COMILLAS
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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

Incorporating Hydrogen into openMASTER for Decarbonizing the Spanish Energy System

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Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

"Incorporating Hydrogen into openMASTER for Decarbonizing the Spanish Energy System"

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Diego

Fdo.: Diego Maté Pulido Fecha: 30/07/ 2024

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: José Carlos Romero Mora Fecha: ..01./ .07../ 2024

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A mis directores, por la labor y el tiempo dedicado.

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INCORPORACIÓN DEL HIDRÓGENO A OPENMASTER PARA LA DESCARBONIZACIÓN DEL SISTEMA ENERGÉTICO ESPAÑOL

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ABSTRACTO

1. Introducción

El objetivo de este proyecto es investigar, identificar y definir las diversas tecnologías de hidrógeno dentro del sistema energético español, así como aquellas susceptibles de integrarse en un futuro cercano. Nuestro objetivo es definir la cadena de valor del hidrógeno en el contexto energético español e incorporarla en openMASTER, un modelo computacional para planificación energética a largo plazo.

Posteriormente, analizaremos el impacto de integrar el hidrógeno en el modelo, creando casos de estudio basados en diferentes objetivos de descarbonización. Nuestro objetivo final es determinar si el hidrógeno puede ser una solución viable para lograr un sistema energético limpio, seguro y financieramente sostenible.

Este proyecto es altamente relevante y significativo, ya que explora el potencial del hidrógeno para cumplir con los objetivos de la UE para 2030 y 2050, y lograr la sostenibilidad energética a largo plazo.

2. Estructura del Proyecto

El proyecto está estructurado siguiendo una metodología de tres fases para completar sistemáticamente las tareas y desarrollar un proceso de pensamiento coherente que nos permitirá alcanzar conclusiones lógicas. Los pasos son los siguientes:

- **Definición de Tecnologías y Parámetros:** esta fase implica una revisión exhaustiva de la literatura para identificar recursos aplicables, teorías y tecnologías clave para la cadena de valor del hidrógeno. Incluye la definición de los parámetros necesarios para definir cada tecnología, así como sus proyecciones temporales, subdivididas en las etapas clave de generación, distribución y demanda.
- **Validación de Teorías mediante Modelado en Excel:** se desarrollará un modelo en Excel para probar la naturaleza lógica y realista de las suposiciones relacionadas con la generación y la demanda. Esta fase permitirá ajustar las suposiciones antes de incorporarlas al modelo final.
- **Modelado en openMASTER y Casos de Estudio:** con las tecnologías validadas y sus respectivos parámetros clave, la información se volcará a openMASTER. Este modelo, incorporando las tecnologías de oferta y demanda de hidrógeno, permitirá la generación de escenarios y el análisis de resultados para llegar a conclusiones.

Este enfoque estructurado conllevará una validación exhaustiva y una implementación práctica de la cadena de valor del hidrógeno.

3. Descripción del modelo - openMASTER

El Modelo de Análisis de Planes Energéticos Sostenibles de código abierto (openMASTER) es una herramienta desarrollada por la Universidad Pontificia Comillas para el modelado integral de sistemas energéticos y la planificación estratégica. Es un modelo modular de equilibrio parcial “bottom-up” que respalda políticas energéticas sostenibles.

Capacidades:

- Simula y analiza el rendimiento y la sostenibilidad de los sistemas energéticos.
- Identifica trayectorias óptimas para la transición energética, integrando tecnologías renovables y aquellas emergentes, como el hidrógeno.

Características Clave:

- Equilibra la precisión técnica con interfaces con facilidad de uso para el usuario.
- Utiliza la programación lineal para optimizar métricas de sostenibilidad.
- Permite la visualización resultados mediante diagramas de Sankey.
- Ofrece amplia modularidad y flexibilidad para modelar diversas a escalas, desde micro redes hasta sistemas nacionales.
- Promueve la colaboración y la transparencia como plataforma de código abierto.
- Facilita la planificación de escenarios y el análisis estratégico.

Rol en el Proyecto de Hidrógeno:

- Permite el estudio de la viabilidad del uso del hidrógeno para el almacenamiento de energía renovable y como sustituto de los combustibles fósiles.
- Define e integra la cadena de valor del hidrógeno en el sistema energético.
- Simula escenarios para evaluar el impacto de las tecnologías de hidrógeno en los objetivos de descarbonización para 2030 y 2050.
- Apoya la planificación estratégica y la toma de decisiones a través de casos de estudio sobre la sostenibilidad y viabilidad económica de las tecnologías de hidrógeno.

El proyecto tiene como objetivo aprovechar el modelo openMASTER para evaluar exhaustivamente el potencial del hidrógeno en el contexto nacional, asegurando una transición efectiva hacia un sistema energético sostenible alineado con los objetivos ambientales y económicos a largo plazo.

4. Resultados

Tras la fase de modelado, los resultados del modelo pueden resumirse en las siguientes ideas principales:

- La producción de hidrógeno se alinea con las variaciones del PIB, lo que es un indicador en cuanto a la precisión del modelo para reflejar las condiciones económicas.

- La capacidad instalada se ajusta entre los escenarios de producción baja y media, en línea con el programa Hydrogen Accelerator de la UE dentro de la iniciativa REPower EU.
- La salud económica afecta la demanda y, consecuentemente, al despliegue proporcional de los métodos de producción de manera proporcional. La única excepción es en el refino de petróleo, que aumenta durante las crisis económicas debido a que el petróleo es una fuente de energía estable.
- Las fuentes de energía renovable continúan creciendo proporcionalmente, independientemente del escenario económico, sustentando el compromiso de la UE con la transición energética.
- Los electrolizadores alcalinos son los elegidos en el corto plazo, dominando hasta aproximadamente 2040. En consonancia con esta premisa, se espera que los electrolizadores PEM se vuelvan más competitivos después de 2040 debido a una curva de aprendizaje más pronunciada, eventualmente superando a los electrolizadores alcalinos como la tecnología principal para nuevos proyectos.
- Las emisiones se proyectan en disminución de forma consistente, reflejando el aumento en el uso de energías renovables e hidrógeno.
- Los niveles de emisiones se correlacionan con el PIB, puesto que una mejor situación económica conlleva una mayor cantidad de emisiones debido a la consecuente expansión industrial y el respectivo aumento de las demandas.

5. Conclusiones

Después de la realización de este proyecto, se pueden extraer cuatro conclusiones clave del análisis final:

- **Papel del Hidrógeno en la Transición Energética**: este proyecto demuestra que el hidrógeno es crucial para alcanzar los objetivos de la transición energética y de la descarbonización. Los resultados de las simulaciones de openMASTER confirman que la producción de hidrógeno se alinea con el comportamiento del PIB, mostrando su escalabilidad de la mano del crecimiento económico. Esta integración no solo demuestra ser factible, sino también positiva de cara a satisfacer las demandas energéticas.
- **Impacto en la Descarbonización**: el aumento en el despliegue de hidrógeno y la transición a fuentes renovables conducen a una reducción significativa de las emisiones de CO2. El análisis en detalle resalta las aplicaciones técnicas del hidrógeno y sus beneficios, destacando su contribución a los objetivos de desarrollo sostenible.
- **Tecnología de Electrolizadores**: el análisis favorece la tecnología de electrólisis PEM a largo plazo, proyectada a superar a la tecnología alcalina en 2040 atendiendo al ritmo de su curva de aprendizaje. Las estrategias futuras deberían priorizar este cambio tecnológico para un despliegue óptimo.
- **Enfoque Integral en las Soluciones Energéticas**: mientras que el hidrógeno juega un papel fundamental, el proyecto enfatiza que es solo un componente de una solución energética compleja. La revisión de la literatura identifica vacíos en las

políticas que a menudo se centran estrechamente en facetas energéticas específicas. Destaca así la importancia de integrar el hidrógeno y otros componentes, como la electrificación, en una red energética cohesiva e integral, de cara a lograr de manera efectiva los objetivos de transición energética.

INCORPORATING HYDROGEN INTO OPENMASTER FOR DECARBONIZING THE SPANISH ENERGY SYSTEM

Author: Maté Pulido, Diego
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Collaborating Entity: ICAI – Universidad Pontificia Comillas (Instituto de Investigación Tecnológica)

ABSTRACT

1. Introduction

The objective of this project is to investigate, identify, and define various hydrogen technologies within the Spanish energy system, as well as those likely to become integral in the near future. Our aim is to outline the hydrogen value chain in the Spanish energy context and incorporate it into openMASTER, an optimization model for long-term strategic energy planning.

We will then analyse the impact of integrating hydrogen into the model, creating case studies based on different decarbonization goals. Our ultimate aim is to determine whether hydrogen can be a viable solution for achieving a clean, safe, and financially sustainable energy system.

This project is highly relevant and significant as it explores hydrogen's potential to meet the EU's 2030 and 2050 targets and achieve long-term energy sustainability.

2. Project outline

The project is structured in a three-phase methodology to systematically complete tasks and develop a coherent thought process that will allow us to achieve logical conclusions. The steps are as follows:

- **Definition of Technologies and Parameters**: this phase involves an extensive literature review to identify applicable resources, theories, and key technologies for the hydrogen value chain. It includes the definition of necessary parameters and their temporal projections, subdivided into the key stages of production, distribution, and demand.
- **Proof Theories via Excel Modelling**: an Excel model will be developed to test the logical and realistic nature of assumptions related to production and demand. This phase will allow for fine-tuning of the assumptions before incorporating them into the final model.
- **Modelling on openMASTER and Case Studies**: with the validated technologies and their relevant parameters, the information will then be programmed into openMASTER. This virtual model, incorporating hydrogen supply and demand technologies, will enable the scenario generation and outcome analysis to draw conclusions.

This structured approach will enable thorough validation and practical implementation of the hydrogen value chain model.

3. Description of the model - openMASTER

The open-source Model for the Analysis of Sustainable Energy Roadmaps (openMASTER) is a sophisticated tool developed by Universidad Pontificia Comillas for comprehensive energy system modelling and strategic planning. It is a modular, bottom-up partial equilibrium model that supports sustainable energy policies.

Capabilities:

- Simulates and analyses the performance and sustainability of energy systems.
- Identifies optimal pathways for energy transition, integrating renewable and emerging technologies like hydrogen.

Key Features:

- Balances technical accuracy with user-friendly interfaces.
- Uses linear programming to optimize for sustainability metrics.
- Visualizes results with Sankey diagrams.
- Offers modularity and flexibility to model various scales, from microgrids to national systems.
- Promotes collaboration and transparency as an open-source platform.
- Facilitates scenario planning and strategic analysis.

Role in the Hydrogen Project:

- Studies the feasibility of using hydrogen for renewable energy storage and as a fossil fuel substitute.
- Defines and integrates the hydrogen value chain into the energy system.
- Simulates scenarios to evaluate the impact of hydrogen technologies on decarbonization goals for 2030 and 2050.
- Supports strategic planning and decision-making through case studies on the sustainability and economic viability of hydrogen technologies.

The project aims to leverage openMASTER to thoroughly evaluate hydrogen's potential in the national context, from the perspective of ensuring an effective transition towards a sustainable energy system aligned with long-term environmental and economic objectives.

4. Results

After modelling, outputs from the model produce a series of results that can be summarised in the following key ideas:

- Hydrogen production aligns with GDP variances, indicating the model's accuracy in reflecting economic conditions.
- The installed capacity fits between low and medium production scenarios, consistent with the Hydrogen Accelerator EU program under the REPower EU initiative.
- Economic health impacts demand and, consequently, production methods proportionally. The only exception is oil refinery, which increases during economic distress due to oil being a stable energy source.

- Renewable energy sources continue to grow proportionally, regardless of the economic scenario, underscoring the EU's commitment to the energy transition.
- Alkaline Electrolysers are preferred in the near term, dominating until around 2040. Consistently with that premise, PEM Electrolysers are expected to become more competitive post-2040 due to a steeper learning curve, eventually overtaking alkaline electrolysers as the primary technology for new projects.
- Emissions are projected to decrease consistently, reflecting the increased use of renewables and hydrogen.
- Emission levels correlate with GDP, with higher economic activity leading to more emissions due to industrial expansion and increased production demands.

5. Conclusions

After the realisation of this project, four key take-aways could be drawn from the final analysis. They are the following:

- **Role of Hydrogen in the Energy Transition:** this project demonstrates that hydrogen is crucial for achieving energy transition and decarbonization goals. Results from openMASTER simulations confirm that hydrogen production aligns with GDP behaviour, showing scalability alongside economic growth. This integration not only proves feasible but also beneficial for meeting energy demands.
- **Decarbonization Impact:** increased deployment of hydrogen and transition to renewables lead to significant emissions reduction. Detailed analysis across various aspects highlights the technical applications and benefits of hydrogen, suggesting its contribution to sustainable development goals.
- **Electrolyser Technology:** analysis favours PEM electrolysis technology in the long term, projected to surpass alkaline technology by 2040 due to advancements in its learning curve. Future strategies should prioritize this shift in technology for optimal deployment.
- **Holistic Approach to Energy Solutions:** while hydrogen plays a pivotal role, the study emphasizes that it is one component of a broader energy system solution. The literature review identifies gaps in policies that often focus narrowly on specific energy facets. It stresses the importance of integrating hydrogen and other components like electrification into a cohesive energy network to effectively achieve ambitious energy transition goals.

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CHAPTER 1. INTRODUCTION

1.1 OVERVIEW

In the current context, the energy transition presents itself as the great challenge for the upcoming decades. Many technologies and resources will need to be combined effectively and strategically to fulfil the decarbonization goals and needs resulting from the current pace of development. Hydrogen is being called upon to play a pivotal role in the new scheme of the energy network that is to come. The study of such role will constitute the focal point of this paper.

The goal of this project is to investigate, identify and define the different hydrogen technologies existing within the hydrogen within the Spanish energy system as well as those susceptible of becoming an integral part of it within the foreseeable future.

By doing so, we aim to determine the hydrogen value chain within the Spanish energy context in order to incorporate it into openMASTER, a computational model for long-term strategic planning of energy systems.

Finally, we will study the impact of the addition of such energetic vector into the model, generating case studies according to the different decarbonization objectives, with the end goal of drawing conclusions regarding whether hydrogen is or may be a viable solution to achieving a clean and safe energy system while ensuring the operation remains financially sustainable.

Therefore, it is a work of eminent relevance and interest, as it aims to delve into the options presented by hydrogen in order to meet the EU's 2030 and 2050 targets and achieve long-term energy sustainability.

1.2 PROJECT MOTIVATION

On one hand, the motivation is driven by the current context and the opportunity it presents, as we are at a pivotal moment to work on this topic for the following three reasons:

- Since 2020, the EU has been promoting ambitious goals regarding the hydrogen strategy. The energy crisis and the war in Ukraine have made hydrogen play an increasingly central role in climate and energy policy plans. The most recent revisions of the plans raise the previously established goals and aim to focus the strategy solely on green hydrogen. Therefore, we can see that this is a relevant and timely project, aligned with the energy objectives that regulations will prioritize in the coming years.
- A recent brief study by DNV (*Análisis de datos en el sector eléctrico*, s. f.), reported by "El periódico de la energía," («Así es el impresionante cambio que ha dado el mercado eléctrico español en los cinco últimos años», 2023) reveals the changes that the Spanish electricity sector has undergone in the past five years. The most notable aspect is that renewable energies now play a practically dominant role, partially complemented by nuclear power, with the sector being almost entirely decarbonized. Hence, this recent change in the sector aligns with the study's aim of seeking to implement a technology that allows maximum utilization of green energy at all levels.
- In 2024, there will be a pertinent review of the Government's hydrogen roadmap. The previous version falls short of the current EU objectives (Gubinelli, 2023), so a significant push for hydrogen is expected in this next iteration, in terms of strategic plans and investment budgets. This is a critical moment for conducting a project like this, as it can be very useful and have many applications for potential professional development in this area.

On the other hand, there is also a more personal motivation, driven by the personal interests of this author. They are as follows:

- Due to family encouragement since childhood, I have always been motivated by the world of energies, particularly renewables, in which I firmly believe the solution to decarbonization can be found.
- It is the engineering field that my degree has given me access to and that has most caught my attention. I enjoy studying it leisurely on my own, and I intend to develop the bulk of my professional career in this field, having had internship opportunities in important companies in the sector.
- After installing self-consumption photovoltaic panels in the family home, I concluded that there is a lack of green storage complement to the installed renewable production. While at a small scale, this could be resolved with a battery, or even a good contract that values surpluses and generates a virtual battery, I believe that for large-scale applications of these production methods, the solution could be found in green hydrogen, produced using renewable energies and with possibilities for large-scale distribution and application.

1.3 PROJECT OUTLINE

For the realization of this project, a three-phase methodology was introduced in order to correctly space the required tasks and build a coherent thought process that would allow for the achievement of a logical conclusion. Such phases were as follows:

1. **Definition of technologies and parameters:** this phase implied a thorough investigation of the existing bibliographic resources in order to determine those that were applicable, given the objectives of this project, and select the key theories that would be the base for our model of the hydrogen value chain.
   By doing so, we selected the theoretical base pertaining to our study which allowed us to define the key technologies that would be applied to our model as well as the parameters that were required to define such working pieces, with their corresponding projections in time to account for the temporal evolution of our model.
   In is worth highlighting that this was also subdivided into subphases, aligning with those of the H2 value chain: production, distribution and demand.

2. **Proof theories via Excel modelling:** given the complex theoretical background supporting the model, particularly in terms of how future projections of key figures were being calculated by the different studies, certain assumptions had to be contemplated.

   To proof that our assumptions were logical and realistic, an excel model for production and demand was built in order to determine whether the scenarios that we had designed in both areas would hold correspondingly. This allowed us to fine tune our assumptions with a holistic approach before taking our conclusions to the final model.

3. **Modelling on openMASTER and case studies:** having defined and proofed the key technologies and parameters that are required to build the H2 value chain, the next step would be to program such information in openMASTER.

   After the parameters were coded, the virtual model was complete with the hydrogen technologies of supply and demand, thus allowing us to generate the scenarios that we had priorly proofed in Excel in order to study the outcomes and draw conclusions on our assumptions.

1.4 PROJECT GOALS

In this work, the following objectives are pursued:

- Study the feasibility of applying the concept of hydrogen as an energy vector to achieve a renewable storage solution and as a substitute for fossil fuels. The focus is on technologies complementary to renewable energies that allow the production of green hydrogen, aiming to align the plan with the 2050 objectives and to find a viable long-term energy solution.
- Define the hydrogen value chain with the identified technologies and incorporate it into the openMASTER model for long-term energy planning. This involves sizing based on the current energy production context at the national level and adapting to the existing regulations and roadmap.

- Examine the impact of hydrogen in the model and generate case studies based on the requirements of the 2030 and 2050 decarbonization objectives. The goal is to draw conclusions regarding the feasibility and sustainability of achieving these objectives according to the current strategic planning of the energy system. The ultimate aim is to identify possible logical improvement proposals if such conclusions are reached.

1.5 ALIGNMENT WITH SDGS

We can identify a direct alignment with the following Sustainable Development Goals (SDGs) (*THE 17 GOALS | Sustainable Development*, s. f.):

- **7 – Affordable and Clean Energy:** This project primarily seeks to investigate the potential for hydrogen and its technologies to be part of the solution to this issue, contributing to the creation of net-zero emissions and financially sustainable energy scenarios.
- **9 – Industry, Innovation, and Infrastructure:** This is a project that studies the development of entirely new industries and infrastructures, thereby providing a significant evolutionary component to many existing ones.
- **13, 14, and 15 – Climate Action, Life Below Water, and Life on Land:** Numerous studies support the need to evolve our methods of producing, transporting, and consuming energy to take care of our planet. This project aims to develop an energy planning model that allows us to discern whether we are on the right path to achieving decarbonization within the established timeframes.
- **11, 12 – Sustainable Cities and Communities, and Responsible Consumption and Production:** Along the same lines as the previous point, the resulting model from this project seeks to propose options for achieving sustainability at the societal level.

In a somewhat more indirect manner, this project can also be seen as aligning with the objectives of **Good Health and Well-being**, as it would contribute to caring for the climate and air quality, with its consequent impact on health. Additionally, it aligns with **Decent**

Work and Economic Growth, as the hydrogen industry will bring numerous jobs and allow Spain to establish itself as a European power in the new order that this transformation stablish, leading to a period of significant growth and economic prosperity.

CHAPTER 2. DESCRIPTION OF THE MODEL

1.1 THE MODEL - OPENMASTER

The open-source Model for the Analysis of Sustainable Energy Roadmaps (openMASTER) is a sophisticated, modular tool designed to facilitate comprehensive energy system modelling and strategic planning. Developed by the Universidad Pontificia Comillas, openMASTER serves as a bottom-up partial equilibrium model, primarily aimed at evaluating and designing sustainable energy policies.

It is worth noting that openMASTER (Rodriguez-Matas et al., s. f.) is the open source version and Pyomo enabled version of MASTER (López et al., 2013), developed in 2012 using the GAMS programming language.

1.2 CAPABILITIES

openMASTER is used to simulate and analyse the performance and sustainability of various energy systems. It helps in identifying optimal pathways for energy transition, focusing on maximizing sustainability while adhering to technical and economic constraints. The model supports the integration of different energy technologies, including renewable sources and emerging solutions like hydrogen, into a cohesive and efficient energy framework.

1.3 KEY FEATURES

- **Technical Accuracy and Simplicity:**
    - Balances detailed technical accuracy with user-friendly interfaces.
    - Employs linear programming to satisfy energy demands while optimizing for sustainability metrics, such as cost, emissions, and externalities.
- **Visualization with Sankey Diagrams:**

  - Presents results through Sankey diagrams, offering a clear and intuitive visualization of energy flows, which helps users understand complex data more easily.

- **Modularity and Flexibility:**
  - Highly modular design allows for customization to fit specific scenarios and requirements.
  - Can model various scales, from local microgrids to national or international energy systems. In the case of this particular project, the Spanish national energy system will be used in the modelling.
- **Open-Source Platform:**
  - As an open-source tool, it encourages collaboration and continuous improvement from the global community.
  - Enhances transparency and allows for peer review and validation.
- **Scenario Planning and Strategic Analysis:**
  - Facilitates the creation and comparison of different energy scenarios.
  - Assists in long-term strategic planning by evaluating the impact of various policies and technologies on energy sustainability.

1.4 ROLE IN THE HYDROGEN PROJECT

In the context of this hydrogen project, the openMASTER model plays a crucial role in several ways:

- **Viability Study:** openMASTER helps in studying the feasibility of using hydrogen as an energy vector for renewable energy storage and as a substitute for fossil fuels. This aligns with our goal of exploring hydrogen technologies as a tailored complement to renewable energy.
- **Value Chain Definition:** using the model, we are able to define and integrate the hydrogen value chain into the broader energy system. This involves assessing the

production, storage, and distribution of hydrogen within the existing energy infrastructure.

- **Scenario Analysis and Impact Assessment:** the model allows for the simulation of different scenarios to evaluate the impact of hydrogen technologies on achieving decarbonization goals for 2030 and 2050. This allows us to gain insight into how hydrogen interacts within the national energy system depending on the given goals, thus shedding light on the most sustainable and viable pathways for hydrogen integration into the energy system.
- **Strategic Planning:** by incorporating hydrogen into the openMASTER model, we can generate case studies that provide insights into the long-term sustainability and economic viability of hydrogen technologies. This supports strategic decision-making and helps propose logical improvements to current plans.

By leveraging the capabilities of openMASTER, this project can comprehensively evaluate the potential of hydrogen technologies, ensuring that the transition towards a sustainable energy system is both effective and aligned with long-term environmental and economic goals.

CHAPTER 3. STATE OF THE ART

Firstly, on the national level, we have the "Hydrogen Roadmap" (*Hoja de Ruta del Hidrógeno*, s. f.): the first official document that begins to define the role of hydrogen in the Spanish energy scenario. This document dates back to 2020 and is pending a review and its pertinent updates in 2024. Hydrogen is presented as one of the keys to achieving the decarbonization of the Spanish economy by the 2050 target through the creation of innovative industrial value chains in Spain and integration into a new high value-added green economy in Europe. Among the most important sections, we find the key projects identified to employ hydrogen in Spain, an extensive summary of the available technologies in this field as of the document's date, and the first outlines of the necessary regulatory framework to carry out this evolution.

On the other hand, Europe has been addressing the issue earlier, as the aforementioned document stems from a series of prior European initiatives. The most notable ones shaping the national roadmap are the "European Hydrogen Strategy" (COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A Hydrogen Strategy for a Climate-Neutral Europe, 2020), drafted as part of the European Green Deal, and the European Commission's "Annual Sustainable Growth Strategy" (*The Autumn Package Explained - European Commission*, s. f.). Both documents recognize that hydrogen presents a clear opportunity for Spain to position itself as a technological leader in this field for three reasons:

- The country's natural conditions for hydrogen production, referring to, among other things, access to the sea (as a potential source of water for hydrogen electrolysis) and the already existing conditions that allow for high levels of renewable production (sun, wind, etc.).

- Its strategic geographical position for distribution, exemplified by the pioneering H2MED project (*H2med - The H2med Project*, s. f.), which aims to establish a hydrogen corridor connecting Portugal and France, with Spain at its centre, to supply Europe.
- The commitment to renewable technologies for energy production, which presents a clear compatibility with using hydrogen as an energy vector to store and distribute energy surpluses. This would allow for greater penetration of renewable energies into the system, as the combination of both technologies ensures a sustainable, stable, and reliable energy source.

Additionally, these documents began to outline the strategy for addressing the transition and deployment of hydrogen technologies, as well as the scale of the transformation in question. Three distinct phases are established:

1. **2020 – 2024:** The European goal will be to deploy 6 GW of installed electrolyser capacity to produce 1 million tons of renewable hydrogen. This phase aims to decarbonize current hydrogen production by installing electrolysers near existing industrial demand centres and supplying them with local renewable energy. The first hydrogen refuelling stations will also be implemented.
2. **2024 – 2030:** Scaling up to 40 GW of installed electrolyser capacity to achieve European production of 10 million tons of hydrogen. The goal of this phase is for hydrogen to become an intrinsic part of the energy system, playing a key role in balancing and flexibly managing a renewable energy-based electricity system, producing hydrogen using surpluses to use it as a "buffer," thereby improving energy supply security. New applications in industry and transport, particularly maritime, will also begin to be introduced.
3. **2030 – 2050:** In this phase, hydrogen technologies are expected to reach full maturity and begin to be deployed on a large scale, even reaching hard-to-decarbonize sectors.

Following the introduction of the European objectives, it has been studied and determined that Spain should aim to supply 10% of the installed capacity in Europe. That is, of the 40

GW established as the European milestone to be achieved before 2030, Spain must contribute 4 GW.

However, the recent war in Ukraine has led Europe to seek solutions to replace Russian gas. To this end, the "REPowerEU" plan emerged in 2022 (*REPowerEU*, s. f.), which includes a highly relevant document, the "Hydrogen Accelerator" (*RePowerEU Plan*, s. f.), which updates the goals for installed electrolyser capacity in Europe by 2030 to 160 GW. Therefore, Spain is expected to update its goals, remaining around the 10% European criterion, in its new 2024 roadmap.

The Spanish landscape is promising, as a recent census of hydrogen projects by AeH2 (Spanish Hydrogen Association) identified a volume of 79 GW of electrolysers for 2030 (#, 2023), reflecting that the interest of companies in Spain is even greater than the goals seem to suggest.

However, it is crucial to understand that there are various types of hydrogen, defined based on the production technology used and the emissions it entails. The only one that truly does not entail direct CO2 emissions is green hydrogen, so if decarbonization goals are pursued, the planning seems to need to focus exclusively on this alternative.

Therefore, the current situation is somewhat stagnant, as it requires the updating and establishment of a solid regulation that clearly defines the concept and margins that certify hydrogen as green, to which strategic planning can adhere. This will allow for resolving the chaos currently experienced in the sector, with multiple projects under development that follow different lines of thought and where there is no clarity on whether a path that contributes to the global goal is truly being followed (García-Conde, s. f.).

CHAPTER 4. HYDROGEN

1.1 THE CONCEPT OF ENERGY VECTOR

The concept of energy vectors, as articulated by Fabio Orecchini (Orecchini, 2006), refers to carriers that store, transport, and deliver energy from production to consumption points efficiently. Unlike traditional fuels, which are directly consumed, energy vectors like electricity and hydrogen allow for greater flexibility and optimization within energy systems. Energy vectors can be sourced from a variety of primary energies, converted, and then used in different forms, providing a crucial bridge between renewable energy sources and end-use applications.

Hydrogen as an Energy Vector

Hydrogen is a particularly valuable energy vector due to its versatility and potential for sustainability. According to both Orecchini and Abdin (Abdin et al., 2020), hydrogen can be produced from renewable energy sources via water electrolysis, which involves splitting water molecules into hydrogen and oxygen using electricity, which can be renewable (derived from wind, solar, or hydroelectric power) in case we are the goal is to produce green hydrogen in particular (Guilbert & Vitale, 2021).

Key takeaways from the potential of hydrogen, and green hydrogen in particular, as an energy vector are:

- **Production and Storage**: hydrogen can be generated when renewable energy production exceeds demand, stored for long periods, and later converted back to electricity or used as a direct fuel. This ability to store energy over long durations addresses the intermittency of renewable sources.

- **Transportation and Distribution**: hydrogen can be transported through pipelines or in liquefied form, allowing for efficient distribution across regions. This makes it an ideal candidate for regional energy hubs and long-distance energy transport.
- **Versatile Applications**: hydrogen's use spans various sectors. In transportation, it powers fuel cell vehicles, providing a clean alternative for buses, trucks, and trains. In industry, hydrogen can replace fossil fuels in processes requiring high temperatures, such as steel manufacturing and chemical production. In power generation, hydrogen can be used in fuel cells to provide electricity, particularly as a backup for renewable energy sources.
- **Environmental and Economic Benefits**: hydrogen as an energy vector supports the decarbonization of multiple sectors, reducing greenhouse gas emissions and reliance on fossil fuels. It also enhances energy security by enabling local production from renewable resources, decreasing dependence on imported fuels.

Relevance to Spain's Decarbonization Goals

Incorporating hydrogen as an energy vector into Spain's energy strategy aligns with the country's objectives to reduce carbon emissions and enhance the sustainability of its energy system (*Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030*, s. f.). By leveraging its abundant renewable resources («España, el país del sol, lo tiene todo para liderar el hidrógeno renovable en Europa», 2023), Spain can produce green hydrogen, supporting the decarbonization of its industrial, transportation, and power sectors. This transition not only contributes to global climate goals but also bolsters Spain's energy independence and economic resilience (Hernando & Jaén, s. f.).

1.2 HYDROGEN COLOURS

Based on the raw materials required and the CO2 emissions generated from the different production processes, hydrogen types arise, and they are classified using a colour scheme. The national hydrogen roadmap (*Hoja de Ruta del Hidrógeno*, s. f.) recognises the following main colours of hydrogen:

- **Renewable Hydrogen or Green Hydrogen:** hydrogen generated from renewable electricity, using water as the raw material, through an electrolysis process. Additionally, hydrogen obtained through biogas reforming or biochemical conversion of biomass, provided that sustainability requirements are met, is considered renewable.
- **Blue Hydrogen:** hydrogen produced similarly to grey hydrogen but with carbon capture, utilization, and storage (CCUS) techniques applied, which can reduce CO2 emissions by up to 95% during the process.
- **Grey Hydrogen:** hydrogen produced from natural gas or other light hydrocarbons such as methane or liquefied petroleum gases through reforming processes. Currently, 99% of the hydrogen consumed in Spain is of this type (data from 2020, as per the mentioned roadmap document).

In addition to the aforementioned types, there are others with very diverse environmental impacts, such as black or brown hydrogen, derived from coal, nuclear energy, or grid electricity, which are not included in the above classification due to the difficulty in quantifying the environmental impact of their production and consumption.

Other types not observed in the roadmap

There are some other types of hydrogen worth mentioning that were not included in the 2020 version of the national hydrogen roadmap, probably due to the novelty of their concept. However, it is worth mentioning them since they will come up later on the project and could be included in the 2024 update of the roadmap, given their economic and environmental interest (Ajanovic et al., 2022). They are as follows:

- **Turquoise Hydrogen:** this type of hydrogen is derived from hydrocarbons and is generated through a pyrolysis reaction (thermal degradation at extremely high temperatures in the absence of oxygen)(*Turquoise hydrogen production by methane pyrolysis*, s. f.). Its great advantage is that the process does not generate carbon dioxide (CO2) or carbon monoxide (*Achieving Net Zero*, s. f.), but it is highly inefficient and, therefore, not widely used currently.

- **Pink and Violet Hydrogen:** both types of hydrogen are generated through the electrolysis of water (*What Are The Colours Of Hydrogen And What Do They Mean?*, s. f.). If electrolysis is conducted with electricity from nuclear power, it is referred to as pink hydrogen (Fernández-Arias et al., 2024). If nuclear energy is combined with heat and thermochemical reactions, it is called violet hydrogen («In a Nutshell», s. f.).
- **HyBECCS ("Golden Hydrogen"):** HyBECCS (biohydrogen with CCS) leads to negative emissions and "cleans" the atmosphere as it is produced from electricity generated by renewable energy sources, where the carbon dioxide produced in the process is not emitted into the atmosphere but instead it is transformed into a pressurized stream for liquefaction and transportation for subsequent use or storage, thereby enabling decarbonization. This concept is supported by research conducted at Universidad Pontificia Comillas, which highlights the feasibility and cost-effectiveness of producing golden hydrogen (Yagüe Muñoz et al., 2024).

CHAPTER 5. H2 VALUE CHAIN

This chapter focuses on the identification and definition of the hydrogen value chain, with the aim of being able to establish its key components and parameters in order to introduce them into the openMASTER model.

To achieve that, the hydrogen value chain has been broken up into stages, aligning with the model requirements, in order to identify how at each different module of openMASTER the energy vector may have a use case.

Such schematization corresponds with the following stages:

- Production.
- Distribution.
- Demand.

It is worth highlighting that, from this stage on, this paper will indistinctively use the terms hydrogen and green hydrogen to refer to the latter, unless specified. This is because, given the aims of the project, the framework was developed aiming to only produce green hydrogen due to the decarbonisation nature of the objectives.

1.3 PRODUCTION

At this early stage of the value chain, we will focus on identifying which H2 production technologies are optimal given the Spanish energy context.

H2 production processes

When it comes to hydrogen production, many solutions, processes and techniques exist or are in late development stages. However, two main paths are highlighted within the national roadmap (*Hoja de Ruta del Hidrógeno*, s. f.):

- **Electrolysis:** this technology involves the dissociation of water molecules into oxygen and hydrogen gases through a direct electric current supplied by a power source connected to two electrodes (CORPORATIVA, s. f.). The process occurs on the surface of the electrodes, where the water molecules break apart. There are several types of electrolysers, which is the apparatus that enables the production of hydrogen through the application of this principle. They can be grouped into:
    - Alkaline Electrolysers: The electrolyte here is an alkaline solution, typically potassium hydroxide (KOH). These are the most common today due to their economic viability and technological maturity. They operate at a low current density, which means a lower hydrogen yield per volume of equipment. Hydrogen production is limited to an operating range of 20-100% of nominal capacity because gases generated at the anode and cathode can diffuse through the diaphragm (Amores et al., 2021).
    - Proton Exchange Membrane (PEM) Electrolysers: In these electrolysers, the electrolyte is a solid polymer that conducts protons. This reduces system-level corrosion issues compared to alkaline electrolysers but introduces corrosion problems in individual components (Millet et al., 2010). PEM electrolysers require precious metals, leading to higher costs. However, they can operate at higher current densities and adapt easily to fluctuating systems, such as renewable energy sources.
    - Anion Exchange Membrane (AEM) Electrolysers: AEM electrolysers are a variant of alkaline electrolysers, using an anionic exchange membrane as the electrolyte. This technology is more cost-effective than PEM electrolysers since the membrane does not require precious metals as catalysts, using non-noble metals instead. AEM electrolysis is low-cost and highly stable for hydrogen production, although it is still in the research phase (*Low cost hydrogen production by anion exchange membrane electrolysis: A review - ScienceDirect*, s. f.).
    - Solid Oxide Electrolysers (SOEC): This is the least developed technology. The electrolyte is made from ceramic materials, reducing manufacturing

costs. SOECs are highly energy-efficient but require temperatures above 700°C to operate (Zarabi Golkhatmi et al., 2022). Unlike other types, they can convert the generated hydrogen back into electricity using reversible devices, providing grid balancing services.

There are other processes for producing green hydrogen from water dissociation, such as thermolysis, which involves breaking down water using concentrated solar energy (Suárez González et al., 2011). These methods are currently at a low technological maturity and rely on thermochemical cycles to reduce the necessary operating temperatures. Photoelectrochemical methods (Ahmed & Dincer, 2019) can also harness solar radiation to initiate water dissociation. It is worth noting that, given the high-temperature nature of the SOEC technologies, they are arguably better suited to work alongside power sources such as nuclear generation. Given the national context in Spain, where nuclear plants are programmed to be shut down in upcoming years, SOEC technology was not included in the openMASTER modelling resulting from this project.

Moreover, regarding AEM electrolysers, given that they are a variant of alkaline electrolysers and are currently still in the research phase, the distinction was not made in the openMASTER modelling, thus not specifically including this type of electrolysers either.

To summarize, in light of the points analysed in this section, the choice was made to move forward with alkaline and PEM electrolysers exclusively.

- **Gas reforming:** this methods involve converting hydrocarbons, such as natural gas or biogas, into hydrogen through various chemical processes (Lamb et al., 2020). These processes typically occur in reactors under high temperature and pressure conditions, with the aid of catalysts. The primary methods are as follows, each with distinct mechanisms and efficiency levels:
    - <u>Steam Methane Reforming (SMR):</u> through this process («Hydrogen Production», s. f.), high-temperature and high-pressure steam reacts with

hydrocarbons in a reactor (reformer) in the presence of a metal-based catalyst. This reaction produces synthesis gas, a mixture of hydrogen and carbon monoxide. Typically, the process includes two Water Gas Shift (WGS) (Mosca et al., 2020) stages to increase hydrogen yield (and primarily CO2) and a final hydrogen purification stage.

- Partial Oxidation (POX): POX involves the incomplete combustion of hydrocarbons (*Partial Oxidation - an overview | ScienceDirect Topics*, s. f.). Here, the hydrocarbon reacts with oxygen in less than stoichiometric amounts (oxygen-deficient) in a reactor at very high temperatures (1,300°C-1,500°C). This process generates synthesis gas. POX is faster but less efficient compared to SMR.
- Autothermal Reforming (ATR): ATR (*Autothermal Reforming - an overview | ScienceDirect Topics*, s. f.) combines elements of both SMR and POX. In this process, a steam stream is added to the partial oxidation process, creating a similar reaction to SMR. The primary difference between ATR and SMR is that ATR uses oxygen directly as a heat source to generate steam, while SMR relies on the heat from burning oxygen. The drawback of ATR is its lower efficiency compared to SMR.

The electrolyser pathway

For our model, we have chosen to focus exclusively on hydrogen production through the electrolyser pathway, as opposed to gas reforming. This decision is based on several key advantages of electrolysers, including their environmental benefits, cost efficiency, modularity and technological advancements.

- **Environmental Impact:** electrolysis, when powered by renewable energy sources, produces "green hydrogen," with zero greenhouse gas emissions during operation (*The Electrolysis of Water*, s. f.). This stands in stark contrast to traditional gas reforming methods, which inherently produce significant CO2 emissions. Although reforming processes can incorporate Carbon Capture, Utilization, and Storage

(CCUS) to mitigate these emissions (*How Carbon Capture Technologies Support the Power Transition – The Role of CCUS in Low-Carbon Power Systems – Analysis*, s. f.), they still involve the extraction and combustion of fossil fuels (Nnabuife et al., 2023), which have additional environmental impacts. Biogases can also be applied in these processes in order to tame the environmental footprint, yet the variant still represents a small fraction of the overall reforming generation scene, and many are still in a development phase. In contrast, electrolysers completely eliminate these issues by relying solely on water and electricity, thus making it a clear choice given the decarbonisation nature of the goals of this paper.

- **Cost Efficiency: t**he cost efficiency of electrolysers has improved significantly due to advancements in technology and the decreasing cost of renewable energy. Although the initial capital costs for some electrolysers, especially Proton Exchange Membrane (PEM) and Solid Oxide Electrolysers (SOEC), are higher due to the use of precious metals, the operational costs could decrease over time (Kiemel et al., 2021). This is particularly true when electrolysers are integrated with surplus renewable energy, reducing dependency on volatile fossil fuel prices associated with gas reforming. Additionally, as the scale of production and technological advancements continue, the costs associated with electrolysers are expected to decrease further due to economies of scale, the irruption of multi-stack systems and the increase in the use of less novel materials (*Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5C Climate Goal*, s. f.).
- **Modularity and Scalability:** electrolysers offer superior modularity and scalability compared to gas reforming processes. They can be easily scaled up or down to match the available renewable energy supply and specific hydrogen demand (Lange et al., 2024). This flexibility makes electrolysers ideal for integration with distributed renewable energy systems, such as solar and wind farms, enhancing energy security and grid stability. Gas reforming plants, on the other hand, are typically large-scale and less adaptable to fluctuating production scales. Furthermore, given that gas reforming in the context of this project would only make sense with the application

of CCUS technology, it is worth noting that it requires a significant investment in infrastructure (*CCUS Technologies | AGCS*, s. f.), which would only be made when and if hydrogen reaches a certain scale.

- **Technological Advancements:** recent advancements in electrolyser technology have resulted in significant improvements in efficiency and cost-effectiveness (*Innovation Trends in Electrolysers for Hydrogen Production*, 2022). For example, innovations in Anion Exchange Membrane (AEM) and Solid Oxide Electrolysers (SOEC) designs are making these systems more robust and capable of operating under a wider range of conditions. These technological improvements further justify the preference for electrolysers over traditional gas reforming methods.
- **Future-Oriented Development vs. Retrofitting:** CCUS technologies are primarily aimed at retrofitting existing gas reforming plants to make them more environmentally friendly by capturing and storing CO2 emissions (*CCUS in the Transition to Net-Zero Emissions – CCUS in Clean Energy Transitions – Analysis*, s. f.). While CCUS can reduce the carbon footprint of existing infrastructure, it represents an incremental improvement rather than a transformative shift. On the other hand, electrolysers represent a forward-looking approach to hydrogen production. By building new infrastructure centred around renewable energy and electrolyser technology, we can create a truly sustainable and future-proof hydrogen economy. This future-oriented approach aligns better with the goals of this project, which focus on long-term sustainability and environmental stewardship.
- **Energy Storage and Grid Services:** electrolysers also play a critical role in energy storage and grid services. They can convert excess renewable energy into hydrogen, providing a means of storing energy for use when renewable generation is low (*What is an electrolyzer and what is it used for? | Accelera*, s. f.). Furthermore, technologies like SOECs can convert stored hydrogen back into electricity, offering valuable grid balancing services and enhancing overall energy system resilience (Samani et al., 2020). This dual functionality is not possible with gas reforming processes.
- **Sustainability and Policy Alignment:** focusing on electrolyser technology aligns with global sustainability goals and policies aimed at reducing carbon footprints and

transitioning to renewable energy sources (Sampson, 2023). Governments and organizations worldwide are increasingly supporting the development and deployment of electrolysers through subsidies, grants, and favourable regulations, further boosting their economic attractiveness. While CCUS can make gas reforming processes greener, they still fall short of the environmental and sustainability benefits offered by electrolysers.

In conclusion, electrolysers provide a greener, more cost-effective, and more flexible solution for hydrogen production compared to gas reforming methods. By leveraging renewable energy sources, electrolysers can produce hydrogen with minimal environmental impact, aligning with global sustainability goals and future energy needs. This makes electrolysers a superior choice for hydrogen production given the specifics of this project. It is still worth noting that other techniques, like that for HyBECCS, could still perform an important role in the future of the energy transition.

Operation Schemes for Electrolysers

The operational schemes available for electrolysers significantly impacts both economic feasibility and environmental certification. This section examines three primary operational schemes, highlighting their respective advantages and challenges based on the information available through the “Informe annual 2022-2023” (*Informe anual Cátedra de Estudios sobre el Hidrógeno 2022-2023. De la planificación a la ejecución: examinando los factores de éxito para el desarrollo del hidrógeno en España*, s. f.) written by the “Cátedra estudios sobre el hidrógeno Comillas”.

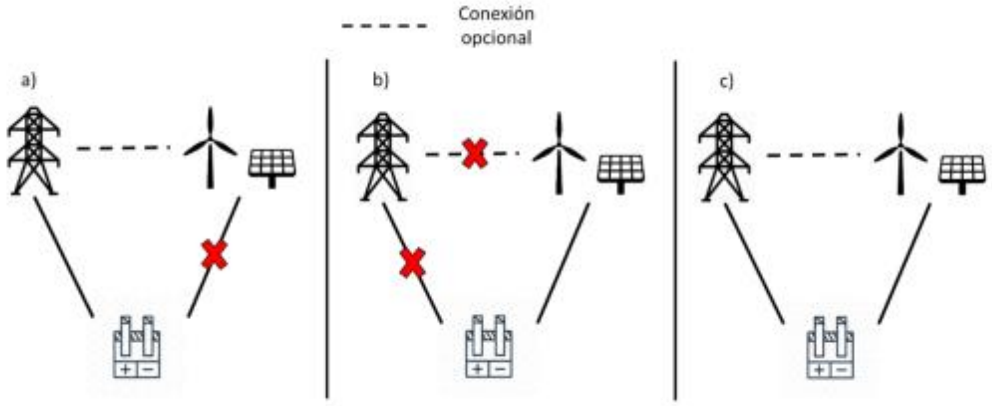


Figure 1. Operation Schemes. Source: Cátedra de Estudios Sobre el Hidrógeno Comillas

a) <u>Grid-Connected Operation:</u> this format of operation allows electrolysers to operate based on the availability of grid electricity. There are several operational strategies within this scheme:

   a. **Power Purchase Agreements (PPA):** under PPA contracts, electrolyser operation is limited by the hours specified in the agreement. This ensures predictable costs but restricts flexibility in operation hours.

   b. **Market-Based Electricity Purchase:** electrolysers can purchase electricity from the daily market, enabling flexibility in operation hours. However, extended operation during peak demand hours can escalate operating expenses (OPEX) due to higher electricity prices. Conversely, limiting annual operating hours can increase initial investment costs (CAPEX).

   c. **Combination of Strategies:** hybridizing PPA contracts with market purchases offers a balanced approach, managing operational costs while potentially certifying produced hydrogen as Renewable Fuel of Non-Biological Origin (RFNBO). Administrative complexities and connection fees are key considerations, particularly for large-scale projects.

Grid-connected operation minimizes space requirements by leveraging existing infrastructure and supports electrolyser participation in ancillary services markets, enhancing revenue streams.

b) Island Operation: based on renewable energy sources, restricting electrolyser operation to renewable energy availability. Key features include:
   a. **Certification Advantages:** hydrogen produced in this mode can easily qualify as RFNBO if sourced from recently constructed, additional renewable plants meeting regulatory criteria.
   b. **Economic Considerations:** elimination of grid connection fees and charges reduces operational costs. However, the limited hours of renewable energy availability increase CAPEX impacts, elevating production costs. Moreover, the inability to provide grid services limits revenue opportunities.

   Island operation simplifies administrative processes but requires additional approvals for renewable facility construction and environmental impact assessments, demanding ample space for integrated infrastructure and storage systems.

c) Hybrid Operation: integrates aspects of both grid-connected and island schemes, offering synergistic benefits:
   a. **Flexibility and Revenue:** combining renewable and grid electricity reduces CAPEX burdens while enabling flexibility in operation hours and revenue generation through ancillary services and grid sales.
   b. **Administrative Complexity:** however, hybrid schemes require navigating administrative procedures from both grid connection and renewable facility construction perspectives, potentially delaying project implementation.
   c. **Space Requirements:** although hybrid models reduce space needs compared to pure island operations, significant land remains necessary for renewable plant integration.

Selecting an optimal operational scheme for electrolysers involves navigating trade-offs between economic viability, environmental certification and administrative complexity. Grid-connected, island and hybrid operations each offer distinct advantages and challenges, depending on project scale, regulatory environment and market conditions. Future advancements in renewable energy integration and regulatory frameworks will continue to shape the evolution of electrolyser operational strategies in the burgeoning green hydrogen sector.

For the inclusion of hydrogen in the openMASTER model, with the aim of simplifying the integration of the productive scheme, we have decided to allow for the electrolysers to only operate connected to the grid, thus limiting the choice of operation scheme alternatives within the model. The PNIEC states that from 2030 the national electric mix in Spain will be considered decarbonised (*Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030*, s. f.), thus allowing us to assume under this premise that virtually all hydrogen production in the model will be green and altering minimally the original aim of our case study.

Electrolysers in openMASTER

In light of the prior sections, the choice was made to model hydrogen production within openMASTER exclusively based on electrolysers with alkaline and PEM technologies operating in a grid connected format.

Such technologies have to be defined in the model by a series of key parameters, which have been compiled in the following table:

Electrolyser Parameters	Alkaline electrolyser			PEM Electrolyser		
	2021	2030	2050	2021	2030	2050
Electric efficiency (%LHV)	63-70	65-71	70-80	56-60	63-68	67-74
Average lifetime of stack (in thousands of working hours)	60	90	100	30	60	100
	90	100	150	90	90	150
CAPEX ($/kWe)	500	400	200	1100	650	200
	1400	850	700	1800	1500	900
OPEX Fixed (3% CAPEX) (lower bound)	15	12	6	33	19.5	6
OPEX Fixed (3% CAPEX) (upper bound)	42	25.5	21	54	45	27
OPEX Variable (cost of electricity and water)						

Table 1. Electrolyser Parameters

CAPEX by Scenarios			
Electrolyser	Scenario	CAPEX 2020 $/kW	% of improvement YoY
Alkaline	Low	571	0.5
	Mid	988	2
	High	1268	2.5
PEM	Low	385	0.5
	Mid	1182	2
	High	2068	2.5

Table 2. Alternative Capex Calculation Method

The first table shows the comprehensive list of parameters that, after thorough analysis and comparison of various sources, were agreed as most representative and thus were introduce in the openMASTER model to define the productive technologies.

We will now proceed to go line by line, justifying the choice of parameters:

- Electric efficiency: refers to the useful power output divided by the electric power consumed in the generation process. This data was sourced from the National Spanish Roadmap for H2 (*Hoja de Ruta del Hidrógeno*, s. f.), which we have validated against the levels that have also been defined by the IEA (the most relevant authority in the field) (*Electrolysers - Energy System*, s. f.).
- Average lifetime of stack: as we have already mentioned, one of the constraining factors for electrolysis was the stack. It is a key component with a limited lifetime and high cost of replacement, which means that it is de facto one of the main cost drivers for electrolysis (*What is an electrolyzer and what is it used for? | Accelera*, s. f.). The expectation is that development in technologies will not only prolong stack durability, but also allow for multi-stack settings, thus allowing for economies of scale to improve overall costs (Luxa et al., 2022). The range of values provided accounts for variations resulting from the behaviour resulting from the variety in electrolyser sizes and models, thus the resulting uncertainty from projecting into the future.
- CAPEX: it is well known that the energy industry and its projects are more often than not CAPEX intensive. The production infrastructure required to be able to electrolyse hydrogen is not different, which much capital becoming tied up before the project even becomes operational (Martin, 2024). However, it is worth reminding that the investments are proportional to the scale of deployment that is being tackled, with noticeable benefits of economies of scale as the production facilities gain in size (installed capacity).

  On the main table, we find CAPEX value ranges and their evolution into the future provided by the national roadmap (*Hoja de Ruta del Hidrógeno*, s. f.) and, once again, coincidental to the projections of IEA (*Electrolysers - Energy System*, s. f.).

The range, again, accounts for the variety in electrolyser sizes, models and uncertainty of projections. A secondary table shows another method for calculating CAPEX values and their evolution into the future for electrolysers (Christensen, s. f.). In this case, a current (2020, referring to the time of the study) capital investment value is set and an evolution factor was calculated that would apply depending on the scenario. Thus, we can calculate the series into the future, knowing the CAPEX value year on year. By calculating for the same times as on the main table, and assuming that the scenarios provided a similar format of range, we can provide an additional benchmark other than that of the IEA. We can conclude that the projections from the national roadmap are reasonable and, thus, deemed valid for our model.

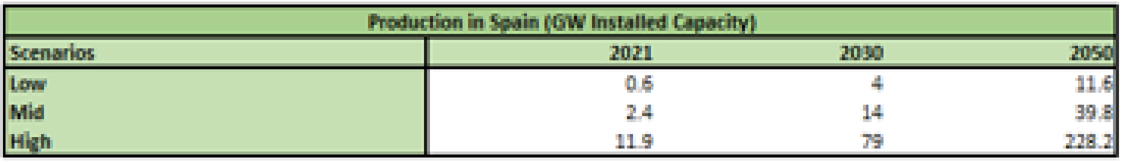
- OPEX: operational costs for the electrolysers are often divided into fixed and variable, according to the nature of specific costs. On the fixed side, it is often assumed that they can be summarized in a 3% of the CAPEX costs (Christensen, s. f.), thus justifying the resulting ranges in the table. It is worth noting that this assumes that OPEX and CAPEX evolve in the same way looking forward into the future, which is a shaky premise. In terms of the variable part, the main ones are the cost of electricity and water (*3 Cost Elements of Green Hydrogen - RNO Consulting*, 2023), which we highlight in the table as relevant, but are not determined in the scope of this project, since it is already an integral part of the model.

A key aspect to pick up from the tables is the comparison of values for alkaline and PEM. Given that PEM is a newer technology and still in earlier stages of development compared to alkaline (*Energies | Free Full-Text | Forecasting Development of Green Hydrogen Production Technologies Using Component-Based Learning Curves*, s. f.), its values seem worse at the current time (2021 in terms of the table and model). However, we can see that its learning curve will start to catch up to that of alkaline electrolysers, thus showing converging values into the future. The argument is made that plant size, measured in terms of installed capacity, plays a factor in how values such as that of capex evolve in comparison between alkaline and PEM. From 2030, we can expect the CAPEX of the smaller electrolysers to even out between both technologies for plants in the range of 1 to 10 MW, with the bigger plants (100MW +) following suit after (Reksten et al., 2022).

Be it as it may, it is interesting to keep in mind that currently alkaline technologies hold the upper hand, but that the expectation is that PEM technology will eventually become the dominant force. We will later see if the model outputs correspond to such theories.

The production scenarios

Having analysed the available technologies and the current and future characteristics of each of the alternatives, it is also important to analyse the potential for deployment of green hydrogen production that could be expected, Accounting for a wide range of factors, many already presented, the different authors and bibliographic resources showcase varying levels of optimism regarding hydrogen production. Consequently, to account for this degree of variability in our study, we have decided to create 3 potential production scenarios according to varying levels of the afore mentioned optimism. We will later on compare them with demand scenarios generated by the same logic in order to calibrate the coherence of our work. Such generation scenarios are compiled in the following table.



Production in Spain (GW Installed Capacity)			
Scenarios	2021	2030	2050
Low	0.6	4	11.6
Mid	2.4	14	39.8
High	11.9	79	228.2

Table 3. Hydrogen Generation Scenarios

The deployment of hydrogen production is, as seen on the table, calibrated by level of installed capacity in GW nationally, and its pertinent evolution into the future. The first scenario corresponds to the “National Roadmap for Hydrogen” (*Hoja de Ruta del Hidrógeno*, s. f.), the mid scenarios accounts for the adjustments proposed by the EU through the “Hydrogen Accelerator” (*RePowerEU Plan*, s. f.) and, finally, the high optimism proposal corresponds to a census by the AeH2 (Spanish Hydrogen Association) (*Censo de proyectos de hidrógeno - Asociación Española del Hidrógeno*, s. f.).

1.4 DISTRIBUTION

Hydrogen, derived from various processes, can take multiple states. Selecting the optimal method for its distribution, encompassed by both the phases of transport and storage, involves evaluating several factors, such as the production and consumption flow rates at each point, the distance from the production site to consumption points, the complementarity of end uses, and the suitability for final conditioning and use in different consumption types.

Through this section, the aim will be to present and directly compare the available and known alternatives for storage and transport, in order to shed light on what we can expect heading forward and pick-out key aspects that may determine what solution ends up seeing greater success.

The "state of the matter"

Hydrogen, as afore mentioned, is an element that is most commonly found in gaseous form but that can also take other forms, referring not only to states but also to plausible combinations to other substances, in order to increase efficiency during storage and distribution. During this section, we will analyse the possible alternatives of interest.

Given that both hydrogen and natural gas are gases, they share many properties and thus, much of the knowledge, techniques and infrastructure for the latter is trying to be applied to hydrogen. This will be a common theme that can be appreciated throughout this section.

- **Gaseous Hydrogen:** the usual format in which we can find hydrogen in nature and in the different production processes.
    - Advantages:
        - Hydrogen, due to its low density, is relatively easy to store as compressed gas (*Compressed Hydrogen Storage - an overview | ScienceDirect Topics*, s. f.), making it suitable for mobility applications.

        - Can be transported via dedicated hydrogen pipelines (*Building the Future*, s. f.).
        - Injection into the existing natural gas grid is possible after necessary processes (odorization, quality control, volume measurement). This concept is known as blending and its main selling point is that it would allow to reduce costs dramatically since it would benefit from the state-of-the-art natural gas infrastructure available in Spain (*Hydrogen Blending as a Pathway Toward U.S. Decarbonization*, s. f.).
    - Disadvantages:
        - High costs are associated with large-scale storage and long-distance transport due to low energy density (*The hydrogen storage challenge: Does storage method and size affect the cost and operational flexibility of hydrogen supply chains? - ScienceDirect*, s. f.).
        - Blending with natural gas can reduce the intrinsic value of renewable hydrogen and complicate separation at the point of use.
- **Liquefied Hydrogen:** through similar processes to those developed for natural gas, liquefication of hydrogen is also a possibility, even if perhaps less well known.
    - Advantages:
        - Ideal for storing large quantities of hydrogen.
        - Efficient in terms of transport volume, suitable for applications requiring significant hydrogen amounts (Geng & Sun, 2023).
    - Disadvantages:
        - Requires constant energy input to maintain a liquid state.
        - Less practical for long-term storage due to energy requirements.
- **Combined Hydrogen:**

- Synthetic Methane: produced by combining hydrogen with CO_2 or biomass (*What is synthetic methane?*, s. f.), allowing use of existing natural gas infrastructure.

- Synthetic Liquid Fuels: can be renewable depending on the raw material, including synthetic diesel, kerosene, and methanol. Through REPowerEU (*REPowerEU*, s. f.), we can see that this type of fuels will play a key role in the energetic transition, so it is another alternative worth considering as aa additional step in the hydrogen upgrading process. It is particularly clear in the SAF case, where the aviation and related industry will have to compromise in the following years due to the set quotas required in the fuel mixes both for planes and airports (*Fit for 55 and ReFuelEU Aviation | EASA*, s. f.).

Small-Scale Storage Options

As we have presented throughout the prior section, the hydrogen state can be a limiting factor when considering storage alternatives. Gaseous hydrogen tends to be designated for small storage solutions (*Hydrogen Storage*, s. f.). Some of the possible alternatives are the following:

- **High-Pressure Tanks**
    - Advantages:
        - Suitable for gaseous hydrogen storage at 350 or 700 bar for vehicles and 200 to 1,000 bars for hydrogen refuelling stations (*Addcomposites*, s. f.).
        - Made from strong materials like steel or composites, allowing for high-capacity transport by road.
    - Disadvantages:

        - Limited by volume, given hydrogen's lower energy density per unit volume compared to other fuels.
        - Potential for underground tanks in populated areas, capable of pressures up to 800 bar, is under study (*Underground Hydrogen Storage to Support Renewable Energy | Institute of Energy and the Environment*, 2023).

- **Solid Materials**
    - <u>Advantages:</u>
        - Certain metals and alloys form metal hydrides, storing more hydrogen per unit volume (e.g., iron, nickel, chromium, lithium, magnesium).
    - <u>Disadvantages:</u>
        - Generally heavier than pure hydrogen storage options.
        - Development is ongoing to optimize these materials for practical use (*Solid-State Hydrogen Storage Techniques at a Glance*, 2022).
- **Natural Geological Storage**
    - <u>Advantages:</u>
        - Utilizes salt caverns, aquifers, and depleted natural gas or oil fields.
        - Offers high efficiency and low operational costs for long-term storage (*Storing Hydrogen in Underground Salt Caverns*, s. f.).
    - <u>Disadvantages:</u>
        - Geographical availability and minimum pressure requirements limit current use.
        - Ongoing research is needed to ensure safe, large-scale use.

Large-Scale Storage Solutions

These alternatives, as introduced priorly, will be focused to liquefied hydrogen. An extra dimension needs to be kept in mind here, which is the actual liquefaction stage prior to the storing (*Hydrogen Liquefaction - an overview | ScienceDirect Topics*, s. f.), which continues to add to the complexity of the matter as well as to the tally of costs to account for in the analysis.

- **Geological Storage:** the concept can also be argued to be valid to scale-up.
- **Chemical Storage**
  - Ammonia:
    - Hydrogen can be stored and transported in the form of ammonia (NH_3), which can be converted back to hydrogen («Ammonia's Role in a Net-Zero Hydrogen Economy», s. f.).
    - Allows the use of existing infrastructure for storage and transport.
  - Liquid Organic Hydrogen Carriers (LOHC):
    - LOHCs are organic compounds that can absorb and release hydrogen through chemical reactions (*LOHC - Liquid Organic Hydrogen Carrier (I) - H2Vector Energy Technologies*, s. f.).
    - Provide a safe and efficient way to store and transport hydrogen at ambient conditions.
- **Cryogenic Storage**
  - Advantages:
    - Suitable for storing very large amounts of hydrogen in liquid form at cryogenic temperatures (*Cryogenic Hydrogen Storage & Cooling*, s. f.).
    - High energy density per volume compared to gaseous hydrogen.

  - Disadvantages:
    - Requires specialized, insulated storage tanks to maintain low temperatures.
    - Energy-intensive process due to cooling requirements.

Transport Options

Given the required conditions for hydrogen generation, particularly in the case regarded within the scope of this project which only accounts for green hydrogen, the possible areas suitable for generation are often limited. Hydrogen clusters can be a potential solution to avoid distribution (*Industrial Clusters Using Green Hydrogen Can Drive Clean Energy Transition in Europe and China*, 2021), since the concept implies that industry should be concentrated around hydrogen generation facilities or the other way around. However, as we will later see, potential applications are not only limited to industrial uses (*Hoja de Ruta del Hidrógeno*, s. f.), thus the energy vector will need to be made available widely. Consequently, the transport stage of the value chain presents a potential bottleneck for which several alternatives exist.

- **Road Transport**
  - Hydrogen can be transported in liquid or compressed form via tanker trucks (*Gaseous Hydrogen Delivery*, s. f.).
  - Flexibility in distribution with different purities and quantities available in bottled form.
- **Rail Transport**
  - Rail tankers can carry larger volumes compared to road transport (*Hydrogen Rail | Accelera*, s. f.), ranging from 2,900 to 9,100 kg.
- **Maritime Transport**
  - Large cargo ship tanks can transport up to 70 tons of hydrogen.

  - Suitable for transferring large quantities over long distances (*On the bulk transport of green hydrogen at sea: Comparison between submarine pipeline and compressed and liquefied transport by ship - ScienceDirect*, s. f.).

Cost Considerations

The method of transport depends on the volume and distance of the hydrogen to be transported. Pipelines and trucks are common for urban and interurban transport, while rail and maritime transport are more suited for intercontinental distances. Liquid organic hydrogen carriers (LOHC) and ammonia also offer efficient alternatives based on distance and volume requirements.

Overall, transport and storage costs can constitute a significant portion of the total energy cost (Borsboom-Hanson et al., 2022), potentially impacting hydrogen's competitiveness against other energy sources.

Distribution in openMASTER

Transportation and storage are an integral part of the hydrogen value chain and, as so, need to be analysed and reported to ensure a comprehensive understanding for the reader of this paper.

However, given that openMASTER is a single-node model, the dimension encompassing hydrogen distribution is not contemplated in the same sense as that of production and demand. Rather than thoroughly parametrising the different alternatives, it is defined as a simple tax that must be paid for the distribution of the energy vector from the generation side to that of the demand. Thus, the model is not fully representative in this sense, allowing for future iterations and improvements where this situation could be targeted. Nevertheless, when analysing the final results and trying to reach conclusions on hydrogen potential and applicability, it is vital to have a sense of the complexity and requirements of the distribution stage of the value chain.

1.5 DEMAND

The final phase in the value chain comprises the diverse array of end uses for renewable hydrogen. Such applications vary widely, depending on whether hydrogen is used directly as an energy carrier or as a raw material in various products (*All about hydrogen as fuel: Is it already a reality? | Repsol*, s. f.). When utilized in its pure form, hydrogen can serve as a fuel, an energy vector, or as an industrial feedstock.

Main target sectors

Through a review of available bibliographic resources, several key sectors have been identified where green hydrogen will be most applicable and significantly advantageous in replacing fossil fuels and other high-impact resources.

They can be grouped as follows:

- **Industry:** as of 2020, 500,000 tons of grey hydrogen were consumed annually in industrial product manufacturing plants (such as ammonia) and refineries (*Hoja de Ruta del Hidrógeno*, s. f.). These sectors are challenging to electrify with renewable sources due to the high heat capacity required (+400ºC) (*How to Electrify Industry | Systems Change Lab*, s. f.), which hydrogen can provide. H2 is also often used as raw material for many processes. The potential for decarbonization is high in these industries, since by switching from grey to green hydrogen a significant difference could be made. Three subsectors are most likely to be at the forefront of hydrogen adoption:
    - **Refining Industry:** hydrogen can be used for hydrotreating (removing impurities from crude oil) (*An Overview of Hydrotreating | AIChE*, s. f.) and hydrocracking (upgrading heavier crudes)(*Hydrocracking - Set Laboratories*, s. f.). These are applications where hydrogen is used as a raw material.
    - **Chemical Industry:** hydrogen is used as a raw material for producing chemicals such as methanol and ammonia.

  - **Metallurgical Industry:** Hydrogen is used as a fuel for creating alloys like steel, which require high energy inputs to reach high temperatures. It is also used as a reducing agent for alloy generation, replacing coal. One particular such use case as a reduction agent that has gained a lot of traction as of recently due to hydrogen potential is DRI (*Green Steel: pathways for the new hydrogen-powered DRI-EAF projects - Energy Post*, s. f.).

  Hydrogen can also serve as an energy resource in many processes due to its higher energy content compared to conventional fossil fuels.

- **Sector Integration:** green hydrogen is a key tool for integrating different energy sectors due to its versatility as an energy vector. It will provide greater flexibility, availability, and energy security, enhancing the efficiency and profitability of the energy transition and contributing to the decarbonization of the economy (*Role of Hydrogen Storage in Sector Integration Perspective - Hydrogen Europe*, s. f.). Hydrogen will play the following roles to enable sector interaction:
  - **Energy Storage:** the “Energy Storage Strategy” (*El Gobierno aprueba la Estrategia de Almacenamiento Energético, clave para garantizar la seguridad del suministro y precios más bajos de la energía*, s. f.) and PNIEC (*Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030*, s. f.) recognize the potential of renewable hydrogen fuel cells and "Power to X" technologies to solve this pressing issue.
  - **Electric Sector:** by applying it to store surplus renewable energy (*The Use of Hydrogen as an Energy Storage System*, s. f.),hydrogen would allow for further optimization of energy distribution and a holistic integration of the subsectors. It offers large-scale resilience and flexibility, allowing for better grid management.
  - **Gas Sector:** green hydrogen could leverage existing infrastructure and increase integration with the electric sector. Nevertheless, we must highlight that blending hydrogen with natural gas still presents certain challenges (Ecology, s. f.), such as loss of intrinsic value and technical difficulties in gas separation at consumption points.

  - **Circular Economy:** H2 can be produced via gasification from biomass, renewable biogas, or waste. This approach profits from the use of agricultural and industrial waste to decarbonize the gas sector (*If H2 Is the Missing Piece, How Will It Fit in the Zero Carbon Puzzle?*, s. f.). Many projects are currently underway in Spain under the application of this idea (*Proyectos de Economía Circular*, s. f.).
- **Mobility:** hydrogen fuel cells in Fuel Cell Electric Vehicles (FCEVs) convert hydrogen back into electricity (*FCEVs | Hydrogen Mobility Europe*, 2015). This reduces the battery size compared to electric vehicles but has lower efficiency (since we must consider for the efficiency calculations the energy needed to produce, compress, and store hydrogen in vehicles). Fuel Cell Hybrid Vehicles (FCHVs), which combine both technologies, could offer significant advantages, particularly in heavy transport: smaller batteries, shorter recharge times, etc.
  - **Road Transport:** by 2019, even if there were only 10 demonstration vehicles in Spain, the world count for hydrogen-run road transport alternatives was as high as 12,000 operating units, with hot pockets in Japan, Canada and Germany. Heavy-duty vehicles and industrial vehicles are seen as the most beneficial applications, with some initiatives having been bought to live at a national level, of which we can highlight hydrogen fueled public buses in main cities like Madrid (Nuevo, 2024).
  - **Rail Transport:** this is arguably the transport sector with less applicability, with experts reducing its potential use to rail lines that are difficult to electrify, since if electrification is available, it usually makes sense cost wise. At the national level, we have some initiatives by Renfe in collaboration with Enagas and the UE, currently focused on testing potential technologies in a facility in Asturias (*El tren demostrador del proyecto fch2rail, inicia pruebas en vía*, s. f.).
  - **Maritime Transport:** Applicable to both vessels and port and terminal machinery. An example of such initiatives is the H2Ports project, by which a pilot hydrogen operation is being developed in the port of Valencia to use

green hydrogen in their logistical operations and thus reduce their carbon impact (*València, Puerto del Hidrógeno*, 2023). On the vessels´ side, we have seen compromise by big shipping companies such as Maersk, which we expect to be a key driver for increased hydrogen application heading forward (Ship & Bunker News Team To contact the editor responsible for this story email us at editor@shipandbunker. com, s. f.).

  - **Aviation:** for aircraft, and airport and terminal machinery. Hydrogen is also used to produce synthetic fuels like bio-kerosene and other SAFs, which are crucial for the development of the aviation industry. As of recently, it has been made public that a quota of them is soon to become of mandatory use in airports and aircraft according to recent EU regulations (*REPowerEU*, s. f.), with forecasts within the regulation to progressively increase the percentage of usage.

- **Other Sectors:** in domestic and tertiary sectors, which represent approximately 30% of Spain's energy consumption, hydrogen can be applied to cogeneration and micro-generation systems, as well as thermal uses.

The focus in openMASTER

Given the limited time constraints for this project, decisions had to be made regarding the scope of the demand side that was to be modelled in openMASTER. After careful consideration, the decision was made to focus on the industrial applications of hydrogen demand technologies, justified by the identification of a greater theoretical base and a more mature perception of the sector in terms of the adoption of the hydrogen lifecycle.

To create the digital reproduction for the industry, a clear logical process was established by which, with certain assumptions, the potential for consumption of H2 heading into the future by each subsector of the national industrial scheme was defined. Such process had the following stages:

1. On a first phase, we aligned with the EUROSTAT criteria applied by the MITECO for the classification of the Spanish industrial landscape into subsectors. In doing so,

it allowed us to use the energy balances that the ministry compiles every year for each of these areas of industry. The balances are calculated according to the Eurostat methodology. Since they are divided not only by subindustry, but also by fuel types, they were vital in terms of gaining an understanding on the current fuel supply strategies for each of these sections. We will later see how this was used in order to project how hydrogen would affect the different balances depending on a series of scenarios that we built.

2. Since the scope of this project looks forward into the future, with key dates for comparison being 2030 and 2050, it was required that we developed an understanding of how energy consumption will evolve in the industry during this timeline. With such aim, we projected the growth in demand for electricity according to three different possible scenarios indexed to Spanish GDP evolution. This was done by using the methodology presented in the report "Scenarios for the energy sector in Spain 2030 – 2050" by Economics for energy (EENDA, s. f.). The three resulting scenarios and their context as defined by such report were:
   a. **Decarbonization:** also referred to as the scenario for maintenance of current policies. This scenario assumes a firm global commitment to greenhouse gas emission reductions per the Paris Agreement, with favorable political, social, and economic conditions. Sustained global economic growth allows for financing decarbonization efforts. Significant reductions in coal and oil prices and a slight increase in gas prices are expected due to changes in demand. Technological innovation, especially in renewable energy and energy efficiency, will lead to widespread adoption by 2050. In Spain, population and GDP are projected to grow steadily, with the country aiming for a 40% reduction in emissions by 2030 and a 95% reduction by 2050, compared to 1990 levels.
   b. **Stagnation:** in this scenario, from 2030 to 2050, the geopolitical landscape evolves linearly, with China and India becoming increasingly influential, leading to changes in international political-economic balances. Global demand for services, including energy, rises with the economic growth of

these emerging economies. Coal prices remain stable until 2030, then moderately decline until 2050 due to reduced demand. Gas prices increase between 2015 and 2030 and then stabilize, reflecting its role as a backup in a renewable-dominated energy mix. Oil prices decline moderately due to reduced demand from the transportation sector's gradual electrification and the rise of gas as a transitional fuel. International decarbonization efforts are tepid, with countries meeting only the minimal commitments of the Paris Agreement. Public pressure is insufficient to drive more ambitious policies, resulting in progress that falls short of Paris Agreement targets. Spain experiences demographic and economic growth similar to the decarbonization scenario. The country aims for a 43% reduction in emissions for ETS sectors and a 26% reduction for diffuse sectors by 2030 but does not meet the 2050 decarbonization targets. European policy also includes renewable energy penetration and energy efficiency scenarios.

c. **Technological advancement:** finally, according to this scenario’s assumptions, between 2015 and 2050, technological progress is unprecedented, with significant advancements in renewable energy, storage, fracking, and combined cycle gas technologies. Innovation drives economic growth, exceeding 2% annually and peaking at 5.5%, while dramatically reducing technological costs. Decarbonization is significant, driven primarily by innovation rather than climate change concerns. This leads to substantial reductions in renewable technology costs. Fuel prices decrease similarly to the decarbonization scenario, with clear reductions in oil and coal prices and a slight decrease in gas prices. Spain, spurred by EU innovation plans, experiences robust economic growth from 2015 to 2050, marked by significant infrastructural investments that improve its economic competitiveness.

Given the scenarios, the report then provides reasoned projections, according to the expected context afore-mentioned, on how GDP values will behave in the years regarded within the scope of the project. We collected that data in the following table:

GDP Projections	CAGR	2030 (M€)	2050 (M€)
Decarbonisation	1.50%	1,344,798.37 €	1,811,248.42 €
Stagnation	1.00%	1,248,783.49 €	1,523,753.17 €
Technological Advancement	2.50%	1,557,845.99 €	2,552,712.05 €

Table 4. GDP Projection Scenarios

Then, the impact of the GDP trends on energy demands per industry sector needed to be assessed. To do so, a formula is provided by the same source:

$$Industry\ Demand = \frac{Consumption}{GVA} * (GDP * GVA\ in\ \%\ form)$$

Equation 1. Industry Demand Formula

As we can see, the GVA was required to help ponder the GDP effects on the demand per industry subsector. Thus, we sourced that data (*Valor Añadido Bruto(32450)*, s. f.) using the INE (Instituto Nacional de Estadística). We adjusted for the sectors relevant to the MITECO classification.

It was then straightforward to apply all the compiled data in a formula to end up with the relevant levels of industry energy consumption in upcoming years, depending, of course, on the assumptions for the different scenarios. It is worth noting that the base data from which we have started projections is that for 2021, which is the same year from which we will be introducing renewable hydrogen in the model in openMASTER. The resulting values for future demand are compiled in the table in the following page.

It is worth noting that these calculations apply to the aggregate fuel demand per subindustry. Therefore, we then had to assume that energy balance in relative terms would still remain the same. Thus all different fuel types would increase heading into 2030 and 2050 but the proportion within each subsector would remain the same.

Demands (GWh)	Demand 2021	Decarbonisation 2030	Decarbonisation 2050	Stagnation 2030	Stagnation 2050	Technological Advancement 2030	Technological Advancement 2050
Iron and Steel	21,945.21	26,686.99	35,943.51	24,781.61	30,238.28	30,914.84	50,657.56
Chemical and Petrochemical	42,537.67	51,728.92	69,671.36	48,035.62	58,612.58	59,924.00	98,192.45
Non-Ferrous Metals	13,134.89	15,972.99	21,513.30	14,832.56	18,098.54	18,503.48	30,320.11
Non-Metallic Minerals	47,674.95	57,976.23	78,085.58	53,836.89	65,691.23	67,161.03	110,051.16
Transport Equipment	6,585.32	8,008.23	10,785.92	7,436.46	9,073.90	9,276.92	15,201.32
Machinery	10,502.94	12,772.35	17,202.50	11,860.44	14,471.99	14,795.79	24,244.62
Extractive Industries	5,456.53	6,635.54	8,937.11	6,161.78	7,518.54	7,686.76	12,595.66
Food, Beverages, and Tobacco	31,494.27	38,299.35	51,583.67	35,564.88	43,395.91	44,366.86	72,700.27
Pulp, Paper, and Printing	19,993.91	24,314.06	32,747.52	22,578.11	27,549.58	28,165.98	46,153.24
Wood and Wood Products	7,465.10	9,078.11	12,226.90	8,429.96	10,286.15	10,516.30	17,232.18
Construction	14,755.26	17,943.48	24,167.26	16,662.36	20,331.25	20,786.15	34,060.52
Textile and Leather Products	241,548.03	293,740.12	395,625.36	272,767.89	332,828.66	340,275.45	557,580.95

Table 5. Industry Demand Projections per Sector and Scenario

3. As a next step, we decided that to address the issue of how hydrogen would impact the different demands per subsector, the best procedure would be to study each case individually, analyzing the exposure of the different fuel types consumed to the potential case of renewable hydrogen technology enabling substitution at a gain (in terms of costs, carbon impact, etc.).

   It is important that we establish at this point that this approach is based on the premise that the energy mix will evolve heading forward, since according to our current decarbonization path and its associated strategies fossil fuels and other high emitting energy sources will need to be replaced. However, it is important that we keep a certain perspective on the topic, since it is clear that hydrogen is not the only solution that will play a role in this energy transition.

   Following such a premise, a theoretical basis had to be found to determine what percentage of each type of fuel would be substituted by H2. Once again, we stress that the fact that hydrogen substitutes a percentage doesn't mean the rest of each fuel type usage will be the same, other solutions may come into play that escape the scope of this paper.

   Two main general criteria were defined to help make sense of this process before going into the specific assumptions. They are as follows:

   a. **The temperature criteria:** a common theme when it comes to hydrogen adoption is to categorize plausible sectors by the term "difficult to electrify"**.** This is because, at least with the current technology and prices (and their current respective expectations of improvement heading in the mid-term), electrification if available and suitable for the specific requirements, will almost certainly be a better solution than introducing hydrogen, from a cost-benefit perspective (*How to Electrify Industry | Systems Change Lab*, s. f.).

      Therefore, by keeping that in mind, we have established our first criteria for hydrogen adoption, but we need to be more specific to be able to apply it in a precise manner to the subindustries in our scope. In that sense, we found that the barrier is determined by the temperature of the processes required by the operations involved in each of these sectors. If, at any point in the value chain, the temperature requirements surpass the 400ºC limit, then the process can be considered hard to electrify. Thus, the process is likely to be using other types of fuels at the moment, such as natural gas or fossil fuels, which have greater energetic density. The natural conclusion, as per the context of this project, is to assume that hydrogen will play a key role in the future, allowing for the decarbonization of the processes without sacrificing energy density requirements. For such temperature requirements, we decided to use the following table of values as a benchmark:

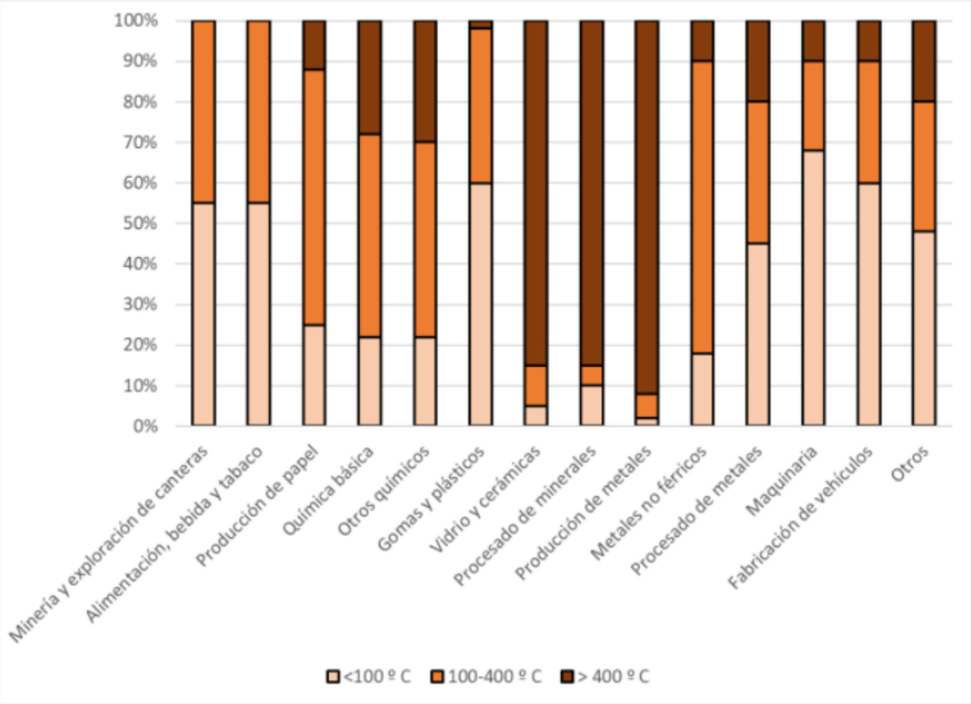


Figure 2. Working Temperatures per Industrial Sector. Source: Cátedra de Estudios Sobre el Hidrógeno de Comillas.

As a result, the following sectors were depicted as difficult to electrify:

- Iron and steel.
- Chemical and petrochemical.
- Non-ferrous metals.

- Non-Metalic minerals.

We have now established our first clear assumption, which is that hydrogen has a higher potential for fuel substitution in these four subindustries.

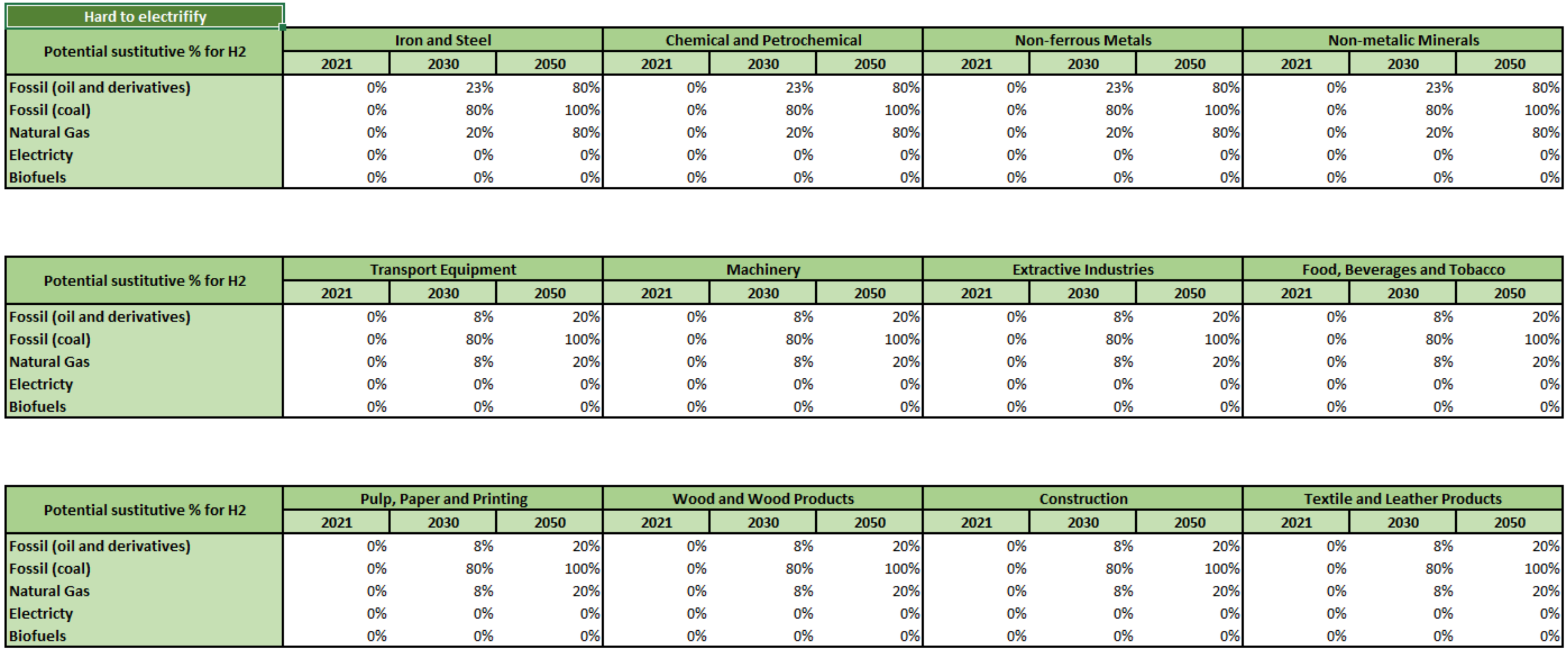
b. **The fuel criteria:** the MITECO classification system for the energy balance data distinguishes a wide variety of highly specific fuel types that are consumed in the Spanish industrial scene. However, to aid with the process of making sense of the theory to produce reasonable assumptions, the fuel types were condensed into five main groups:
   - Fossil (oil and derivatives)
   - Fossil (coal)
   - Natural Gas
   - Electricity
   - Biofuels

Given the current EU policies, which back the energy transition through various plans and rulings (*RePowerEU Plan*, s. f.), the decarbonization of the economy seems certain. This has led us to establish that hydrogen has a high potential for substitution in those areas where fossil fuels (oil derivatives and coal) and natural gas, the carbon heavy sources, are employed. In particular, we placed high substitutive percentages in the case of coal, where there is clear national regulation aiming for its complete eradication on a large scale (Benito, 2020).

In the case of electricity, the case for application seems distinct given the criteria in the different sectors of the temperature, which makes electrification hard given its lower energetic density compared to hydrogen. Therefore, we have established that both technologies will be complementary rather than competing with one another. We acknowledge that this may not be of absolute precision, given that there may be intermediate cases, but the overall effect evens out given the scale of the energy demand by the Spanish industry.

Finally, regarding the case of biofuels, little to no information was found to be available or clear enough to make a reasoned estimation. However, we have come to notice that many biofuels use hydrogen as raw material (*Hidrógeno como combustible*, s. f.), in a sense working as fuels where hydrogen is being upgraded. Therefore, we feel it is safe enough to establish that not substitution potential is to be expected in this area. Even if this is not valid for all particular cases, the relative weight of biofuels within the industry energy demand is small, thus not having an impact great enough to arguably skew the results.

Having established these general criteria to enable the reader to begin to understand our expectations for future hydrogen adoption, we can now dive into the specific percentages that we set for each subindustry and its consumed fuel types. They are compiled over the next two tables:



Hard to electrifify

Potential sustitutive % for H2	Iron and Steel			Chemical and Petrochemical			Non-ferrous Metals			Non-metalic Minerals		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	23%	80%	0%	23%	80%	0%	23%	80%	0%	23%	80%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	20%	80%	0%	20%	80%	0%	20%	80%	0%	20%	80%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Potential sustitutive % for H2	Transport Equipment			Machinery			Extractive Industries			Food, Beverages and Tobacco		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Potential sustitutive % for H2	Pulp, Paper and Printing			Wood and Wood Products			Construction			Textile and Leather Products		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 6. Hydrogen Substitution Potential Assumptions

For the table of specific percentages picked, general criteria for both electric and biofuels explains the null potential for substitution applied. In other cases, further explaining is due to understand the reasoning behind the precise numbers.

c. **Fossil fuels (oil derivatives)**: we began our assumptions based on the Spanish law titled "Law for climate change and energy transition" (*Ley de Cambio Climático y Transición Energética*, s. f.), which states that fossil fuels reduction will hit 23% on its path to 100% disappearance by 2050 (Ara, 2021). Even if the 2030 percentage of reduction seems somewhat reasonable, the 2050 percentage seems somewhat far-fetched given the constant stream of information that we are receiving warning that the world is falling behind the objectives set by the main decarbonization pathways (*Only a Fifth of Companies on Track for Net Zero, with Heavy Industry Key to Breaking Decarbonization Stalemate, Accenture Reports Find*, s. f.).

In contrast, Repsol recently altered its strategy to align with its new objective to reduce fossil fuel production by half by 2030 doubling down on their renewable energy production (elEconomista.es, 2023). Repsol is one of the main representatives in the Spanish energy sector and can arguably be considered a trend driver in the national market. Thus, their strategic choices and projected paths can be extrapolated to the rest of the main players.

By crossing both ideals, we arrived at the reasonable in between point of assuming an 80% reduction of fossil fuel of oil derivative type by 2050, maintaining the 2030 levels of 23% given that adjustment of strategies to decelerate the current reduction pace will require a reasonable timespan in terms of reflecting in the results.

Energy consumption will still grow in the industry, so new fuel sources will need to fill the void.

In terms of the hard to electrify sectors, we assume that the totality of this reduction will be taken over by renewable hydrogen, even if other renewable gases will still play a role and should be kept in mind.

On the other hand, in terms of the other subindustries, as explained before, electrifying will be the main pathway to account for the reduction fossil fuels. Thus, in these cases, we have assumed that green hydrogen will play a residual role of up to 20% in 2050, which, by lineal extrapolation, results in an 8% substitution potential in 2030.

d. **Fossil (carbon):** as argued before, Spain has a very strict policy to extinguish coal plants in the near future. Therefore, the percentages were calculated to adjust to the current pace of eradication. From 2011 to 2021, they use of coal generation facilities reduced by 88% on the national scale (Pascual, 2022), covering only 2% of national demand in 2021. It is reasonable to assume that policies for generation plants will be shadowed in terms of industrial coal usage. Those levels are arguably residual, so we could have assumed given 2021 levels and the pace of descaling that by 2030 coal would be of null generation. The PNIEC argues that coal consumption will have completely disappeared by 2025 (*Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030*, s. f.). As proven by the case of oil, it is better to play it safe in these cases, since public and private interests don't always see eye to eye. Therefore, as a reasonable medium we suggested that the remaining coal consumption will disappear by 2050, with 80% of 2021 levels already eradicated by 2021. In this case, we assume that the reduction is directly substituted by renewable hydrogen for all sectors.

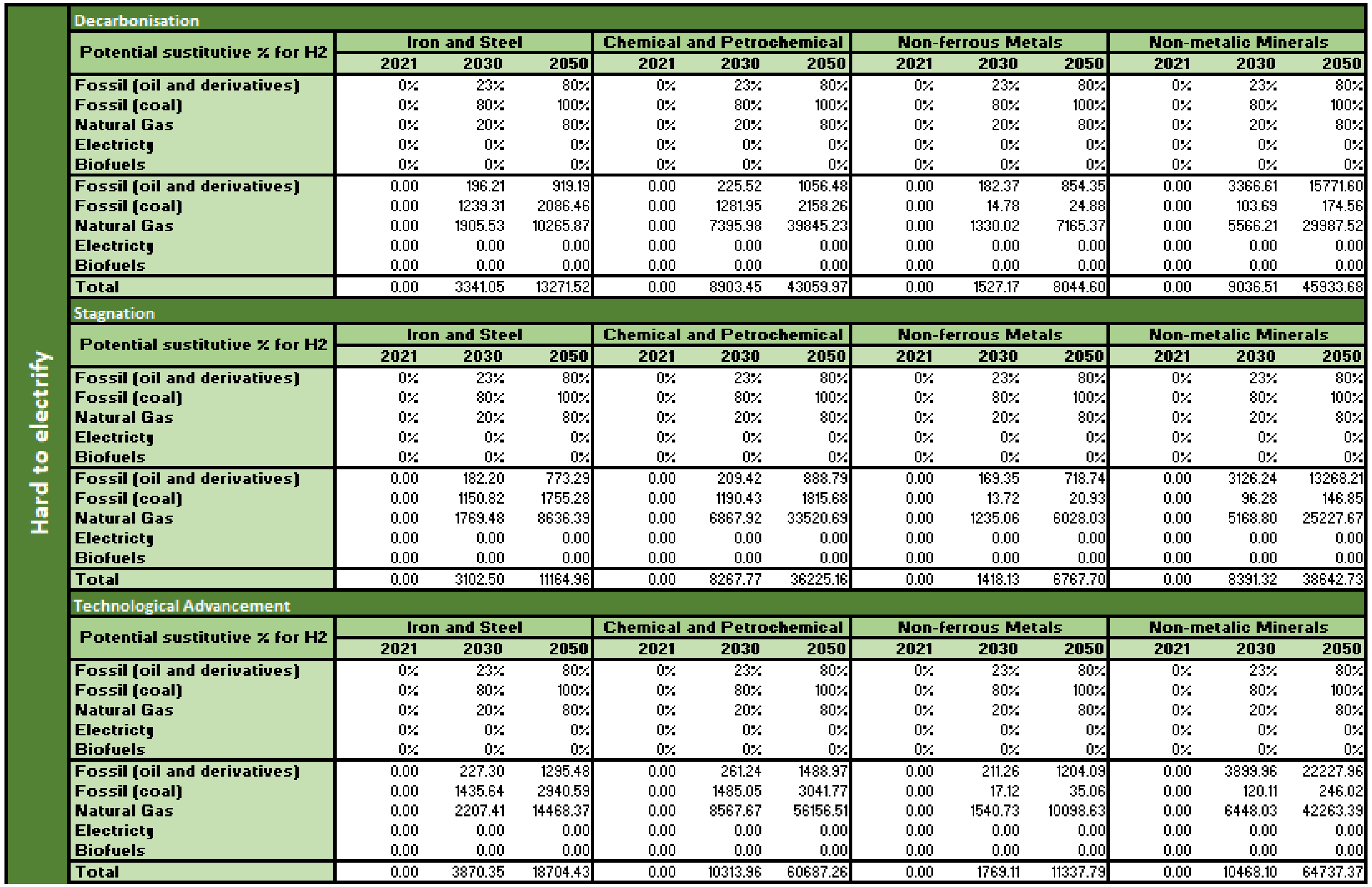
e. **Natural gas:** the case for natural gas presents great resemblance to that for oil derivatives. However, we have in this case based our assumptions on a project that focuses on the decarbonization of the Spanish transport sector through the application of hydrogen (Maestre et al., 2023). Such study works through the premise the hydrogen will benefit, admittedly through required retrofits, from the natural gas distribution infrastructure and the NGV (Natural Gas Vehicles) refueling stations in order to achieve the objectives. Thus, hydrogen will progressively increase its quota in the distribution network, through blending an increasing it percentual presence in the distributed mix. The paper concludes that the process will naturally result in the complete substitution of natural gas by H2 at some point in the mid to long terms. Aligning with the prior credo for fossil fuels of oil derivatives, we established a 25% progress in such process by 2030, with the total substitution being achieved by 2050.

This natural gas reduction leaves a void for energy that must be covered since the industry is projected to continue its trend of growth. Once again, acknowledging the potential of other renewable gases, we reduced such numbers by a safety margin, ending up with 80% hydrogen substitution for the projected natural gas demand by 2050, which then took us to a 20% hydrogen adoption level in 2030 in the hard to electrify sectors.

However, when it comes to the rest of sectors, we again work under the assumption that even if gas natural levels go down, hydrogen may not be the optimal solution from a cost-benefit perspective. Given that we expect that electrification will supply a substantial quota of the energy balance, we have aligned hydrogen levels with those expected in these same sectors for oil-derivative fossil fuels, since the case, properties and policies are reasonably similar.

The assumptions hold for each of the three different GDP levels since trends are the same and changes are only the proportion regarding overall demand size. Therefore, it would seem that the energy transition holds a priority standard in the EU, enabling us to produce this work under the premise that it will not be subject to foreseeable economic conditions (*Why geopolitics must not derail the energy transition - or investors' resolve | AXA*, s. f.). However, it is clear that is by no means true, since the economic conditions will determine whether funding can be produced. However, none of the three GDP scenarios built for the model presents significant levels of distress to reasonably expect deviations from the general plan. As we will see in upcoming pages, we have crossed the expectation for our scenarios with the 2024 proposed revision of the PNIEC´s expected GDP projections («La propuesta de actualización del PNIEC 2023-2030», s. f.), which sheds light on the current pace of progress.

The case scenarios the result in terms of expected energy balance per industry sector and per type of fuel (in GWh) are as follows:



Hard to electrify

Decarbonisation

Potential sustitutive % for H2	Iron and Steel			Chemical and Petrochemical			Non-ferrous Metals			Non-metalic Minerals		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	23%	80%	0%	23%	80%	0%	23%	80%	0%	23%	80%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	20%	80%	0%	20%	80%	0%	20%	80%	0%	20%	80%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	196.21	919.19	0.00	225.52	1056.48	0.00	182.37	854.35	0.00	3366.61	15771.60
Fossil (coal)	0.00	1239.31	2086.46	0.00	1281.95	2158.26	0.00	14.78	24.88	0.00	103.69	174.56
Natural Gas	0.00	1905.53	10265.87	0.00	7395.98	39845.23	0.00	1330.02	7165.37	0.00	5566.21	29987.52
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	3341.05	13271.52	0.00	8903.45	43059.97	0.00	1527.17	8044.60	0.00	9036.51	45933.68

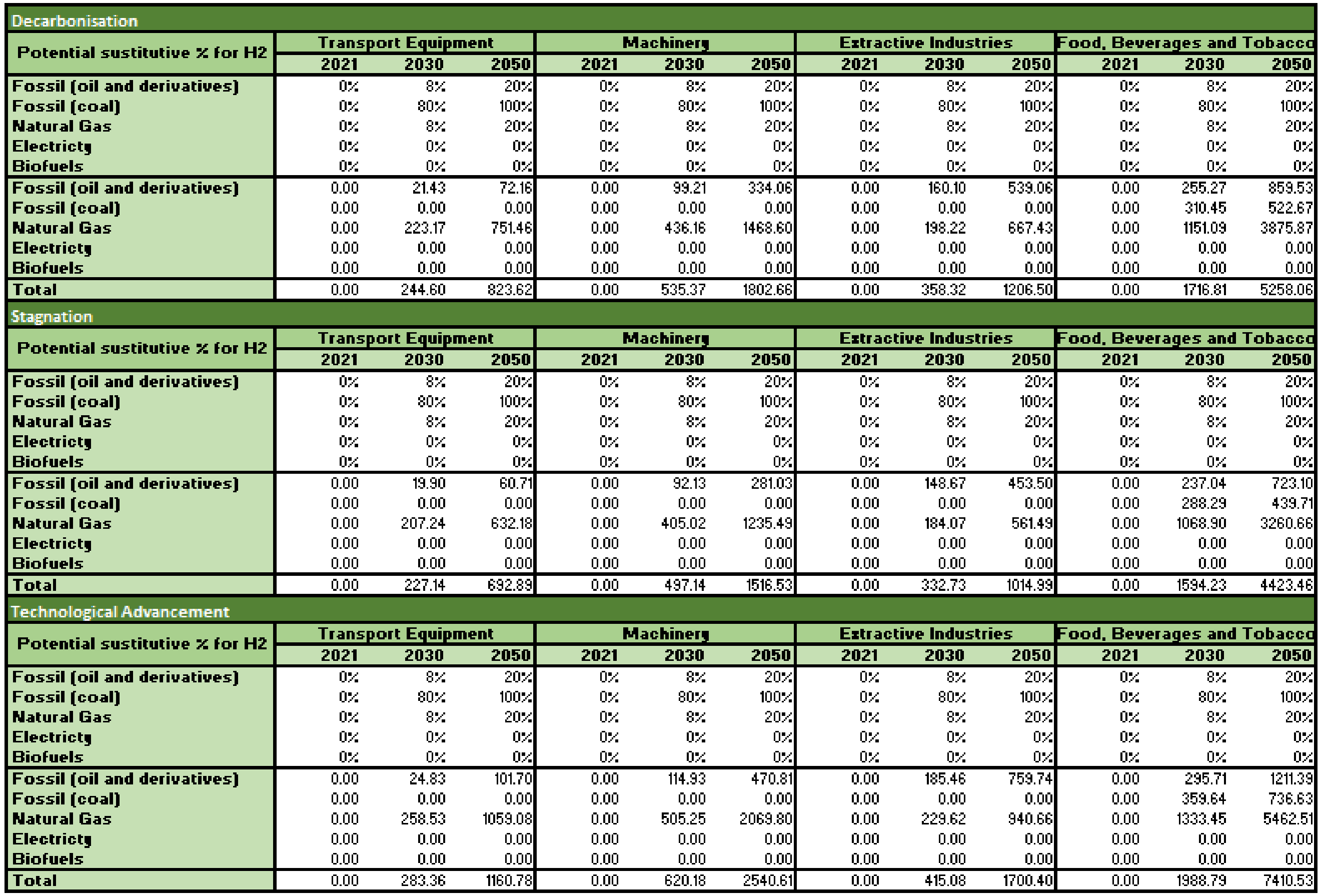
Stagnation

Potential sustitutive % for H2	Iron and Steel			Chemical and Petrochemical			Non-ferrous Metals			Non-metalic Minerals		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	23%	80%	0%	23%	80%	0%	23%	80%	0%	23%	80%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	20%	80%	0%	20%	80%	0%	20%	80%	0%	20%	80%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	182.20	773.29	0.00	209.42	888.79	0.00	169.35	718.74	0.00	3126.24	13268.21
Fossil (coal)	0.00	1150.82	1755.28	0.00	1190.43	1815.68	0.00	13.72	20.93	0.00	96.28	146.85
Natural Gas	0.00	1769.48	8636.39	0.00	6867.92	33520.69	0.00	1235.06	6028.03	0.00	5168.80	25227.67
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	3102.50	11164.96	0.00	8267.77	36225.16	0.00	1418.13	6767.70	0.00	8391.32	38642.73

Technological Advancement

Potential sustitutive % for H2	Iron and Steel			Chemical and Petrochemical			Non-ferrous Metals			Non-metalic Minerals		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	23%	80%	0%	23%	80%	0%	23%	80%	0%	23%	80%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	20%	80%	0%	20%	80%	0%	20%	80%	0%	20%	80%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	227.30	1295.48	0.00	261.24	1488.97	0.00	211.26	1204.09	0.00	3899.96	22227.96
Fossil (coal)	0.00	1435.64	2940.59	0.00	1485.05	3041.77	0.00	17.12	35.06	0.00	120.11	246.02
Natural Gas	0.00	2207.41	14468.37	0.00	8567.67	56156.51	0.00	1540.73	10098.63	0.00	6448.03	42263.39
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	3870.35	18704.43	0.00	10313.96	60687.26	0.00	1769.11	11337.79	0.00	10468.10	64737.37

Table 7. Hydrogen Demand Projections per Sector and Scenario.



Decarbonisation

Potential sustitutive % for H2	Transport Equipment			Machinery			Extractive Industries			Food, Beverages and Tobacco		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	21.43	72.16	0.00	99.21	334.06	0.00	160.10	539.06	0.00	255.27	859.53
Fossil (coal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	310.45	522.67
Natural Gas	0.00	223.17	751.46	0.00	436.16	1468.60	0.00	198.22	667.43	0.00	1151.09	3875.87
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	244.60	823.62	0.00	535.37	1802.66	0.00	358.32	1206.50	0.00	1716.81	5258.06

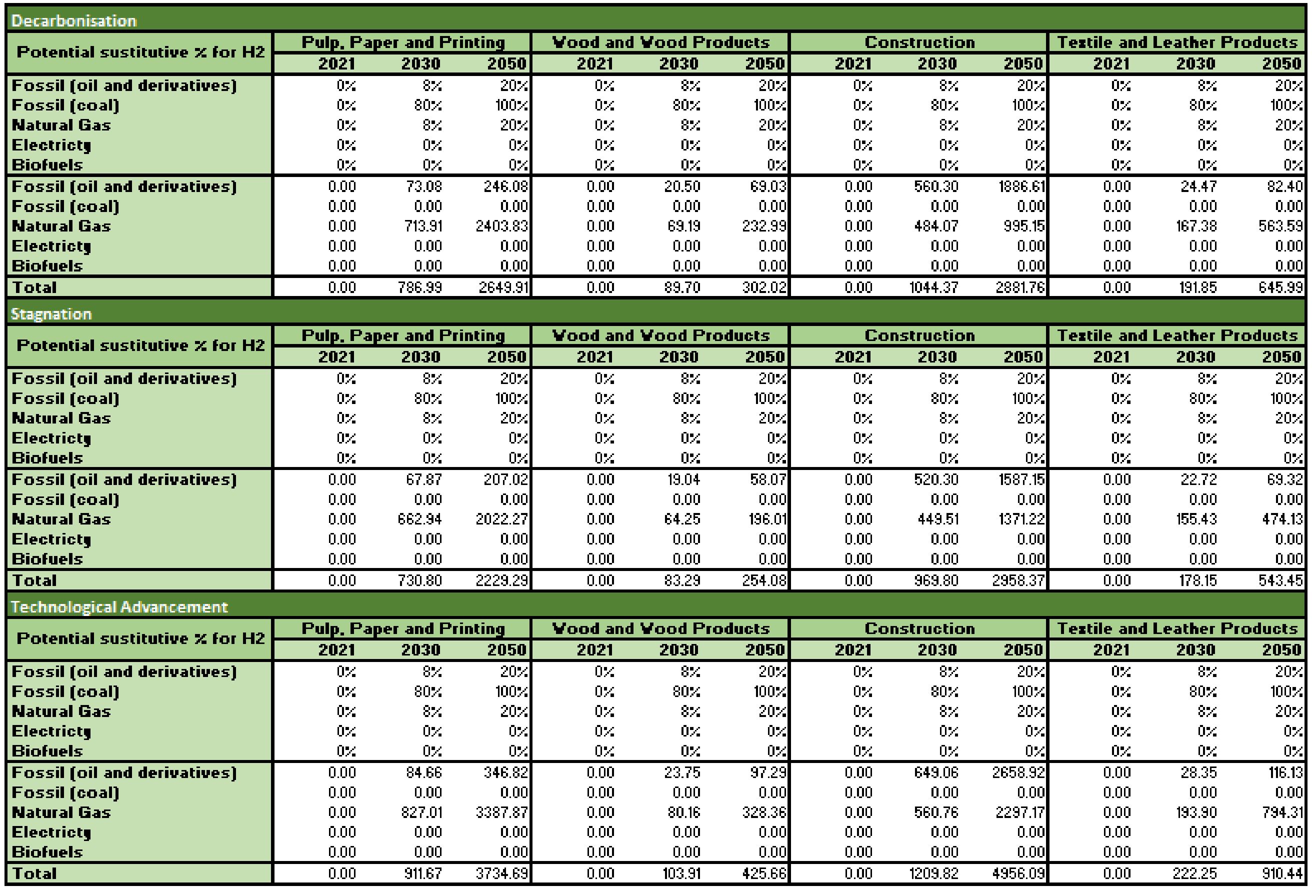
Stagnation

Potential sustitutive % for H2	Transport Equipment			Machinery			Extractive Industries			Food, Beverages and Tobacco		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	19.90	60.71	0.00	92.13	281.03	0.00	148.67	453.50	0.00	237.04	723.10
Fossil (coal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	288.29	439.71
Natural Gas	0.00	207.24	632.18	0.00	405.02	1235.49	0.00	184.07	561.49	0.00	1068.90	3260.66
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	227.14	692.89	0.00	497.14	1516.53	0.00	332.73	1014.99	0.00	1594.23	4423.46

Technological Advancement

Potential sustitutive % for H2	Transport Equipment			Machinery			Extractive Industries			Food, Beverages and Tobacco		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	24.83	101.70	0.00	114.93	470.81	0.00	185.46	759.74	0.00	295.71	1211.39
Fossil (coal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	359.64	736.63
Natural Gas	0.00	258.53	1059.08	0.00	505.25	2069.80	0.00	229.62	940.66	0.00	1333.45	5462.51
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	283.36	1160.78	0.00	620.18	2540.61	0.00	415.08	1700.40	0.00	1988.79	7410.53

Table 8. Hydrogen Demand Projections per Sector and Scenario.



Decarbonisation

Potential sustitutive % for H2	Pulp, Paper and Printing			Wood and Wood Products			Construction			Textile and Leather Products		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	73.08	246.08	0.00	20.50	69.03	0.00	560.30	1886.61	0.00	24.47	82.40
Fossil (coal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	713.91	2403.83	0.00	69.19	232.99	0.00	484.07	995.15	0.00	167.38	563.59
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	786.99	2649.91	0.00	89.70	302.02	0.00	1044.37	2881.76	0.00	191.85	645.99

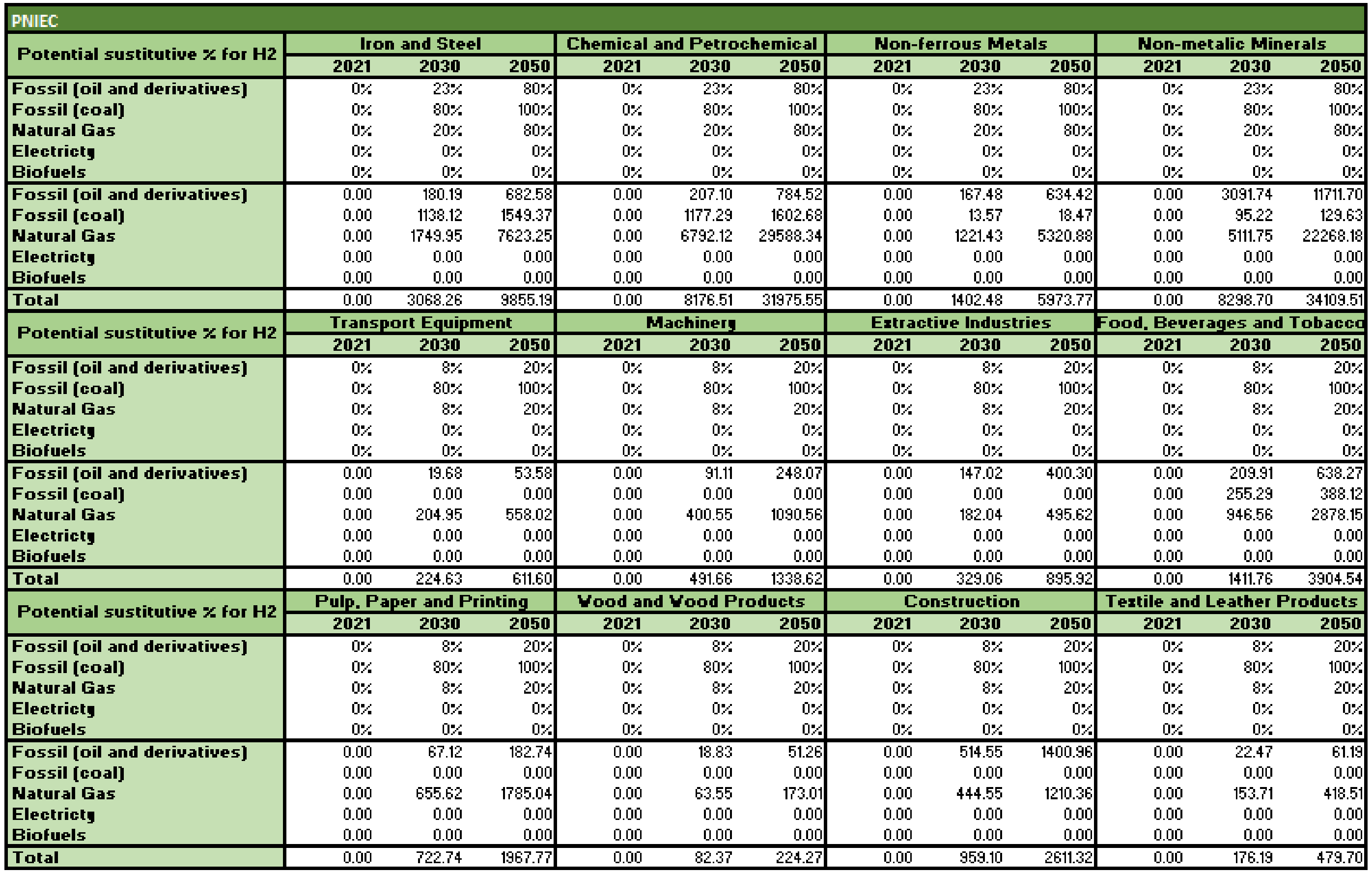
Stagnation

Potential sustitutive % for H2	Pulp, Paper and Printing			Wood and Wood Products			Construction			Textile and Leather Products		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	67.87	207.02	0.00	19.04	58.07	0.00	520.30	1587.15	0.00	22.72	69.32
Fossil (coal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	662.94	2022.27	0.00	64.25	196.01	0.00	449.51	1371.22	0.00	155.43	474.13
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	730.80	2229.29	0.00	83.29	254.08	0.00	969.80	2958.37	0.00	178.15	543.45

Technological Advancement

Potential sustitutive % for H2	Pulp, Paper and Printing			Wood and Wood Products			Construction			Textile and Leather Products		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	84.66	346.82	0.00	23.75	97.29	0.00	649.06	2658.92	0.00	28.35	116.13
Fossil (coal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	827.01	3387.87	0.00	80.16	328.36	0.00	560.76	2297.17	0.00	193.90	794.31
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	911.67	3734.69	0.00	103.91	425.66	0.00	1209.82	4956.09	0.00	222.25	910.44

Table 9. Hydrogen Demand Projections per Sector and Scenario.



PNIEC												
Potential sustitutive % for H2	**Iron and Steel**			**Chemical and Petrochemical**			**Non-ferrous Metals**			**Non-metalic Minerals**		
	2021	**2030**	**2050**	**2021**	**2030**	**2050**	**2021**	**2030**	**2050**	**2021**	**2030**	**2050**
Fossil (oil and derivatives)	0%	23%	80%	0%	23%	80%	0%	23%	80%	0%	23%	80%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	20%	80%	0%	20%	80%	0%	20%	80%	0%	20%	80%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	180.19	682.58	0.00	207.10	784.52	0.00	167.48	634.42	0.00	3091.74	11711.70
Fossil (coal)	0.00	1138.12	1549.37	0.00	1177.29	1602.68	0.00	13.57	18.47	0.00	95.22	129.63
Natural Gas	0.00	1749.95	7623.25	0.00	6792.12	29588.34	0.00	1221.43	5320.88	0.00	5111.75	22268.18
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	3068.26	9855.19	0.00	8176.51	31975.55	0.00	1402.48	5973.77	0.00	8298.70	34109.51
Potential sustitutive % for H2	**Transport Equipment**			**Machinery**			**Extractive Industries**			**Food, Beverages and Tobacco**		
	2021	**2030**	**2050**	**2021**	**2030**	**2050**	**2021**	**2030**	**2050**	**2021**	**2030**	**2050**
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	19.68	53.58	0.00	91.11	248.07	0.00	147.02	400.30	0.00	209.91	638.27
Fossil (coal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	255.29	388.12
Natural Gas	0.00	204.95	558.02	0.00	400.55	1090.56	0.00	182.04	495.62	0.00	946.56	2878.15
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	224.63	611.60	0.00	491.66	1338.62	0.00	329.06	895.92	0.00	1411.76	3904.54
Potential sustitutive % for H2	**Pulp, Paper and Printing**			**Wood and Wood Products**			**Construction**			**Textile and Leather Products**		
	2021	**2030**	**2050**	**2021**	**2030**	**2050**	**2021**	**2030**	**2050**	**2021**	**2030**	**2050**
Fossil (oil and derivatives)	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Fossil (coal)	0%	80%	100%	0%	80%	100%	0%	80%	100%	0%	80%	100%
Natural Gas	0%	8%	20%	0%	8%	20%	0%	8%	20%	0%	8%	20%
Electricty	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biofuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fossil (oil and derivatives)	0.00	67.12	182.74	0.00	18.83	51.26	0.00	514.55	1400.96	0.00	22.47	61.19
Fossil (coal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	655.62	1785.04	0.00	63.55	173.01	0.00	444.55	1210.36	0.00	153.71	418.51
Electricty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biofuels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.00	722.74	1967.77	0.00	82.37	224.27	0.00	959.10	2611.32	0.00	176.19	479.70

Table 10. Hydrogen Demand Projections per Sector and Scenario.

4. As a final step before establishing the final demand parameters that will make it onto the openMASTER model, we have compared the full scope of both the resulting generation and demand scenarios generated during this project in order to calibrate the coherence of our progress.

   To do so, we crossed our provided parameters for PEM and alkaline electrolyzes with the identified plausible production scenarios that may arise, thus calculating the annual production (in GWh) that we can expect for our key dates accordingly.

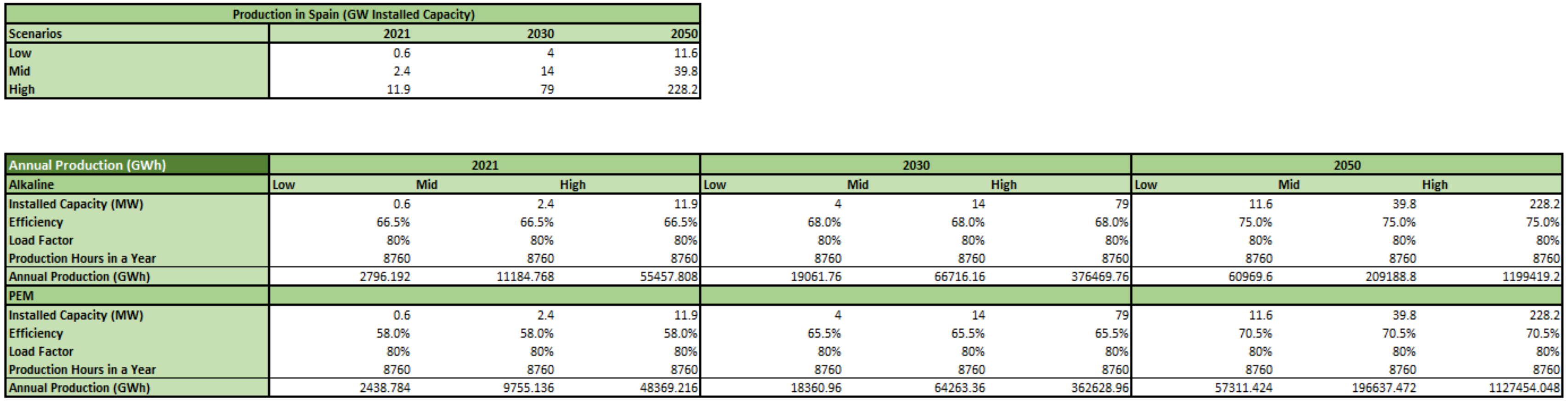
   The following formula was used:

$$\begin{aligned} &Annual\ Production \\ &\qquad = Installed\ Capacity\ (GW) * Efficiency \\ &\qquad * Production\ hours\ in\ year * Load\ Factor \end{aligned}$$

Equation 2. Annual Hydrogen Production via Electrolysis

We assumed a standard load factor of 80%. The efficiency parameters were simplified into an average from the specifications provided for each type of electrolyser.

Such renewable hydrogen generation capacity results are presented in the next page:



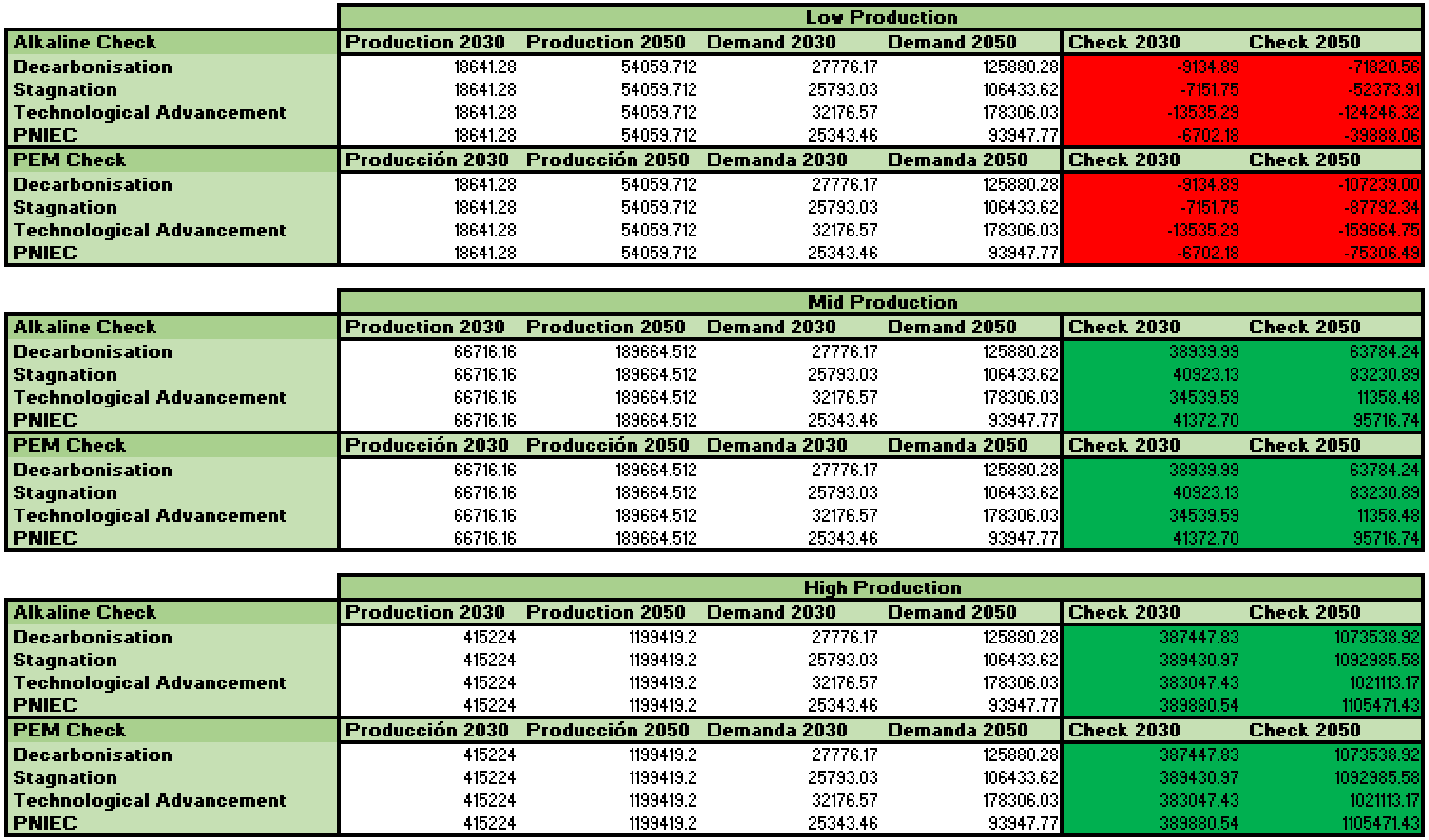
Production in Spain (GW Installed Capacity)			
Scenarios	**2021**	**2030**	**2050**
Low	0.6	4	11.6
Mid	2.4	14	39.8
High	11.9	79	228.2

Annual Production (GWh)	**2021**			**2030**			**2050**		
Alkaline	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Installed Capacity (MW)	0.6	2.4	11.9	4	14	79	11.6	39.8	228.2
Efficiency	66.5%	66.5%	66.5%	68.0%	68.0%	68.0%	75.0%	75.0%	75.0%
Load Factor	80%	80%	80%	80%	80%	80%	80%	80%	80%
Production Hours in a Year	8760	8760	8760	8760	8760	8760	8760	8760	8760
Annual Production (GWh)	2796.192	11184.768	55457.808	19061.76	66716.16	376469.76	60969.6	209188.8	1199419.2
PEM									
Installed Capacity (MW)	0.6	2.4	11.9	4	14	79	11.6	39.8	228.2
Efficiency	58.0%	58.0%	58.0%	65.5%	65.5%	65.5%	70.5%	70.5%	70.5%
Load Factor	80%	80%	80%	80%	80%	80%	80%	80%	80%
Production Hours in a Year	8760	8760	8760	8760	8760	8760	8760	8760	8760
Annual Production (GWh)	2438.784	9755.136	48369.216	18360.96	64263.36	362628.96	57311.424	196637.472	1127454.048

Table 11. Annual Production of Hydrogen via Electrolysis per Generation Scenario

We now have calculated both generation capacity and demand required by the industry in GWh of green hydrogen for all our presented scenarios at both stages of the value chain. Therefore, we are now in a position to understand the resulting balances between the two, allowing us to draw conclusions of feasibility and, therefore, of coherence in our assumptions.

Such check is presented in the following table, where we also accounted for the current PNIEC expectations, to provide a sense on where the Spanish responsible bodies believe themselves to be in the process.



	Low Production					
Alkaline Check	**Production 2030**	**Production 2050**	**Demand 2030**	**Demand 2050**	**Check 2030**	**Check 2050**
Decarbonisation	18641.28	54059.712	27776.17	125880.28	-9134.89	-71820.56
Stagnation	18641.28	54059.712	25793.03	106433.62	-7151.75	-52373.91
Technological Advancement	18641.28	54059.712	32176.57	178306.03	-13535.29	-124246.32
PNIEC	18641.28	54059.712	25343.46	93947.77	-6702.18	-39888.06
PEM Check	**Producción 2030**	**Producción 2050**	**Demanda 2030**	**Demanda 2050**	**Check 2030**	**Check 2050**
Decarbonisation	18641.28	54059.712	27776.17	125880.28	-9134.89	-107239.00
Stagnation	18641.28	54059.712	25793.03	106433.62	-7151.75	-87792.34
Technological Advancement	18641.28	54059.712	32176.57	178306.03	-13535.29	-159664.75
PNIEC	18641.28	54059.712	25343.46	93947.77	-6702.18	-75306.49

	Mid Production					
Alkaline Check	**Production 2030**	**Production 2050**	**Demand 2030**	**Demand 2050**	**Check 2030**	**Check 2050**
Decarbonisation	66716.16	189664.512	27776.17	125880.28	38939.99	63784.24
Stagnation	66716.16	189664.512	25793.03	106433.62	40923.13	83230.89
Technological Advancement	66716.16	189664.512	32176.57	178306.03	34539.59	11358.48
PNIEC	66716.16	189664.512	25343.46	93947.77	41372.70	95716.74
PEM Check	**Producción 2030**	**Producción 2050**	**Demanda 2030**	**Demanda 2050**	**Check 2030**	**Check 2050**
Decarbonisation	66716.16	189664.512	27776.17	125880.28	38939.99	63784.24
Stagnation	66716.16	189664.512	25793.03	106433.62	40923.13	83230.89
Technological Advancement	66716.16	189664.512	32176.57	178306.03	34539.59	11358.48
PNIEC	66716.16	189664.512	25343.46	93947.77	41372.70	95716.74

	High Production					
Alkaline Check	**Production 2030**	**Production 2050**	**Demand 2030**	**Demand 2050**	**Check 2030**	**Check 2050**
Decarbonisation	415224	1199419.2	27776.17	125880.28	387447.83	1073538.92
Stagnation	415224	1199419.2	25793.03	106433.62	389430.97	1092985.58
Technological Advancement	415224	1199419.2	32176.57	178306.03	383047.43	1021113.17
PNIEC	415224	1199419.2	25343.46	93947.77	389880.54	1105471.43
PEM Check	**Producción 2030**	**Producción 2050**	**Demanda 2030**	**Demanda 2050**	**Check 2030**	**Check 2050**
Decarbonisation	415224	1199419.2	27776.17	125880.28	387447.83	1073538.92
Stagnation	415224	1199419.2	25793.03	106433.62	389430.97	1092985.58
Technological Advancement	415224	1199419.2	32176.57	178306.03	383047.43	1021113.17
PNIEC	415224	1199419.2	25343.46	93947.77	389880.54	1105471.43

Table 12. Cross Checking of Generation and Demand Scenarios.

As mentioned in the corresponding section, the low generation scenario corresponds to objective figures set by the national roadmap, which date back to 2020. Since, reviews and updates have been conducted on a European level that have yet to be aligned with the Spanish regulatory entities. The mid scenario is built on the Hydrogen Accelerator proposed by the EU, which is the current regulated track that the commission is taking, and expectations are that the national roadmap will continue to align with the new production expectations, covering the 10% of European green hydrogen production that the EU attributes Spain to have the capacity to deliver. Finally, the high scenario corresponds to a project census for hydrogen projects conducted by AeH2, which presents the relevant figures to build the scenario.

In consequence, we can interpret from this information that the mid production scenario is the current track we are in, with the high scenario consisting of a hopeful future and the low corresponding to outdated productive figures that are expected to be surpassed.

With such interpretation in mind, we can establish that the acceleration proposed by the EU proves to be vital in order for production to be able to grow at a pace that enables it to cover demand´s projected acceleration. Without it, according to our hydrogen consumption projections at industry level, Spain would not have been able to cope with its own requirements. The high scenario evidently covers all possibilities, since it presents what at this point in time could be considered a very optimistic expectation. It is worth remembering that criteria of projected census are for those projects that are projected to occur, but no specifications are given regarding stage of the project (FID, FEED, etc.).

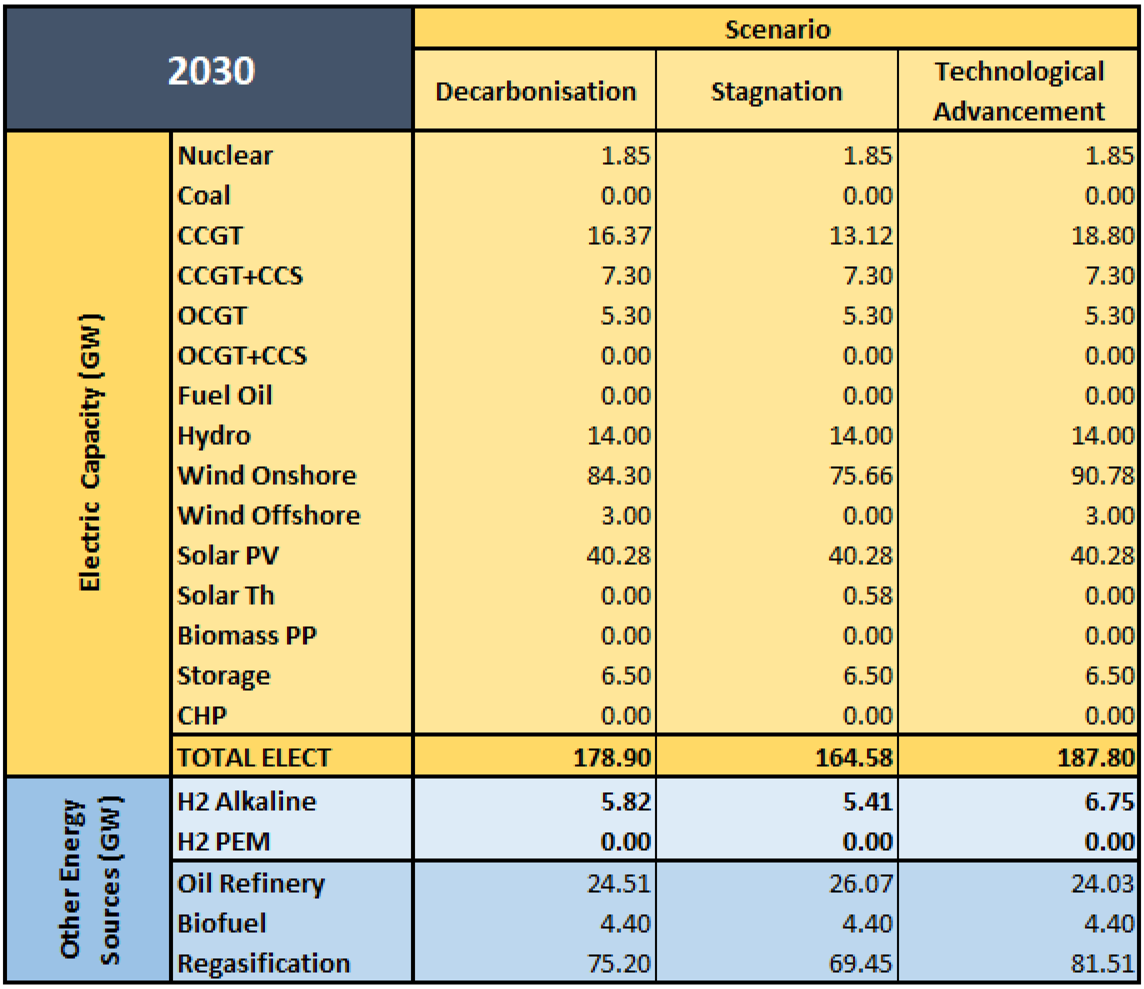
Therefore, we can at this point in the work conclude that the assumptions for generation and demand seem coherent, thus enabling us to move on to the application of the parameters onto openMASTER.

CHAPTER 6. ANALYSIS & RESULTS

After feeding our parameters for generation and demand, the openMASTER performs a series of computational calculations in order to produce the results. These results comprise a vast array of parameters that determine the configuration of the Spanish energetic landscape at the defined points in time. Our aim in this section is to determine whether our assumptions translate through the model to the expected outcomes per the reasonings followed throughout this project, thus proving that the hydrogen value chain has been incorporated with consistency. With such goal in mind, we will only analyse a certain series of result that serve the purpose.

Firstly, we will analyse the evolution of the generation park resulting from the adaptation to the demand for a new energy vector in the market. Given that we only started renewable hydrogen introduction into the model in the year 2021, we must allow for a reasonable time period for the changes to become substantial and coherent. Moreover, given that the earliest projections we have, it makes sense to analyse the situation in 2030 in order to produce comparatives with expected results (from the excel model).

The following table compiles the generation capacity installed by openMASTER for Spain in 2030:



2030		Scenario		
		Decarbonisation	Stagnation	Technological Advancement
Electric Capacity (GW)	Nuclear	1.85	1.85	1.85
	Coal	0.00	0.00	0.00
	CCGT	16.37	13.12	18.80
	CCGT+CCS	7.30	7.30	7.30
	OCGT	5.30	5.30	5.30
	OCGT+CCS	0.00	0.00	0.00
	Fuel Oil	0.00	0.00	0.00
	Hydro	14.00	14.00	14.00
	Wind Onshore	84.30	75.66	90.78
	Wind Offshore	3.00	0.00	3.00
	Solar PV	40.28	40.28	40.28
	Solar Th	0.00	0.58	0.00
	Biomass PP	0.00	0.00	0.00
	Storage	6.50	6.50	6.50
	CHP	0.00	0.00	0.00
	TOTAL ELECT	**178.90**	**164.58**	**187.80**
Other Energy Sources (GW)	**H2 Alkaline**	**5.82**	**5.41**	**6.75**
	H2 PEM	**0.00**	**0.00**	**0.00**
	Oil Refinery	24.51	26.07	24.03
	Biofuel	4.40	4.40	4.40
	Regasification	75.20	69.45	81.51

Table 13. Generation Park Results 2030 openMASTER.

As we can appreciate from the results, the model calculates that, given the set parameters for production capabilities and demand requirements amongst others, the difference between the scenarios will concentrate in variations in production capacity for:

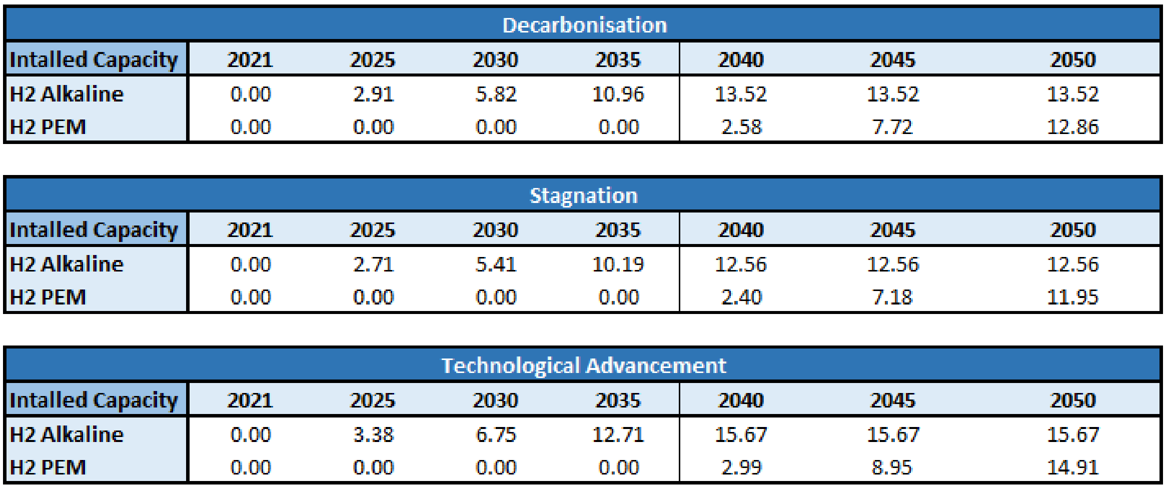
- Power coming from CCGT (Combined Cycle Gas Turbine plant, without carbon capture).
- Power coming from onshore wind production.
- Hydrogen production capacity.
- Oil Refinery.
- Regasification.

Hydrogen production levels vary between scenarios in accordance with variances of GDP assumed for each of them. Thus, the model reproduces expected trends. Moreover, given the GWs of installed capacity installed by openMASTER, the model has installed capacity between the low and the medium production scenario. This is also what was expected, since we knew that the national hydrogen roadmap scenarios from 2020 have become outdated during this time and require levels more resembling to those required by the Hydrogen Accelerator EU program within the REPower EU initiative.

The rest of the production methods behave in a similar manner, varying in proportion to the demand variations that occur depending on the economic health at each scenario. For instance, if GDP growth is not as rapid as expected, that may be an indicator of economic slowdown and even recession. As a result, companies may need to cut costs or reduce production to account for variations in demand, thus impacting the overall energy balance amounts. The only generation technique that behaves oppositely is oil refinery, which suggests that the model believes that during times of economic distress, oil in Spain becomes a safe value and energy demand switches to its consumption. It could also be interpreted that, given high levels of oil import in Spain and the economic phenomenon by which when financial distress strikes oil prices go up, the imported oil rises in price which strengthens demand for nationally refined oil. This, however, escapes the scope of this project, so we will not delve into the details.

As expected too, the generation park of Spain into the future keeps growing in its proportion of renewable energy sources. This occurs no matter the scenario in our model, which could be interpreted as a proving factor for the earlier arisen point that the energy transition is of high priority in the EU, with its development not being subject to economic growth trends. However, this too escapes the scope of this project, so we will not delve into the details either.

Moving on with our analysis of the repercussion of renewable hydrogen, we have now seen that the openMASTER installs significant capacity of hydrogen production technologies. However, it is also interesting to understand of which type and in which proportion of the two provided electrolyser variants for this project. Those results are gathered in the following table:



Decarbonisation							
Intalled Capacity	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
H2 Alkaline	0.00	2.91	5.82	10.96	13.52	13.52	13.52
H2 PEM	0.00	0.00	0.00	0.00	2.58	7.72	12.86

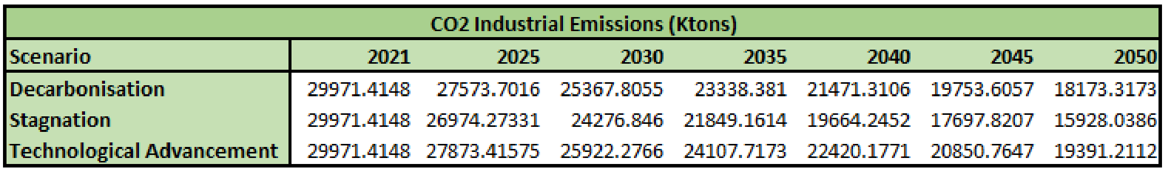
Stagnation							
Intalled Capacity	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
H2 Alkaline	0.00	2.71	5.41	10.19	12.56	12.56	12.56
H2 PEM	0.00	0.00	0.00	0.00	2.40	7.18	11.95

Technological Advancement							
Intalled Capacity	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
H2 Alkaline	0.00	3.38	6.75	12.71	15.67	15.67	15.67
H2 PEM	0.00	0.00	0.00	0.00	2.99	8.95	14.91

Table 14. Installed Electrolyser Capacity per Demand Scenario and Electrolyser Type Results openMASTER.

As we can depict, the model clearly states that alkaline electrolysers are the way forward for the next decade and a half. Clearly, given the data that we provided, the learning curve for PEM does not make the technology worth from a technical standpoint to install until it catches up to alkaline capabilities around the year 2040. From then on, PEM gains ground consistently, with alkaline capacity seemingly becoming stagnated. A takeaway from these could be that, from 2040, available alkaline capacity should be maintained, since it will still be competitive, and the return of maintenance vs new installation might be clear. However, demand growth and consequently the new projects from this point forward will be catered almost exclusively by PEM, since their technology, once it reaches maturity, is superior to that of alkaline electrolysis.

Finally, the last focus of this analysis will be centred on the decarbonisation facet of this project. The emission figures of the configuration resulting from the model´s computations are collected in the following table:



CO2 Industrial Emissions (Ktons)							
Scenario	2021	2025	2030	2035	2040	2045	2050
Decarbonisation	29971.4148	27573.7016	25367.8055	23338.381	21471.3106	19753.6057	18173.3173
Stagnation	29971.4148	26974.27331	24276.846	21849.1614	19664.2452	17697.8207	15928.0386
Technological Advancement	29971.4148	27873.41575	25922.2766	24107.7173	22420.1771	20850.7647	19391.2112

Table 15. CO2 Emissions per Demand Scenario Results openMASTER

As expected, the trend for emissions reduces into the future, consistently with the decarbonization pathways that are being followed in terms of higher renewables and introduction of hydrogen. Thus, they are coherent with estimations of the 2050 strategy (*2050 long-term strategy - European Commission*, s. f.). Moreover, the amounts emitted seem linked to GDP behaviour, since it varies by scenarios. This is easily explained by the contraction and expansion that industrial businesses experience according to economic growth trends, since production levels and cost need to account for demand. It is worth noting that the scenario of PIB that the PNIEC is built upon was conservative, regarding economic growth. So, the reader can calibrate the comparison, it was of the order of the stagnation scenario of this paper. Therefore, even if the decarbonization objectives achieved are in line with those of the PNIEC, it still begs the question of whether the GDP growth expectations are being tamed in order to “control” projected industry growth and demand results, so that the current national policies and actions can seem sufficient.

CHAPTER 7. CONCLUSIONS AND FUTURE DEVELOPMENTS

Throughout this project, we have analyzed the potential role for green H2 in the Spanish energy network, understanding the available technologies encompassing both the generation and demand sides to then model them on openMASTER to gain understanding on if, when and how they could become a working part of the system. In doing so, several key conclusions have been reached.

- Firstly, this project has shown hydrogen is a clear component of the pathway to fulfilling the energy transition and achieving the decarbonization objectives. The results from the computation of openMASTER show that, if made available, the generation park makes room for the installation of electrolysers. Arguably, we have forced this onto the model by setting certain levels of hydrogen demand that can only be fulfilled in this manner, but that does not make it any less true. Through the demand section we studied the different use cases that already exist, thus showing that the demand is there and, perhaps, just needs to be incentivized further. In addition, no matter what scenario we choose, hydrogen production installed was proportional to the behaviour of the GDP, thus showing that scalability of the production and consumption of this energy vector will be done in a relative manner to the behaviour of the economy, not only if the economy is strong enough to "allow it". In conclusion, the incorporation not only proves to be feasible but also beneficial.
- Secondly, the decarbonization results show that the further the deployment of hydrogen and the evolution towards renewables, the less emissions to be found. Moreover, throughout the different sections we have come to appreciate the details and technicalities of the application of the energy vector at hand. In essence, with both this thoughts at hand, we are to conclude that the hydrogen value chain seems

not only to aid in decarbonization per the numbers, but also in many of the sustainable development goals.

- Thirdly, given the analysis performed and the results from the model, the argument for the electrolyser technology for today and for tomorrow seems to be set. Although alkaline technology will continue to dominate the near future, given its higher maturity due to its later stage in its lifecycle, PEM is the answer moving forward as soon as it can catch up in the learning curve (by 2040 given model calculations). Therefore, this should be accounted for in the long-term strategies to be designed and developed moving forward.
- Finally, and the most important conclusion of all, hydrogen is only part of the answer not the only answer. Throughout the literature revision for this project, we have identified that much of the regulation or policies that are announced seem to campaign or cater for one facet exclusively of the energy system only. Hydrogen roadmaps or SAF policies for instance make their energy components to be the solution to many or most issues, but without a clear track, plan, and dimension on how that should integrate within the whole energetic network. However, as proved by the resulting generation park of the openMASTER model, hydrogen plays a role, but it is only a component a wide array required to make the system work. We may also add the role of electrification as an even more important player yet, as evidence not only by the generation results but also by the assumption analysis undertook during the demand section of this paper. Therefore, and to summarise the point being made, its is important that policy makers and decision takers going forward keep the greater picture in their best interest, since only by the efficient cohesion of all the parts can the ambitious challenge that the energy transition presents be achieved.

In addition, the magnitude of the challenge at hand has meant that during the realization of this work assumptions had to be made and a certain scope for the project had to be defined. Thus, the resulting model is not an absolute digital twin of the national electric network. Moreover, key aspects like financing or regulation have been mentioned at points but did not constitute a major constraint for the computational part. Thus, the results are in some way biased. Consequently, it is evident that further improvements to this work could be achieved, of which a few worth highlighting are noted below.

- Firstly, it is worth remembering that this project decided after analysis and justification to only pursue the electrolytic format of green hydrogen generation. Therefore, further pieces of work could complement this project by crossing scenarios with alternative processes for hydrogen production. In addition, this project only contemplates electrolysers working in connection to the grid. Therefore, in further works alternative connection modes could be assessed. In particular, the case for island operation in hydrogen clusters would be of great interest given the actuality of the topic.
- Secondly, the transport and storage problematic were presented an analyzed so that the reader could begin to grasp a sense of the dimension of the issue at hand. For further iterations, including it into the openMASTER model would add another variable of complexity to be reasoned with. In this case, the topic of blending also presents a particular case of high interest, given the value that it would report if truly the natural gas infrastructure could be easily exploited for renewable hydrogen.
- Thirdly, due to time constraints the scope of potential demands had to be adjusted. There is still plenty of work to be tackled in that area given the further potential areas that would benefit from hydrogen adoption.
- Finally, the economic and financial aspect has been present through the project but did not actually constitute a constraint for the model at hand, other than limiting growth rates and consequently energy demands in the form of GDP evolution for the scenarios. The energy transition is going to be expensive, therefore the EU cannot only force it through regulation but must also motivate it through financing for objectives. Consequently, the study of how the requirements for Spain could be financed and assessing the realism behind the scheme could be a vital further step on this work. There is also the aspect of the price of hydrogen in this area, which is affected by the cost of production and determines whether the demand materializes in the end.

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