MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

INFLUENCE OF IMPORT DEPENDENCE OF THE SYNTHETIC FUELS ON THE DESIGN OF THE EUROPEAN ENERGY SYSTEM

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Madrid

Mayo 2023

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

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EL DIRECTOR DEL PROYECTO

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Fdo.: Julian Walter Fecha: 15/ 05/ 2023

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INFLUENCIA DE LA DEPENDENCIA DE LAS IMPORTACIONES DE COMBUSTIBLES SINTÉTICOS EN EL DISEÑO DEL SISTEMA ENERGÉTICO EUROPEO

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Director: Walter, Julian.
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RESUMEN DEL PROYECTO

En el contexto de la descarbonización de Europa, donde los combustibles sintéticos pueden desempeñan un papel crucial, esta investigación se centra en el impacto de importar estos combustibles en el diseño del Sistema Energético Europeo, con especial atención a sus implicaciones económicas. A través de un estudio teórico y un análisis basado en simulaciones, se ha demostrado que incorporar las importaciones de combustibles sintéticos puede generar ahorros económicos para el sistema, siempre y cuando se actúe con moderación. Sin embargo, un análisis de sensibilidad mostró que no existen patrones claros en los efectos de importar combustibles sintéticos, lo que significa que cada escenario debe evaluarse individualmente para determinar su viabilidad económica.

Palabras clave: Hidrógeno, combustibles sintéticos, importaciones, Sistema Energético Europeo, optimización económica.

1. Introducción

En respuesta a la necesidad de abordar el cambio climático y el calentamiento global, y en el contexto del compromiso de Europa de convertirse en neutral en carbono para 2050, se ha observado un crecimiento exponencial en tecnologías renovables como la energía fotovoltaica y eólica en los últimos años. Sin embargo, alcanzar estos objetivos requiere más que simplemente adoptar tecnologías individuales; es necesaria una combinación de múltiples tecnologías. En este escenario, los combustibles sintéticos pueden desempeñar un papel importante, especialmente en sectores difíciles de electrificar. Estos combustibles pueden ser producidos internamente o importados, pero su producción requiere cumplir con varios requisitos como condiciones climáticas favorables, disponibilidad de agua y disponibilidad de terreno. Por lo tanto, este estudio tiene como objetivo investigar el impacto específico de importar combustibles sintéticos en el diseño del nuevo Sistema Energético Europeo.

2. Estructura del proyecto

Con el fin de lograr el objetivo de este trabajo, la tesis se estructura en tres partes distintas, como se ilustra en la Ilustración 1.1. En primer lugar, se lleva a cabo un análisis teórico exhaustivo para explorar las posibles oportunidades de importar combustibles sintéticos en Europa. Los hallazgos obtenidos en este análisis se utilizan como datos de entrada para la siguiente etapa, que implica el desarrollo de una función integradora que permite simular el diseño óptimo de un Sistema Energético Europeo, considerando la importación de dichos combustibles y su viabilidad económica. Por último, se realiza un análisis detallado mediante una serie de simulaciones diversas, para poder evaluar el impacto de la inclusión de las importaciones de combustibles sintéticos en el sistema energético existente.

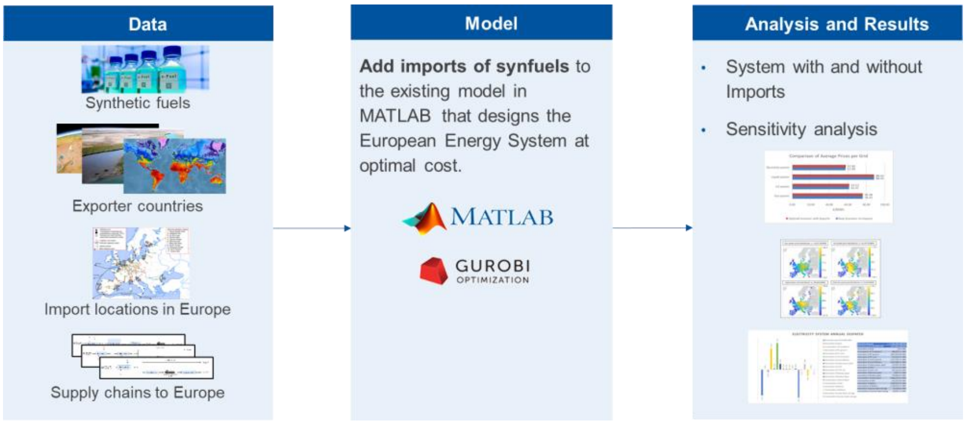

Ilustración 1.1 Estructura de trabajo.

3. Descripción del modelo/sistema/herramienta

Esta sección proporciona una explicación detallada de cada una de las partes mencionadas en la sección anterior.

Análisis Teórico

En este apartado, se llevó a cabo un análisis teórico exhaustivo para estimar tanto las cantidades potenciales de importación como los precios de importación de cada combustible sintético para Europa. Esta investigación permite definir los combustibles sintéticos incluidos en el estudio, así como los países exportadores, las cadenas de suministro para transportar los combustibles a Europa y los posibles puntos de importación dentro de Europa.

Si bien los combustibles sintéticos tienen diversas aplicaciones, el enfoque de este estudio es la inyección de dichas importaciones a tres redes existentes dentro del modelo: la red de hidrógeno, la red de gas y la red de líquidos. En consecuencia, el estudio considera el metano sintético para la red de gas, los combustibles Fischer-Tropsch para la red de líquidos y el hidrógeno verde para la red de hidrógeno. Además, en previsión de una alta demanda futura de hidrógeno, se incluyó el amoníaco y el metanol verdes como portadores de energía para el hidrógeno debido a sus propiedades de transporte superiores para largas distancias. Estos combustibles se importarán desde los países exportadores incluidos en el estudio a través de gasoductos o barcos hacia los puntos de importación definidos en Europa. Como ejemplo de los resultados encontrados, la Ilustración 1.2 presenta una visión general completa de las localidades de importación identificadas en Europa.

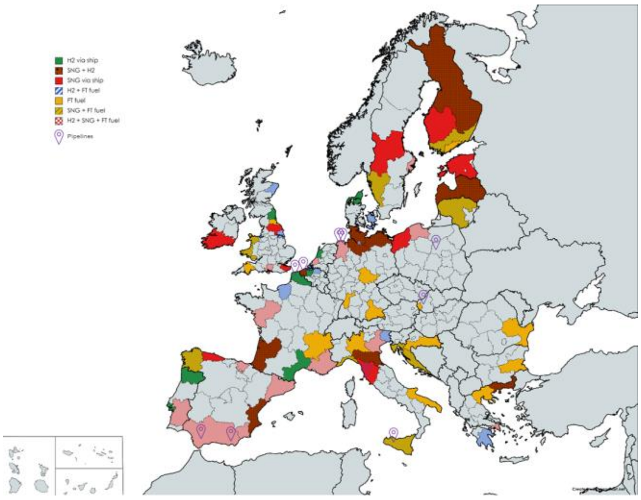

Ilustración 1.2 Puntos de importación localizados en Europa.

Los resultados completos de este análisis se recopilan en forma de tablas, que se pueden encontrar en el APPENDIX I Base Scenario Input Data.

Desarrollo de la Función

El propósito de esta parte de la tesis es crear una función para un modelo existente que permita la incorporación de las importaciones. El modelo, desarrollado en MATLAB y resuelto utilizando Gurobi, es un problema de optimización económica que determina el diseño óptimo del sistema energético europeo. La función a desarrollar es una función genérica aplicable a cualquier combustible y se basa en una optimización lineal (problema LP). Esta función incorpora las restricciones físicas identificadas en el análisis teórico, así como restricciones adicionales para facilitar el análisis posterior.

Análisis Práctico basado en Simulaciones

Para lograr el objetivo de esta tesis, se realizó un análisis práctico a través de la comparación de múltiples simulaciones basadas en un escenario base dado. Este análisis se divide en dos partes. La primera parte implica un análisis comparativo entre el escenario base, que no incluye importaciones de combustibles sintéticos, y otro escenario con la inclusión de estas importaciones. En la segunda parte, se realizó un análisis de sensibilidad para evaluar el comportamiento del sistema bajo diferentes escenarios, que incluyen escasez de combustible, promoción de importaciones y aumento de precios. El propósito de estos análisis es determinar el impacto que incluir importaciones de combustibles sintéticos tiene en el diseño del Sistema Energético Europeo.

4. Resultados

En base a las simulaciones realizadas, se observó que la inclusión de importaciones de combustibles sintéticos resulta en una reducción de los costos totales del Sistema Energético Europeo en comparación con un escenario sin estas importaciones. Sin embargo, se determinó que estas importaciones deberían cubrir menos del 1% de la demanda total. A pesar de ser una contribución limitada, su inclusión genera ahorros significativos de más de 110 M€.

Los resultados también revelaron información interesante sobre los costos de importar combustibles sintéticos en diferentes regiones de Europa. Los países de Europa Central, como Alemania y Polonia, experimentaron costos de importación más altos en comparación con los países de Europa Occidental, como Irlanda o España. Esta variación se debe a factores como la proximidad geográfica a los países exportadores y la infraestructura de transporte.

Durante el análisis de sensibilidad, resultó desafiante identificar patrones generales en el comportamiento del sistema al variar los datos de entrada relacionados con las importaciones. Esto se debe a la compleja interconexión de los diferentes subsistemas dentro del modelo, como se observa en el caso de la electrólisis, donde se requiere electricidad para satisfacer la demanda de hidrógeno. Por lo tanto, el impacto de la inclusión de las importaciones en la reducción de costos varía en cada escenario simulado y cada situación debe ser examinada individualmente.

El único patrón claro observado fue que promocionar la importación de combustibles sintéticos por parte de Europa mostró una correlación exponencial con los costos del sistema. A medida que las importaciones superaban el nivel óptimo, el sistema se volvía exponencialmente más costoso. Esto destaca la importancia de gestionar y optimizar cuidadosamente los niveles de importación para garantizar la rentabilidad y eficiencia en el sistema energético europeo.

La Ilustración 1.3 presenta la solución del modelo para cada escenario simulado, ilustrando el costo óptimo del sistema en cada caso. Proporciona una representación visual completa de los resultados discutidos, mostrando tanto el análisis comparativo entre un escenario con y sin importaciones como los resultados del análisis de sensibilidad para cada escenario simulado.

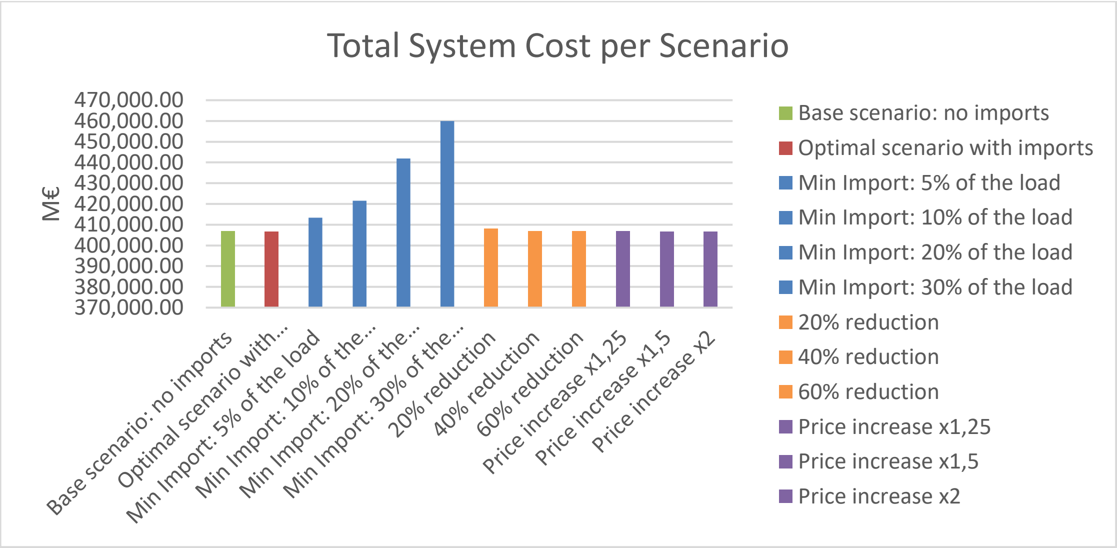

Ilustración 1.3 Coste total del sistema para cada escenario simulado.

5. Conclusiones

El objetivo de este trabajo era examinar el impacto que importar combustibles sintéticos suponía en el diseño del Sistema Energético Europeo, con un enfoque en los aspectos económicos. A través de un análisis teórico para evaluar las posibilidades y costos de importar combustibles sintéticos en Europa, la integración de estas importaciones en el modelo existente y la realización de simulaciones en varios escenarios, se ha concluido que la importación de combustibles sintéticos puede generar ahorros económicos para el Sistema Energético Europeo, pero realizándose en cantidades moderadas. También se ha observado que, si bien las importaciones de combustibles sintéticos generalmente ofrecen beneficios económicos, esto no siempre es así, ya que la disponibilidad y el precio de los combustibles importados desempeñan un papel significativo. Basándose en estos hallazgos, se recomienda realizar un análisis de sensibilidad más exhaustivo para identificar patrones adicionales.

6. Referencias

[1] International Energy Agency- IEA: The Future of Hydrogen. Seizing today’s opportunities, 2019.

[2] Karlsruhe Institute of Technology (KIT): Power-to-Liquid (E-Fuels).

[3] Pfennig, Böttgera, Häcknera, Geigera, Zink, Bisevic, Jansen: Global GIS-based potential analysis and cost assessment of Power-to-X fuels in 2050, 2022.

[4] European Commission: A Hydrogen Strategy for a climate neutral Europe, 2020

INFLUENCE OF IMPORT DEPENDENCE OF THE SYNTHETIC FUELS ON THE DESIGN OF THE EUROPEAN ENERGY SYSTEM

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ABSTRACT

In the context of synthetic fuels potentially playing a crucial role in decarbonising Europe, this thesis investigates the impact of importing such fuels on the design of the European Energy System, with a specific emphasis on its cost implications. Through a theoretical study to assess the import possibilities of synthetic fuels in Europe, followed by an analysis based on simulations, it has been found that incorporating synthetic fuel imports can result in cost savings for the European Energy System, but moderation is crucial. However, a sensitivity analysis revealed that the inclusion of synthetic fuel imports does not exhibit discernible patterns and may not consistently result in cost reductions across all scenarios. Therefore, it is essential to individually evaluate the economic feasibility of importing such fuels for each situation.

Keywords: Hydrogen, Synthetic fuel, Imports, European Energy System, cost optimization.

1. Introduction

In response to the need to address climate change and global warming, and within the context of Europe's commitment to becoming climate neutral by 2050, there has been observed exponential growth in renewable technologies such as photovoltaic and wind power in recent years. However, achieving these goals requires more than just the adoption of individual technologies; a combination of multiple technologies is necessary. In this context, synthetic fuels can play a crucial role, especially in sectors that are challenging to electrify. These fuels can be produced domestically or imported, but their production requires meeting several requirements such as favourable weather conditions, water availability, and land availability. Therefore, this study aims to investigate the specific impact of importing synthetic fuels on the design of the new European Energy System.

2. Scope of the Thesis

To accomplish the objective of this work, the thesis is structured into three distinct parts, as illustrated in Figure 1.1. Firstly, a theoretical analysis was undertaken to explore the potential opportunities for importing synthetic fuels in Europe. The findings from this analysis serve as input data for the subsequent stage, which involves the development of a function that integrates the importation of synthetic fuels into an existing model, thereby simulating the design of an economically optimal European Energy System. Finally, with the availability of the input data and the integration of the function into the system, the third part encompasses an analysis conducted through a series of diverse simulations, aimed at assessing the impact of incorporating synthetic fuel imports on the pre-existing energy system.

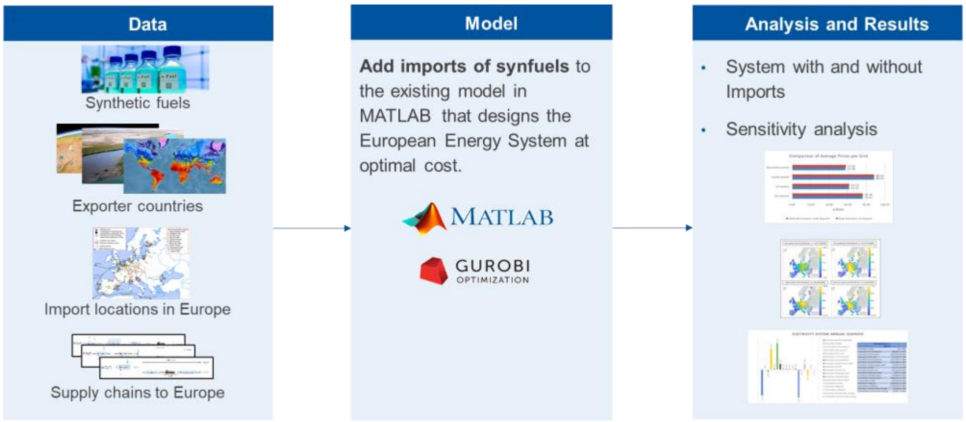

Figure 1.1 Overview of the thesis scope.

3. Description of the Model

This section provides a comprehensive explanation of each of the parts mentioned in the previous section.

Theoretical Analysis

In this section, an in-depth theoretical analysis was conducted to estimate both the potential import quantities and import prices of each synfuel for Europe. Extensive research was undertaken to define the synthetic fuels included in the study, as well as the exporting countries, supply chains for transporting the fuels to Europe, and potential import locations within Europe. This analysis enables the estimation of potential import quantities and import prices of each synfuel for Europe.

As the results of this analysis serve as the input data for the simulated scenario, although synthetic fuels have various applications, the focus of this study is on injecting imports into three existing networks within the model: the hydrogen network, gas network, and liquid network. Consequently, the study considers synthetic methane for the gas network, generic FT fuels for the liquid network, and green hydrogen for the hydrogen network. Additionally, in anticipation of a high future demand for hydrogen, green ammonia and green methanol have been included as energy carriers for hydrogen due to their superior transport properties over long distances. These fuels will be imported from the exporting countries included in the study via pipeline or ship to the defined import points in Europe. As an example of the results found, Figure 1.2 presents a comprehensive overview of the import locations identified in Europe.

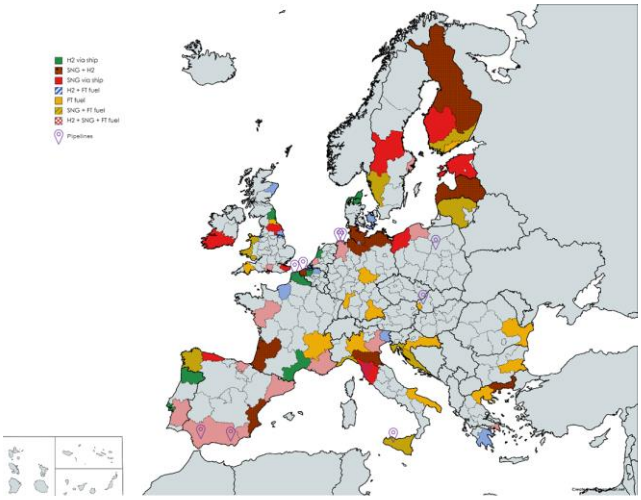

Figure 1.2 Import locations identified in Europe.

The complete results of this analysis are compiled in the form of tables, which can be found in APPENDIX I Base Scenario Input Data.

Development of the Function

The purpose of this section is to create a function for an existing model that enables the incorporation of imports. The model, developed in MATLAB and solved using Gurobi, is an economic optimization problem that determines the optimal design of the European energy system. The function to be developed, while applicable to any fuel, is based on linear optimization (LP problem) and incorporates the physical constraints identified in the theoretical analysis, as well as additional constraints for ease of subsequent analysis.

Practical Analysis based on simulations

To achieve the objective of this thesis, a practical analysis was conducted through the comparison of multiple simulations based on a given base scenario. This analysis is divided into two parts. The first part involves a comparative analysis between the base scenario, which does not include synthetic fuel imports, and another scenario with the inclusion of these imports. In the second part, a sensitivity analysis was performed to assess the system's behavior under different scenarios, including fuel shortage, promotion of imports, and price increase. The purpose of these analyses is to determine the impact of including synthetic fuel imports on the system design and to examine the system's response and performance under various conditions.

4. Results

Based on the conducted simulations, in the comparative analysis between a scenario with and without synthetic fuel imports, it was observed that including these imports results in a reduction in the total costs of the European Energy System. However, the optimal solution indicates that less than 1% of the demand should be covered by these imports. Despite their small contribution to the overall technology mix, their inclusion leads to savings of over M€ 110.

Additionally, the results revealed interesting insights regarding the cost of importing synfuels in different regions of Europe. Central European countries, such as Germany and Poland, experienced higher import costs compared to western European countries like Ireland or Spain. This variation can be attributed to factors such as geographical proximity to exporting countries, transportation infrastructure, and availability of alternative energy sources.

During the sensitivity analysis, it was challenging to identify general patterns regarding the system's behavior when varying the input data related to imports. This complexity arises from the interconnectedness of different subsystems within the model, as seen in the case of electrolysis, where electricity is required to meet hydrogen demand. Therefore, the impact of import inclusion on cost reduction varies in each simulated scenario, and each situation must be individually examined.

The only clear pattern observed was that the promotion of imports by Europe exhibited an exponential correlation with system costs. The more imports exceeded the optimal level, the exponentially more expensive the system became. This emphasizes the importance of carefully managing and optimizing import levels to ensure cost-effectiveness and efficiency in the European energy system.

Figure 3 presents the solution for each simulated scenario, illustrating the optimal cost of the system in each case. It provides a comprehensive visual representation of the discussed results, encompassing both the comparative analysis between a scenario with and without imports and the outcomes of the sensitivity analysis for each simulated scenario.

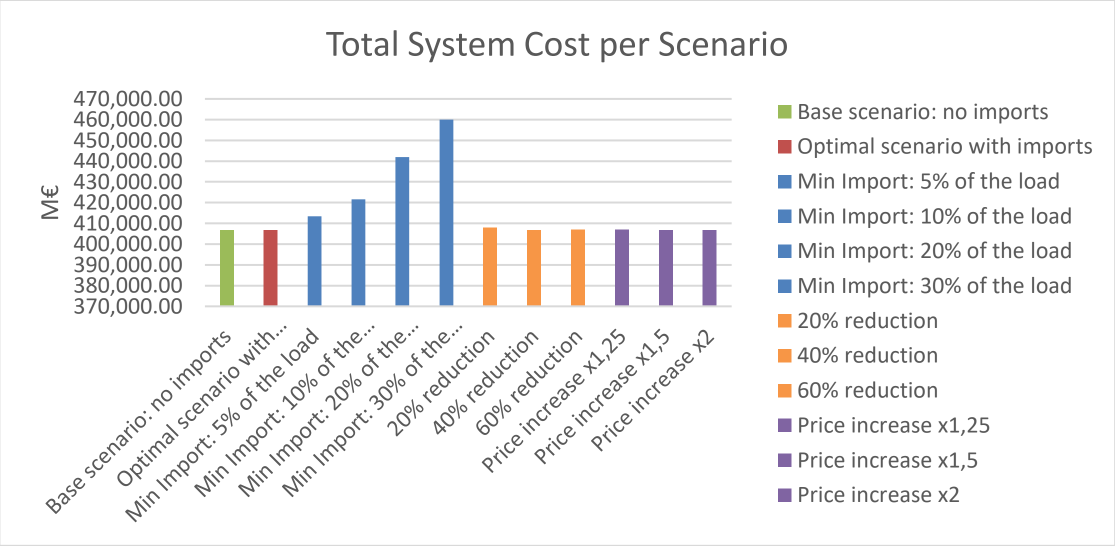

Figure 1.3 Total system cost of each scenario.

5. Conclusions

The aim of this thesis was to examine the impact of importing synthetic fuels on the design of the European Energy System, with a focus on economic aspects. Through a theoretical analysis to assess the potentials and costs of importing synthetic fuels in Europe, integrating these imports into the existing model, and conducting simulations of various scenarios, it has been concluded that importing synthetic fuels can result in cost savings for the European Energy System, but in moderate quantities. It has also been observed that while synthetic fuel imports generally provide economic benefits, it is not always the case, as the availability and pricing of fuels for importation play a significant role. Based on these findings, further in-depth exploration of the sensitivity analysis is recommended to identify more patterns.

6. References

[1] International Energy Agency- IEA: The Future of Hydrogen. Seizing today’s opportunities, 2019.

[2] Karlsruhe Institute of Technology (KIT): Power-to-Liquid (E-Fuels).

[3] Pfennig, Böttgera, Häcknera, Geigera, Zink, Bisevic, Jansen: Global GIS-based potential analysis and cost assessment of Power-to-X fuels in 2050, 2022.

[4] European Commission: A Hydrogen Strategy for a climate neutral Europe, 2020

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List of Abbreviations

EU	European Union
PV	Photovoltaics
PtX	Power-to-X
PtG	Power-to-Gas
e-fuels	Electricity-based fuels
SNG	Synthetic natural gas
LNG	Liquefied Natural Gas
CO2	Carbon dioxide
DAC	Direct air capture
CH4	Methane
H2	Hydrogen
H2O	Water
CH3OH	Methanol
FT	Fischer-Tropsch
O&M	Operation and Maintenance
CAPEX	Capital expenditures
OPEX	Operational expenditures
CCGT	Combined cycle gas turbine

kW	Kilowatt
MW	Megawatt
GWh	Gigawatt per hour
TH	Thermal
Km	Kilometre
LP	Linear Programming
CPI	Consumer Price Index
MD	Model definition
SMR	Steam methane reformer
SDGs	Sustainable development goals

Chapter 1. INTRODUCTION

1.1 MOTIVATION

In response to the imperative need to address global warming and climate change, the European Commission has established the goal of transforming Europe into a carbon-neutral continent by 2050, in accordance with the Paris Agreement of 2015 [Eur19]. To achieve this objective, a transition to a sustainable energy system is necessary. Europe has made significant strides in increasing the proportion of renewable energy used in electricity generation, but other energy-intensive sectors such as transportation, heating, and industry continue to rely heavily on fossil fuels. Decarbonising these industries will require new technologies, regulations, and substantial investments in renewable energy infrastructure.

It is widely recognised that attaining climate neutrality by 2050 will necessitate the adoption of an extensive array of renewable energy technologies. Power plants based on wind and photovoltaics (PV) are essential components of this transition, but their deployment alone will not be enough to accomplish net-zero emissions. To truly decarbonise the energy system, these technologies must be integrated with other solutions that can provide renewable energy in difficult-to-electrify sectors.

Energy carriers, such as synthetic fuels and hydrogen derived from renewable sources, have been recognised as viable alternatives to fossil fuels in situations where the direct use of renewable electricity is not feasible. Nevertheless, there are significant challenges impeding their widespread adoption, including technical, economic, and regulatory barriers. Furthermore, the production of these fuels is subject to specific climatic and spatial requirements, making it necessary to meet the demand for these energy sources through a combination of large-scale domestic production and imports from non-European regions [Par21]. This is directly related to Europe's need to design an energy system that not only achieves climate neutrality but also provides energy independence. In light of recent events, the significance of energy independence in Europe has become even more imperative and crucial. The Russian attack on Ukraine and consequent disruption of gas supplies to Europe have brought to light the vulnerability of the European Energy System and the need to reduce reliance on external energy sources [Eur23a].

Despite the challenges, there is growing recognition of the importance of investing in the production and import of synthetic fuels and hydrogen derived from renewable sources as part of a comprehensive plan to achieve climate neutrality by 2050. This successful integration of synthetic fuels into the European energy system demands careful planning and optimisation to reduce the use of non-renewable resources, ensure cost-effectiveness, and achieve maximum energy independence.

In this context, the purpose of this study is to examine the effect of import reliance on synthetic fuels on the design of the European energy system.

1.2 GOALS AND STRUCTURE OF THE WORK

The aim of this study is to investigate the influence of importing synthetic fuels produced from renewable electricity on the design of the optimal European Energy System for a 2050 climate neutral scenario. Specifically, the focus is on how importing synthetic fuels affects to the design of the European Energy System. To achieve this goal, a comprehensive analysis of the potential synthetic fuels that can be imported into Europe, the potential exporter countries, and the possible supply chains and import locations in Europe has been conducted.

From the information gathered from the analysis, import capacities and costs are assessed, which will serve as input data for an existing optimisation model in MATLAB that simulates the design of the European Energy System. The optimisation model will be modified to include the import part, allowing the investigation of the impact of synthetic fuel imports on the European energy system.

The structure of this study is organised as follows:

Chapter 1 introduces the background of the study, the research problem, and the objectives.

Chapter 2 presents an overview of selected synthetic fuels, followed by a theoretical analysis to select the export countries, supply chains, and import locations in Europe included in this work.

Chapter 3 details the methodology used in the study, including a comprehensive explanation of the optimisation model employed in the investigation and the utilised input base scenario, which is the result of the theoretical analysis conducted in Chapter 2.

Chapter 4 presents and discusses the results of the study conducted to assess the influence of synthetic fuel imports on the design of the European Energy System.

Chapter 5 concludes the work by summarising the main findings, discussing the limitations of the study, and providing suggestions for future research.

Chapter 2. THEORETICAL BASIS

This chapter seeks to provide a comprehensive overview of the renewable energy carriers included in this study as potential replacements for fossil fuels in Europe. The theoretical basis for selecting exporting countries and associated supply chains will also be identified, along with the criteria for identifying import locations in Europe.

2.1 ENERGY CARRIERS

In this section, the energy carriers considered in this study to replace the current demand for fossil fuels are presented. These energy carriers will be Power-to-X-based (PtX), as they are all produced from renewable sources. This work plans to import and inject these electricity-based fuels (e-fuels) into three grids in the model: the hydrogen grid, the gas grid, and the liquids grid.

2.1.1 GREEN HYDROGEN

Hydrogen (H_2) is the most abundant chemical element in nature. It is lightweight and storable, but it is never found alone in nature; it is always accompanied by other chemical elements. The way pure hydrogen is separated is what makes it a green energy carrier or not. Nowadays, there are mainly three types of hydrogen: grey, blue, and green. As the colours indicate, grey hydrogen is the least sustainable since it is obtained from fossil fuels blue hydrogen is obtained from natural gas by capturing carbon; and green hydrogen, which is the only one considered in this work, is obtained from renewable energy, thus releasing zero emissions to the atmosphere [Acc22].

Green hydrogen is produced from renewable sources of electricity through a process called electrolysis, where water is split into hydrogen and oxygen using an electric current [Eur19]. With the existing technology, by introducing 10 to 12 litres of water and 57 kWh of renewable electricity, it can be obtained approximately 1 kg of hydrogen, which is equivalent to about 33.3 kWh_{th} [Ene21]. For this reason, this process is ideal in case of electricity generation surplus. Figure 2.1 illustrates the electrolysis process.

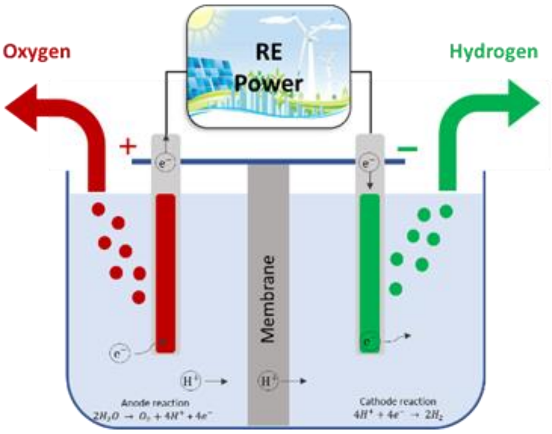


Figure 2.1 Electrolysis process to obtain green hydrogen.

In terms of applications, green hydrogen shows numerous potential applications across various sectors, including power generation, transport, industry, heating and cooling, and energy storage [Int19a]. To meet these demands, the import of liquid and gaseous hydrogen will be studied, with the aim of feeding it all into the hydrogen grid included in the model.

2.1.2 SYNTHETIC METHANE

Synthetic methane, or synthetic natural gas (SNG), is a type of renewable natural gas that can be produced through various processes such as gasification, anaerobic digestion, and power-to-gas technology. In this work, only the production of synthetic methane from green hydrogen will be considered.

The production of this Power-to-Gas (PtG) fuel typically involves a two-step process. The first step is the production of green hydrogen through the process of electrolysis using renewable electricity [Eur20]. Then, the hydrogen produced in this step is combined with carbon dioxide (CO_2) in a process called methanation. This CO_2 can come from a variety of sources, such as direct air capture (DAC) or industrial processes. During methanation, the hydrogen reacts with the CO_2 under high pressure and temperature in the presence of a catalyst, producing methane (CH_4) and water vapour (H_2O).

The resulting green synthetic methane is chemically identical to natural gas and can be used as a fuel for heating, electricity generation, and transportation. To achieve climate neutrality, any CO_2 emissions generated during the production or use of green synthetic methane are offset through various means, such as carbon capture [Kia21]. Figure 2.2 shows the PtG process to obtain green synthetic methane, which is called the Sabatier process in the name of the inventor.

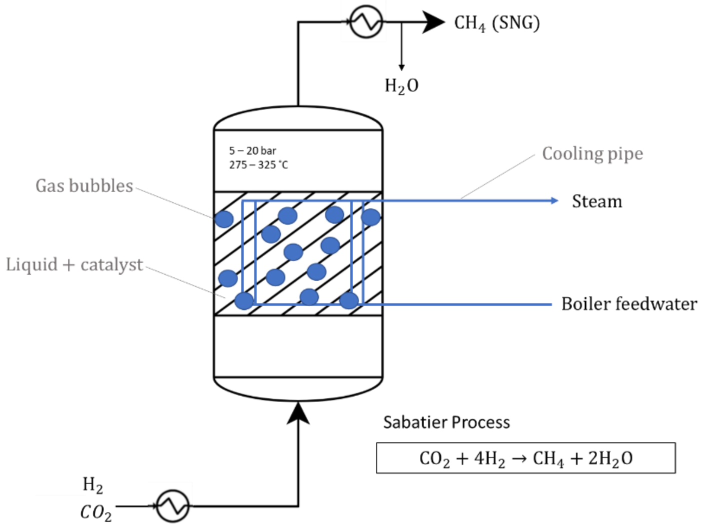


Figure 2.2 Methanation through the Sabatier Process.

Regarding its applications, synthetic methane is intended to replace the current demand for fossil-based natural gas in Europe, and therefore, in this work, it will be injected into the gas grid included in the model. It should be noted that while it could have been technically used as a hydrogen carrier, this will not be the case in this scenario.

2.1.3 GREEN METHANOL

Methanol (CH_3OH) is a widely used chemical compound due to its various industrial applications. However, its production from natural gas results in greenhouse gas emissions. Based on its sustainability, methanol production can be classified as grey, blue, or green, where grey methanol is not renewable, blue methanol captures and stores carbon generated during production, and green methanol is produced only from renewable sources. This work only considered green methanol, and depending on the production process, two types of green methanol can be obtained [Ibe23].

- Biomethanol: produced from the gasification of sustainable biomass sources such as livestock, agricultural and forestry residues, and municipal waste.
- e-methanol: produced from green hydrogen and captured carbon dioxide.

Despite the fact that both options present various potential applications in different industries, including transportation, chemical manufacturing, energy storage, and marine fuel, this study does not directly consider a demand for green methanol. Instead, the study focuses on using green methanol in liquid form as a carrier for transporting hydrogen over long distances to Europe, which could be a more cost-effective and practical approach than directly transporting hydrogen gas. For this reason, only e-methanol is included in this study, and Figure 2.3 shows the process to produce green methanol from hydrogen [Bos20].

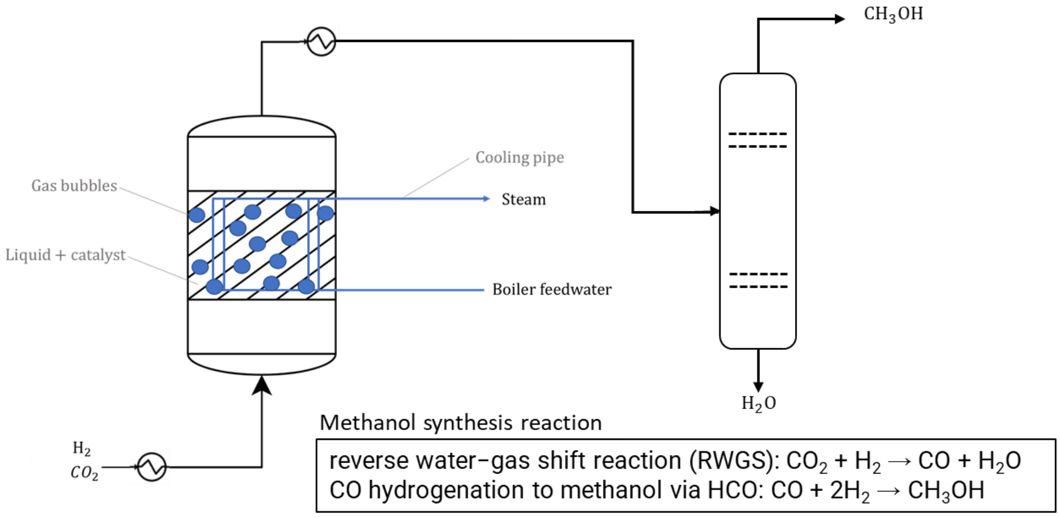


Figure 2.3 Methanol synthesis from green hydrogen [Liu10].

2.1.4 GREEN AMMONIA

Ammonia is a fuel that can be stored and transported easily, and it is commonly used for agricultural fertilisers. However, the conventional Haber-Bosch process used to produce ammonia results in a significant amount of carbon dioxide emissions.

Fortunately, green ammonia can be produced sustainably through a process that uses renewable hydrogen and nitrogen from water electrolysis and air separation, respectively. This process runs the Haber-Bosch process with sustainable electricity instead of producing hydrogen via methane steam reforming. By using this method, the electrification of the Haber-Bosch process is achieved, resulting in a completely renewable and carbon-free approach. This is in contrast to the traditional method, which generates 1.4% of global CO_2 emissions and consumes 1% of global total energy production [Cap19]. An illustration of the production of green ammonia through the Haber-Bosch process is shown in Figure 2.4.

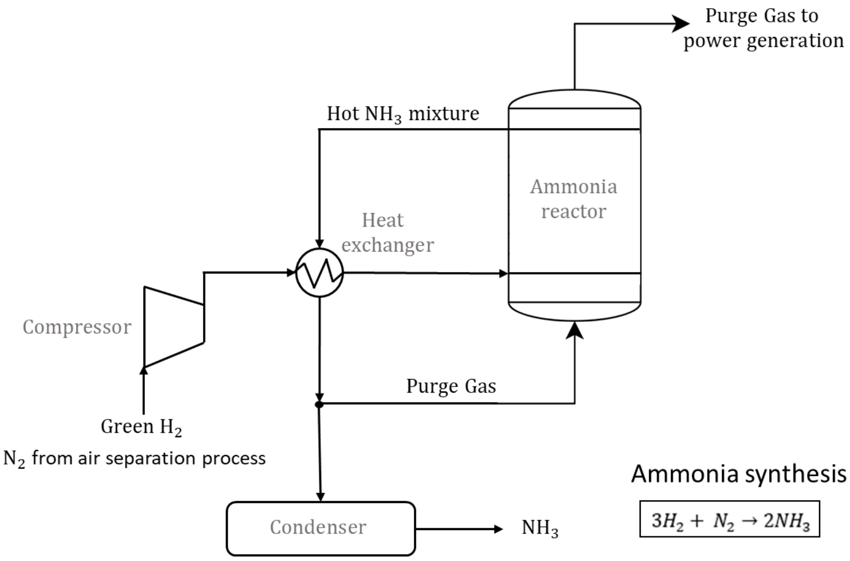


Figure 2.4 Haber-Bosch process to obtain green ammonia [Dar22].

Even though green ammonia has great potential applications such as an energy storage solution, a substitute for maritime fuel oil, or a replacement for current ammonia demand, in this study, as there is no specific demand for green ammonia contemplated, it will be used as a hydrogen carrier because it could present a more cost-effective option than directly importing hydrogen.

2.1.5 FISCHER-TROPSCH FUELS

The Fischer-Tropsch process, a hydrocarbon synthesis process that turns carbon-based materials like natural gas, coal, or biomass into liquid hydrocarbons, produces Fischer-Tropsch (FT) fuels, which are synthetic fuels. Later, the obtained hydrocarbon mixture can be separated and purified to obtain different fuels, such as green diesel and synthetic gasoline. For the production of e-fuels via the FT process, the synthesis gas is produced from green hydrogen and CO2 and introduced in the FT reactor to obtain long-chain hydrocarbon molecules that can be later upgrated [Kar20]. Figure 2.5 illustrates how sustainable FT-fuels can be obtained.

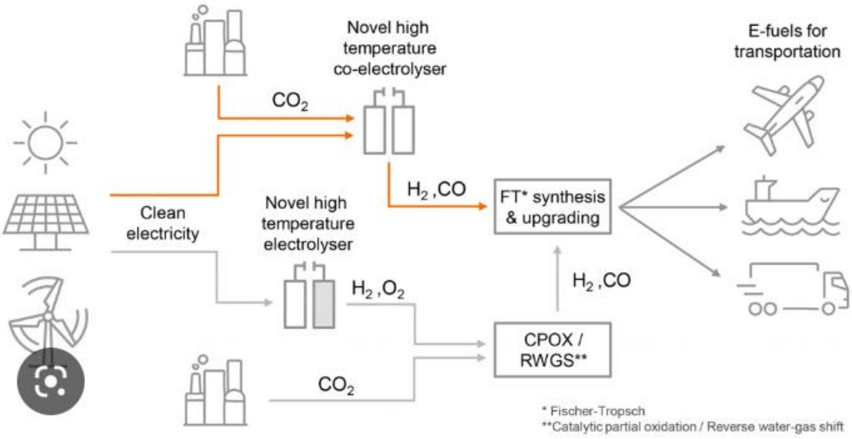


Figure 2.5 Fischer-Tropsch synthesis for the production of e-fuels [e-F22].

FT-fuels, unlike other synthetic fuels such as methane or methanol, are highly compatible with conventional transportation fuels. For this reason, these fuels aims to replace conventional transportation fuels. However, due to the ongoing electrification of the automotive industry, they may be more suitable for use in hard-to-electrify transports, particularly long-distance vehicles such as aeroplanes. Consequently, this work includes a specific demand for these fuels, and all FT-fuel imports will be injected into the existing liquids grid.

2.2 CRITERIA TO IDENTIFY POTENTIAL EXPORTING COUNTRIES

After the overview of the production processes of the PtX fuels presented in the previous section, it is evident that their production is energy-intensive and can lead to high losses, resulting in economic challenges in regions with less favourable renewable energy resources and corresponding land availability. This situation presents a new market opportunity, where countries with the most favourable conditions can export their PtX fuels to regions where production costs are higher than import costs, leading to an increase in global PtX fuel trade. It should be noted that currently there is no PtX fuel market, and it is still early to determine its commercial potential.

To be identified as a potential exporter of PtX fuels, a set of requirements must be met. However, meeting all of these requirements is often challenging and can limit the number of locations that are suitable for the production and export of PtX fuels.

The following requirements are considered essential for identifying favourable countries for exporting PtX fuels [Pfe22] [Gui22]:

- **Prevailing weather conditions**: countries with a high level of solar irradiation and wind are more favourable for PtX fuel production as they provide abundant renewable energy sources at a lower cost. Meeting this requirement has a major impact on the final production cost of PtX fuels in different regions.
- **Water availability**: countries with ample water resources are more suitable for PtX fuel production as they require significant quantities of water in the production process, particularly in the electrolysis of water to produce green hydrogen.
- **Availability of land**: countries with a large amount of available land can support the deployment of large-scale renewable energy systems necessary for PtX fuel production. When assessing the availability of land, it is important to differentiate between nature conservation areas and other land uses. Due to limited land availability and high population density, Europe may need to import PtX fuels from other regions.

- **Political and economic stability**: countries with stable political and economic conditions are more likely to have favourable market conditions for exporting PtX fuels.
- **Infrastructure and logistics**: countries with well-established infrastructure and logistics networks, such as ports and pipelines, are more favourable for exporting PtX fuels.
- **Regulatory framework**: countries with a supportive regulatory framework for renewable energy and PtX fuel production are more favourable for exporting PtX fuels.

In conclusion, the identification of potential exporting countries for PtX fuels requires careful consideration of both technical and socio-economic factors. While the criteria presented here are important, assessing their fulfilment can be challenging given the young state of the technology and the competition for land from other, more established renewable energy sources. Nonetheless, continued analysis and investment in PtX technology will be critical to ensuring the development of a sustainable and resilient energy system for the future [Pfe22].

2.3 TRANSPORT OPTIONS AND SUPPLY CHAIN TO EUROPE

There are multiple means of transportation available for hydrogen and synthetic fuels, but the two most promising options for long-distance transport (over 1,500 km) are pipelines and shipping. Pipeline transportation is economically viable at high volumes due to economies of scale in pipeline construction and high fixed costs, and it is also a good option for shorter distances. However, shipping is the preferred choice for long-distance and deep-sea transport, especially when retrofitting existing natural gas pipelines is not feasible. According to the International Energy Agency, pipelines become less cost-effective than shipping at around 3,500 km [ALG22].

In this work, the alternatives illustrated in Figure 2.6 will be considered to transport the renewable electricity-based fuels included in this study.

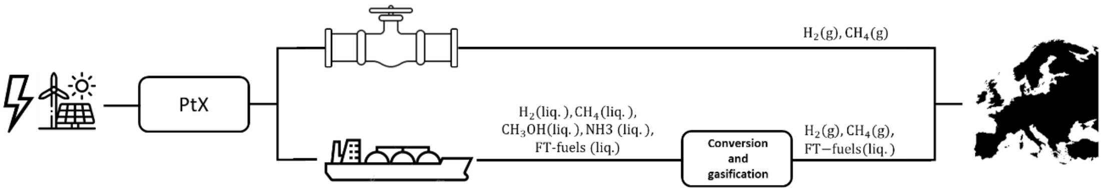


Figure 2.6 Overview of the supply chains considered in this work to import to Europe.

To transport FT-fuels, only their import via ship was considered in this study. For the gas system, gaseous synthetic methane via pipeline and liquefied synthetic methane via ship were both taken into consideration. Finally, to meet the demand for H_2, gaseous H_2 via pipeline, liquefied H_2 via ship, or H_2 derivatives such as green ammonia or methanol via ship were analysed.

The transportation of gaseous H_2 via ship was not consider a viable option due to its low volumetric energy density, which limits the amount that can be transported in a single vessel and increases the cost per unit of energy (the same applies to the gaseous transport of SNG via ship). Liquid H_2, on the other hand, has a higher energy density, but the process of liquefaction consumes a significant amount of its energy content, and the loading and unloading of liquid H_2 are challenging, which can induce H_2 losses. H_2 carriers, such as green ammonia or methanol, have higher energy density, lower volatility, and easier storage requirements, making them easier to transport [Pfe22] [Gui22].

2.4 CRITERIA TO IDENTIFY POTENTIAL IMPORT LOCATIONS IN EUROPE

When contemplating the importation sites for synthetic fuels in Europe, it is necessary to consider multiple criteria. Initially, pre-existing ports that possess the requisite infrastructure for the management and preservation of synthetic fuels favourable sites for imports. Moreover, the presence of pre-existing import pipelines in certain locations can confer benefits by reducing the expenses and duration of constructing new infrastructure. On the other hand, the criterion of proximity to consumption holds significant importance as it has the potential to lower transportation expenses and enhance the efficacy of the supply chain, but it is also important to consider at the same time locations that have adequate space for the storage and handling of synthetic fuels, as this can offer versatility in the supply chain and mitigate the likelihood of supply interruptions [Ham23].

In general, it is advisable to strike a balance between various criteria when choosing import locations for synthetic fuels in Europe in order to establish a dependable, economically viable, and environmentally sustainable supply chain.

For this reason, during the selection process of import locations for the case study, special emphasis will be given to pre-existing ports and pipelines in Europe, as the utilisation of existing infrastructure can be translated into minimising additional costs.

Chapter 3. MODELLING

This chapter aims to enhance the existing optimisation model by introducing synthetic fuel imports. The current model has proven its effectiveness in minimising investment and operation costs, but it lacks a sophisticated consideration of imports from areas outside its boundaries. Integrating synthetic fuel imports will further improve the validity of the model. To study the influence of such imports on the design of the European Energy System, they will be included in the model through the design of a new function. This function will also allow for the implementation of certain restrictions on the imports to study their behaviour in the system. With this new addition, the model will be able to better account for the role that synthetic fuel imports can play in achieving a sustainable and cost-efficient energy system in Europe.

3.1 CREATION OF THE BASE SCENARIO

This section aims to provide essential input data regarding imports for the existing optimisation model. The focus will be on selecting exporting countries, supply chains for each synthetic fuel, and import locations in Europe based on the information gathered in Chapter Chapter 2. The creation of this scenario will help to determine the necessary data regarding import capacities, import costs, and installation expenses required at various ports across Europe.

3.1.1 SELECTION OF POTENTIAL EXPORTERS FOR EUROPE

Identifying potential export countries for PtX fuels requires a comprehensive analysis that considers both technical and socio-economic factors. To estimate the import costs to Europe in this work, based on the results obtained by Pfennig et al. [Pfe22] and the Global PtX Atlas [Fra22] developed by the Fraunhofer Institute, the six most promising production countries have been identified.

Fraunhofer conducted an extensive evaluation of potential areas for PtX fuel production, where they considered only onshore wind power, ground-mounted photovoltaic energy, or a combination of both as electricity sources. This evaluation includes the following analyses:

- Preliminary socio-economic analyses
- GIS-based area identification for PtX applications
- Derivation of PtX generation volumes
- Volatile characteristics of PtX generation
- Cost ranges of PtX fuels
- Import costs of PtX fuels into the EU

The following bullet points highlight the key results from the analysis that assess potential capacity, socio-economic aspects, and production costs to each non-European country.

- Global analysis identified over 32 million km² of potential areas for onshore wind and PV systems, of which 2.6 million km² remain for PtX technologies, distributed across 97 countries, with 42 having potentials bigger than 2,500 km².
- Inland waters with good conditions for wind energy and/or PV and without water stress are attractive sites for PtX, and the United States, Argentina, and Australia have the most significant potential. In Africa, PtX potentials are mostly found near coastal waters.
- 10 countries account for 80% of the global PtX potential area.
- The United States has the largest PtX potential, followed by Australia, Argentina, and Russia.
- The United States and Australia have both high PtX potential and high socioeconomic potential.
- Other countries with high potential in both categories are Canada and Chile.
- African countries like Egypt and Libya have high PtX area potential but lower socioeconomic potential.
- Australia has the largest PtX potential at pure PV locations, Russia at pure wind locations, and the United States at hybrid locations.

Based on the presented results, the following six countries have been selected as PtX potential export countries: the United States, Australia, Argentina, Egypt, Canada, and Chile. Figure 3.1 compiles the results of this section in graphical form.

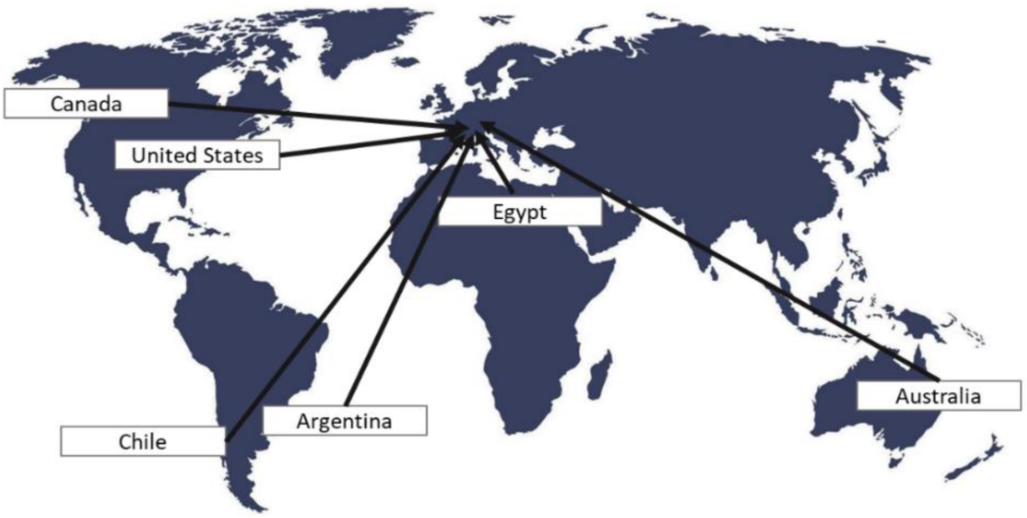


Figure 3.1 Selected potential export countries of PtX fuels via ship to Europe.

These six countries will be used to estimate the average price for production and transportation via ship of the studied e-fuels.

In addition to these exporters, the current countries that export natural gas to Europe via pipeline are also considered in this work when estimating the transportation costs of the studied energy carriers via pipeline. Figure 3.2 shows the considered export countries for Europe via pipeline.

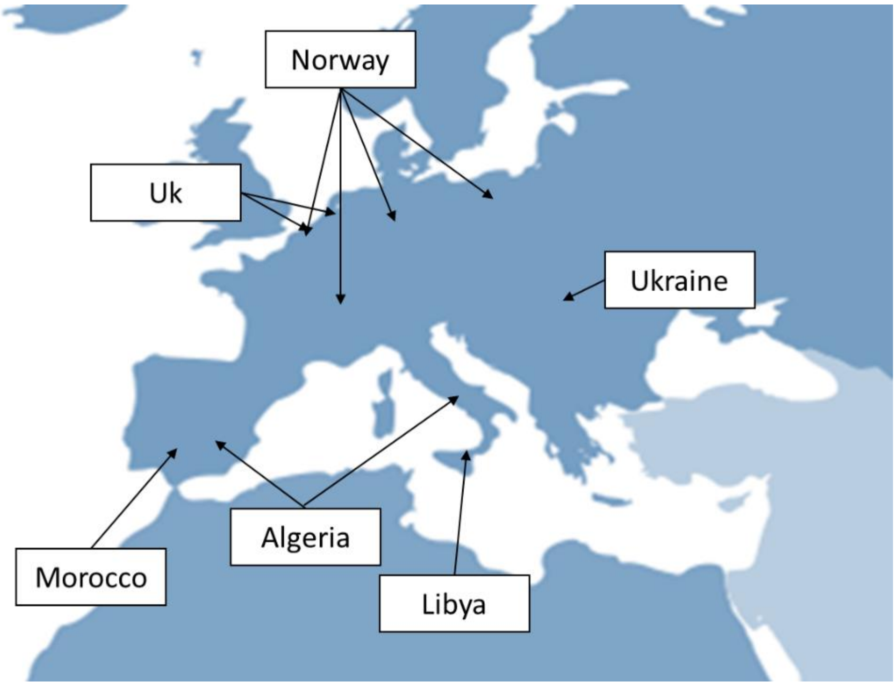


Figure 3.2 Selected potential export countries of PtX fuels via pipeline to Europe.

3.1.2 IDENTIFICATION OF IMPORT LOCATIONS IN EUROPE

Extensive research was carried out to determine the optimal import locations in Europe for the PtX fuels included in the study. The research involved an analysis of existing pipelines and ports, as well as planned projects, given that the field is still in its early stages. Proximity to demand criteria is considered to minimise transport costs and emissions, accounting for the fact that there is a higher demand for these fuels in the north of Europe than in the south [Gui22]. However, all projects and planned projects found on European territory were ultimately included in the investigation of import locations, in order to generate a complete scenario. Subsequently, the optimisation problem will determine a solution that considers the proximity criteria, as the demands included in the model are shaped to meet this criterion.

In order to study the import locations in Europe for liquid SNG, the current NG terminals were examined, while for SNG gas, the existing NG pipelines were utilised. This was done with the aim of substituting the demand for NG with SNG. To import liquid H_2, the main European ports were studied, focusing on those with existing H_2 projects as well as those currently importing methanol and ammonia. For importing H_2 gas, this study proposes the construction of a new hydrogen pipeline network parallel to the existing NG pipelines with similar capacities. Finally, the existing ports in Europe used for importing petroleum were examined to consider their potential use in importing FT-fuels.

The outcome of this research can be found in APPENDIX I Base Scenario Input Data, where a comprehensive list of these projects is available, including their expected import capacities and a cost estimation calculated based on the assumptions considered in Subsection 3.1.3.

3.1.3 COSTS FOR THE CONSIDERED SUPPLY CHAINS

This subsection will analyse the studied supply chains of the different energy carriers imported into Europe and utilise this data to estimate the total import cost of each energy carrier, from production to injection into the corresponding grid. The costs presented in this subsection follow the calculation methodology explained in Section 3.2.

Supply chain: SNG system

The considered supply chain for importing synthetic methane into Europe begins with the production of green hydrogen through electrolysis, which involves using renewable energy sources to split water into hydrogen and oxygen. The hydrogen is then combined with CO_2 obtained through DAC technology, which captures CO_2 from the atmosphere. The resulting mixture of hydrogen and carbon dioxide is then fed into a methanation process, where it reacts to produce CH_4, the main component of natural gas. The produced synthetic methane can then be transported to Europe using pipelines or liquefied natural gas (LNG) tankers, depending on the distance and infrastructure availability. In Europe, the synthetic methane may undergo regasification if transported as LNG or be injected directly into the existing SNG grid. The described process is visually represented in Figure 3.3.

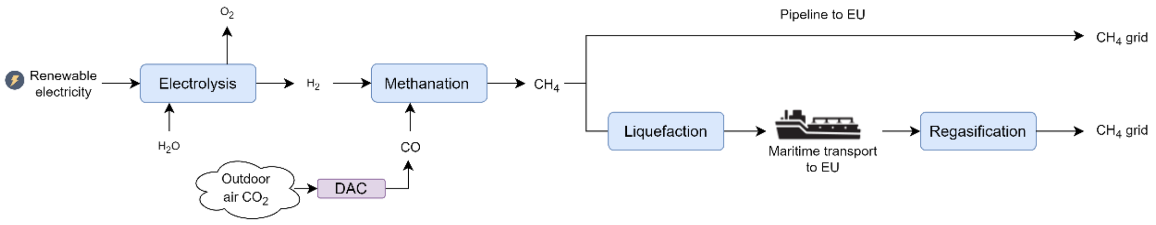


Figure 3.3 Considered supply chain for importing SNG to Europe.

In the context of importing SNG by ship, the import costs, including manufacturing and shipping, are estimated using the prices published in the Global PtX Atlas [Fra22]. Table 3.1**¡Error! No se encuentra el origen de la referencia.** displays these estimated costs for the particular scenario, where the average import costs were weighted considering the production capacities of SNG in each country.

Import Country	SNG Export Countries						
	USA	**AUS**	**ARG**	**EGY**	**CAN**	**CHL**	**weighted average import Cost (€/MWh)**
Belgium	133.00	140.00	117.00	125.00	118.00	119.00	129.69
Croatia	135.00	138.00	118.00	123.00	120.00	120.00	130.30
Cyprus	135.00	136.00	119.00	122.00	120.00	121.00	130.02
Denmark	134.00	140.00	118.00	126.00	119.00	120.00	130.46
Estonia	134.00	141.00	119.00	126.00	119.00	120.00	130.88
Finland	134.00	141.00	119.00	126.00	119.00	120.00	130.88
France	134.00	138.00	117.00	123.00	119.00	119.00	129.59
Germany	134.00	140.00	118.00	125.00	118.00	120.00	130.35
Greece	135.00	137.00	118.00	122.00	120.00	120.00	130.01
Ireland	133.00	138.00	117.00	125.00	118.00	119.00	129.24
Italy	134.00	137.00	118.00	122.00	118.00	120.00	129.48
Latvia	134.00	141.00	118.00	126.00	119.00	120.00	130.69
Lithuania	134.00	141.00	118.00	126.00	119.00	120.00	130.69
Netherlands	133.00	140.00	117.00	125.00	118.00	119.00	129.69
Poland	134.00	140.00	118.00	126.00	119.00	120.00	130.46

Portugal	133.00	139.00	116.00	124.00	118.00	118.00	129.17
Spain	133.00	138.00	116.00	124.00	118.00	119.00	128.98
Sweden	133.00	140.00	118.00	126.00	118.00	120.00	129.98

Table 3.1 Average import cost via ship of SNG for each importing country considered in this study.

Other expenses associated with the import structure in Europe must also be addressed. In this scenario, the present LNG terminals will be used to import liquefied SNG directly without repurposing [Joh09]. However, because an LNG terminal has a usual lifetime of around 30 years and the modelled scenario is for the year 2050, the infrastructure will most likely be updated by that time [ESF21]. As a result, using the approach described in Section 3.2, Table 3.2 shows the additional expenditures that must be accounted for when importing LSNG.

<table>
<tr><th colspan="7">LNG Terminal: Dunkirk</th></tr>
<tr><th>Import Capacity (MWh)</th><th>Start year</th><th>CAPEX (€)</th><th>OPEX (€/MWh)</th><th>Lifetime (years)</th><th>CAPEX annuity (€/MW) in year 2050</th><th>OPEX (€/MWh) in year 2050</th></tr>
<tr><td>1.27E+08</td><td>2017</td><td>1.50E+09</td><td>0.02</td><td>30</td><td>3448.74</td><td>0.03</td></tr>
<tr><th colspan="7">FSRU Wilhelmshaven</th></tr>
<tr><th>Import Capacity (MWh)</th><th>Start year</th><th>CAPEX (€)</th><th>OPEX (€/MWh)</th><th>Lifetime (years)</th><th>CAPEX annuity (€/MW) in year 2050</th><th>OPEX (€/MWh) in year 2050</th></tr>
<tr><td>7.33E+07</td><td>2022</td><td>4.25E+08</td><td>0.15</td><td>30</td><td>1693.72</td><td>0.25</td></tr>
</table>

Table 3.2 Additional costs incurred in Europe to import liquefied SNG via ship [Flu22], [Glo22].

Regarding the estimated total costs of SNG via pipeline, this study assumes that in 2050, SNG will be imported to Europe through the existing NG pipelines. All the costs related to this type of import are included in APPENDIX I Base Scenario Input Data, along with the estimating capacity of each pipeline based on the production cost predictions from Fraunhofer [Fra22] and the CAPEX and OPEX estimations of Guidehouse Netherlands [Gui22].

Supply chain: FT-fuels system

The production of renewable FT-fuels involves several steps, including green electrolysis, methanation, and the FT process. Once the liquid FT-fuels are obtained, they are transported to Europe via ship and stored in fuel tanks. In Europe, the fuels are injected into the liquids grid of the model, which is a virtual system that connects the imports and generation of these liquids with the demands via road transport. The considered import supply chain is illustraded in Figure 3.4.

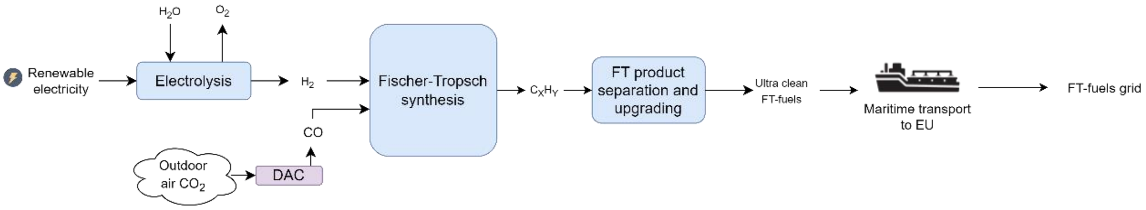


Figure 3.4 Considered supply chain for importing FT-fuels to Europe.

However, the considered scenario assumes that the import of FT-fuels will be done via actual oil ports, which would require additional costs in terms of infrastructure repurposing. To calculate the total costs associated with the import of FT-fuels to Europe, the estimated production and ship transportation costs from each exporting country to each importing country in Europe have been calculated using data from the Fraunhofer-developed Global PtX Atlas [Fra22]. These costs are shown in Table 3.3.

Import Country	FT-fuel Export Countries						
	USA	AUS	ARG	EGY	CAN	CHL	weighted average import Cost (€/MWh)
Belgium	131.00	133.00	114.00	123.00	116.00	115.00	126.31
Croatia	132.00	132.00	114.00	122.00	117.00	116.00	126.54
Cyprus	132.00	131.00	114.00	122.00	117.00	116.00	126.32
Denmark	132.00	133.00	114.00	124.00	116.00	115.00	126.81
Estonia	132.00	134.00	114.00	124.00	117.00	115.00	127.08
Finland	132.00	134.00	114.00	124.00	117.00	115.00	127.08

France	132.00	132.00	114.00	122.00	117.00	115.00	126.50
Germany	132.00	133.00	114.00	124.00	116.00	115.00	126.81
Greece	132.00	132.00	114.00	122.00	117.00	115.00	126.50
Ireland	131.00	132.00	114.00	123.00	116.00	115.00	126.09
Italy	132.00	132.00	114.00	122.00	116.00	115.00	126.45
Latvia	132.00	134.00	114.00	124.00	117.00	115.00	127.08
Lithuania	132.00	134.00	114.00	124.00	117.00	115.00	127.08
Netherlands	131.00	133.00	114.00	123.00	116.00	115.00	126.31
Poland	132.00	133.00	114.00	124.00	116.00	115.00	126.81
Portugal	131.00	133.00	113.00	123.00	116.00	115.00	126.12
Spain	131.00	132.00	113.00	123.00	116.00	115.00	125.89
Sweden	131.00	133.00	114.00	124.00	116.00	115.00	126.37

Table 3.3 Average import cost via ship of FT-fuels for each importing country considered in this study.

Additionally, the costs associated with the repurposing of a generic oil port and operation and maintenance (O&M) costs for a 2050 scenario are included in Table 3.4.

Average costs: Vopak Oil Terminal Eemshaven in the Netherlands							
Import capacity (MWh)	Start year	CAPEX (€)	OPEX (€/MWh)	Lifetime (years)	Repurposement saves % in comparison to building a new port	OPEX (€/MW) in year 2050	CAPEX annuity in Year 2050 (€/MW)
7.70E+06	2014	8.00E+08	3.12	30	40.00	51.21	3.12

Table 3.4 Additional costs incurred in Europe to import FT-fuels via ship [Vop23].

Supply chain: H_2 system

As the need for hydrogen is predicted to rise in Europe by 2050 due to its great energy potential, many solutions for importing hydrogen are being investigated.

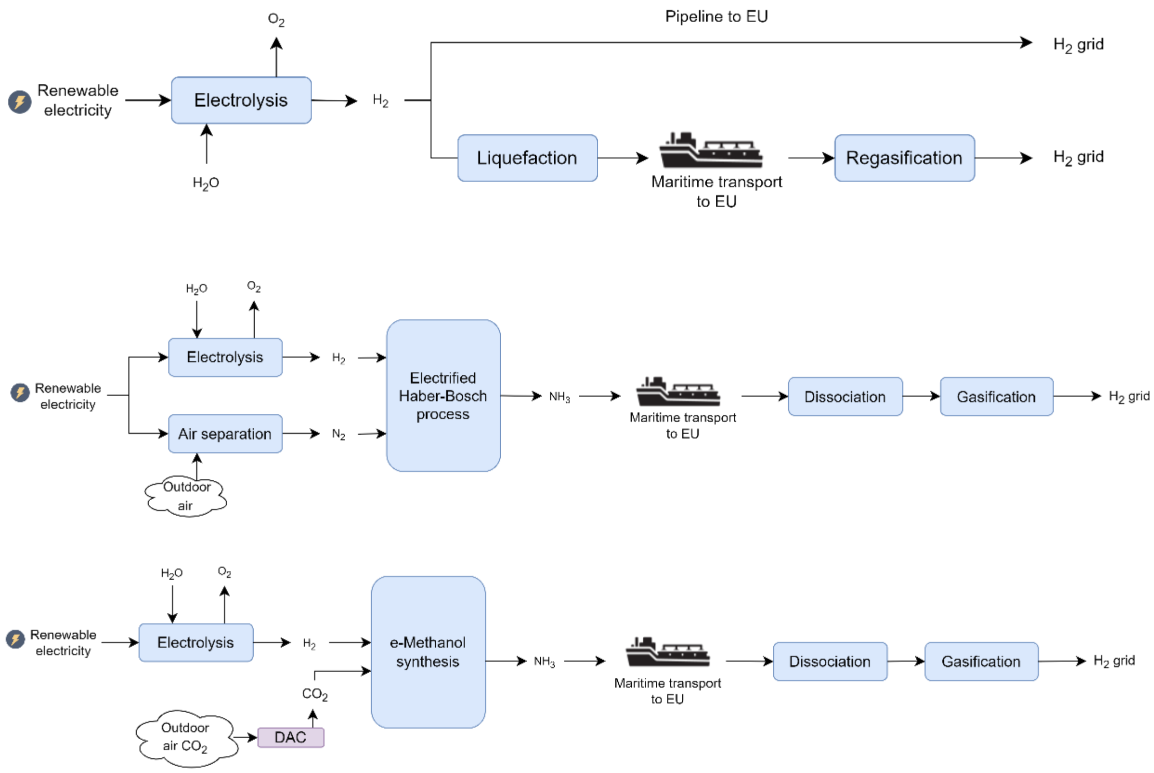


Figure 3.5 Considered supply chains for importing hydrogen to Europe.

One considered approach is to import H_2 via pipelines by building new pipes parallel to existing natural gas pipelines. For this approach, Table 3.5 and Table 3.6 show the expected expenses that need to be considered.

H_2 Production Cost					
Morocco	Algeria	Libya	Norway	UK	Ukraine
91.30	92.40	92.60	95.00	100.00	124.50

Table 3.5 Assumed production cost of H2 via new pipelines [Fra22].

New H_2 Pipelines						
Diameter (inch)	48.00	42.00	40.00	32.00	36.00	24.00
Total cost (€/MWh H_2/1000Km)	5.00	7.00	8.00	10.00	10.00	10.00
CAPEX (% of total cost)	71.00	71.00	71.00	71.00	71.00	71.00

OPEX (% of total cost)	29.00	29.00	29.00	29.00	29.00	29.00
Lifetime	50.00	50.00	50.00	50.00	50.00	50.00

Table 3.6 Costs incurred by European countries to import H2 via new pipelines [Gui22].

Another transport option included in this study is the importation of liquid hydrogen using special ships that maintain the temperature required for delivery. In this scenario, the import costs were calculated using the prices published in the Global PtX Atlas [Fra22], just like the import costs of SNG or FT-fuels. Table 3.7 displays the weighted import pricing.

Import Country	**H_2 Export Countries**						
	USA	**AUS**	**ARG**	**EGY**	**CAN**	**CHL**	**weighted average import Cost (€/MWh)**
Belgium	113.00	152.00	113.00	105.00	101.00	117.00	120.82
Croatia	120.00	142.00	116.00	94.00	110.00	123.00	122.02
Cyprus	122.00	136.00	115.00	90.00	111.00	124.00	121.14
Denmark	115.00	154.00	115.00	107.00	103.00	120.00	122.85
Estonia	117.00	157.00	118.00	109.00	106.00	122.00	125.32
Finland	117.00	157.00	118.00	109.00	106.00	122.00	125.32
France	115.00	143.00	112.00	96.00	105.00	118.00	119.05
Germany	114.00	153.00	115.00	106.00	103.00	119.00	122.09
Greece	119.00	138.00	115.00	91.00	109.00	122.00	120.20
Ireland	110.00	142.00	112.00	104.00	99.00	115.00	116.84
Italy	117.00	140.00	113.00	93.00	99.00	120.00	118.99
Latvia	117.00	156.00	117.00	109.00	106.00	122.00	124.90
Lithuania	116.00	156.00	117.00	108.00	105.00	121.00	124.32
Netherlands	113.00	152.00	113.00	105.00	101.00	118.00	120.85
Poland	115.00	154.00	116.00	107.00	104.00	120.00	123.09
Portugal	111.00	147.00	108.00	99.00	101.00	114.00	117.35
Spain	112.00	145.00	108.00	98.00	102.00	115.00	117.35
Sweden	113.00	154.00	116.00	107.00	102.00	120.00	122.14

Table 3.7 Average import cost via ship of liquefied H2 for each importing country considered in this study.

Furthermore, existing European ports should be updated to integrate hydrogen regasification units and tank storage. As a result, Table 3.8 contains the additional expenditures that Europe must bear in order to acquire liquid hydrogen for injection into the H_2 grid.

H_2 regasification		H_2 storage in EU	
CAPEX [€/(tH_2*yr)]	3,500.00	CAPEX (€/MWh)	16,700.00
OPEX (% of CAPEX)	4.00	OPEX (% of CAPEX)	1.50
efficiency (%)	95.20	efficiency (%)	99.90

Table 3.8 Additional costs incurred in Europe to import liquefied H2 via ship [Pfe22].

The import of green methanol via ship is another possibility for transferring H_2. Table 3.9 shows the import costs for this option based on data from the Global PtX Atlas [Fra22] and **¡Error! No se encuentra el origen de la referencia.** shows the additional expenses that importing nations must bear in order to import H_2 via green methanol. These costs mostly involve the cost of updating European ports to incorporate H_2 separation units and storage tanks.

Import Country	Green Methanol Export Countries						
	USA	AUS	ARG	EGY	CAN	CHL	weighted average import Cost (€/MWh)
Belgium	132.00	139.00	116.00	124.00	117.00	118.00	128.69
Croatia	134.00	136.00	117.00	121.00	119.00	120.00	129.05
Cyprus	134.00	135.00	117.00	120.00	119.00	120.00	128.76
Denmark	132.00	139.00	117.00	124.00	117.00	119.00	128.92
Estonia	133.00	140.00	118.00	125.00	118.00	119.00	129.88
Finland	133.00	140.00	118.00	125.00	118.00	119.00	129.88
France	132.00	137.00	116.00	122.00	118.00	118.00	128.16
Germany	132.00	139.00	117.00	124.00	117.00	119.00	128.92
Greece	133.00	136.00	117.00	121.00	119.00	119.00	128.58
Ireland	131.00	136.00	116.00	124.00	116.00	118.00	127.54
Italy	133.00	136.00	116.00	121.00	116.00	119.00	128.24
Latvia	133.00	140.00	117.00	125.00	118.00	119.00	129.69

Lithuania	133.00	140.00	117.00	125.00	118.00	119.00	129.69
Netherlands	132.00	139.00	116.00	124.00	117.00	118.00	128.69
Poland	132.00	140.00	117.00	124.00	117.00	119.00	129.14
Portugal	131.00	138.00	115.00	123.00	117.00	117.00	127.74
Spain	132.00	137.00	115.00	122.00	117.00	118.00	127.92
Sweden	132.00	140.00	117.00	124.00	117.00	119.00	129.14

Table 3.9 Average import cost via ship of green methanol for each importing country considered in this study.

SMR plant	
CAPEX [€/MW]	37,000.00
OPEX (€/MWh)	1.50
efficiency (%)	85.00

Table 3.10 Additional costs incurred in Europe to import H2 via methanol [Pfe22].

Finally, this research includes the feasibility of importing H_2 via ship using ammonia as the energy carrier. Table 3.11 and Table 3.12 include pertinent information on the import expenses under consideration.

Import Country	**Green Ammonia Export Countries**						
	USA	**AUS**	**ARG**	**EGY**	**CAN**	**CHL**	**weighted average import Cost (€/MWh)**
Belgium	107.00	121.00	97.00	102.00	93.00	100.00	106.92
Croatia	110.00	117.00	98.00	98.00	97.00	102.00	107.53
Cyprus	111.00	115.00	98.00	96.00	97.00	103.00	107.42
Denmark	108.00	122.00	98.00	103.00	94.00	101.00	107.92
Estonia	109.00	123.00	99.00	104.00	95.00	102.00	108.92
Finland	109.00	123.00	99.00	104.00	95.00	102.00	108.92
France	108.00	118.00	96.00	98.00	95.00	101.00	106.37
Germany	108.00	122.00	98.00	102.00	94.00	101.00	107.86
Greece	110.00	116.00	98.00	97.00	96.00	102.00	107.19
Ireland	106.00	117.00	97.00	101.00	92.00	100.00	105.48
Italy	109.00	117.00	97.00	97.00	92.00	101.00	106.55

Latvia	109.00	123.00	99.00	104.00	95.00	102.00	108.92
Lithuania	108.00	123.00	98.00	103.00	95.00	102.00	108.24
Netherlands	107.00	121.00	97.00	102.00	93.00	100.00	106.92
Poland	108.00	122.00	98.00	103.00	94.00	101.00	107.92
Portugal	106.00	119.00	95.00	100.00	93.00	99.00	105.49
Spain	107.00	118.00	95.00	99.00	94.00	99.00	105.68
Sweden	107.00	122.00	98.00	103.00	94.00	101.00	107.49

Table 3.11 Average import cost via ship of green ammonia for each importing country considered in this study [Fra22].

Ammonia Cracking unit	
CAPEX (€/MW)	40,000.00
OPEX (€/MWh)	1.50
efficiency (%)	85.00

Table 3.12 Additional costs incurred in Europe to import H2 via ammonia [own assumptions based on [Int19b]].

In this subsection, all the costs associated with importing synthetic fuels for the design of the European Energy System have been included. These costs, along with the import capacities for each fuel and location, serve as input data for the optimisation model used in this study. The model will be used to complete the main investigation of this work.

The complete input data to create an import scenario is included in APPENDIX I Base Scenario Input Data.

3.2 CAPEX AND OPEX CALCULATION

This section includes the methodology used to predict the estimated costs associated with the European terminals. These calculations aim to translate current average industry costs into 2050 average industry costs for the distinct infrastructure required. However, due to the complexity of these systems and the multitude of factors involved, predictions can be highly uncertain and subject to change over time.

This calculation method only applies to the costs of the supply chain incurred in European territory, as the predicted import costs related to fuel production and transport are calculated based on the information included in the Global PtX Atlas from Fraunhofer [Fra22].

3.2.1 CAPEX CALCULATION

To calculate the costs associated with investments, several factors must be considered. This analysis is based on the year 2050, when the infrastructure required for importing synthetic fuels into Europe should be in place. However, since construction of new infrastructure or repurposing of existing infrastructure typically takes 8 to 12 years to complete and not all plants will be built simultaneously, it is assumed that the construction of necessary plants will occur linearly over the next 27 years, and it is assumed to do the calculations that on average, their investments will be done in 14 years, in 2037.

To begin the analysis, average data on the cost of each technology investment has been obtained. However, as these investments will be paid off in 14 years on average, the investment costs must be adjusted for inflation. The assumed inflation rate is 2%, as it is the percentage aligned with the goals of the European Central Bank [Eur23b]. The updated investment costs will then be divided by the plant lifespan to calculate the annual depreciation cost for each plant, which reflects the CAPEX for the plant on an annual basis. This is the easiest way to introduce the investment costs into the existing model that simulates them on an hourly basis. To simplify it, no financing cost has been considered in this scenario. Equation 3.1 shows the formula used to update the costs for future scenarios, and equation 3.2 represents the formula used to calculate the annual linear depreciation of each plant.

$$NPV = \frac{1}{(1+r)^n} * NFV \tag{3.1}$$

Where:

$NPV =$ Net Present Value

$NFV =$ Net Future Value

$r =$ discount rate

$n =$ number of years

$$Annual\ depreciation\ cuote = \frac{V_o - V_r}{n} \tag{3.2}$$

Where:
V_o is the initial investment value

V_r is the residual value

n represents the lifetime in years

3.2.2 OPEX CALCULATION

In addition to CAPEX, operational expenditures for each type of plant must also be projected. To do so, average data on the O&M costs associated with each type of plant has been obtained. These costs will be adjusted based on inflation to reflect the scenario in 2050. To calculate this projected OPEX, equation 3.1 has been used.

In order to calculate the total operational expenditure (OPEX) cost, it is necessary to add the import costs from [Fra22] to the O&M costs.

By considering the estimated costs of investments and projected operational costs, a comprehensive understanding of the costs associated with investments can be developed.

3.3 DESCRIPTION OF THE EXISTING OPTIMISATION MODEL

The goal of this study is to determine how synthetic fuel imports affect the optimal design of the European Energy System. An economic optimisation model is used to accomplish this, simulating the European Energy System and determining its optimal design. The model is created in MATLAB and solves the optimisation problem using Gurobi. The system is made up of four systems:

- the electric system,
- gas system,
- hydrogen system,
- and a liquid system.

According to the desired study period, which in this case is one year, each node has been assigned an hourly load profile for each of the four systems. The model includes several generating technologies, like PV plants or combined cycle gas turbine (CCGT) plants, as well as several storage technologies, like batteries or salt caverns, to help with sector coupling and meet demand. The model also includes several constraints, such as energy supply and demand balance and infrastructure limitations.

The model has been designed to function independently of the input scenario by incorporating a structure called model definition (MD). The MD file contains the input data for each scenario and enables the inclusion of relevant information. This approach ensures that the model remains adaptable and can incorporate new data or changes in the input scenarios as required. The MD structure also allows for the organisation and management of the input data, making it easier to maintain and update the model. By utilising this design, the model can generate results for each scenario, even when new input data is introduced. In this MD file, the input data collected in Section 3.1 is included.

This whole model aims to minimise the total cost of the energy system while satisfying all the constraints, and the output of the model provides an optimised investment of plants, storages, and transmission lines and an optimised energetic mix to satisfy the demand. This information can be used to make informed policy decisions for the European energy system and contribute to a sustainable energy future.

3.4 LP PROBLEM

The existing optimisation model represents an LP problem, or Linear Programming problem. This is a mathematical optimisation problem in which a linear objective function is maximised or minimised subject to a set of linear constraints. In essence, LP is a tool for making decisions by optimising a particular outcome while considering several constraints that must be met [Don89], [Col20].

An LP problem can take many different forms, but in this case, the standard form has been used, which presents the following characteristics:

- it is a maximisation program,
- and all variables are restricted to be nonnegative.

And, since the implementation of this model is developed in a coding environment, the matrix form is used, which can be written as [Mic15]:

$$\text{Min } \ \mathrm{z} = \ c^T x \tag{3.3}$$

Subject to:

$$\mathrm{Ax} = b \tag{3.4}$$

$$\mathrm{x} \geq 0 \tag{3.5}$$

$$c = \begin{pmatrix} C_1 \\ \vdots \\ c_n \end{pmatrix}, \ b = \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix}, \ x = \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \tag{3.6}$$

Where c^T denote the transpose of the vector c , which is a vector of coefficients that represent the objective function to be maximised, x is a vector of decision variables, b is a vector of constants representing the right-hand side of the constraints, and A is a matrix of coefficients that represents the constraints on the decision variables.

This theory will be applied to include the import of synthetic fuels to the existing model.

3.4.1 IMPORT FUNCTION

One of the main tasks of this work is to implement a function in the existing MATLAB model to include the import of synthetic fuels in the group of technologies that contribute to satisfying the gas, hydrogen, and liquid fuel demands.

For this reason, the function *addImportFuelToNode* has been created as an LP problem and aims to describe the import of fuel to each node in the energy system, so that it can be included in the optimisation model.

The function needs to:

- Add to each node of the system the hourly maximum import capacity of the fuel.
- Add to each node of the system the hourly minimum import capacity of the fuel.
- Add to each node of the system the total OPEX cost related to the import of the fuel and minimise it.
- Add a restriction to limit the amount of fuel that can be annually imported into the whole system.
- Add a restriction to limit the amount of fuel that can be annually imported by each node of the system.

The LP model that incorporates all these requirements for a period study of a year is formulated as follows:

Objective function:

$$\text{Min } \ z = \sum_{n=1}^{N} \sum_{t=1}^{T} (import_{n,t} \cdot OPEX_n) \tag{3.7}$$

Subject to:

$$import_{t,n} \geq 0 \qquad \forall\, t,n \tag{3.8}$$

$$import_{t,n} \geq min_n \qquad \forall\, t,n \tag{3.9}$$

$$import_{t,n} \leq max_n \qquad \forall\, t,n \tag{3.10}$$

$$\sum_{n=1}^{n} import_{t,n} \leq totalImport \tag{3.11}$$

$$\sum_{t=1}^{T} import_{t,n} \leq nodetotalImport_n \qquad \forall\, n \tag{3.12}$$

Where:

N is the total number of nodes, T is the total length of the time horizon, in this case, 8,760 hours per year, $OPEX_n$ is the operational expenditure per unit of energy consumed at node n, $import_{n,t}$ is the amount of energy imported at node n during time slice t, $totalImport$ is the allowed total amount of fuel imported for the whole system over the whole period of study, min_n is the minimal imported quantity of fuel allowed at node n during time slice t, max_n is the maximal imported quantity of fuel allowed at node n during time slice t, and $nodetotalImport_n$ is the maximal imported quantity of fuel allowed at node n during the whole period of study.

With this model, the lower bound and upper bound of the import capacity are restricted at node level for each hour in equations 3.9 and 3.10, but the import capacity is also restricted at the system level for the whole period of study, which in this case is the year 2050. This restriction corresponds to equation 3.11. Additionally, the import capacity is restricted annually per node in equation 3.12.

The function *addImportFuelToNode* is designed as a generic function that can be used to import any fuel into the system.

As the existing model was developed in MATLAB, this function was also created in MATLAB. In this case, the model definition includes the input data compiled in Section 3.1, where the imports of synthetic fuels are included to inject them into the gas, hydrogen, and liquid grids.

Chapter 4. ANALYSIS: FUEL IMPORTATION IMPACT ON THE DESIGN OF THE EUROPEAN ENERGY SYSTEM

The aim of this chapter is to investigate the role that synthetic fuel imports can play in achieving a sustainable and cost-efficient energy system in Europe. To do so, the chapter will begin by considering the baseline scenario without imports. From there, the optimal scenario will be studied, including the option to use imports in the design of the energy system. Subsequently, based on this optimal scenario, secondary scenarios will be considered to do a sensitivity analysis and study how the system varies.

4.1 BASE SCENARIO: NO IMPORTS INCLUDED

According to the baseline scenario described in Subsection 3.3, the model presents an optimal total system cost of 406,788.032 M€. This cost is distributed among the four subsystems of the model as shown in Figure 4.1, where it can be seen that the highest system costs occur in the expansion and operation of electricity infrastructure (grid, power plants, etc.). The liquid system has the lowest system cost, at about 2%.

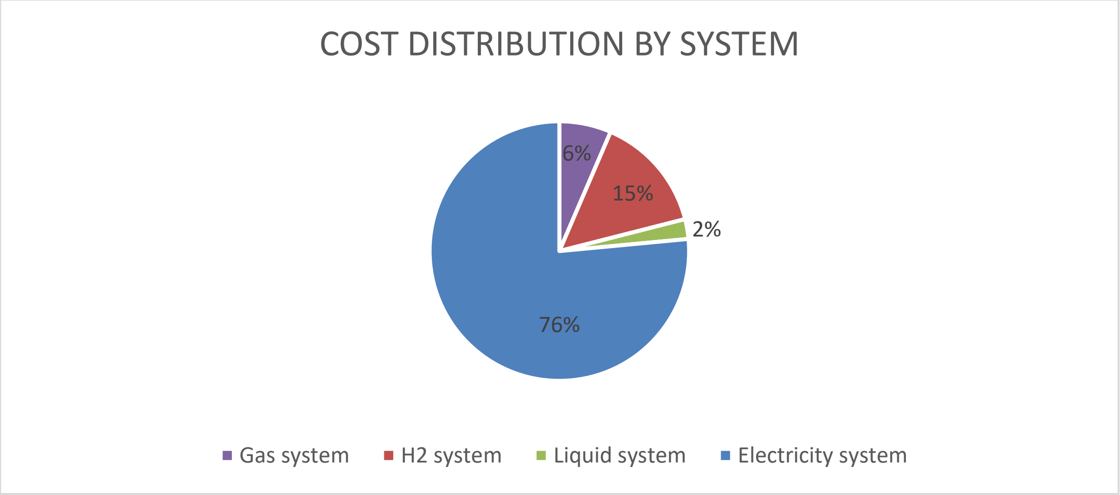


Figure 4.1 Base scenario: cost distribution per system.

The results depicted in Figure 4.2 show the price variation for each energy carrier and their average energy costs across different regions of the system. It can be observed that energy costs are cheaper in the southern parts of Europe than in the central and northern parts.

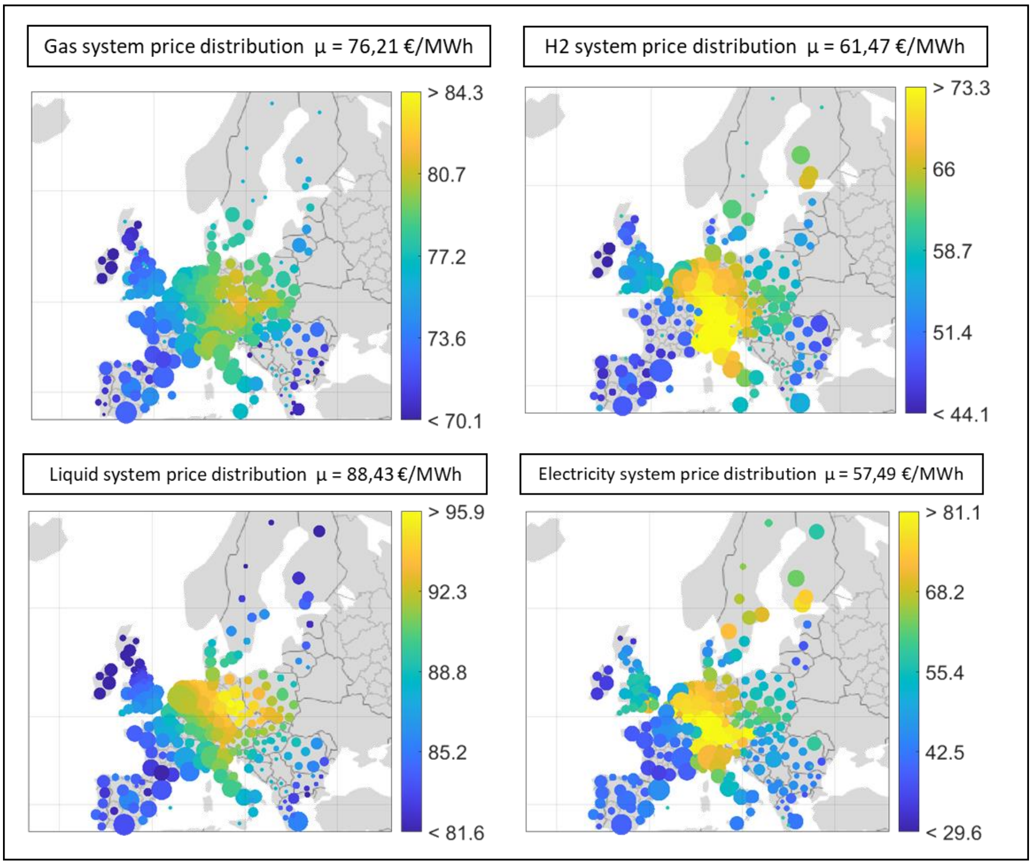
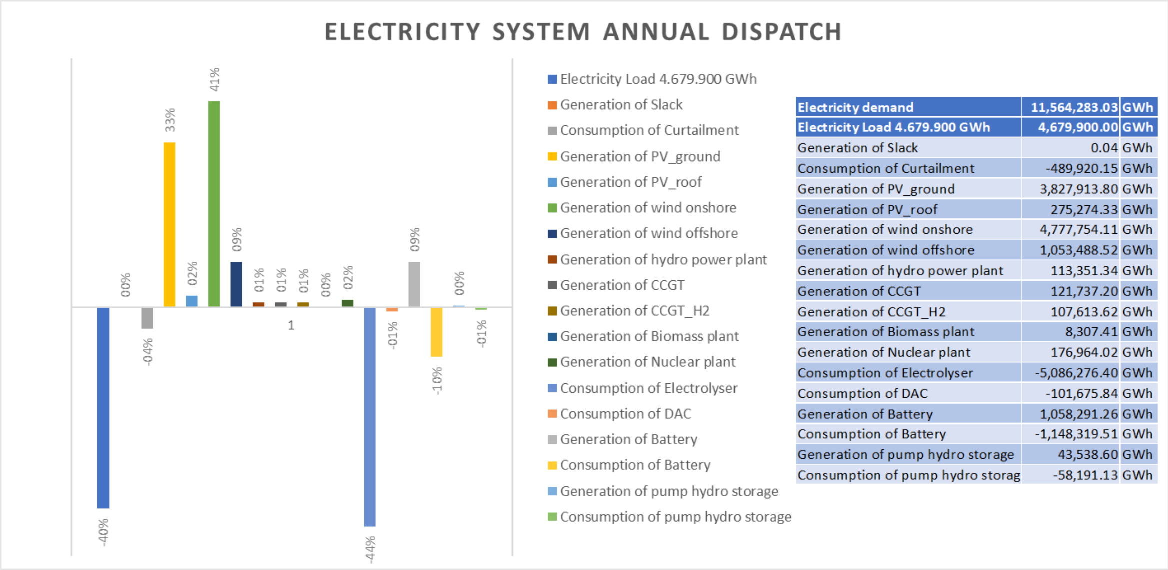


Figure 4.2 *Base scenario: price distribution across the system.*

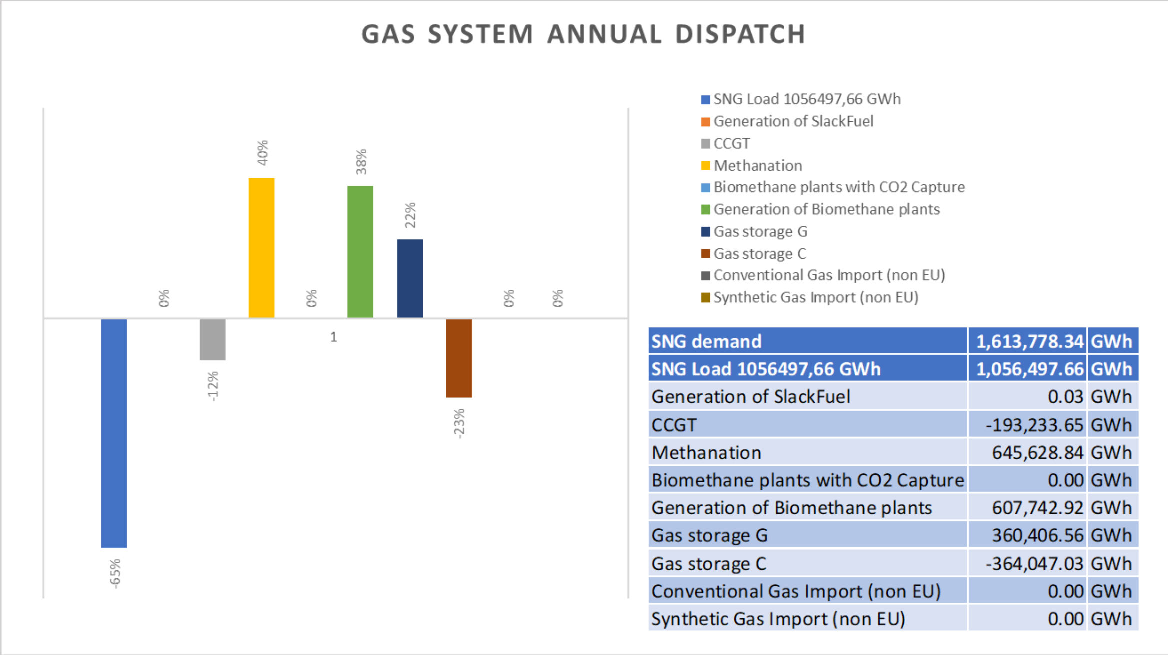
Regarding the electricity system, it includes 6,901,659 MW of installed capacity and an annual demand of 11,564,283 GWh, mainly satisfied by wind onshore and ground-mounted PV technologies, as shown in Figure 4.3.



Electricity demand	**11,564,283.03**	**GWh**
Electricity Load 4.679.900 GWh	**4,679,900.00**	**GWh**
Generation of Slack	0.04	GWh
Consumption of Curtailment	-489,920.15	GWh
Generation of PV_ground	3,827,913.80	GWh
Generation of PV_roof	275,274.33	GWh
Generation of wind onshore	4,777,754.11	GWh
Generation of wind offshore	1,053,488.52	GWh
Generation of hydro power plant	113,351.34	GWh
Generation of CCGT	121,737.20	GWh
Generation of CCGT_H2	107,613.62	GWh
Generation of Biomass plant	8,307.41	GWh
Generation of Nuclear plant	176,964.02	GWh
Consumption of Electrolyser	-5,086,276.40	GWh
Consumption of DAC	-101,675.84	GWh
Generation of Battery	1,058,291.26	GWh
Consumption of Battery	-1,148,319.51	GWh
Generation of pump hydro storage	43,538.60	GWh
Consumption of pump hydro storag	-58,191.13	GWh

Figure 4.3 Base scenario: technological mix of the electricity system.

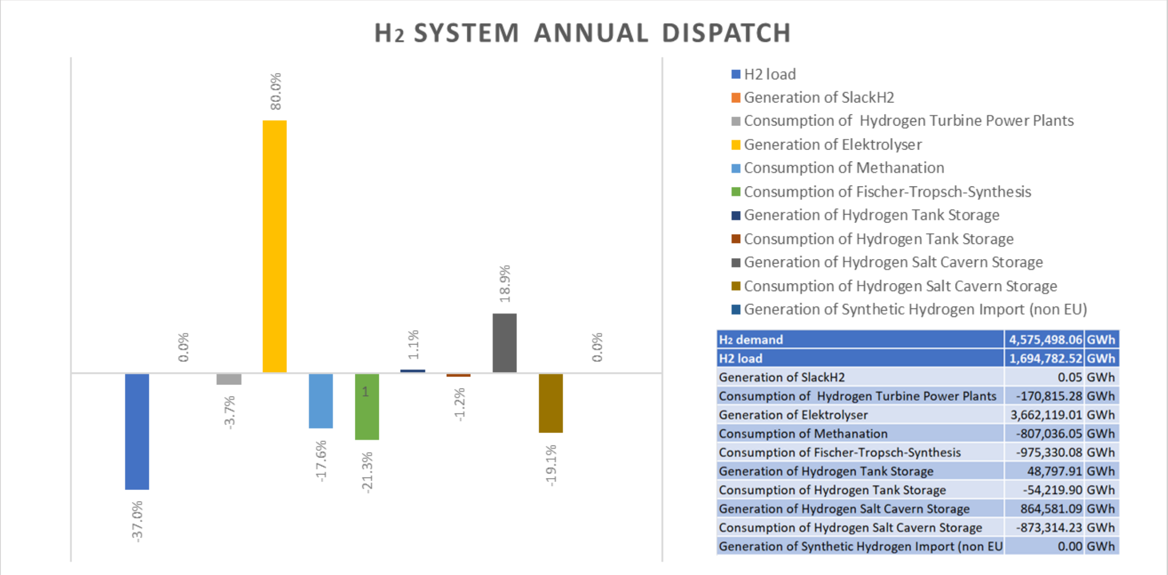
For the gas system, it includes 780,573 MW of installed capacity and an annual demand of 1,613,778.34 GWh, mainly satisfied by methanation and biomethane plants, as shown in Figure 4.4.



SNG demand	**1,613,778.34**	**GWh**
SNG Load 1056497,66 GWh	**1,056,497.66**	**GWh**
Generation of SlackFuel	0.03	GWh
CCGT	-193,233.65	GWh
Methanation	645,628.84	GWh
Biomethane plants with CO2 Capture	0.00	GWh
Generation of Biomethane plants	607,742.92	GWh
Gas storage G	360,406.56	GWh
Gas storage C	-364,047.03	GWh
Conventional Gas Import (non EU)	0.00	GWh
Synthetic Gas Import (non EU)	0.00	GWh

Figure 4.4 Base scenario: technological mix of the gas system.

In the case of the H_2 system, it includes 1,932,160 MW of installed capacity and an annual demand of 4,575,498.06 MWh, mainly satisfied by the electrolyser plants, which are the only existing technology to generate H_2, together with the storage facilities. These results are shown in Figure 4.5.

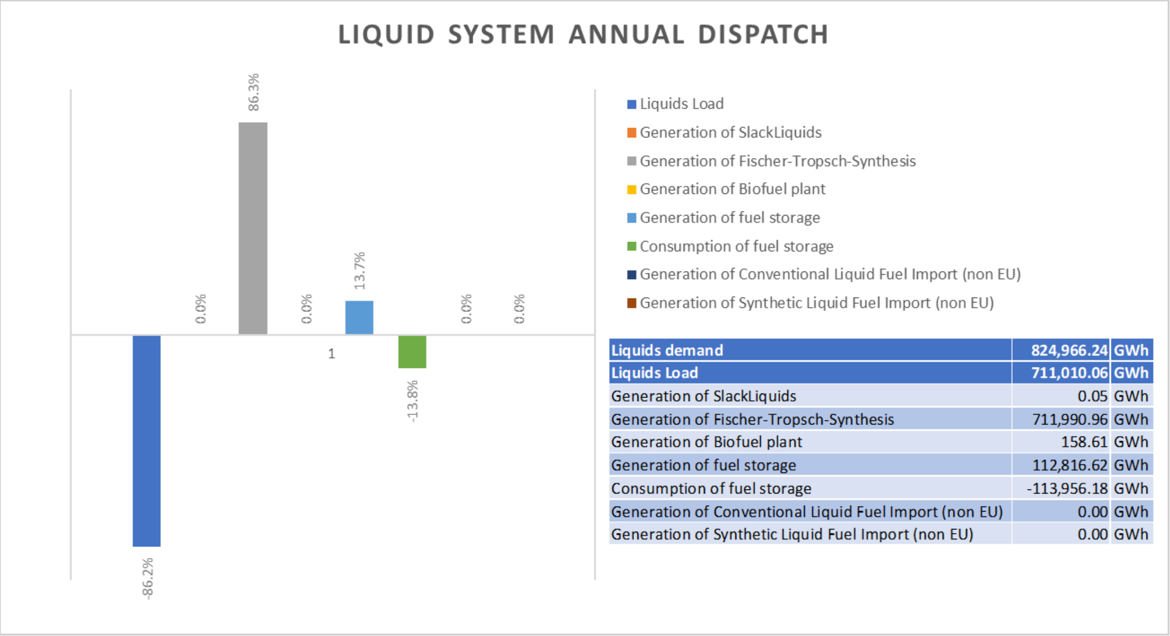


H₂ demand	**4,575,498.06**	**GWh**
H2 load	**1,694,782.52**	**GWh**
Generation of SlackH2	0.05	GWh
Consumption of Hydrogen Turbine Power Plants	-170,815.28	GWh
Generation of Elektrolyser	3,662,119.01	GWh
Consumption of Methanation	-807,036.05	GWh
Consumption of Fischer-Tropsch-Synthesis	-975,330.08	GWh
Generation of Hydrogen Tank Storage	48,797.91	GWh
Consumption of Hydrogen Tank Storage	-54,219.90	GWh
Generation of Hydrogen Salt Cavern Storage	864,581.09	GWh
Consumption of Hydrogen Salt Cavern Storage	-873,314.23	GWh
Generation of Synthetic Hydrogen Import (non EU	0.00	GWh

Figure 4.5 Base scenario: technological mix of the H_2 system.

Regarding the liquid system, it includes 2,799,679 MW of installed capacity and an annual demand of 824,966.24 MWh, mainly satisfied by Fischer-Tropsch synthesis technology, as the other generation technology, the biofuel plant, presents higher costs and the same availability in each region of the system. Figure 4.6 shows which technologies contribute to satisfying the demand in this base scenario.

In this case, the installed capacity of liquid production plants seems to be slightly higher in comparison with the demand, but this is mainly due to the fuel storage technology.



Liquids demand	**824,966.24**	**GWh**
Liquids Load	**711,010.06**	**GWh**
Generation of SlackLiquids	0.05	GWh
Generation of Fischer-Tropsch-Synthesis	711,990.96	GWh
Generation of Biofuel plant	158.61	GWh
Generation of fuel storage	112,816.62	GWh
Consumption of fuel storage	-113,956.18	GWh
Generation of Conventional Liquid Fuel Import (non EU)	0.00	GWh
Generation of Synthetic Liquid Fuel Import (non EU)	0.00	GWh

Figure 4.6 Base scenario: technological mix of the liquid system.

After studying the base scenario, it can be seen that the results are consistent, as the system is choosing to install the cheapest technologies and produce as much energy as possible with them before building others, thus reducing costs.

4.2 OPTIMAL SCENARIO INCLUDING SYNTHETIC FUEL IMPORTS

After analysing the scenario on which this thesis is based, in this new scenario, synthetic fuel imports are included without any additional restrictions other than the physical constraints of the system. Specifically, the import potential introduced in the model includes the possibility of importing annually 6,093,007,108 MWh of SNG at an average price of 129.81 €/MWh, 942,401,000 MWh of H_2 at an average price of 115.71 €/MWh, and 5,157,003,949 MWh of FT-fuels at an average price of 126.85 €/MWh. This amount of energy could satisfy 100% of the load associated with SNG and liquids and 56% of the load associated with H_2. With regard to prices, although both the CAPEX and OPEX necessary to import synthetic fuels were studied in Chapter 3, only the OPEX associated with importation has been considered in the system [Fra22].

The results of this simulation present a total annual cost of the system of 406,676.94 M€, which implies that including imports in the system results in a maximum cost reduction of 111.09 M€. Importing 87.19 GWh of SNG, 1,746.62 GWh of H_2, and 41.90 GWh of liquids helps to achieve this reduction. These imports correspond to less than 1% of each demand. Therefore, to optimise costs, imports must be included since they allow saving money on the construction of plants that may not produce at maximum capacity, but since imports are expensive, it is not economically viable to cover too much demand with them. This result is due to the fact that the operational costs of the plants in the system have zero or very low OPEX, so despite having high CAPEX, the system optimises so that the plants that are built produce at maximum capacity, thus reducing the production costs within the system and making the imports more expensive.

As synthetic fuel imports are minimal, there are no major changes observed in the distribution of costs according to the type of system. Figure 4.7 shows this distribution, which is identical to that of the base scenario.

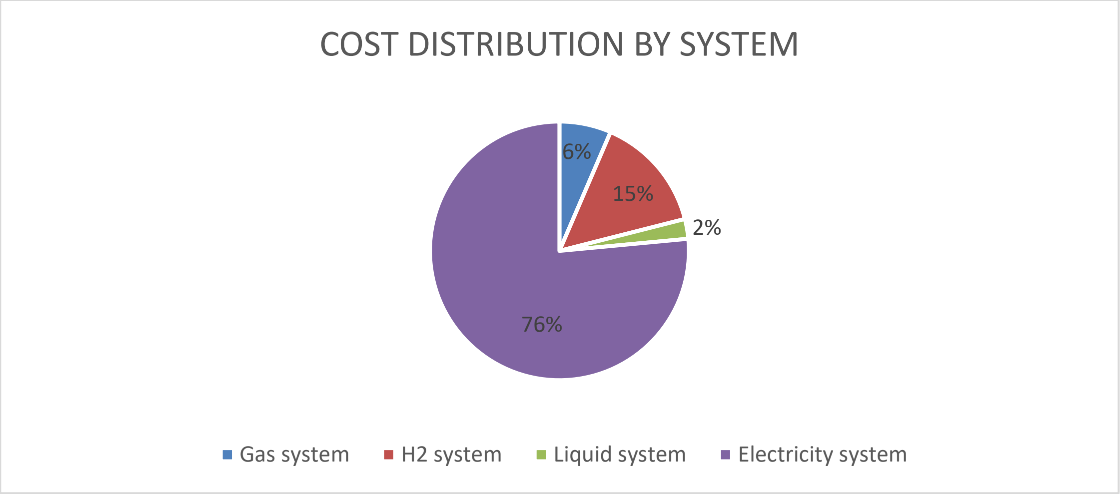


Figure 4.7 Optimal scenario with imports: cost distribution per system.

On the other hand, annual demands do show a slight variation with respect to the base scenario. Specifically, it is observed that the demand for gas and electricity increases slightly while the demand for H_2 and liquids decreases. In turn, the average prices of energy produced do not undergo major changes, although it is observed that the price of electricity increases by 0.63%, that of hydrogen increases by 0.10%, that of liquids remains constant, and that of gas is reduced by 0.04%. Figure 4.8 shows the prices for each scenario.

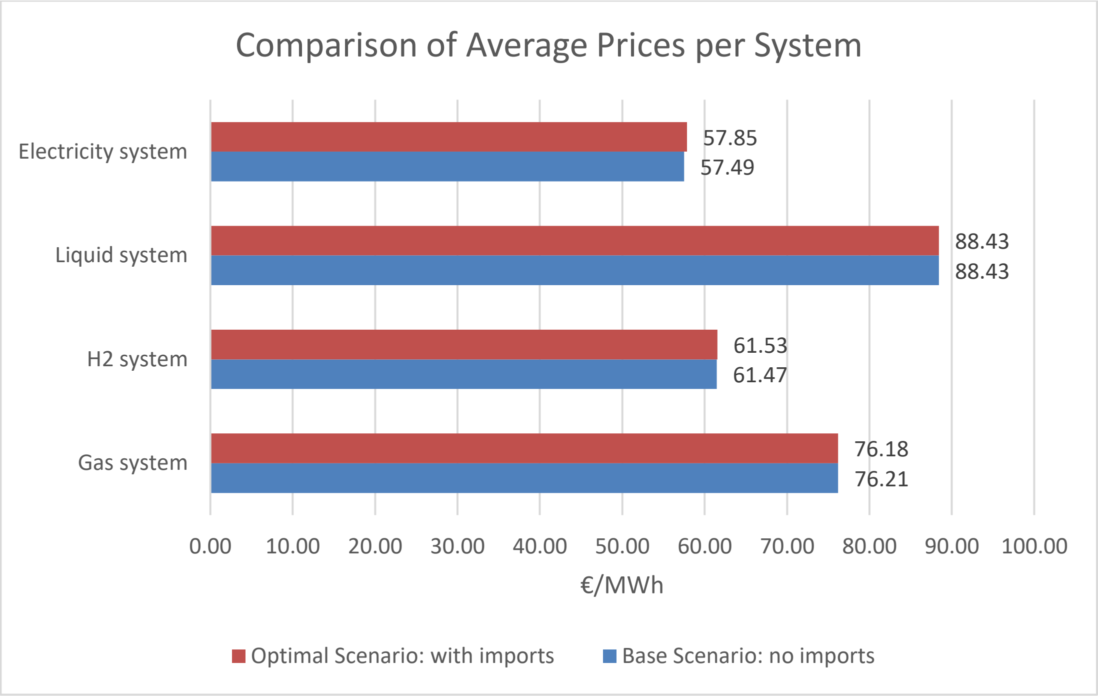


Figure 4.8 Comparison between scenarios: average energy prices per system.

With regard to the variation in prices by regions, the inclusion of imports into the system does not modify the price distribution of the base scenario since imports are minimal and import prices do not vary excessively among the different European regions. Figure 4.9 presents these results, where, again, higher energy costs are observed in central and northern Europe with respect to the south.

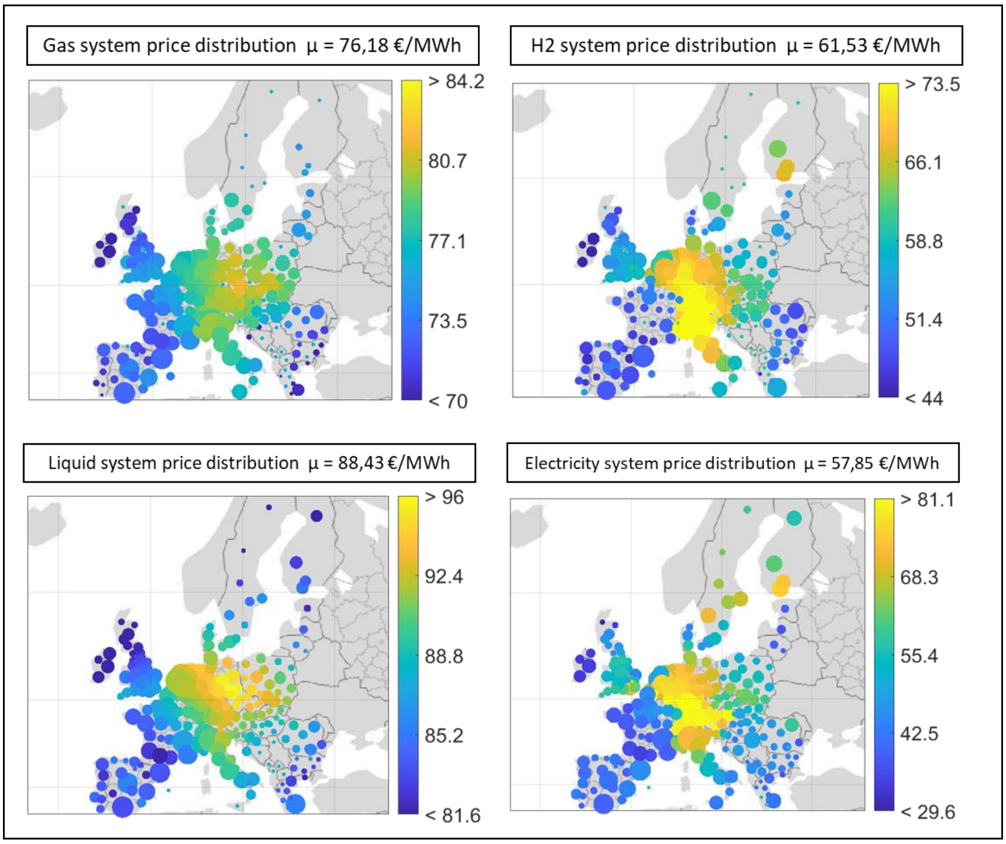


Figure 4.9 Optimal scenario with imports: price distribution across the system.

According to the technological mix, since imports are minimal, there is practically no variation, although a slight variation is observed in the installed capacity of each technology, as shown in Figure 4.10. The most notable changes are the reduction in the storage technologies of the fuel systems and the increase in battery technology. These variations may be due to the fact that, thanks to imports, it is not necessary to build as much plant in certain nodes, thus reducing installed capacity. On the other hand, since the demand for electricity increases and no imports have been added to this system compared to the base scenario, the installed capacity of batteries increases, among other reasons.

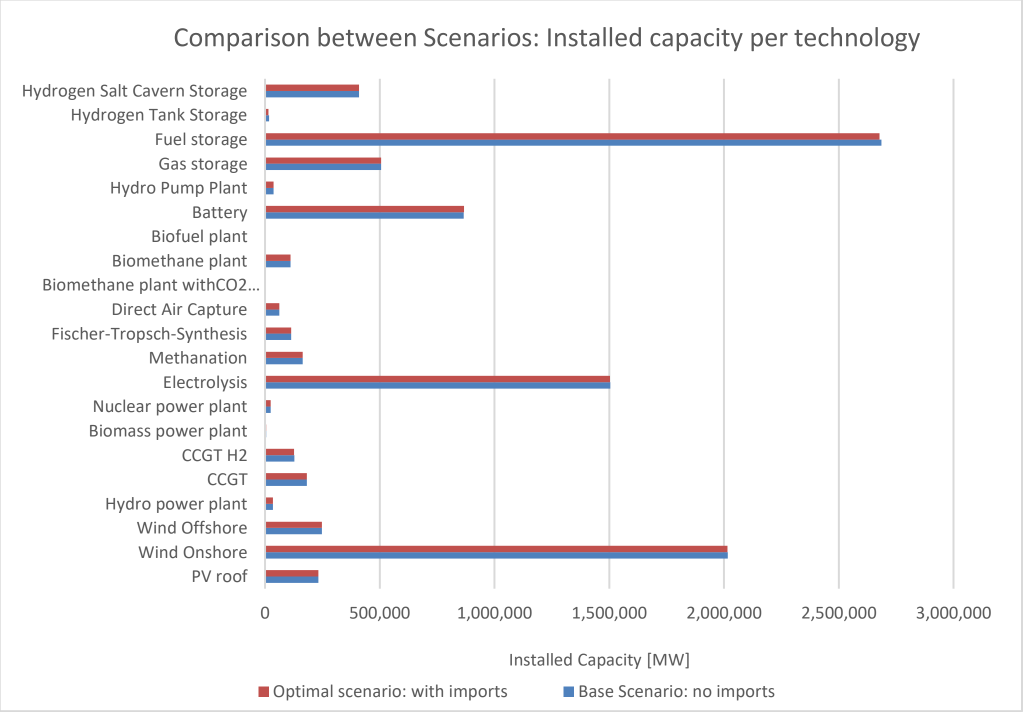
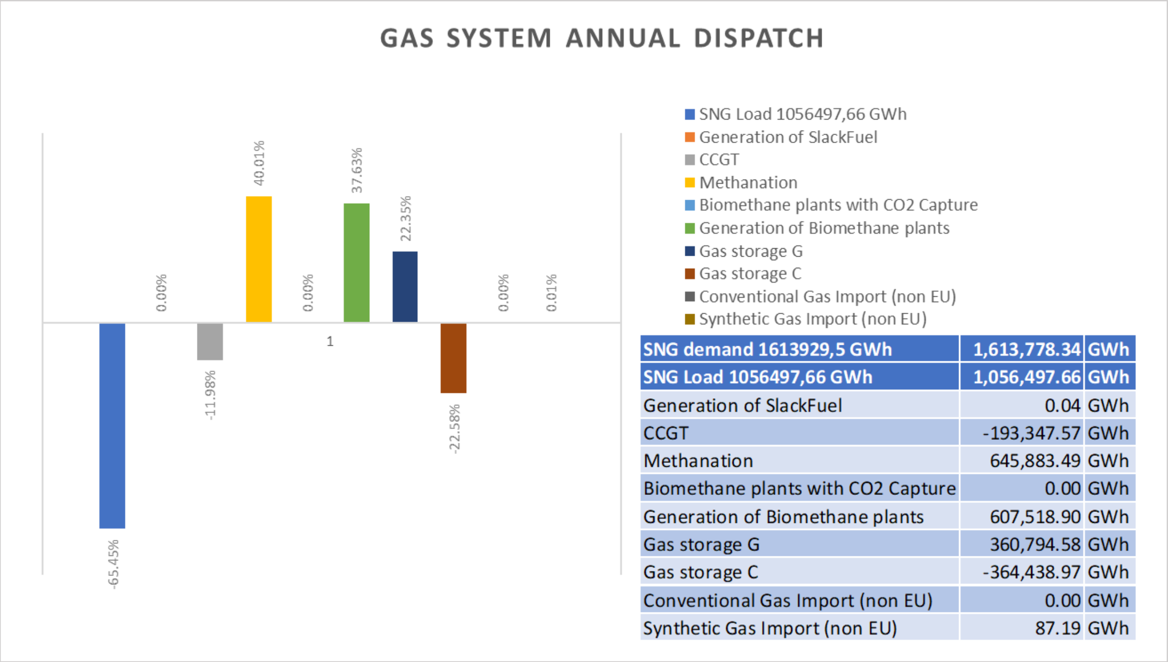


Figure 4.10 Comparison between scenarios: installed capacities per technology.

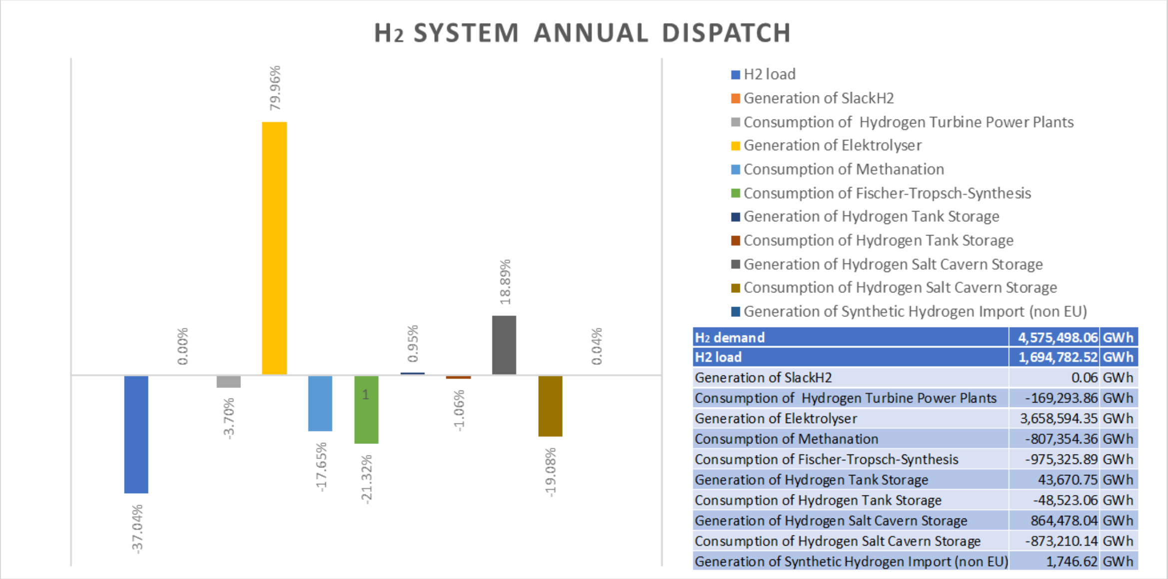
Finally, regarding the energy generation of each plant to meet the demand, no relevant changes have been found with respect to the base scenario, which indicates that the introduction of imports to the system does not imply designing a completely different system.

Figure 4.11, Figure4.12 , Figure 4.13, and Figure 4.14 show how the produced energy is distributed among the technologies included in the system.



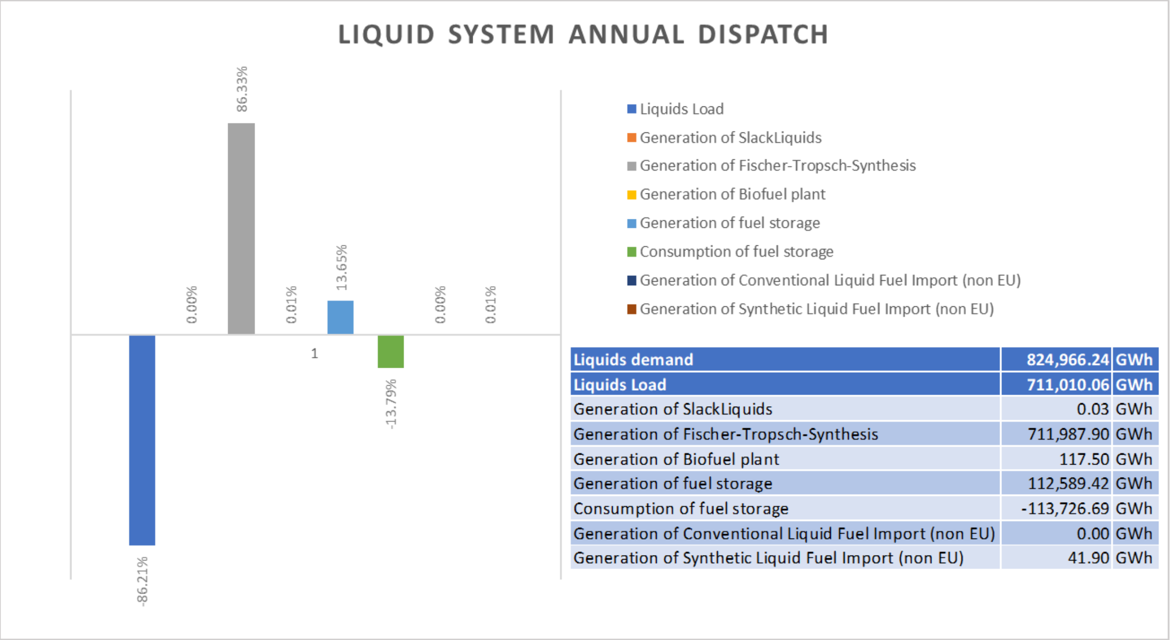
SNG demand 1613929,5 GWh	**1,613,778.34**	**GWh**
SNG Load 1056497,66 GWh	**1,056,497.66**	**GWh**
Generation of SlackFuel	0.04	GWh
CCGT	-193,347.57	GWh
Methanation	645,883.49	GWh
Biomethane plants with CO2 Capture	0.00	GWh
Generation of Biomethane plants	607,518.90	GWh
Gas storage G	360,794.58	GWh
Gas storage C	-364,438.97	GWh
Conventional Gas Import (non EU)	0.00	GWh
Synthetic Gas Import (non EU)	87.19	GWh

Figure 4.11 Optimal scenario with imports: technological mix of the gas system.



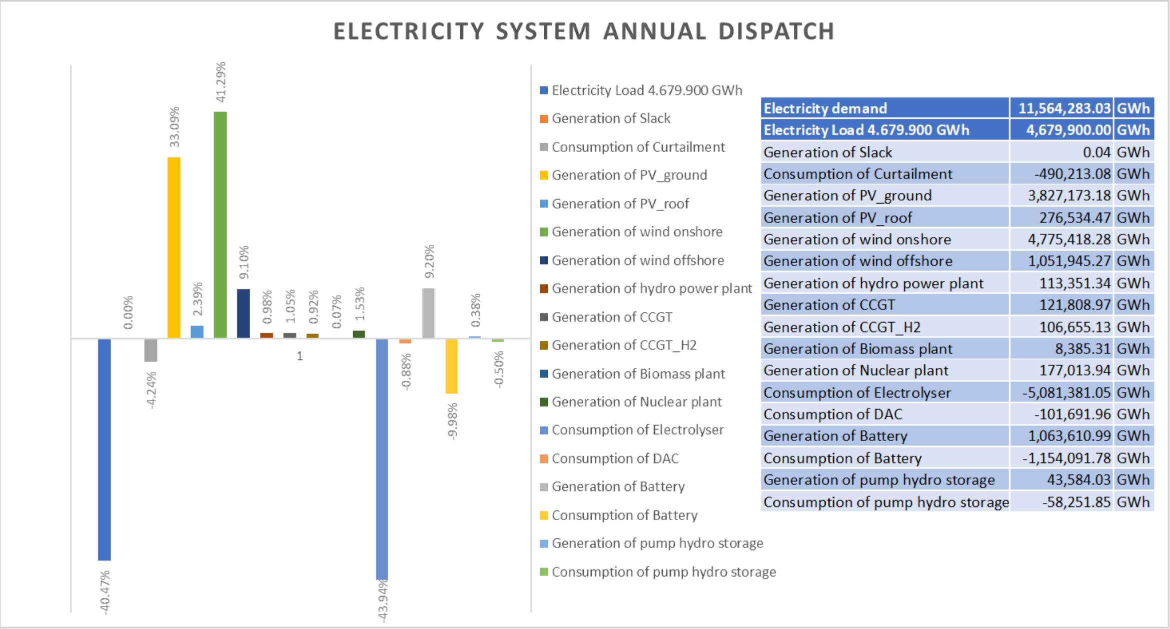
H_2 demand	**4,575,498.06**	**GWh**
H2 load	**1,694,782.52**	**GWh**
Generation of SlackH2	0.06	GWh
Consumption of Hydrogen Turbine Power Plants	-169,293.86	GWh
Generation of Elektrolyser	3,658,594.35	GWh
Consumption of Methanation	-807,354.36	GWh
Consumption of Fischer-Tropsch-Synthesis	-975,325.89	GWh
Generation of Hydrogen Tank Storage	43,670.75	GWh
Consumption of Hydrogen Tank Storage	-48,523.06	GWh
Generation of Hydrogen Salt Cavern Storage	864,478.04	GWh
Consumption of Hydrogen Salt Cavern Storage	-873,210.14	GWh
Generation of Synthetic Hydrogen Import (non EU)	1,746.62	GWh

Figure 4.12 Optimal scenario with imports: technological mix of the H2 system.



Liquids demand	**824,966.24**	**GWh**
Liquids Load	**711,010.06**	**GWh**
Generation of SlackLiquids	0.03	GWh
Generation of Fischer-Tropsch-Synthesis	711,987.90	GWh
Generation of Biofuel plant	117.50	GWh
Generation of fuel storage	112,589.42	GWh
Consumption of fuel storage	-113,726.69	GWh
Generation of Conventional Liquid Fuel Import (non EU)	0.00	GWh
Generation of Synthetic Liquid Fuel Import (non EU)	41.90	GWh

Figure 4.13 Optimal scenario with imports: technological mix of the liquid system.



Electricity demand	**11,564,283.03**	**GWh**
Electricity Load 4.679.900 GWh	**4,679,900.00**	**GWh**
Generation of Slack	0.04	GWh
Consumption of Curtailment	-490,213.08	GWh
Generation of PV_ground	3,827,173.18	GWh
Generation of PV_roof	276,534.47	GWh
Generation of wind onshore	4,775,418.28	GWh
Generation of wind offshore	1,051,945.27	GWh
Generation of hydro power plant	113,351.34	GWh
Generation of CCGT	121,808.97	GWh
Generation of CCGT_H2	106,655.13	GWh
Generation of Biomass plant	8,385.31	GWh
Generation of Nuclear plant	177,013.94	GWh
Consumption of Electrolyser	-5,081,381.05	GWh
Consumption of DAC	-101,691.96	GWh
Generation of Battery	1,063,610.99	GWh
Consumption of Battery	-1,154,091.78	GWh
Generation of pump hydro storage	43,584.03	GWh
Consumption of pump hydro storage	-58,251.85	GWh

Figure 4.14 Optimal scenario with imports: technological mix of the electricity system.

In conclusion, it can be seen from the simulation of this scenario that the inclusion of synthetic fuel imports into the system is beneficial in reducing the overall costs of the system, even if there is a slight increase in the costs of the electricity system and the hydrogen system. The results show that the importation should be done in small quantities, as it is an expensive option, but it becomes attractive when the alternative is building a new plant to meet a small amount of demand. There were no significant changes in the system design when comparing scenarios, as the imports included in the optimal system were minimal. Additionally, there was no observed variation in the distribution of costs across different regions, which remained constant, with higher energy costs in central and northern Europe.

In the following section, a sensitivity analysis will be conducted to examine how restrictions on imports impact this optimal design of the energy system.

4.3 SENSITIVITY ANALYSIS

This section aims to investigate how changes in imports of synthetic fuels affects the optimal solution of the system described in Section 4.2. Specifically, this analysis will examine the effects of three different scenarios: a shortage of imported fuels, changes in fuel prices from existing levels, and policies aimed at increasing imports to Europe. The analysis of these scenarios will provide insight into the sensitivity of the energy system to changes in import.

4.3.1 SCENARIO OF SYNTHETIC FUEL SHORTAGE

In this scenario, where due to external reasons to Europe, a shortage of synthetic fuels may occur, the aim is to observe how the costs and demands of the system vary according to the reduced fuel quantities. Specifically, a reduction of 20%, 40%, and 60% in the amounts of all imports has been studied with respect to the optimum obtained in the scenario presented in Section 4.2.

The results of the study indicate that in the event of an import shortage, the total cost of the system increases, as this is not the optimal scenario with imports. However, the variation of costs is not linear, and it would be more beneficial, for example, to reduce imports by 40% instead of 20% or 60% in the event of a fuel shortage, as shown in Figure 4.15. This may be due to the fact that reducing imports by 20% leads to a new investment in low-producing generation plants, which increases the costs of the system. On the other hand, reducing imports by 40% leads to an increase in installed power but also to higher production, which lowers the extraordinary investment costs incurred compared to the 20% shortage scenario. However, based on the results, it seems that the most economical option in the event of an import shortage would be to design a system without imports.

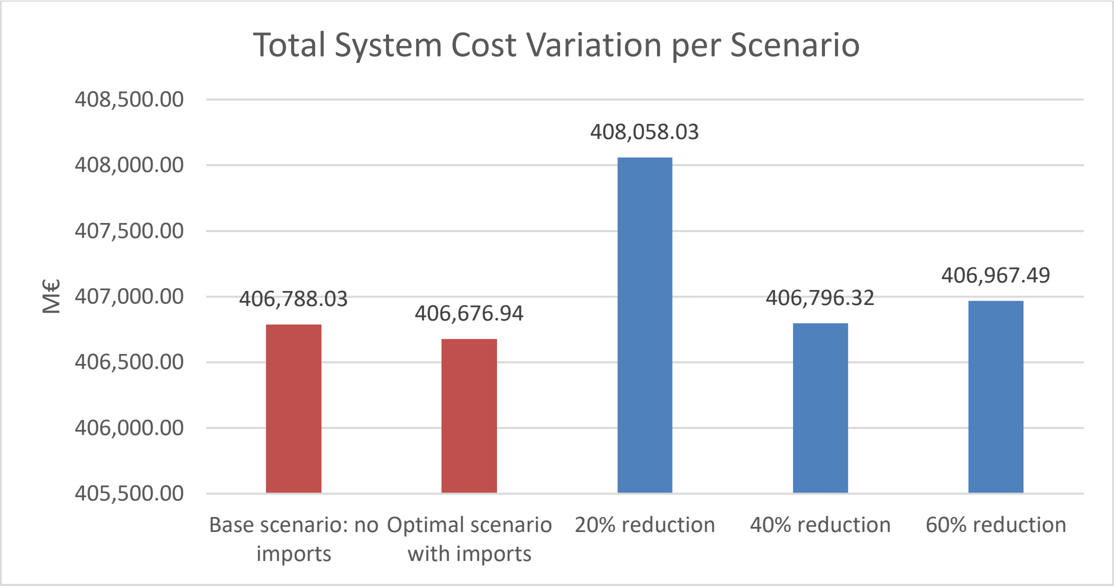


Figure 4.15 Synthetic fuel shortage scenario: system total cost.

Regarding the demand of the system, it can be observed in Figure 4.16 that in the event of a fuel shortage, the demands of all the networks in the system increase slightly despite the increased cost of the system. It can be observed that they increase as the system becomes more expensive. This increase in demand is due to an attempt to optimise the system by increasing production per installed MW as much as possible while considering that the costs of gas, electricity, H_2, and liquid fuels decrease proportionally to the system's demand. Thus, the higher the demand, the lower the cost. The following Figure 4.16 and Figure 4.17 show the demand and installed capacity for this scenario.

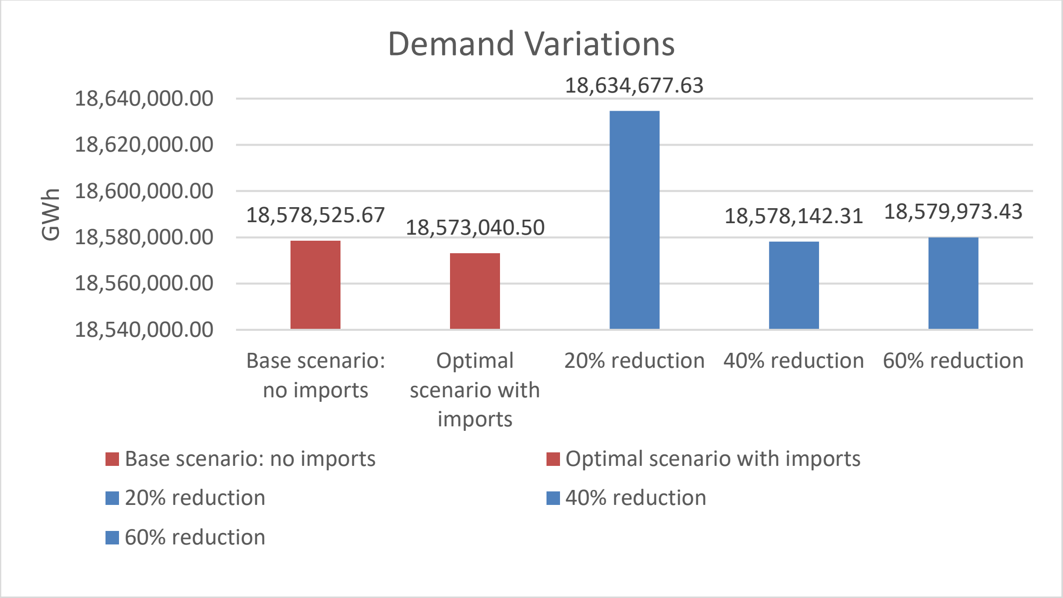


Figure 4.16 Synthetic fuel shortage scenario: demand variation.

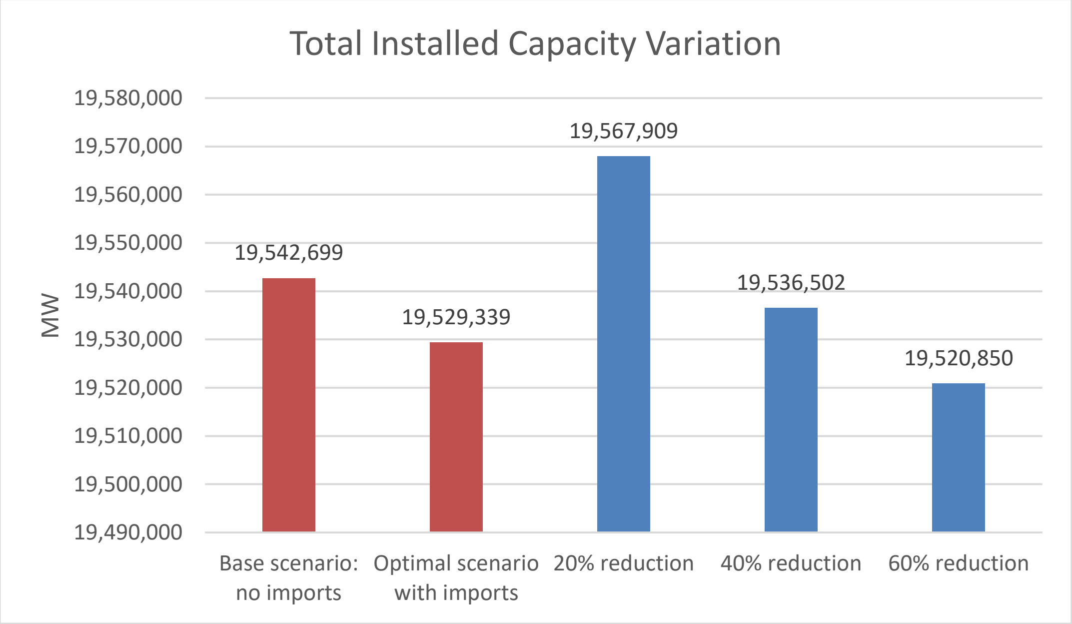


Figure 4.17 Synthetic fuel shortage scenario: total installed capacity variation.

In conclusion, a fuel shortage implies an increase in the total costs of the system, and this increase is not linear. Therefore, a deeper study is necessary to determine the optimal quantity of imports to include in the system to satisfy the demands and ensure that the plants in the system generate as much as possible to lower their investment costs. If there are no means or time to conduct such a study, based on the results obtained, it is recommended not to include synthetic fuel imports in the system in the event of a fuel shortage.

4.3.2 SCENARIO WHERE IMPORTS ARE PROMOTED

In this scenario, Europe decides to encourage the use of synthetic fuel imports, either for political reasons or to use the land designated for synthetic fuel generation for other purposes. To this end, considering that the optimal scenario involves less than 1% of the demand with imports, it has been decided to establish minimum imports corresponding to 5%, 10%, 20%, and 30% of the load. The aim is to assess the expected cost increase relative to the optimal scenario and observe how the system design varies under different import levels.

The results show, as expected, that importing quantities of synthetic fuels above the optimum increases the total cost of the system. In

Figure *4.18*, it can be seen that the further away from the optimum, the costlier the system becomes. Promoting these imports would imply a cost increase of about 2% if covering 5% of the load with imports and 13% if deciding to cover 30% of the load with imports. It seems to be an exponential correlation between the amount of imports imported above the optimum and the total cost of the system.

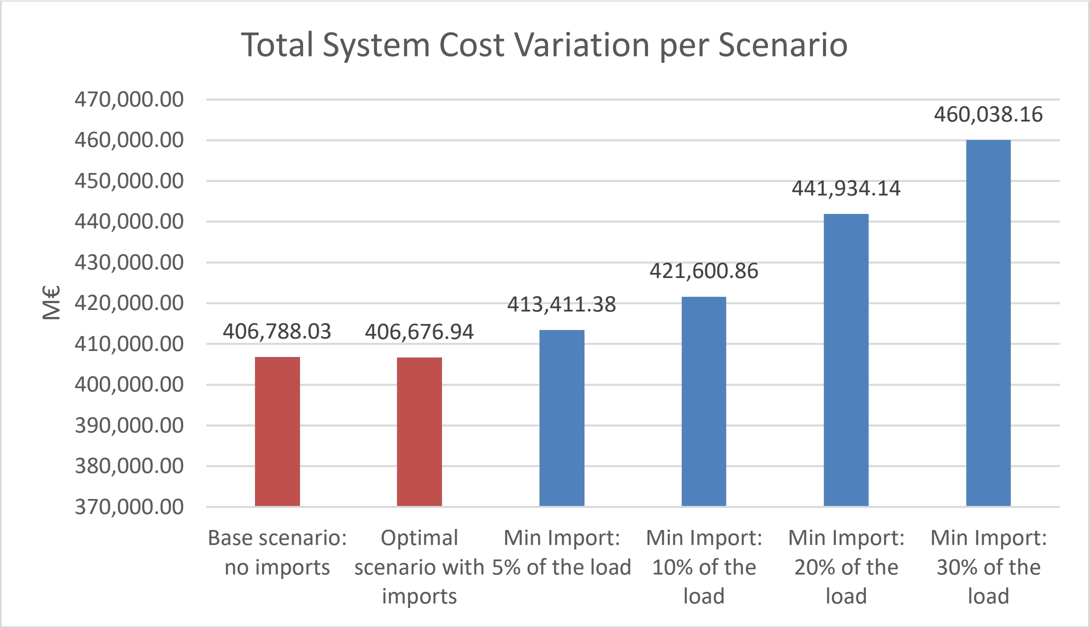


Figure 4.18 Promotion of imports: total system cost.

As the system becomes less efficient, demand also decreases when moving away from the optimum, as shown in

Figure *4.19*. This cost increase and demand reduction are observed not only in systems with imports but also in the electrical system due to the existence of PtX technologies in the system.

Figure 4.19 Promotion of imports: demand variation.

As a result of the above,

Figure *4.20* shows that the installed capacities of almost each technology decrease. However, varying the amount of synthetic fuel imported does not imply changes in the kind of technologies used to generate energy.

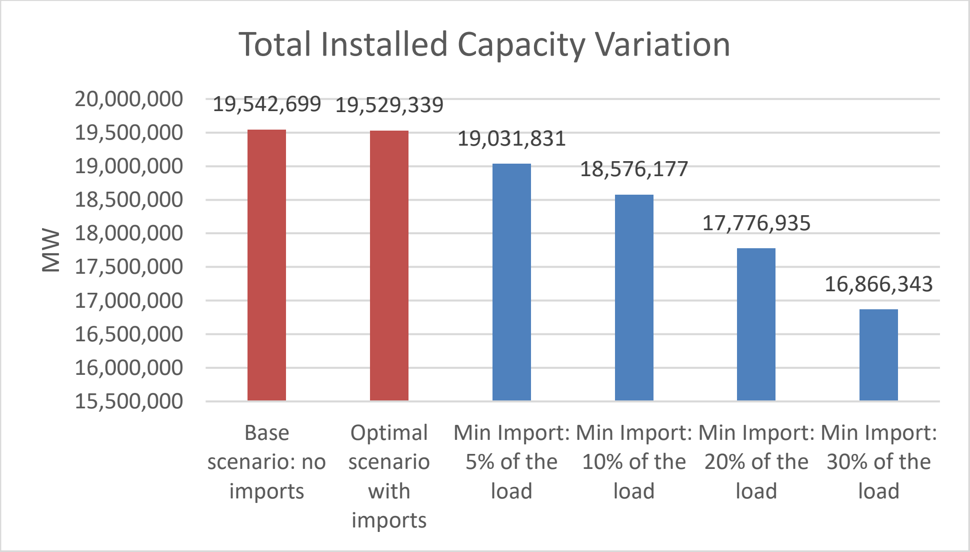


Figure 4.20 Promotion of imports: total installed capacity variation.

On the other hand, prices for gas, H_2, electricity, and liquid fuel decrease because demand for these fuels also decreases as a result of the decrease in efficiency and profitability of the system. This is because prices are largely determined by supply and demand, and if demand decreases, prices also decrease. These pricing changes are depicted in Figure 4.21 for each of the situations evaluated.

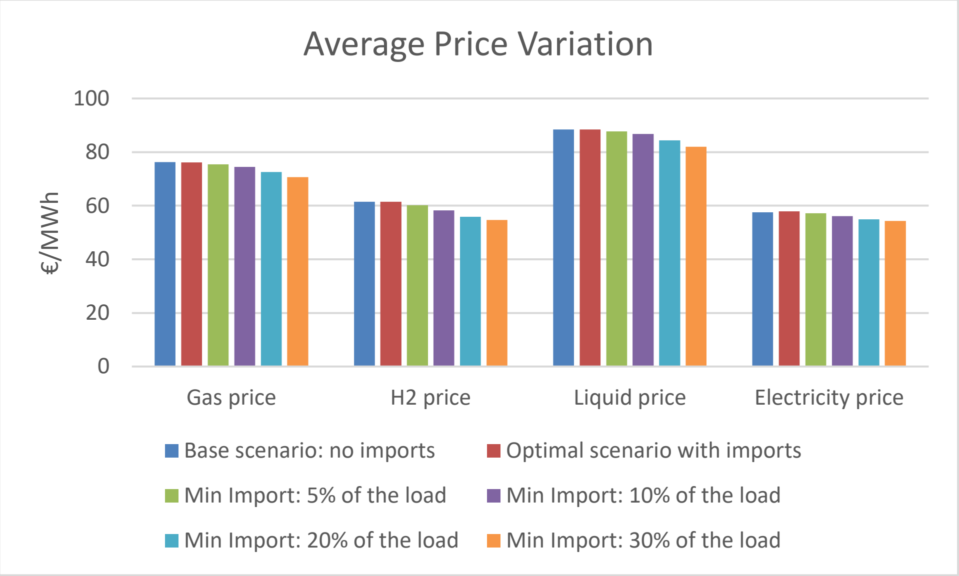


Figure 4.21 Promotion of imports: price variation.

In conclusion, the analysis shows that the quantity of synthetic fuels imported plays a critical role in the design and cost of the energy system. Surpassing the optimal level of synthetic fuel imports can lead to an increase in costs, potentially impacting the profitability of the system, as the cost rises at the same time that demand and installed capacity are reduced. Therefore, it is crucial to carefully consider the optimal level of synthetic fuel imports to achieve a balance between cost and system performance. Additionally, it is essential to assess how much excess cost Europe is willing to incur to allocate land intended for synthetic fuel generation to other purposes, considering that the cost-to-quantity ratio is exponential. These factors must be considered when formulating energy policies to ensure a sustainable and cost-effective energy system.

4.3.3 SCENARIO OF AN INCREASE IN IMPORT PRICES

In recent years, it has been observed that conflicts and geopolitical tensions can cause significant fluctuations in the prices of imported fuels. For this reason, an increase in synthetic fuel import prices may occur. Thus, this scenario aims to investigate the potential effects of an increase in import prices compared to the previously assumed prices. The analysis will enable the assessment of how changes in import prices affect the optimal solution for the system.

In this case, the specific scenario of an increase in H_2 prices will be analysed by considering that the price of H_2 increases by 25%, 50%, and 100% compared to the previously assumed price of 115.71 €/MWh.

After simulating these price increases, it is observed that as the price of H_2 imports increases, the quantity of imports decreases. It is also worth noting that by modifying only the price of H_2 imports, it affects the rest of the imports, as can be seen in

Figure *4.22*, where in response to an increase in this price, imports of all synthetic fuels decrease. This indicates that H_2 imports have a significant influence on the overall import of synthetic fuels.

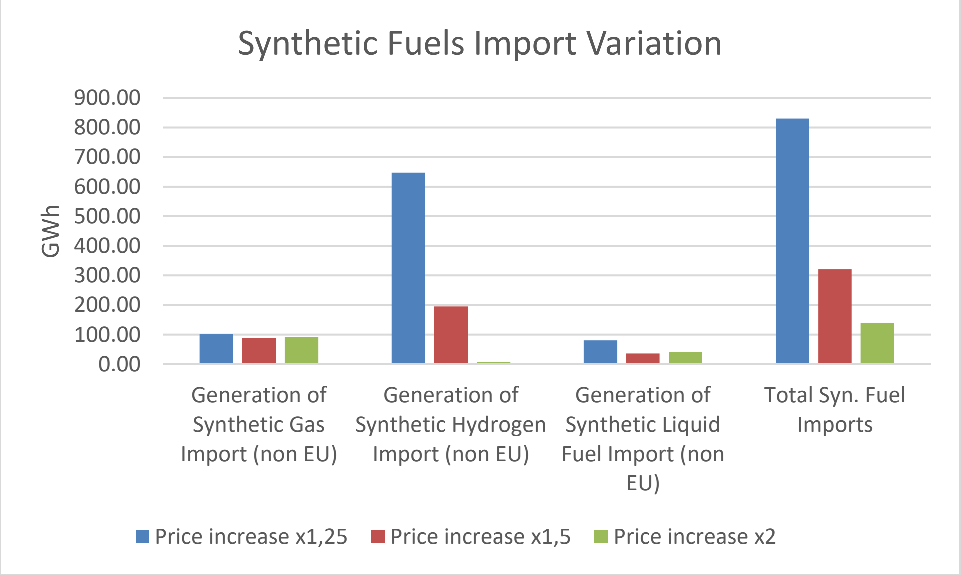


Figure 4.22 Increase in import price: price variation.

The results depicted in

Figure *4.23*,

Figure *4.24*, and Figure 4.25 also indicate that variations in the price of H_2 imports have a significant impact on the overall design of the system. Even a slight change in one of the prices results in an increase in the total cost of the system and an increase in demand, which is directly related to an increase in installed system capacity. There is a direct correlation between total costs, demand, and installed capacity, where more installed capacity and increased demand result in higher costs. Also, optimising the system involves maximising the power generated by the installed capacity to proportionally reduce investment costs, and hence, if a variable changes, the optimised model changes.

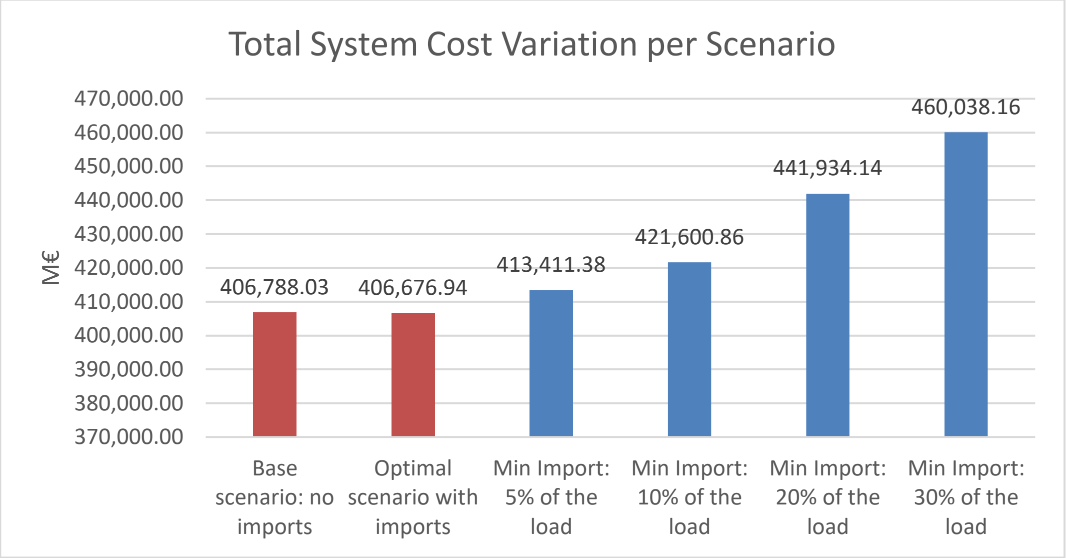


Figure 4.23 Increase in import price: system total cost.

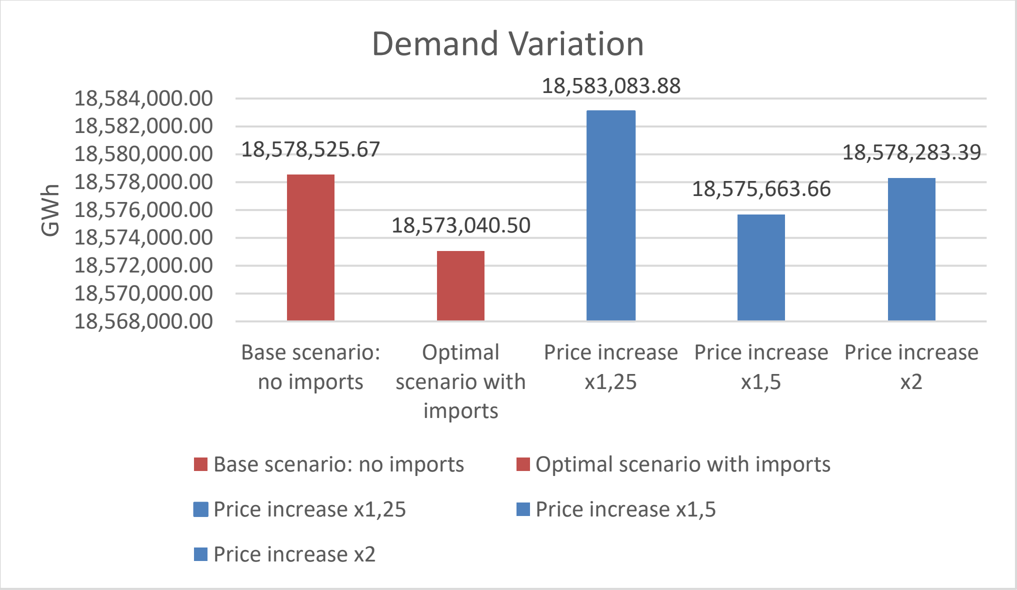


Figure 4.24 Increase in import price: demand variation.

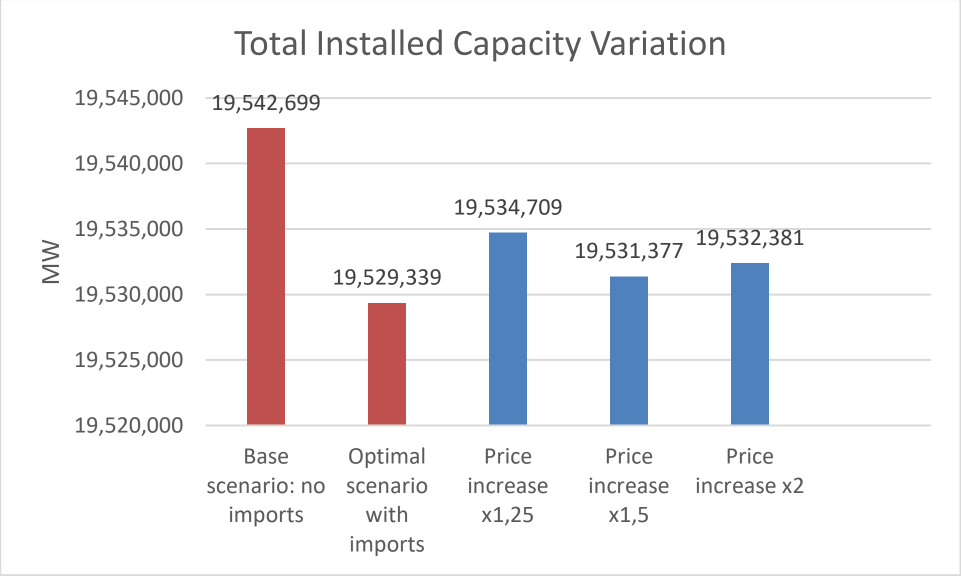


Figure 4.25 Increase in import price: total installed capacity variation.

On the other hand, since imports carry very little weight in the system, in Figure 4.26 it can be observed that there is no significant relationship between the average price of gas, H_2, electricity, and liquids and the increase in the price of H_2 imports, since these average prices vary more depending on demand.

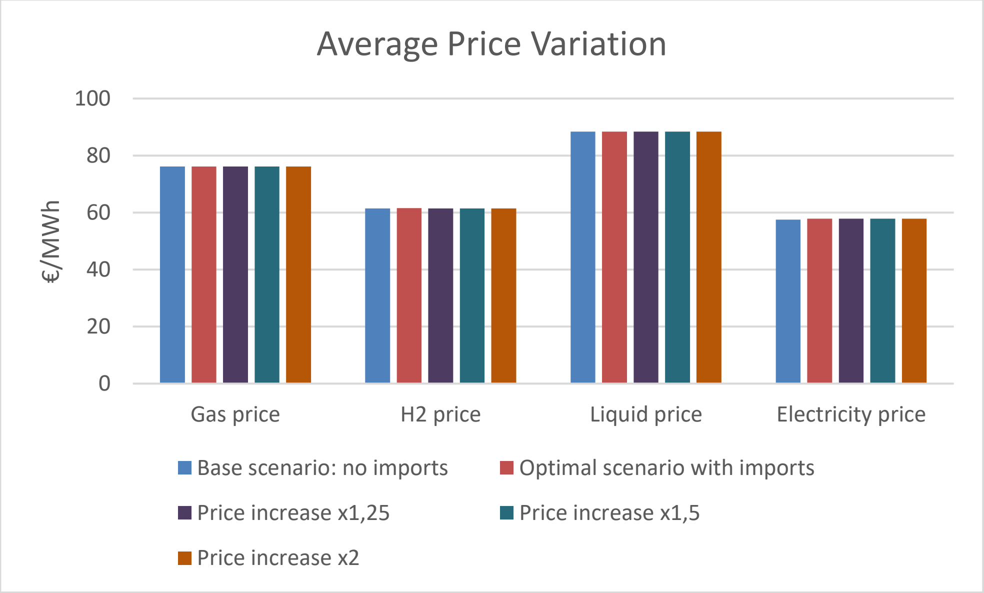


Figure 4.26 Increase in import price: average price variation.

Based on the results, it can be concluded that increasing the price of H_2 imports implies a reduction in the imported quantities of all synthetic fuels. However, it cannot be said that the more expensive the imports, the less is imported, and therefore, the more expensive the system becomes. The results show that the system becomes cheaper when the price increases by 150% compared to 125%. This is largely because imports in the optimal scenario account for less than 1% of the system, which indicates that they are primarily used to avoid building new plants that would produce very little. The variations between each scenario show that the increase in H_2 prices has a negative effect on the costs associated with the design of the energy system, but that this effect is not linear. Therefore, no generalisations can be made beyond the fact that it is still beneficial to consider imports in the system even with increased prices.

4.3.4 CONCLUSIONS

After examining different scenarios, there is a correlation between the results obtained in a scenario of fuel shortage and a scenario of increase in import prices, and this is because, in the end, both scenarios imply a reduction in the imports of synthetic fuels considered in the system. This is in contrast with the other scenario, in which the use of imports is promoted and shows an increase in the amount of imported synthetic fuels into the system. However, among the scenarios studied, it seems that forcing the importation of large quantities of synthetic fuels is the worst scenario, as it implies a high extra cost in the design of the system, due to the exponential relationship between cost and imports.

Chapter 5. SUMMARY AND OUTLOOK

5.1 SUMMARY

The aim of this study was to investigate the effects of including imports of synthetic fuels in the European energy system. To do so, first a theoretical analysis was conducted to obtain possible import prices, supply chains, and favourable export and import locations regarding the import of synthetic fuels to Europe. Then, a function was implemented in the existing model to introduce the imports into the system. Once the input data and the model were updated to include the imports, an analysis was conducted to assess the influence of the imports of synthetic fuels on the design of the energy system.

After comparing the optimal design of a scenario without imports and one with imports, it can be concluded that including imports of synthetic fuels in the energy system can result in a reduction of the total system costs. However, the inclusion of these imports should be done moderately, as they cover less than 1% of the demand in the optimal model due to their high costs compared to the generation within the system.

The sensitivity analysis showed that any variation in imports, due to price increases, reductions in imports, or an imposition to import above the optimum, results in an increase in total system costs, but it does not always result in a cost increase with respect to the base scenario without imports. The optimisation model adjusts the system by modifying the demands and installed capacities, among other things, with the aim of ensuring that the installed capacity produces the maximum amount of energy, thus reducing its fixed investment cost. Therefore, no clear pattern was obtained with respect to imports and the cost reduction or increase. However, it was observed that price increases and fuel shortages affect the model in the same way by reducing the imports in the system. Another finding was that the increase in the price of imported hydrogen affects the amount of all synthetic fuel imported. Additionally, it was observed that importing beyond the optimum results in exponentially higher costs.

Moreover, due to the existence of PtX technologies, it was observed that a variation in the imports of gas, H_2, and liquid systems affects the design of the electricity system, indicating that the design of the systems included in the model is not independent.

In summary, including imports of synthetic fuels in the design of the European energy system can lead to a reduction in system costs. However, this study shows that importing above or below the optimum, as obtained with unlimited imports beyond physical constraints, can result in an additional cost to the system compared to the base scenario without imports. Therefore, before designing the system, a study should be conducted with the actual constraints on imports to determine whether imports would lead to a cost reduction or not.

5.2 OUTLOOK

The results obtained from this study suggest that further investigation is necessary to determine the cost-effectiveness of including imports of synthetic fuels in the European energy system. The results of this study indicate the need for further investigation to determine the cost-effectiveness of including imports of synthetic fuels in the European energy system. In order to achieve this, it is recommended to incorporate the CAPEX associated with imports, which were originally calculated in the preliminary theoretical analysis to generate the input scenario but were ultimately not included due to limitations in the MATLAB function.

Additionally, the current findings demonstrate that imports of synthetic fuels only meet 1% of the energy demand. Therefore, it may be necessary to revise the input data used for the base model and the input data introduced for the imports. One possible explanation for these results is that the generating plants included in the base model have a CAPEX but operate at zero cost, unlike the imports. One option is to re-evaluate the OPEX associated with imports, as they may be too high and may be impacting the overall cost-effectiveness of including synthetic fuel imports in the energy system.

Furthermore, the study highlights the importance of conducting further sensitivity analyses to explore the system's sensitivity to changes in imports. To this end, conducting more simulations with smaller variations would provide a better understanding of the system's behaviour when imports are modified. Moreover, I would recommend including a sensitivity analysis for a scenario in which import prices decrease. This additional analysis would likely provide valuable insights into the reasons why the optimal solution involves such a low level of imports.

Overall, this study provides insights into the potential economic benefits of including synthetic fuel imports in the European energy system, but it also raises important questions about the potential environmental impacts of such a move. The use of synthetic fuels can lead to reduced greenhouse gas emissions, but their production requires significant amounts of energy and resources, which may result in negative environmental impacts. Therefore, it is necessary to conduct further research to determine the potential environmental impacts of including the import of synthetic fuels in the design of the energy system.

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APPENDIX I BASE SCENARIO INPUT DATA

This appendix includes tables containing data calculated from the theoretical analysis conducted in Chapter Chapter 3. These tables show the most relevant data used in the input scenario for synthetic fuel imports.

FT-fuel Ship Imports						
Port	**Crude Oil Capacity (MWh)**	**Facility Import capacity (MW)**	**Import Cost (€/MWh)**	**O&M cost (€/MWh)**	**TOTAL OPEX (€/MWh)**	**TOTAL CAPEX (€/MW)**
Antwerp	408,663,772.52	46,651.12	126.31	5.32	131.63	30,356.27
Burgas	81,099,013.80	9,257.88	126.31	5.32	131.63	30,356.27
Baden-Wurttemberg	198,287,080.60	22,635.51	126.81	5.32	132.13	30,356.27
Bavaria	14,422,963.57	1,646.46	126.81	5.32	132.13	30,356.27
Hamburg	150,606,546.16	17,192.53	126.81	5.32	132.13	30,356.27
Bremen	6,407,468.16	731.45	126.81	5.32	132.13	30,356.27
Bavaria	54,194,109.46	6,186.54	126.81	5.32	132.13	30,356.27
Zealand	51,760,478.00	5,908.73	126.81	5.32	132.13	30,356.27
Attica	67,742,636.83	7,733.18	126.50	5.32	131.83	30,356.27
Attica	18,028,704.47	2,058.07	126.50	5.32	131.83	30,356.27
Thessaloniki	188,258,182.70	21,490.66	126.50	5.32	131.83	30,356.27
Corinth	8,009,335.20	914.31	126.50	5.32	131.83	30,356.27
Galicia	28,119,479.20	3,209.99	125.89	5.32	131.22	30,356.27
Basque Country	80,414,704.60	9,179.76	125.89	5.32	131.22	30,356.27
Catalonia	111,887,541.95	12,772.55	125.89	5.32	131.22	30,356.27
Andalusia	111,887,541.95	12,772.55	125.89	5.32	131.22	30,356.27
Andalusia	28,119,479.20	3,209.99	125.89	5.32	131.22	30,356.27
Murcia	111,887,541.95	12,772.55	125.89	5.32	131.22	30,356.27
Southern Finland	65,950,381.03	7,528.58	127.08	5.32	132.40	30,356.27
Western Finland	295,668,582.86	33,752.12	127.08	5.32	132.40	30,356.27
Calvados	8,012,757.54	914.70	126.50	5.32	131.83	30,356.27
Calvados	3,559,704.53	406.36	126.50	5.32	131.83	30,356.27
Seine-Maritime	83,015,767.02	9,476.69	126.50	5.32	131.83	30,356.27
Seine-Maritime	35,280,272.33	4,027.43	126.50	5.32	131.83	30,356.27
Loire	83,670,303.42	9,551.40	126.50	5.32	131.83	30,356.27

Rhone	12,706,713.95	1,450.54	126.50	5.32	131.83	30,356.27
Bouches-du-Rhone	65,704,129.52	7,500.47	126.50	5.32	131.83	30,356.27
Bouches-du-Rhone	110,159,489.22	12,575.28	126.50	5.32	131.83	30,356.27
Bouches-du-Rhone	30,107,838.59	3,436.97	126.50	5.32	131.83	30,356.27
Sisacko-Moslavacka	43,966,920.68	5,019.05	126.54	5.32	131.86	30,356.27
Licko-Senjska	8,062,846.40	920.42	126.54	5.32	131.86	30,356.27
Primorsko-Goranska	17,253,492.67	1,969.58	126.54	5.32	131.86	30,356.27
Genoa	12,706,713.95	1,450.54	126.45	5.32	131.78	30,356.27
Cremona	83,670,303.42	9,551.40	126.45	5.32	131.78	30,356.27
Taranto	6,675,042.53	761.99	126.45	5.32	131.78	30,356.27
Trieste	87,023,643.74	9,934.21	126.45	5.32	131.78	30,356.27
Messina	83,015,767.02	9,476.69	126.45	5.32	131.78	30,356.27
Syracuse	35,280,272.33	4,027.43	126.45	5.32	131.78	30,356.27
Syracuse	14,652,158.59	1,672.62	126.45	5.32	131.78	30,356.27
Venice	21,870,706.04	2,496.66	126.45	5.32	131.78	30,356.27
Syracuse	12,001,029.28	1,369.98	126.45	5.32	131.78	30,356.27
Klaipeda	57,180,212.80	6,527.42	127.08	5.32	132.40	30,356.27
Klaipeda	373,570,951.60	42,645.09	127.08	5.32	132.40	30,356.27
Zuid-Holland	79,380,612.74	9,061.71	126.31	5.32	131.63	30,356.27
Zuid-Holland	32,967,356.84	3,763.40	126.31	5.32	131.63	30,356.27
Zeeland	186,785,475.80	21,322.54	126.31	5.32	131.63	30,356.27
pomorskie	317,522,450.96	36,246.86	126.81	5.32	132.13	30,356.27
Porto	65,934,713.67	7,526.79	126.12	5.32	131.44	30,356.27
Setubal	54,004,631.76	6,164.91	126.12	5.32	131.44	30,356.27
Constanta	108,009,263.52	12,329.82	127.08	5.32	132.40	30,356.27
Sodermanland	65,612,118.13	7,489.97	126.37	5.32	131.70	30,356.27
Vastra Gotaland	65,612,118.13	7,489.97	126.37	5.32	131.70	30,356.27
Vastra Gotaland	187,634,310.73	21,419.44	126.37	5.32	131.70	30,356.27
Bratislava	60,075,382.79	6,857.92	126.37	5.32	131.70	30,356.27
York	80,414,704.60	9,179.76	129.69	5.32	135.01	30,356.27
Cheshire	80,414,704.60	9,179.76	129.69	5.32	135.01	30,356.27
Lincolnshire	80,414,704.60	9,179.76	129.69	5.32	135.01	30,356.27
Hampshire	80,414,704.60	9,179.76	129.69	5.32	135.01	30,356.27
Essex	80,414,704.60	9,179.76	129.69	5.32	135.01	30,356.27
Pembrokeshire	80,414,704.60	9,179.76	129.69	5.32	135.01	30,356.27
Stirling	80,414,704.60	9,179.76	129.69	5.32	135.01	30,356.27

TableA.1 FT-fuel ship imports input data

SNG Ship Imports

Country	Name of installation	Annual Import Capacity scenario 2050(MWh)	Annual Import Capacity installed (MW)	Import cost (€/MWh)	O&M cost (€/MWh)	CAPEX (€/MW)	OPEX (€/MWh)
Belgium	Zeebrugge LNG Terminal	87,924,999.96	10,037.10	129.69	0.03	3,448.74	129.72
Belgium	Zeebrugge LNG Terminal	0.00	0.00	129.69	0.03	3,448.74	129.72
Germany	Rostock transshipment LNG terminal	0.00	0.00	130.35	0.03	3,448.74	130.38
Germany	LNG Stade GmBh	78,155,555.52	8,921.87	130.35	0.03	3,448.74	130.38
Germany	Wilhelmshaven	97,694,444.40	11,152.33	130.35	0.25	1,693.72	130.60
Germany	Brunsbüttel LNG terminal	78,155,555.52	8,921.87	130.35	0.03	3,448.74	130.38
Estonia	Paldiski LNG Terminal	24,423,611.10	2,788.08	130.88	0.03	3,448.74	130.91
Estonia	TallinnLNG	39,077,777.76	4,460.93	130.88	0.03	3,448.74	130.91
Greece	Revithoussa LNG Terminal	68,386,111.08	7,806.63	130.01	0.03	3,448.74	130.05
Greece	Alexandroupolis LNG terminal	59,593,611.08	6,802.92	130.01	0.25	1,693.72	130.26
Spain	Mugardos LNG Terminal	35,169,999.98	4,014.84	128.98	0.03	3,448.74	129.02
Spain	Mugardos LNG Terminal	0.00	0.00	128.98	0.03	3,448.74	129.02
Spain	Mugardos LNG Terminal	0.00	0.00	128.98	0.03	3,448.74	129.02
Spain	Mugardos LNG Terminal	35,169,999.98	4,014.84	128.98	0.03	3,448.74	129.02
Spain	Gijón (Musel) LNG terminal	68,386,111.08	7,806.63	128.98	0.03	3,448.74	129.02
Spain	Bilbao LNG terminal	85,971,111.07	9,814.05	128.98	0.03	3,448.74	129.02
Spain	Barcelona LNG Terminal	167,057,499.92	19,070.49	128.98	0.03	3,448.74	129.02
Spain	Sagunto LNG terminal	85,971,111.07	9,814.05	128.98	0.03	3,448.74	129.02
Spain	Huelva LNG Terminal	115,279,444.39	13,159.75	128.98	0.03	3,448.74	129.02
United Kingdom	Gibraltar LNG Terminal	1,953,888.89	223.05	129.69	0.03	3,448.74	129.72
Spain	Cartagena LNG Terminal	115,279,444.39	13,159.75	128.98	0.03	3,448.74	129.02
Finland	Rauma LNG terminal	0.00	0.00	130.88	0.03	3,448.74	130.91
Finland	Tahkoluoto/Pori LNG Terminal	976,944.44	111.52	130.88	0.03	3,448.74	130.91

Finland	Hamina LNG terminal	0.00	0.00	130.88	0.03	3,448.74	130.91
Finland	Tornio Manga LNG terminal	3,907,777.78	446.09	130.88	0.03	3,448.74	130.91
France	Dunkerque LNG Terminal	127,002,777.72	14,498.03	129.59	0.03	3,448.74	129.63
France	Montoir-de-Bretagne LNG Terminal	97,694,444.40	11,152.33	129.59	0.03	3,448.74	129.63
France	Montoir-de-Bretagne LNG Terminal	24,423,611.10	2,788.08	129.59	0.03	3,448.74	129.63
France	Montoir-de-Bretagne LNG Terminal	0.00	0.00	129.59	0.03	3,448.74	129.63
France	Fos Cavaou LNG Terminal	80,597,916.63	9,200.68	129.59	0.03	3,448.74	129.63
France	Fos Cavaou LNG Terminal	26,865,972.21	3,066.89	129.59	0.03	3,448.74	129.63
France	Fos Cavaou LNG Terminal	53,731,944.42	6,133.78	129.59	0.03	3,448.74	129.63
France	Fos-Tonkin LNG Terminal	29,308,333.32	3,345.70	129.59	0.03	3,448.74	129.63
Croatia	Krk Island LNG terminal, Omišal	25,400,555.54	2,899.61	130.30	0.25	1,693.72	130.55
Ireland	Cork LNG Terminal	39,077,777.76	4,460.93	129.24	0.25	1,693.72	129.49
Ireland	Shannon LNG terminal	100,625,277.73	11,486.90	129.24	0.03	3,448.74	129.28
Italy	Panigaglia LNG terminal	33,216,111.10	3,791.79	129.48	0.03	3,448.74	129.52
Italy	Porto Empedocle (Sicilia) LNG terminal	78,155,555.52	8,921.87	129.48	0.03	3,448.74	129.52
Italy	Oristano - Santa Giusta LNG Terminal	0.00	0.00	129.48	0.03	3,448.74	129.52
Italy	Porto Levante LNG terminal	74,052,388.86	8,453.47	129.48	0.03	3,448.74	129.52
Italy	Ravena LNG terminal	0.00	0.00	129.48	0.03	3,448.74	129.52
Italy	FSRU OLT Offshore LNG Toscana	37,123,888.87	4,237.89	129.48	0.25	1,693.72	129.73
Lithuania	FSRU Independence	39,077,777.76	4,460.93	130.69	0.25	1,693.72	130.93
Latvia	Kundzinsalas (Riga)	0.00	0.00	130.69	0.03	3,448.74	130.72
Latvia	Skulte LNG terminal	48,847,222.20	5,576.17	130.69	0.25	1,693.72	130.93
Netherlands	Gate terminal, Rotterdam	117,233,333.28	13,382.80	129.69	0.03	3,448.74	129.72
Netherlands	Gate terminal, Rotterdam	39,077,777.76	4,460.93	129.69	0.03	3,448.74	129.72
Poland	Swinoujscie LNG Terminal	48,847,222.20	5,576.17	130.46	0.03	3,448.74	130.50

Poland	Swinoujscie LNG Terminal	24,423,611.10	2,788.08	130.46	0.03	3,448.74	130.50
Poland	Swinoujscie LNG Terminal	0.00	0.00	130.46	0.03	3,448.74	130.50
Poland	FSRU Polish Baltic Sea Coast	81,086,388.85	9,256.44	130.46	0.25	1,693.72	130.71
Portugal	Sines LNG Terminal	74,247,777.74	8,475.77	129.17	0.03	3,448.74	129.20
Sweden	Nynäshamn LNG terminal	2,930,833.33	334.57	129.98	0.03	3,448.74	130.02
Sweden	Göteborg LNG terminal	4,884,722.22	557.62	129.98	0.03	3,448.74	130.02
Sweden	Lysekil LNG Terminal	2,930,833.33	334.57	129.98	0.03	3,448.74	130.02
Sweden	Gävle LNG terminal	2,930,833.33	334.57	129.98	0.03	3,448.74	130.02
United Kingdom	Trafigura Teeside LNG terminal	41,031,666.65	4,683.98	129.69	0.03	3,448.74	129.72
United Kingdom	Port Meridian LNG terminal	48,847,222.20	5,576.17	129.69	0.25	1,693.72	129.93
United Kingdom	Isle of Grain LNG terminal	190,504,166.58	21,747.05	129.69	0.03	3,448.74	129.72
United Kingdom	Isle of Grain LNG terminal	73,270,833.30	8,364.25	129.69	0.03	3,448.74	129.72
United Kingdom	Milford Haven - Dragon LNG terminal	74,247,777.74	8,475.77	129.69	0.03	3,448.74	129.72
United Kingdom	Milford Haven - South Hook LNG terminal	205,158,333.24	23,419.90	129.69	0.03	3,448.74	129.72

Table A.1 SNG ship imports input data

SNG Pipeline Imports						
Name	**Km**	**Pipe Size (inch)**	**Commissioning year**	**Max Import Capacity (MWh)**	**Total OPEX cost (€/MWh)**	**Annuity CAPEX (€/MW)**
Zeepipe I	1,416.00	40	1993	146,541,666.60	0.50	2,519.50
Interconnector	235.00	40	1998	249,120,833.22	0.07	351.64
Europipe I	660.00	40	1995	175,849,999.92	0.37	1,847.98
Europipe II	658.00	42	1999	234,466,666.56	0.14	689.74
Maghreb Europe	1,620.00	48	1996	117,233,333.28	0.63	3,136.80
MEDGAZ	757.00	24	2011	78,155,555.52	0.43	2,169.95
Franpipe	840.00	42	1998	191,481,111.02	0.15	764.90
Transmediterranian	2,475.00	2x48	1983	327,276,388.74	0.61	3,053.35
Green Stream	520.00	32	2004	107,463,888.84	1.96	9,819.56

Baltic pipe	275.00	32	2023	97,694,444.40	0.12	614.22
Transgas	4,000.00	48	1973	1,172,333,332.80	0.98	4,909.78

Table A.2 SNG pipeline imports input data.

H_2 Pipeline Imports						
From	**To**	**Km**	**Pipe Size (inch)**	**Max Import Capacity (MWh)**	**Total OPEX cost (€/MWh)**	**pipeline CAPEX (€)**
Morocco	Spain	1620	48	14,654,166.66	93.65	2,267,044.20
Algeria	Spain	757	24	9,769,444.44	94.60	2,118,706.74
Algeria	Italy	2475	2x48	40,298,958.32	95.99	3,463,539.75
Libya	Italy	520	32	13,432,986.11	94.11	1,455,386.40
Norway	Poland	275	32	12,211,805.55	95.80	769,675.50
Norway	Germany	660	40	21,981,249.99	96.53	1,477,776.96
Norway	Germany	658	42	29,308,333.32	96.34	1,289,136.49
Norway	France	840	42	23,935,138.88	96.71	1,645,706.16
Norway	Belgium	1416	40	18,317,708.33	98.29	3,170,503.30
UK	Belgium	235	40	31,140,104.15	100.55	526,178.16
UK	Netherlands	235	36	23,202,430.55	100.68	657,722.70
Ukraine	Europe (SK)	4000	48	146,541,666.60	136.10	11,195,280.00

Table A.3 H_2 pipeline imports input data

H_2 Ship Imports						
Country	**Port**	**Import Capacity (H_2 gas) (MWh)**	**Installed Import Capacity (H_2 gas) (MW)**	**Import Cost (€/MWh)**	**Total Import CAPEX (€/MW)**	**Total Import OPEX (€/MWh)**
Belgium	Antwerp	31,491,862.21	3,594.96	120.82	62,200.00	2,191.32
Belgium	Ostend	157,459.31	17.97	120.82	62,200.00	2,191.32
Denmark	Kalundborg	2,624.32	0.30	122.85	62,200.00	2,193.35
Denmark	Frederikshavn	262,432,185.12	29,958.01	122.85	62,200.00	2,193.35
Finland	Kemi	13,121.61	1.50	125.32	62,200.00	2,195.82
Finland	Tornio	52,486.44	5.99	125.32	62,200.00	2,195.82
France	Dunkirk	236,188.97	26.96	119.05	62,200.00	2,189.55
France	Fécamp	15,745.93	1.80	119.05	62,200.00	2,189.55
France	Le Havre	10,497.29	1.20	119.05	62,200.00	2,189.55
France	Nantes Saint-Nazaire	5,248.64	0.60	119.05	62,200.00	2,189.55
France	Sete	13,121.61	1.50	119.05	62,200.00	2,189.55
Germany	Bremerhaven	39,364.83	4.49	122.09	62,200.00	2,192.59

Germany	Hamburg	26,243.22	3.00	122.09	62,200.00	2,192.59
Germany	Stade	157,459.31	17.97	122.09	62,200.00	2,192.59
Germany	Wilhelmshaven	23,618.90	2.70	122.09	62,200.00	2,192.59
Latvia	Ventspils	52,486.44	5.99	124.90	62,200.00	2,195.40
Netherlands	Amsterdam	131,216,092.56	14,979.01	120.85	62,200.00	2,191.35
Netherlands	Rotterdam	131,216,092.56	14,979.01	120.85	62,200.00	2,191.35
Netherlands	Terneuzen	5,248.64	0.60	120.85	62,200.00	2,191.35
Netherlands	Vlissingen	15,745.93	1.80	120.85	62,200.00	2,191.35
Portugal	Sines	157,459.31	17.97	117.35	62,200.00	2,187.85
Sweden	Nynäshamn	13,121.61	1.50	122.14	62,200.00	2,192.64
UK	Grangemouth	20,994.57	2.40	122.85	62,200.00	2,193.35

Table A.4 H_2 ship imports via liquid H2 input data

H_2 Ship Imports						
Country	**Port**	**Import Capacity (H_2 gas) (MWh)**	**Installed Import Capacity (H_2 gas) (MW)**	**Import Cost (€/MWh)**	**Total Import CAPEX (€/MW)**	**Total Import OPEX (€/MWh)**
Belgium	Antwerp	2,108.83	0.24	106.92	56,700.00	482.67
Belgium	Ghent	943.71	0.11	106.92	56,700.00	482.67
Belgium	Zeebrugge	2,359.29	0.27	106.92	56,700.00	482.67
France	Dunkirk	42,467.17	4.85	106.37	56,700.00	482.12
France	Le Havre	235.93	0.03	106.37	56,700.00	482.12
France	Marseille	235.93	0.03	106.37	56,700.00	482.12
France	Montoir-de-Bretagne	235.93	0.03	106.37	56,700.00	482.12
France	Sète	235.93	0.03	106.37	56,700.00	482.12
Germany	Brunsbüttel	471.86	0.05	107.86	56,700.00	483.61
Germany	Hamburg	471.86	0.05	107.86	56,700.00	483.61
Germany	Rostock	4,718.57	0.54	107.86	56,700.00	483.61
Greece	Alexandroupolis	707.79	0.08	107.19	56,700.00	482.94
Greece	Kavala	471.86	0.05	107.19	56,700.00	482.94
Greece	Patras	235.93	0.03	107.19	56,700.00	482.94
Greece	Piraeus	1,179.64	0.13	107.19	56,700.00	482.94
Italy	Ravenna	4,718.57	0.54	106.55	56,700.00	482.30
Italy	Trieste	235.93	0.03	106.55	56,700.00	482.30

Italy	Venice	471.86	0.05	106.55	56,700.00	482.30
Netherlands	Rotterdam	23,592.87	2.69	106.92	56,700.00	482.67
Netherlands	Vlissingen/Terneuzen	943.71	0.11	106.92	56,700.00	482.67
Portugal	Sines	28,311.44	3.23	105.49	56,700.00	481.24
Spain	Algeciras	471.86	0.05	105.68	56,700.00	481.43
Spain	Barcelona	235.93	0.03	105.68	56,700.00	481.43
Spain	Bilbao	235.93	0.03	105.68	56,700.00	481.43
Spain	Cartagena	471.86	0.05	105.68	56,700.00	481.43
Spain	Huelva	471.86	0.05	105.68	56,700.00	481.43
Spain	Sagunto	235.93	0.03	105.68	56,700.00	481.43
UK	Aberdeen	235.93	0.03	107.92	56,700.00	483.67
UK	Immingham	943.71	0.11	107.92	56,700.00	483.67
UK	Liverpool	471.86	0.05	107.92	56,700.00	483.67
UK	Southampton	94.37	0.01	107.92	56,700.00	483.67

Table A.5 H_2 ship imports via green ammonia input data

H_2 Ship Imports						
Country	**Port**	**Import Capacity (H_2 gas) (MWh)**	**Installed Import Capacity (H_2 gas) (MW)**	**Import Cost (€/MWh)**	**Total Import CAPEX (€/MW)**	**Total Import OPEX (€/MWh)**
Netherlands	Rotterdam	732.23	0.08	128.69	53,700.00	380.69
Germany	Hamburg	2,928.93	0.33	128.92	53,700.00	380.92
Poland	Gdansk	2,928.93	0.33	129.14	53,700.00	381.14
Belgium	Antwerp	117.16	0.01	128.69	53,700.00	380.69
Spain	Bilbao	1,464.47	0.17	127.92	53,700.00	379.92
Portugal	Lisbon	175.74	0.02	127.74	53,700.00	379.74
France	Marseille	1,464.47	0.17	128.16	53,700.00	380.16
Italy	Ravenna	292.89	0.03	128.24	53,700.00	380.24
Germany	Rostock	878.68	0.10	128.92	53,700.00	380.92
France	Dunkirk	234.31	0.03	128.16	53,700.00	380.16
Portugal	Porto	732.23	0.08	127.74	53,700.00	379.74

Table A.6 H_2 ship imports via green methanol input data

APPENDIX II ADDIMPORTFUELTONODE FUNCTION CODE

```
function [modelDesc] = addImportFuelToNode(nodeID, nodeDesc, T_length, year,...
    T_frame, T_slice,T_length_segmented,importMax,OPEXMWh, CAPEXMW, name,...
    idC0, idV0,
bOutNames,flName,emissionDesc,emid,EMISSIONOp,totalMaxImport,totalMinImport)
%% function without capex

if ~isempty(T_length_segmented)
    T_slice = T_length/length(T_length_segmented);
else
    T_length_segmented = repmat(T_slice,1,T_length/T_slice);
end

nNodes = length(nodeID);
nCons = 1;
nVars = (nNodes*T_length/T_slice);

importMax = nxInputArray(importMax, nodeID);
OPEXMWH = nxInputArray(OPEXMWh, nodeID);
%CAPEXMW = nxInputArray(CAPEXMW, nodeID);
EMISSIONOp = nxInputArray(EMISSIONOp, nodeID);


varInfo = create_model_id(idV0,name,strcat('Import',flName));
varDesc = createVarDesc(varInfo.id*ones(1,nVars),...
                        repmat(T_frame(1:(T_length/T_slice)),1,nNodes),...
                        ones(1,nVars)*str2double(year),...
                        repelem(nodeID,1,T_length/T_slice),...
                        ones(1,nVars));

lb = zeros(1,nVars);
ub =
(repelem(importMax,T_length/T_slice)).*repmat(T_length_segmented',nNodes,1)';
obj = repelem(OPEXMWH,1,T_length/T_slice);

%%
if totalMaxImport ~= -1 && totalMinImport ~= -1
   conInfo = create_model_id(idC0,name,'ImportLimitMax','ImportLimitMin');
   conDesc =
createConDesc([conInfo.id('ImportLimitMax')*ones(nCons,1);conInfo.id('ImportLimit
Min')*ones(nCons,1)],...
                        [zeros(nCons,1);zeros(nCons,1)],...

[ones(nCons,1)*str2double(year);ones(nCons,1)*str2double(year)],...
                       [ones(nCons,1);ones(nCons,1)],...
                        []);
   A = sparse([ones(nCons, nVars);ones(nCons, nVars)]);
```

```
   rhs =
[totalMaxImport'.*ones(nCons,1)*T_length/8760;totalMinImport'.*ones(nCons,1)*T_le
ngth/8760];
   sense = [repmat('<', nCons,1);repmat('>', nCons,1)];
elseif totalMaxImport ~= -1 && totalMinImport == -1
   conInfo = create_model_id(idC0,name,'ImportLimitMax');
   conDesc = createConDesc(conInfo.id('ImportLimitMax')*ones(nCons,1),...
                        zeros(nCons,1),...
                        ones(nCons,1)*str2double(year),...
                       ones(nCons,1),...
                        []);
   A = sparse(ones(nCons, nVars));
   rhs = totalMaxImport'.*ones(nCons,1)*T_length/8760;
   sense = repmat('<', nCons,1);
elseif totalMaxImport == -1 && totalMinImport ~= -1
   conInfo = create_model_id(idC0,name,'ImportLimitMin');
   conDesc = createConDesc(conInfo.id('ImportLimitMin')*ones(nCons,1),...
                        zeros(nCons,1),...
                        ones(nCons,1)*str2double(year),...
                       ones(nCons,1),...
                        []);
   A = sparse(ones(nCons, nVars));
   rhs = totalMinImport'.*ones(nCons,1)*T_length/8760;
   sense = repmat('>', nCons,1);
else

    A = [];
    conInfo = create_model_id();
    conDesc = createConDesc([]);
    rhs = [];
    sense = [];
    nCons = 0;
end
%%
modelDesc.varInfo = varInfo;
modelDesc.conInfo = conInfo;
modelDesc.varDesc = varDesc;
modelDesc.conDesc = conDesc;
modelDesc.A = A;
modelDesc.ub = ub;
modelDesc.lb = lb;
modelDesc.nVars = nVars;
modelDesc.nCons = nCons;
modelDesc.rhs = rhs;
modelDesc.sense = sense;
modelDesc.obj = obj;

if bOutNames
    modelDesc.varNames = concatNameDesc(name,varDesc.busID,varDesc.timeID);
    if (totalMaxImport ~= -1 && totalMinImport ~= -1) || (totalMaxImport == -1 &&
totalMinImport == -1)
```

```
        modelDesc.conNames = 
[repelem(strcat('MaxImport_',flName),1,nCons),repelem(strcat('MinImport_',flName)
,1,nCons)];
    elseif totalMaxImport ~= -1 && totalMinImport == -1
         modelDesc.conNames = [repelem(strcat('MaxImport_',flName),1,nCons)];
    elseif totalMaxImport == -1 && totalMinImport ~= -1
        modelDesc.conNames = [repelem(strcat('MinImport_',flName),1,nCons)];
    end
end

%% external connections
modelDesc = connectToNode(modelDesc, nodeDesc, 
bOutNames,varInfo.id(strcat('Import',flName)),1,'fuel');
modelDesc = connectToNode(modelDesc,emissionDesc, bOutNames, ...
    [ones(1,nVars)*varInfo.id(strcat('Import',flName))],...
    [repelem(EMISSIONOp,1,T_length/T_slice)],'emission');
```

APPENDIX III ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS

This thesis is in line with multiple United Nations Sustainable Development Goals (SDGs). For instance, it directly contributes to SDG 7: Affordably and Clean Energy by aiming to create a climate-neutral energy system based on renewable energy sources and alternate energy carriers such as synthetic fuels produced from renewable sources. This has the potential to cut greenhouse gas emissions while also promoting universal access to clean energy.

Second, it is consistent with SDG 9: Industry, Innovation, and Infrastructure, as achieving a sustainable and pure energy system necessitates the development and implementation of new technologies, regulations, and infrastructure. The project examines and analyses the potential of synthetic fuels as renewable energy carriers, considering transport and supply chain possibilities in Europe.

Third, it contributes to SDG 13: Climate Action by designing an energy system that is consistent with the Paris Agreement's aim of keeping global warming well below 2 degrees Celsius. The project seeks to facilitate the transition to a low-carbon economy and alleviate the effects of climate change by identifying and analysing the import potential and import limits of synthetic fuels in Europe.

Finally, the initiative is consistent with SDG 17: Partnerships for the Goals, as achieving a climate-neutral energy system in Europe involves collaboration among stakeholders from many sectors and nations. Identification and evaluation of import sites and possible constraints necessitate collaboration among European governments as well as countries outside of Europe that can offer synthetic fuels. The project's goal is to enable the development and implementation of a sustainable energy system by developing partnerships and collaboration.

The SDGs mentioned before have a direct relationship with the project, but there are also other SDGs related to this thesis, as if there is a failure in serving the world with energy, all SDGs will fail. For example, this work is also related to SDG 6: Clan Water and Sanitation, as pumping the water requires energy, or it is also in line with SDG 11: Sustainable Cities and Communities, as they require clean energy.

In conclusion, this thesis contributes to the achievement of clean energy, and as a result, it contributes to nearly all of the SDGs.