol derived from the fermentation of food crops or starch crops typically leads to lower production costs than the conversion of lignocellulosic feedstock through hydrolysis and subsequent fermentation. However, the use of food crops as feedstock is limited by current legislation and will gradually be phased out due to their high ILUC (indirect land use change) risk.

7.3 CAPEX

The main challenge of the FT-SPK pathway is the high capital expenditure (CAPEX) related to the gasification and FT units, downsizing the FT unit to match the feedstock supply scale, and integrating distinct units. Due to the complexity of the process, its cost is currently higher than that of fossil paraffin; however, as the scale of the application grows, together with the possibility of using bio-based or circular economy raw materials, it will have more room for maneuver. In this technological route, high capital costs drive production costs, which account for more than 50% of the total (Detsios, 2023).

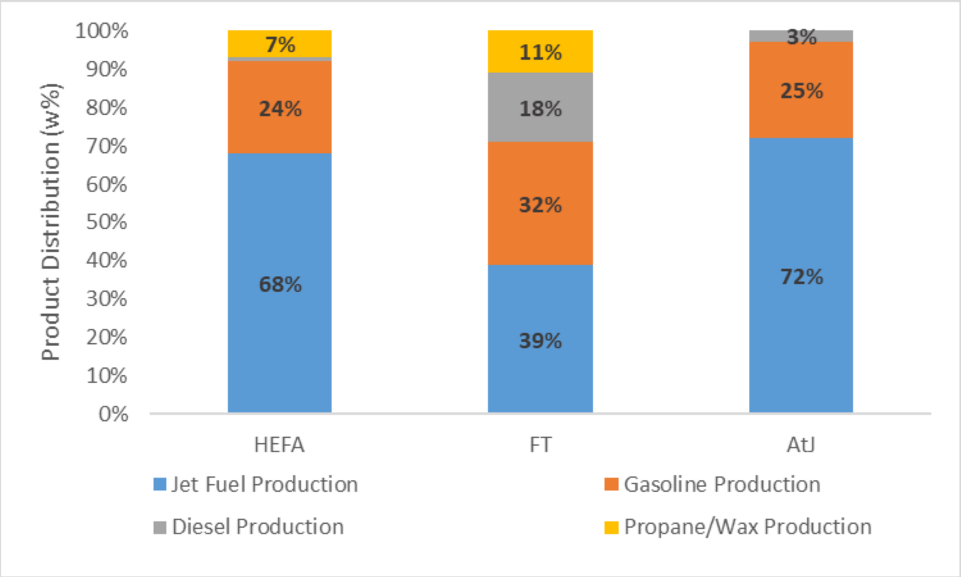
In the case of the ATJ route, CAPEX related to the production of lignocellulosic ethanol is also very significant compared with conventional ethanol production. This fact is due to the much lower nameplate of 2º generation facilities due to limitations on feedstock provisioning. Furthermore, posterior conversion of alcohols requires the combination of different units (dehydration, oligomerization, and hydrotreating), resulting in a complex system.

However, significant CAPEX savings can be realized in the production of ATJ and HEFA jets when existing units initially designed for fossil fuel production are retrofitted. For example, some fossil hydrotreaters can be revamped into HVO units. In the same way, hydrocrackers can be adapted to convert FT waxes into SAF or diesel.

7.4 OPEX

Several factors directly impact OPEX, such as energy or hydrogen costs. Nevertheless, two significant ones are product distribution or selectivity and energy efficiency. Product distribution significantly impacts production costs along with the cost of capital and feeds. The distributions of products from various SAF pathways depend on several factors, including feedstock composition, conversion process, downstream cracking conditions, and market demand (Figure 7.5).

Figure 7.5. Product distribution of renewable fuels for three SAF technologies on a mass basis.



Source: Arpit (2022) and self-elaboration.

The technology route with the highest SAF yield (%w) would be AtJ at 72%. In this process, gasoline (25%) and a small amount of diesel (3%) would be produced as co-products. The second process with the highest yield of SAF would be HEFA, with 68%. In this case, 24% of gasoline and 7% of propane/wax are produced as co-products. FT is the pathway with a more partitioned distribution of products: 39% of SAF, 32% of gasoline, 18% of diesel, and 11% of propane/wax. Depending on the market situation, the production of one or the other co-product may be more interesting, with the contribution to the total margin of each being different. Routes with high energy efficiency will also positively impact their costs compared to other less efficient alternatives (see Table 7.3), understanding energy efficiency as the ratio of the energy content of the end products and the energy input from feedstock and others (e.g., hydrogen, natural gas) (Shahriar& Khanal, 2022).

Table 7.3 SAF production Pathway energy efficiency

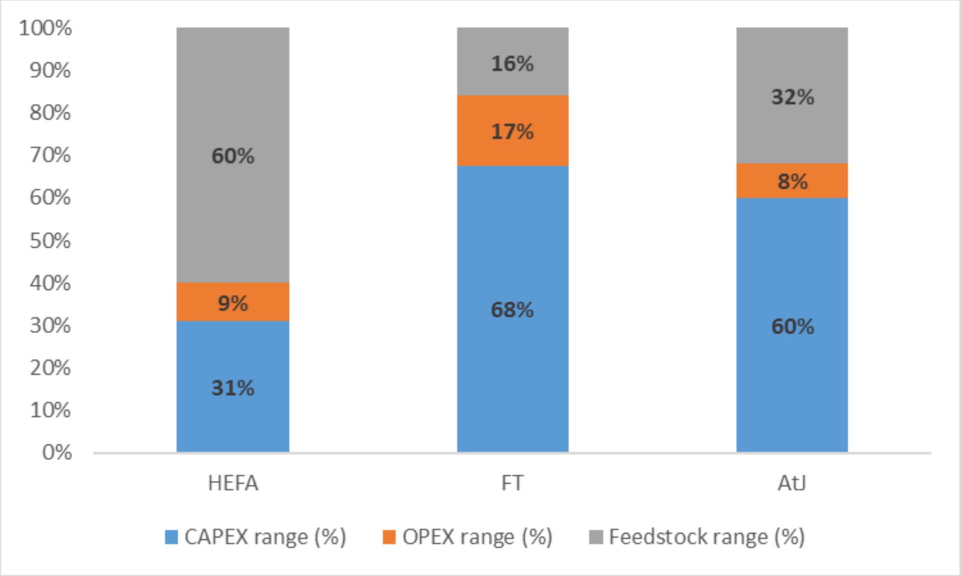
SAF production Pathway	Energy Efficiency (GJ output/GJ input)
HEFA	0,71-0,77
FT	0,91
ATJ	0,4-0,53

Source: Shahriar & Khanal (2022) and self-elaboration

Therefore, feed cost is predominant in the HEFA, and CAPEX is a determining factor in the cost of production in the FT and AtJ processes, as illustrated in Figure 7.6.

In FT and AtJ, CAPEX accounts for more than half of the total cost, with 68% and 60%, respectively. In the case of HEFA, this percentage is reduced to 31%, with the feed cost being the most significant proportion of the total (60%). In FT and AtJ, this percentage drops to 16% and 32%, respectively. As for the other OPEX, HEFA and AtJ show similar 9% and 8% values, respectively. In the case of FT, OPEX would account for 17% of the total.

Figure 7.6 Average CAPEX, OPEX, and feedstock contribution of production costs.



Source: Detsios (2023) and self-elaboration.

Table 7.4 Range CAPEX, OPEX, and feedstock contribution to the MSP formation.

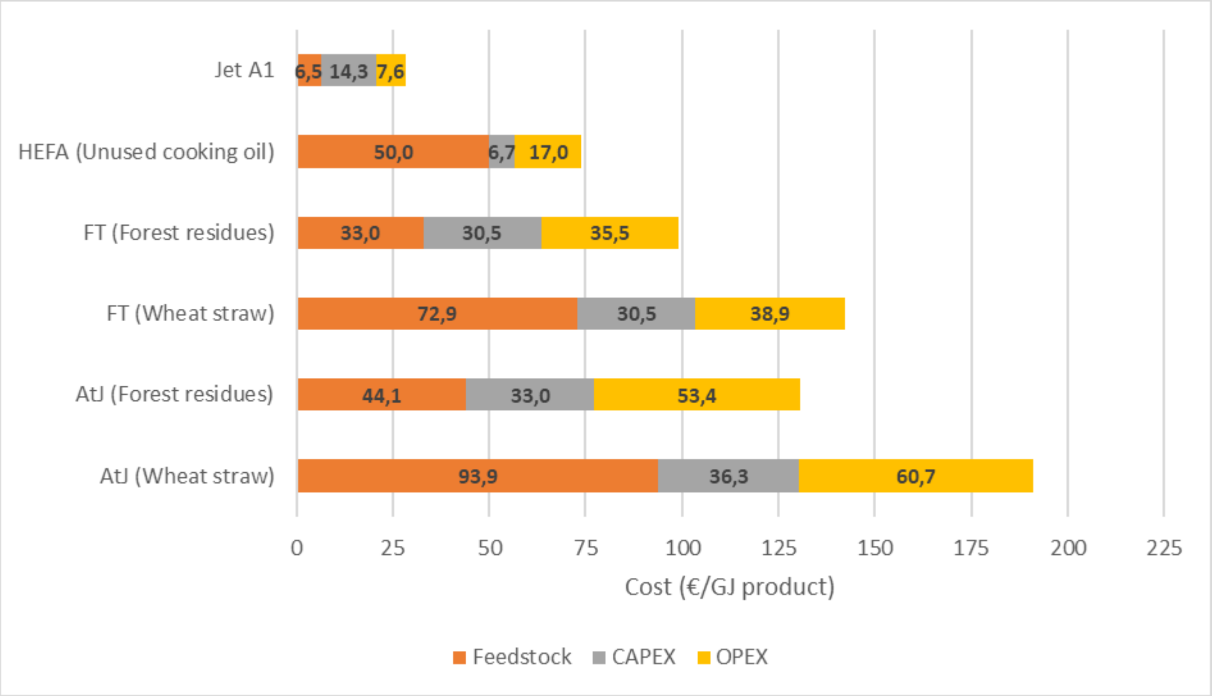
	HEFA	FT	AtJ
CAPEX range (%)	22-40	54-81	45-75
OPEX range (%	8-10	12-21	2-14
Feedstock range (%)	51-69	0-32	20-44

Source: Detsios et al., (2023).

Opex includes fixed and variable costs apart from feedstock. Variable costs include energy costs, chemical and additive costs, and catalysts. The cost of hydrogen is included in these costs. Fixed costs include personnel, maintenance, and insurance premiums, among others.Table 7.4 shows the distribution between Capex, Opex and Feedstock in the contribution to the Minimum Selling Price (MSP) (see in detail in section 7.6)

Figure 7.7 shows the cost breakdown (compared to producing fossil jet fuel) of producing SAF in terms of the feedstock, capital expenditures (CAPEX), and operating and maintenance expenditures (OPEX) for HEFA, FT, and ATJ expressed in €/GJ units.

Figure 7.7 Breakdown cost of producing bio-aviation fuel by HEFA, FT, and AtJ compared to Jet A1.



Source: Doliente (2020) and self-elaboration. Note: Original prices (2019 US $) adjusted for US inflation in 2023 and converted to € using the IMF consumer prices index and exchange rates.

The HEFA option is a mature and promising route for SAF production. It demonstrates the lowest CAPEX and OPEX costs compared to the other routes. According to figure 7.7, the OPEX of the HEFA route using unused cooking oil as feedstock would be an average of 30% of those corresponding to the AtJ route and 46% of those indicated for the FT route. This difference is even more significant for CAPEX, with these costs being, on average, 19% compared to those corresponding to the AtJ process and 22% in the case of FT. (Doliente, 2020). This technological maturity instills confidence in the HEFA option's potential for bio-aviation fuel production.

However, HEFA's feedstock cost is significantly superior to JetA1's. Thus, the cost of sustainable feedstocks could determine this pathway's economic performance (Doliente, 2020).

While the use of MSW with relatively low delivered costs, agroforestry residues, and lignocellulosic energy crops as feedstocks for the yet commercially feasible FT and ATJ shows promise, it is essential to note the potential challenges (Dupuis, 2019). As more advanced technologies become commercially viable, these feedstocks will be critical to the aviation industry's medium—and long-term decarbonization (Lewis, 2019). However, conducting a direct economic comparison of feedstocks is generally challenging due to the many interdependent factors, some spatially and temporally dependent (Doliente, 2020). This underscores the need for careful planning and consideration of feedstock availability in the future of bio-aviation fuel production.

Through process improvements in the medium term, overall production costs could be reduced by 5-27%. In addition, if the increased experience makes it possible to finance plants on more favourable terms, this will further reduce costs by 5-16% (Brown, 2020). The potential for longer-term cost reduction is still being determined, as it hinges on the deployment of technologies and the potential for reducing capital and operating costs, which may vary across different technologies. Additionally, feedstock costs are pivotal in determining overall energy production costs, and there is uncertainty surrounding cost curves as demand increases. With rising demand, there may be a shift towards more expensive feedstocks, and the growing use of feedstocks for energy production could lead to shortages and subsequent price increases. As a result, feedstock availability will play an increasingly important role in determining the affordability of advanced biofuels (Brown, 2020).

7.5 Minimum Selling Price (MSP)

The Minimum Selling Price (MSP) is the breakeven selling price of a product required to achieve a zero net present value at an acceptable minimum internal rate of return. Table 7.5 presents MSPs published for different feeds in various years for three technologies analyzed (HEFA, FT, AtJ).

In the case of HEFA, studies show an MSP range of 0.81–1.84 EUR/L. Those cases in which the feedstock was UCO seem to be the most competitive in terms of cost, reaching MSP values below 1 EUR/L. The range of feedstocks used in the FT-SPK pathway is broadened to include various biogenic residues (e.g., forestry, agricultural, municipal solid waste). This flexibility produces a relatively wide range of MSPs (1.24–3.64 EUR/L). The lowest obtained MSPs refer to using municipal solid waste (MSW) as feedstock since MSW is usually free of charge and has the potential for negative costs (see Chapter 3.3. where MSW and biomass are compared to produce FT products). In the case of AtJ, according to some studies, the minimum selling prices of lignocellulosic feedstock would range between 0.9 EUR/L and 2.72 EUR/L (Detsios, 2023).

Table 7.5 Potential MSP for HEFA, FT, and AtJ

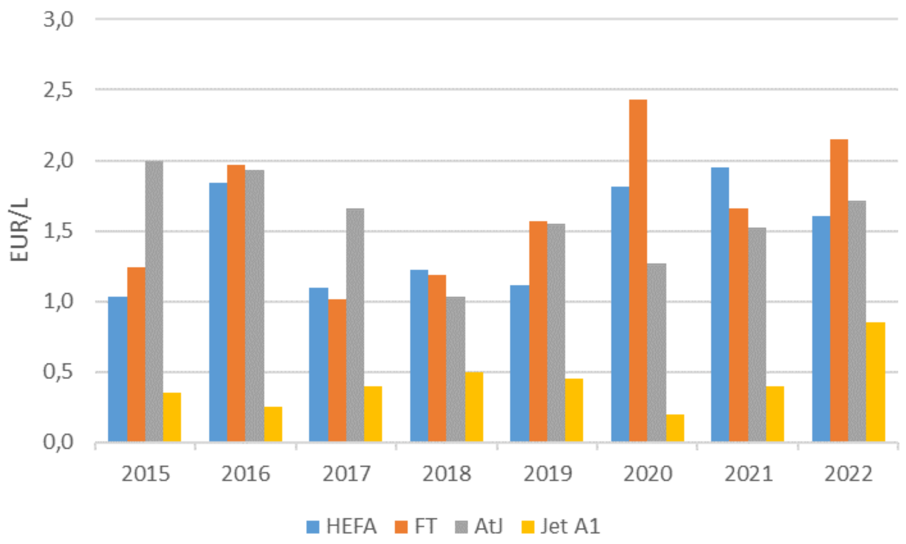
Feedstock Platform	Feedstock	Category	MSP
FP1Food crops	Sugar starch	Corn grain	[1.21 EUR/L (2016)- 0.90 EUR/L (2022)] AtJ
		Sugarcane	[1.27 EUR/L (2020) 2.02 EUR/L (2016)] AtJ
		Corn stover	[3.64 EUR/L (2021)] FT// [1.71 EUR/L(2016)]AtJ
		Wheat straw	[2.72 EUR/L (2015)]AtJ
	Vegetable Oil	Vegetable Oil	[1.84 EUR/L (2016)-1.39 EUR/L (2019)] HEFA
		Soybean oil	[1.23 EUR/L (2017)-1.09 EUR/L (2019)] HEFA
		Palm oil	[0.81 EUR/L-1.04 EUR/L (2018)] HEFA
FP2Energy crops	Oil- tape	Jatropha oil	[1.60 EUR/L (2018)-1.44 EUR/L (2020)] HEFA
FP3Waste	Waste lipids	UCOs	[1.03 EUR/L (2015)- 1.29 EUR/L (2017) 0.88 EUR/L (2019)]HEFA
	Waste Material	MSW	[1.34 EUR/L (2019)-1.55 EUR/L (2022)] FT
	Cellulosic material	Agricultural residues	[1.80 EUR/L (2019)- 2.01 EUR/L (2022)] FT
		Rice husk	[2.22 EUR/L (2022)] FT

		Lignocellulose	[1.97 EUR/L (2016)-2.22 EUR/L (2022)] FT//[1.98 EUR/L(2016) 2.30 EUR/L(2022) 1.71 EUR/L(2020)]AtJ
		Forestry residues	[2.47 EUR/L (2022)-1.82 EUR/L (2018)] FT// [1.98 EUR/L(2015)]AtJ
		Wood chips	[1.24 EUR/L (2015)]FT//[1.28 EUR/L(2015)]AtJ

Source: Detsios (2023) and self-elaboration.

Figure 7.8 provides an overview of the minimum selling prices of the different technology routes compared to the price of conventional jet fuel.

Figure 7.8 MSP for SAF and Jet A-1 global average price evolution in recent years.



Source: Detsios (2023); Wang (2021); Rojas Michaga (2021); Mupondwa (2022); Wei (2019); Kok Siew (2021); Bann (2017), Pooja Suresh (2018); Doliente (2020) and self-elaboration.

Regarding cost parity, HEFA would be the most competitive pathway, although its MSP is still much higher than traditional JetA-1 (van Bavel & Vandu, 2024).

Even assuming some variability between the different years, figure 7.8 shows the significant difference in the MSPs of the three SAF production alternatives compared to the Jet A1, with the HEFA, FT, and AtJ routes having MSP values 3.1, 3.4, and 3.6 times higher on average than those of conventional fossil fuel (given the exceptional situation of the markets in 2020 because of the pandemic, this year it has been excluded from this calculation).

In conclusion:

-We could assert that HEFA using UCO as a feedstock would be the most competitive SAF production route, given its lower minimum sales prices, although still well above those of the Jet A1. This process, which generally has the lowest costs, both OPEX and CAPEX, evidencing greater technological maturity, may face challenges to the availability and cost of the feedstock.

-When valuing a given feedstock, it is essential to consider costs such as cultivation and harvesting, transport and storage, and the cost throughout the supply chain.

-Operational factors such as energy efficiency and revenues from coproducts emerge as critical variables that directly impact the economic viability of the pathway

Chapter 8. Conclusions

The thesis thoroughly and comprehensively describes an innovative platform-based methodology that enables the vision of pathways for evaluating projects in the renewable fuels industry.

The comparison of the economic viability of each of these pathways provides a very useful tool for all actors involved in the production of renewable fuels (players in the feedstock segment, technologists, promoters of production projects, logistic agents in the distribution of the finished product, and policymakers).

The proposed framework simplifies the economic viability analysis exercise for each pathway by grouping the analogous factors that impact the economic viability of each pathway by platform. For example, in the case of the feedstock platform, some of these factors are related to feedstock availability, feedstock generation, type of feedstock, collection system, and sorting. In the case of a technology platform, the technological readiness level, the minimum plant capacity, the range of feedstocks that can be treated, the flexibility to downsize a standard capacity plant, the specific yield of products, and infrastructure limitations are some of the factors to be considered.

As mentioned throughout the thesis, feasibility is not only a techno-economic term for the availability of technologies on an industrial scale with proven yields and economically viable results but also a path of development, hybridization, coupling, and processes, building blocks for improved platforms in competition with fossil fuels and products, electrification, hydrogen, and some other technologies.

The presented pathways framework provides a more accurate vision of the competing alternatives before evaluating an investment in this industry.

Several pathways produce renewable fuels with mature technologies (e.g., Platform FP1 Food crops/FP2 Waste material). These pathways represent the combination of sound feedstock supply chains sugar/starch, proven technologies (e.g., Platform TP2 Catalytic/Transesterification) with high yields, and favorable market prospects (e.g., FUP1 Substitute/ Biodiesel). It will be the leading player in the renewable fuels industry for the remainder of the decade. Therefore, competition for feedstock in the food supply chain, production costs, friction with current logistics systems, and political and financial support are critical to development. At the same time, there are emerging short-term technology opportunities with mature technologies but little development in the value chain (TP2 Catalytic/ Hydrotreating). These pathways capture the value of available feedstocks at significantly lower costs than the previous category (FP2 Waste material/Waste solids/Waste liquids). They can produce fuels that take advantage of existing capillary fuel distribution logistics networks and can be adopted without changing existing ICEs (FUP2 Drop-in/ HVO). At this level, there are opportunities for improvements in existing upstream processes (e.g., waste collection and collection), integration with existing assets, and exploiting opportunities for utilizing existing utilities and production cost reductions. These pathways co-exist with medium-term technology opportunities with scaling technologies (TP3 Thermochemical/ Gasification+FT). The number of projects at this level is increasing. This group includes technologies at TRLs 7-8 and, therefore, is at risk of eventually achieving commercial scale, capable of accessing more competitive and more extensive feedstock sources with incremental yields and more competitive production costs (FP2 Waste material. Waste solids/Waste liquids). They may reach prominence after 2030. Scaling up these final steps requires more budget, effort, knowledge, expertise, support of use cases, and support to become basic engineering processes for the industry and clear business cases for investors.

The TEA analysis of HEFA, FT-SPK, and AtJ Pathways illustrates this competition. Although HEFA is currently the most cost-efficient pathway to produce SAF, the scarcity of feedstocks and expected demand growth force us to focus on developing another pathway, such as ATJ or FT-SPK. These pathways need to be developed and supported to improve competitiveness, and there are many cases of use, geographies, industries, countries, and feedstocks; the best solution is to improve and support technologies to reach that point.

The sensitivity exercise in Chapter 6, comparing (G+FT) versus (G+ME) routes, provides another angle to consider key variables impacting profitability. This example highlights the relevance of supply feedstock cost, where the lowest production costs are achieved on pathways that source MSW as feedstock. In the case of (G+FT) process, CAPEX is significant, while the cost of hydrogen significantly impacts the overall production cost of the (G+ME) process.

In light of the sensitivity exercise's results, the route that is most suitable for economic competitiveness is $(G+ME)_{MSW}$. This is due to lower feedstock costs and less uncertainty in the technology's development. However, to maintain this competitive advantage, electrolytic H_2 costs must be kept at a reasonable level.

What policy prescription can be derived from this research in light of the results?

The regulator confronts different alternatives for decarbonizing the transport sector, such as renewable fuels, H_2, or electrification. Therefore, it must assess the impact of public policies, such as subsidies, incentives, mandatory quotas, or bans, will have on the different options. Each has varying levels of technological maturity and associated investment levels. The best way to undertake this task is to do so unbiasedly and with technological neutrality as the guiding methodology.

Renewable fuel pathways offer a complete vision of the entire value chain and make visible levers for action along the entire production chain. This tool makes it much easier for the regulator to compare the different alternatives for decarbonization in terms of economic efficiencies from a taxpayer's point of view, such as the cost of adoption, speed of deployment, impact on industrialization, resource dependence, and technological independence. Therefore, the regulator should always analyze the alternatives in full pathway mode, not technology mode.

Study limitations.

The scope of this thesis is comprehensive. Nevertheless, some concepts and research areas have not been fully covered and are beyond the scope of this thesis.

The description of feedstock platforms does not include food crop platforms, and a review of a whole body of up-and-coming research associated with algae has also been left out.

When we focused on the technology platform, the biological platform still needs to be addressed, as it is comprehensive and far from our expertise; furthermore, in the thermochemical platform, pyrolysis technology, one of the most promising technologies in the conversion to materials, has yet to be evaluated, as it is still in its infancy, and the reader of the current work might find it excessively long-winded.

In the case of the fuel platform, DME, derived from methanol, one of the most promising fuels for use in ships, has yet to be described because, to describe a drop-in fuel, the explanation of the SAF routes fulfilled its purpose.

Potential areas of future venues

This thesis opens the door to new and promising research areas as a result of all the analyses that have been carried out. Among these future venues, we could highlight those related to the:

i) Comparison of the effects of different regulations on the cost-effectiveness of various pathways.

At present, renewable fuels can not compete with fossil fuels without regulatory and financial support. Therefore, the regulatory framework significantly impacts the renewable fuels industry's global viability and the specific viability of the different pathways.

The policymaker faces a battery of different tools to overcome the funding gap necessary for the industrialization of renewable fuels. The first is to generate consumer demand for renewables downstream in the value chain by establishing a system of quotas on suppliers that impose an obligation to supply these fuels.

On the other hand, the suppliers of these fuels need financial support to make the necessary industrial investments sustainable. The promoters of these investments face two main uncertainties. The first is the CAPEX required to deploy technologies that are not fully developed and whose TRLs are still below the commercialization level (TRL9). In this case, the investment in technologies is promoted through direct investment subsidies or tax incentives to address the funding gap. The other uncertainty is market-related and, therefore, needs another approach. To support the consumption of these renewable fuels by final consumers, there must be no price difference with the fossil alternative (cost parity should be equal), and for this, the regulator can reduce or eliminate the tax burden applied to these renewable fuels during the final supply.

This thesis provides guidance on which economic support measures can significantly impact the development of the renewable fuels industry. In Chapter 6, we show, for example, the sensitivity to different levels of CAPEX subsidy in the case of the two simulated routes

(G+FT) and (G+ME) with the two feedstocks (MSW and lignocellulose) in reducing the cost of production.

ii) Evaluating how renewable fuels compare to other ways of reducing emissions in transportation, such as electricity or H_2.

Comparing the production cost of renewable fuels from a pathway perspective rather than on a technology-by-technology basis gives more accurate and complete values of each alternative's impact. This aim could lead to a fruitful line of research from which to undertake reviews of complete pathways versus complete pathways of power and H_2 production. By looking for net zero systems, these analyses can provide the regulator with an unbiased tool to apply the necessary incentives most effectively.

iii) Complete the study of pathways necessary for switching from a refinery to a biorefinery. Refineries will be one of the key players in the construction of renewable fuel pathways, as most conversion technologies need further upgrading to achieve the required fuel specifications. Most of these upgrading technologies are installed, operated, and amortized in existing refineries, lowering the entry barrier for investment in these technologies. Many of these refineries are already on the road to transforming their processes by modifying the streams and units required to produce renewable fuels, primarily substitutes. It will require considerable infrastructure to generate sufficient solar or wind power (around 6-7 GW per refinery), which will be three times the current amount. Storage systems will be needed to manage the excess power generated. Future refineries would consume 4.3 TW of electricity in 2050 (compared to an estimated 30-60 TW to meet global energy needs). A significant increase in green hydrogen production capacity through electrolyzers will also be needed (Vogt & Weckhuysen, 2024). In-depth studies of the capex required for such transformations in the different pathways are needed.

iv) Completing the analysis to describe and evaluate pathways associated with the Biological Technology Platform.

In this research, we have focused on the catalytic and thermochemical platforms as they are the most promising current developments, hybridizing them with the assets of current petrochemical production. However, the biological platform can develop exponentially if R&D initiatives for obtaining renewable fuels in biological reactors with genetically modified organisms for this purpose are successful. Comparing the development costs of such technologies with those required for developing catalytic and thermochemical platform technologies could be a promising line of future research.

Building a global net-zero energy system is critical to limiting CO2e emissions. The transport sector plays a central role in this aim. However, no simple, fast, affordable, universal (applicable to all modes of transport), and massive (in terms of GHG reduction and terms of application in the diverse mobility alternatives) solution appears in the short term. Society and academia have a growing consensus that the solution will come from applying various technological approaches and changing how society moves and transports goods and services.

The decarbonization of the transport sector entails several technologies with different proposals (BEV, H_2, and synthetic fuels), each with its challenges and promises. Within the synthetic fuels industry, renewable fuels are the most plausible option for obtaining promising results in the short term. To achieve this objective, it is essential to be clear about the end-to-end variables that impact the profitability of the pathways in the different segments (feedstocks, technologies, fuels).

With this thesis, we hope to be closer to achieving that aim.

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Annex 1

Fig A1. (G+ FT)$_{MSW}$ Base Case Breakeven Production Cost Breakdown (€/MWh)

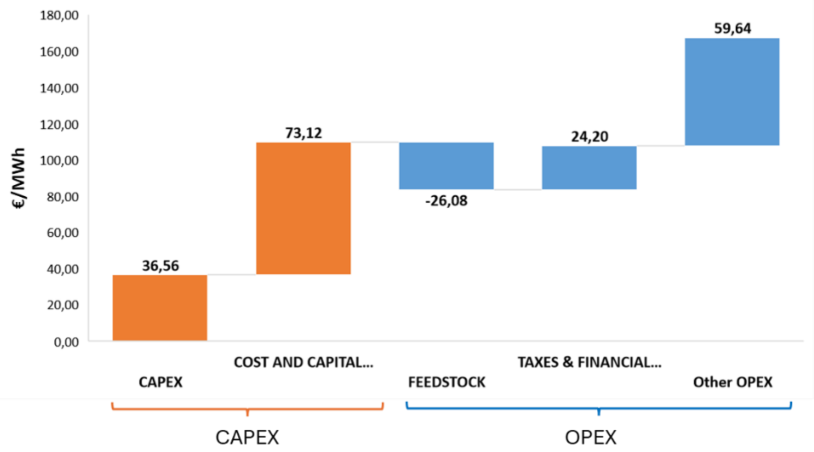


Fig A2. (G+ FT)$_{MSW}$ Base Case Breakeven Production Cost Breakdown distribution (%)

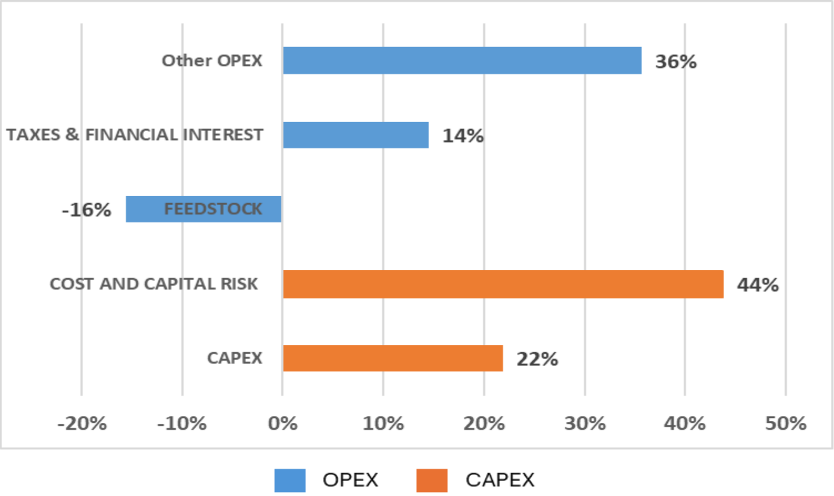


Fig A3 (G+ FT)$_{lignocellulose}$ Base Case Breakeven Production Cost Breakdown (€/MWh)

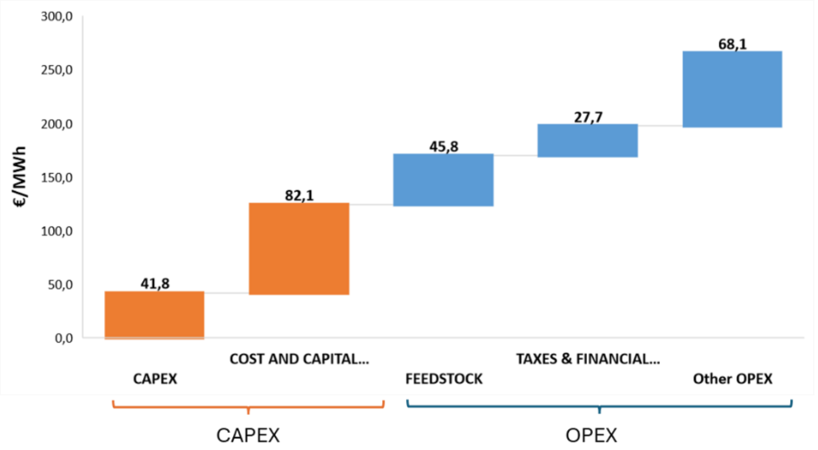


Fig A4. (G+FT)$_{lignocellulose}$ Base Case Breakeven Production Cost Breakdown distribution (%)

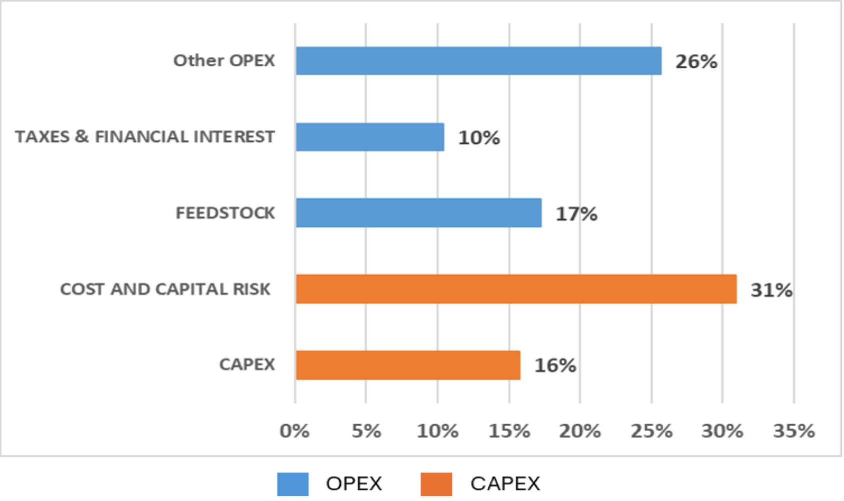


Fig. A5 (G+ME)$_{\text{MSW}}$ Base Case Breakeven Production Cost Breakdown (€/MWh)

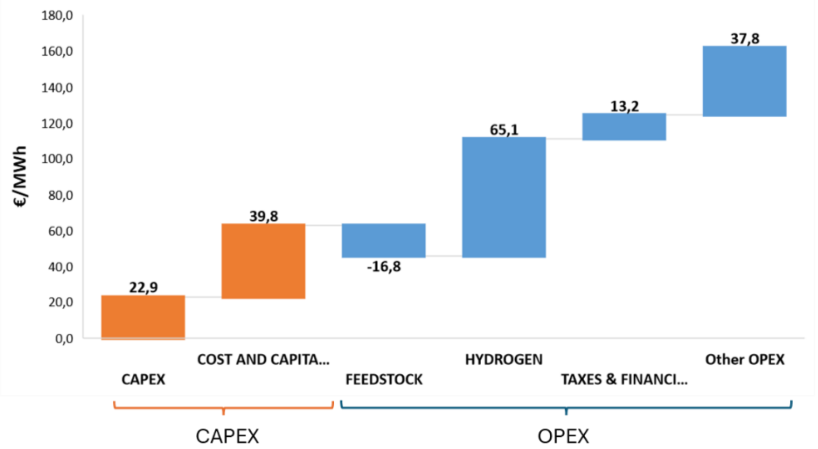


Fig. A6 (G+ME)$_{\text{MSW}}$ Case Breakeven Production Cost Breakdown distribution (%)

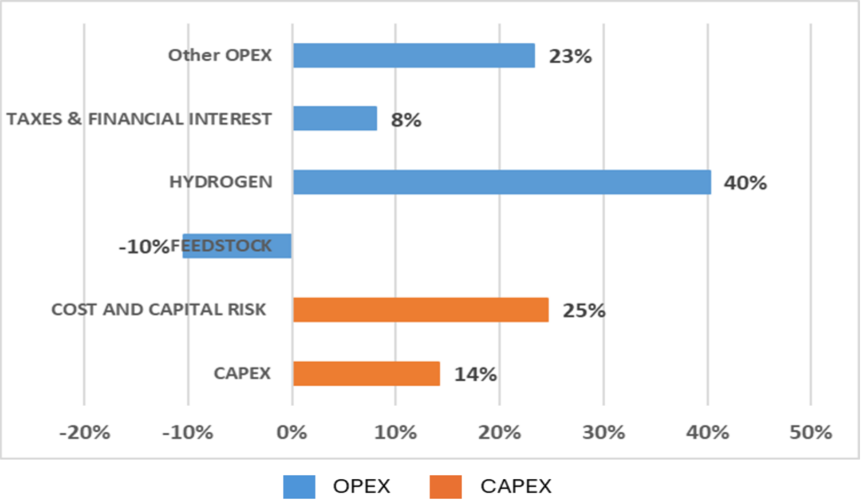


Fig A7. (G+ME)$_{\text{lignocellulose}}$ Case Breakeven Production Cost Breakdown (€/MWh)

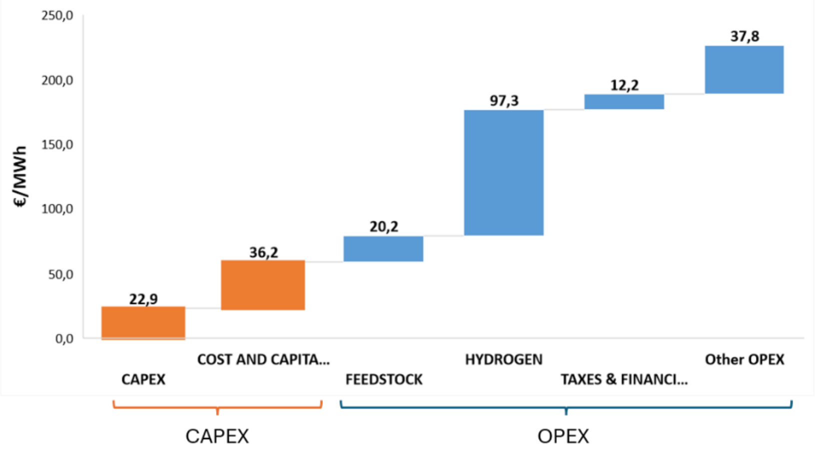
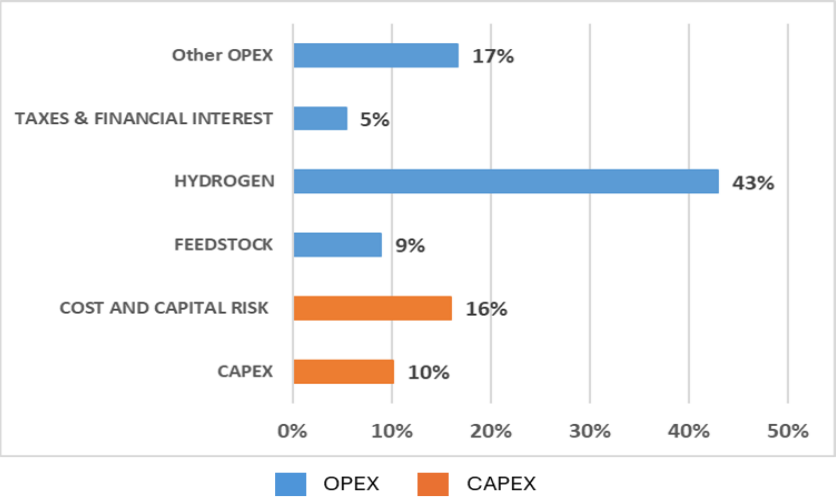


Fig A8. (G +ME)$_{\text{lignocellulose}}$ Case Breakeven Production Cost Breakdown distribution (%)



FigA9 (G+ FT)$_{MSW}$ Sensitive Analysis

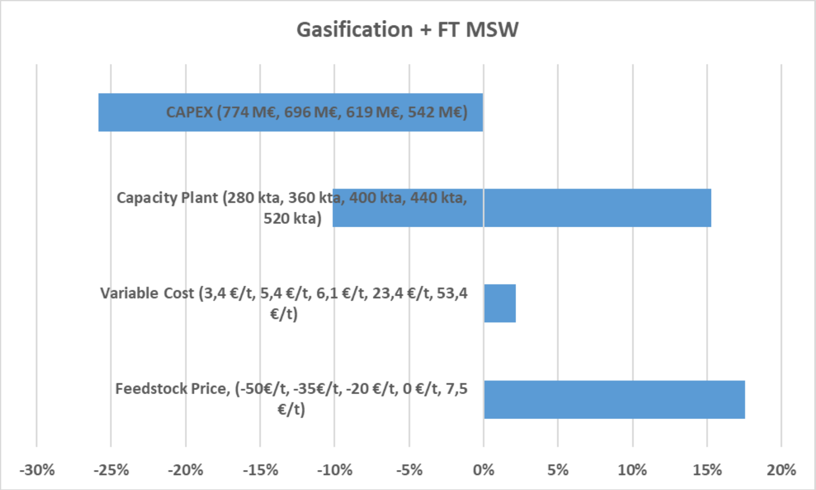
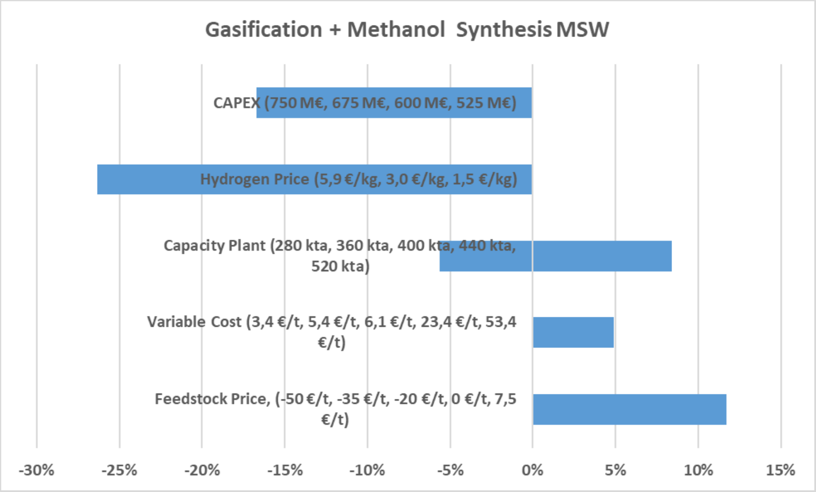


Fig A10 (G +ME)$_{MSW}$ Sensitive Analysis



FigA11(G+ FT)$_{lignocellulos}$e Sensitive Analysis

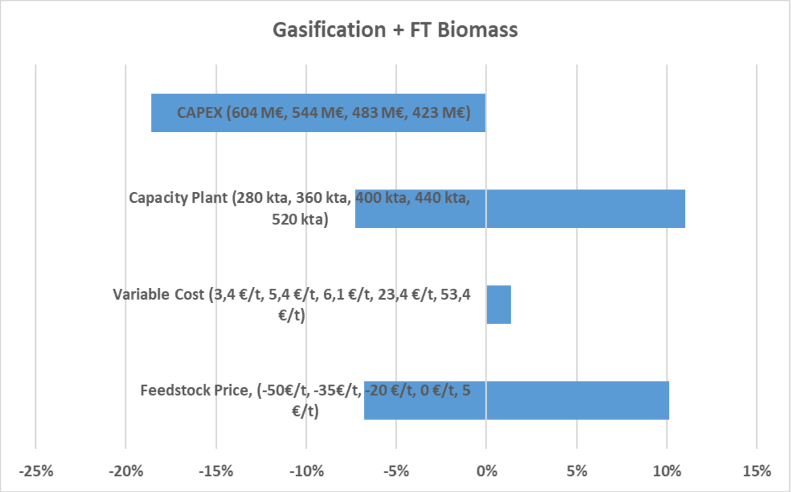
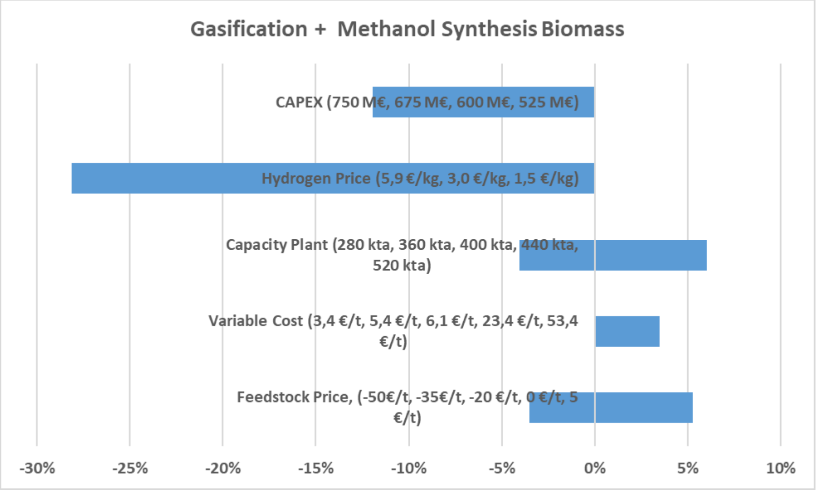
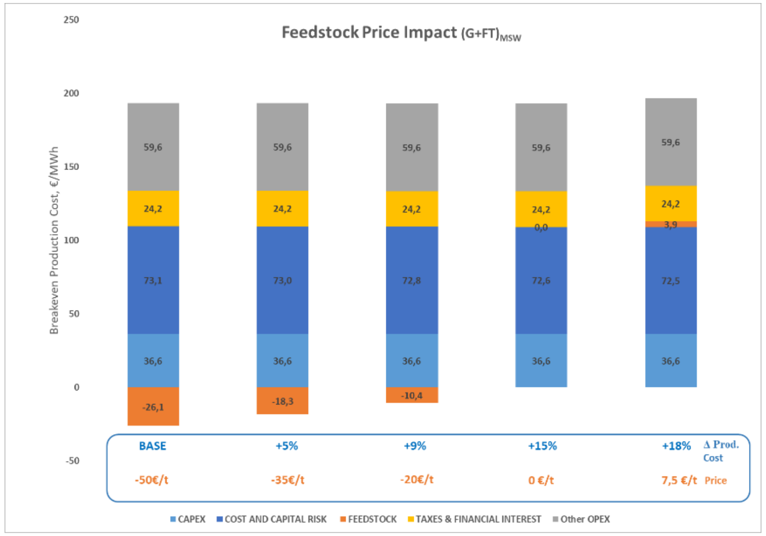


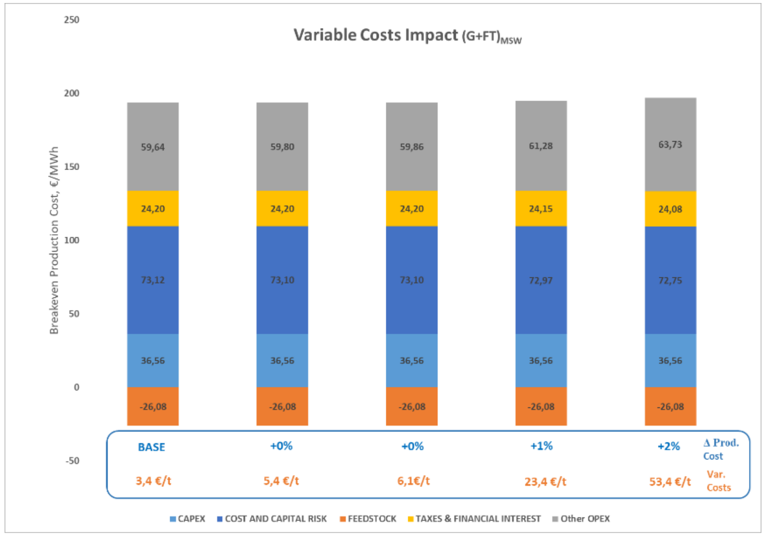
Fig A12 (G + ME)$_{lignocellulose}$ Sensitive Analysis



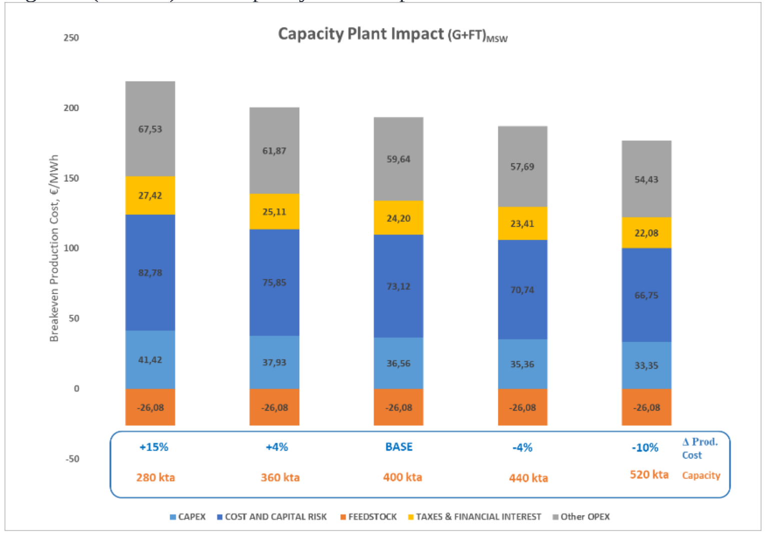
FigA13. (G+ FT)MSW Feedstock Price Impact



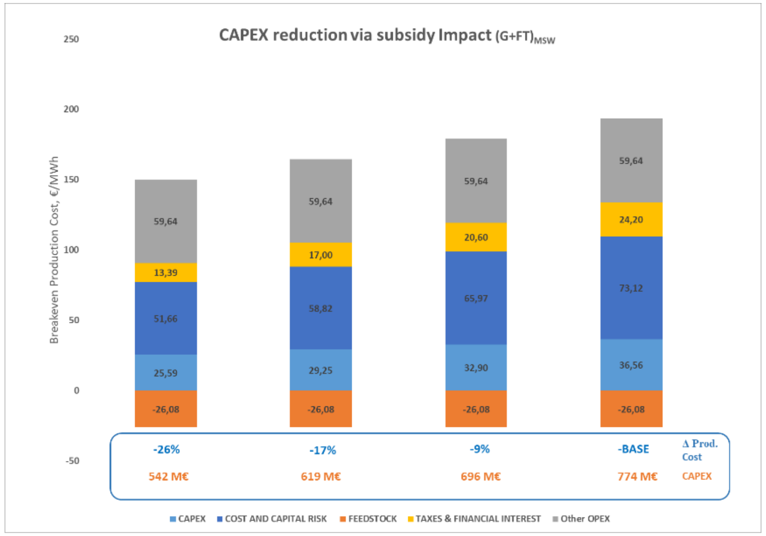
FigA14. (G + FT)MSW Variable Cost Impact



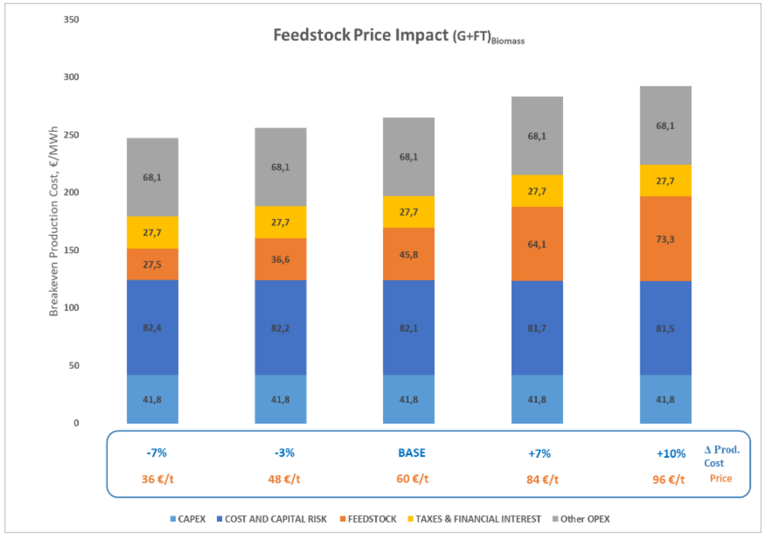
FigA15. (G + FT) MSW Capacity Plant Impact



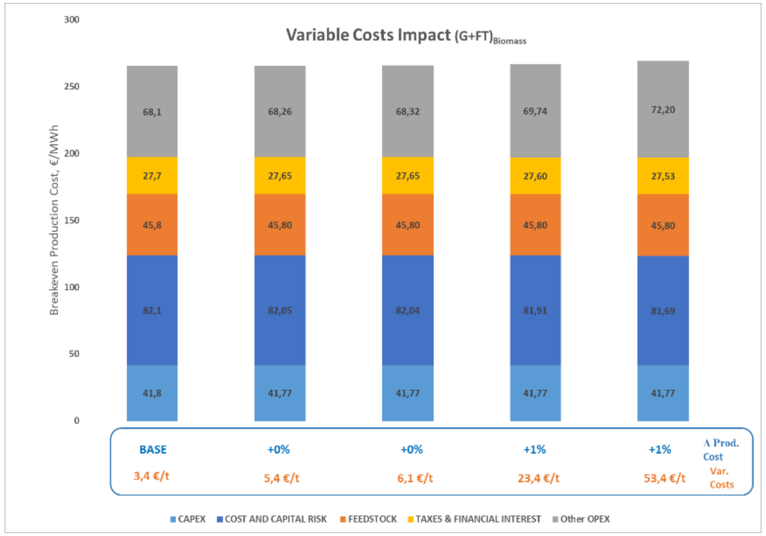
FigA16. (G+ FT) MSW CAPEX Impact



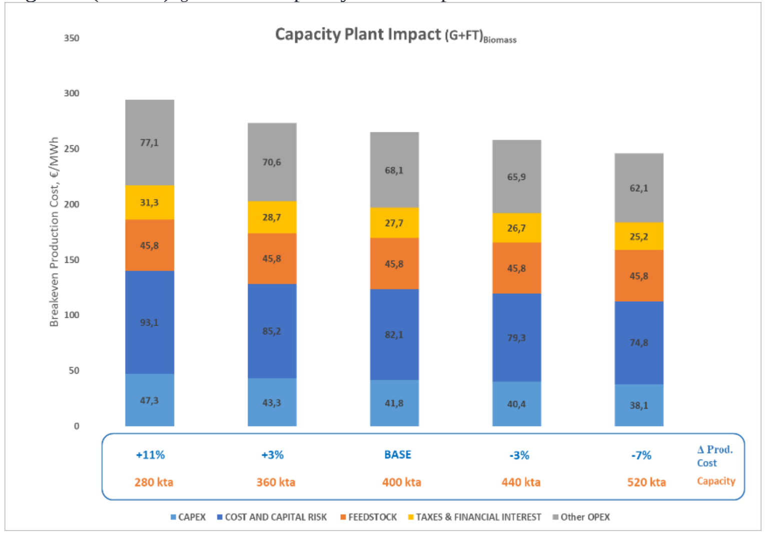
FigA17. (G+ FT)lignocellulose Feedstock Price Impact



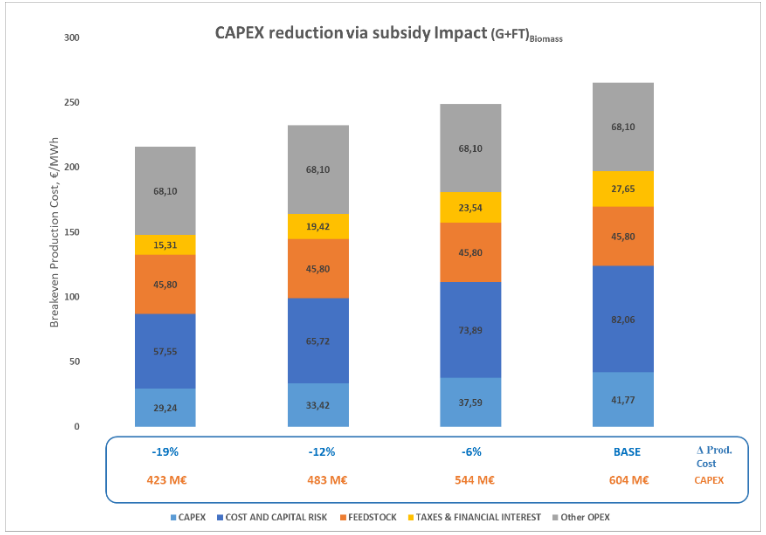
FigA18. (G+ FT)lignocellulose Variable Costs Impact



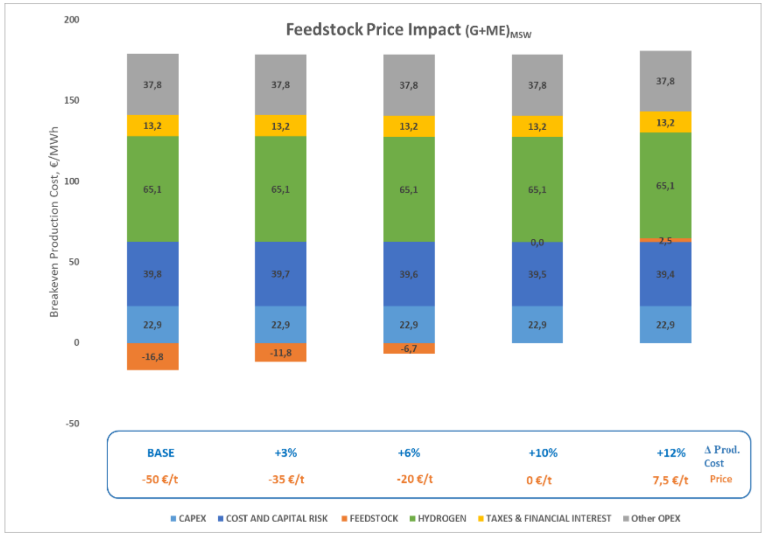
FigA19. (G+ FT)lignocellulose Capacity Plant Impact



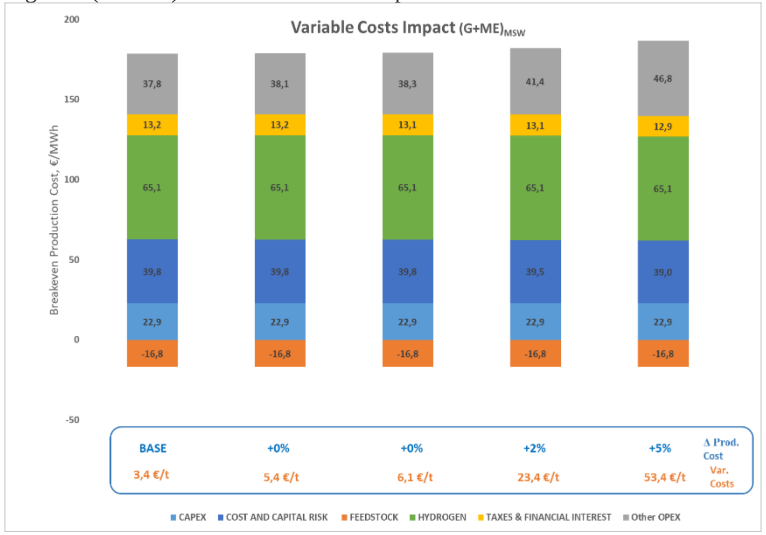
FigA20. (G+ FT)lignocellulose CAPEX Impact



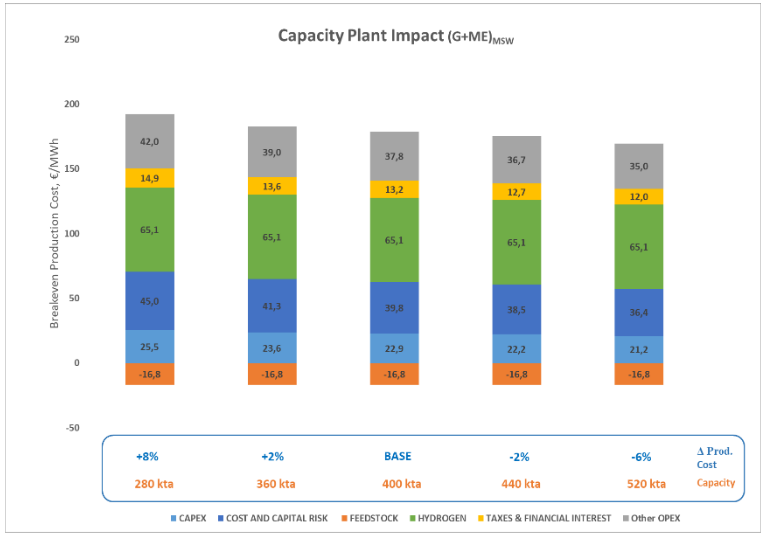
FigA21. (G + ME) MSW Feedstock Price Impact



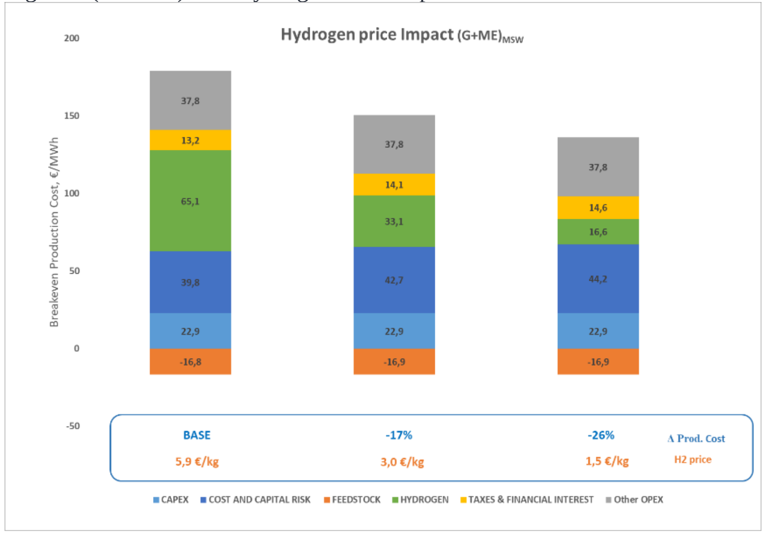
FigA22. (G +ME) MSW Variable Cost Impact



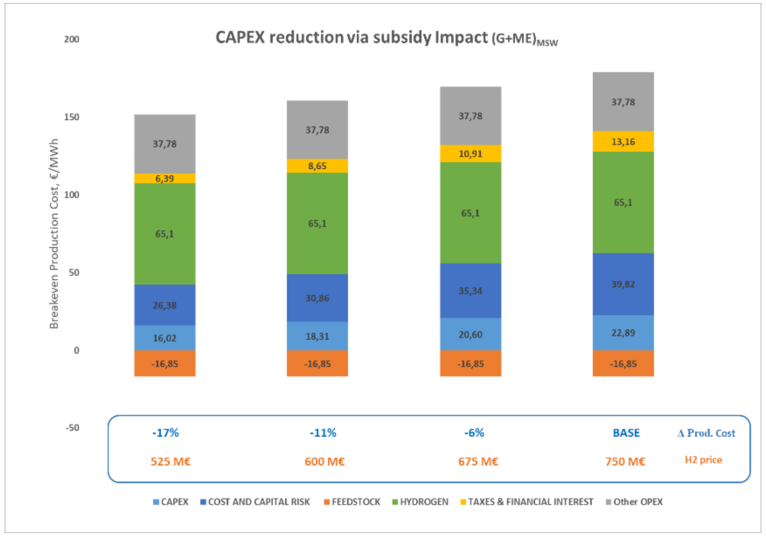
FigA23. (G+ME)MSW Capacity Plant Impact



FigA24. (G + ME) MSW Hydrogen Price Impact



FigA25. (G+ME) MSW CAPEX Impact reduction via subsidy Impact



FigA26. (G + ME)lignocellulose Feedstock Price Impact

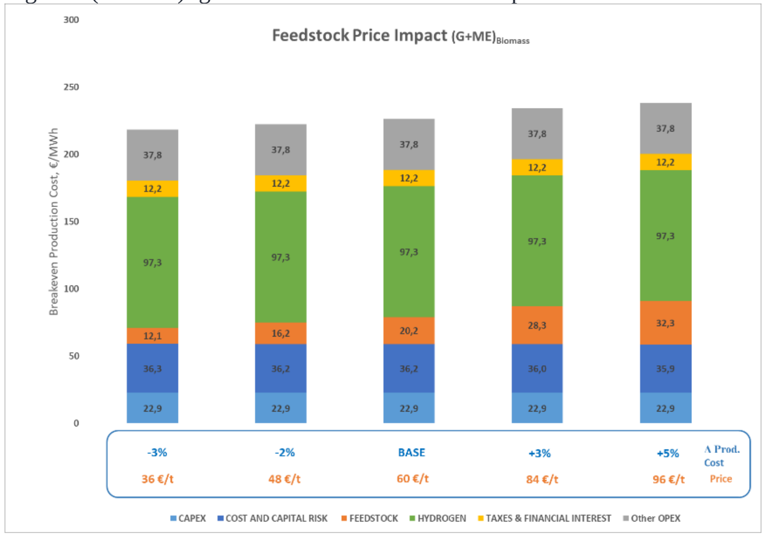


Fig A27. (G + ME)lignocellulose Variable Costs Impact

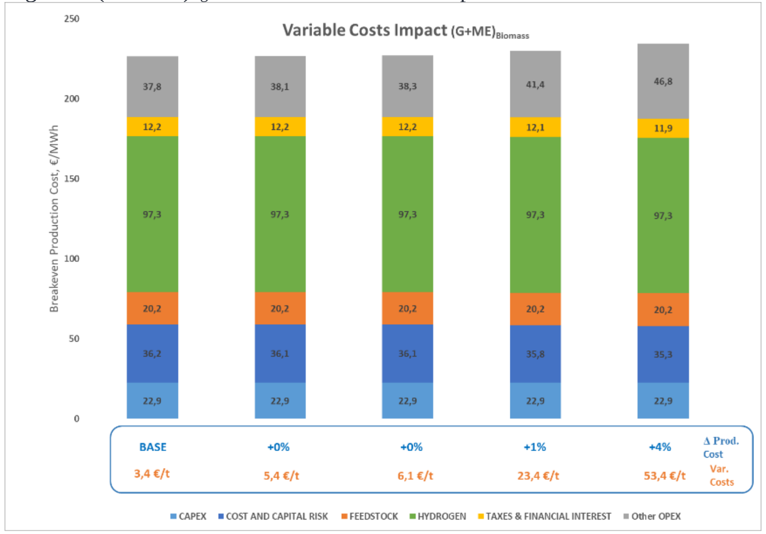


Figure A28. (G + ME) lignocellulose Capacity Plant Impact

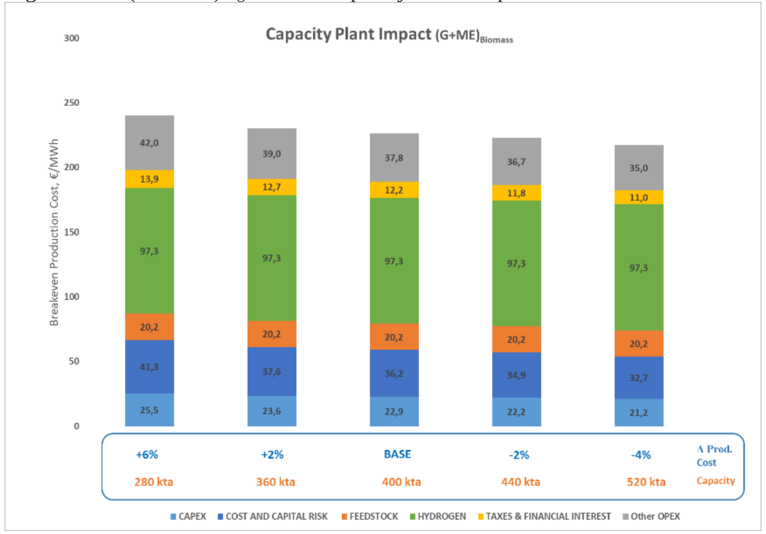


Fig A29. (G + ME)Biomass Hydrogen Price Impact

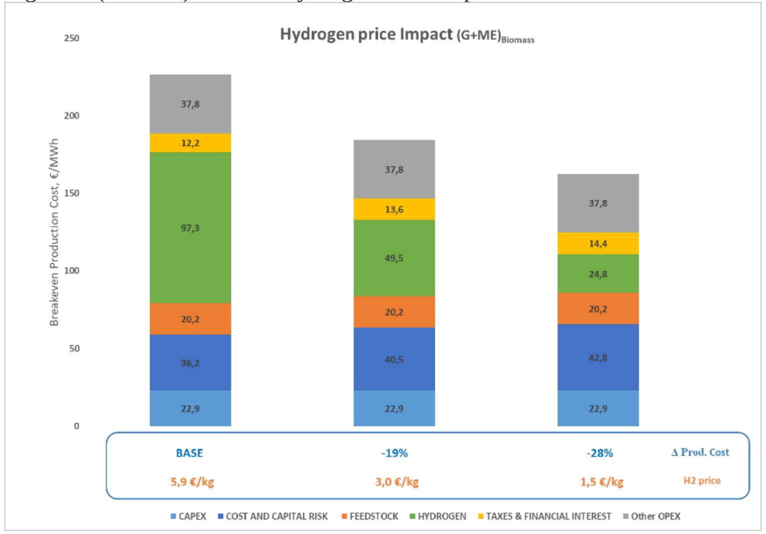


Fig A30. (G + ME)Biomass CAPEX Impact reduction via subsidy Impact