National Technical University of Athens
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"Hydrogen Supply Chain Optimization for Use in Transport and Energy Sectors"

Diploma Thesis

by

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Abstract

The transition to a sustainable energy system has driven the increasing interest in hydrogen as a clean and versatile energy carrier. However, the efficient and cost-effective transportation of hydrogen is crucial for its successful integration into the energy supply chain. This thesis focuses on analyzing and optimizing the hydrogen supply chain, considering various transport methods and their associated costs.

The research begins by identifying key challenges in the hydrogen supply chain, including cost reduction, CO2 emissions reduction, process efficiency, and improving the overall competitiveness of hydrogen. A comprehensive analysis of the importance of hydrogen supply chain management is presented, highlighting the need for optimizing transportation methods to achieve economic viability.

The thesis employs a combination of manual scenario analysis and simulation using the AnyLogic modeling software. The manual analysis examines specific supply chain routes and determines the total amount of hydrogen and the associated costs. The simulation in AnyLogic further investigates various scenarios using different transport methods, such as trucks, pipelines, and shipping, to identify the most cost-effective and efficient options.

The findings from the analysis provide valuable insights into the cost implications of different transport methods for hydrogen distribution. The research highlights the importance of considering not only the cost per kilogram but also other factors such as distance, infrastructure requirements, and operational considerations when selecting the optimal transport method.

The thesis concludes with recommendations for future research, including further optimization of transport methods, exploration of alternative energy carriers, and integration of renewable energy sources in the hydrogen supply chain. The insights gained from this study contribute to the overall understanding of hydrogen supply chain management and support decision-making processes in the energy sector.

Keywords: hydrogen supply chain, transport methods, cost analysis, optimization, AnyLogic modeling, sustainability.

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1. Introduction

1.1 The Role of Hydrogen in Sustainable Energy Transition

As the world grapples with the effects of climate change, a significant shift in energy consumption patterns is required. The focus has turned to renewable and sustainable energy sources to replace the conventional fossil fuels that have been at the core of energy production for decades. One of the promising contenders in this field is hydrogen. Known for its abundance and high energy content, hydrogen stands as a sustainable alternative that could play a pivotal role in the energy transition [International Energy Agency, 2019].

Hydrogen, being a versatile energy carrier, possesses the potential to decarbonize a range of sectors, including power generation, industries, and transport [Hydrogen Council, 2020]. It offers a solution to decarbonizing industrial processes and economic sectors where reducing carbon emissions is both urgent and hard to achieve [https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_1257]. Its only byproduct after combustion is water, making it an environmentally friendly energy source.

One of the significant advantages of hydrogen energy is its storage and transport capabilities. Hydrogen can be stored for long periods and transported over long distances, enabling it to address the intermittency issue inherent with some renewable energy sources like solar and wind [International Renewable Energy Agency, 2019]. This characteristic also makes it possible to relocate energy across the globe.

The value of hydrogen in the energy transition is further enhanced when considering its potential in the production of synthetic fuels. Synthetic fuels, such as synthetic methane or ammonia, produced using hydrogen, can serve as a direct replacement for conventional fossil fuels. This aspect opens the possibility for utilizing existing infrastructure with minor modifications, easing the transition process [European Commission, 2020].

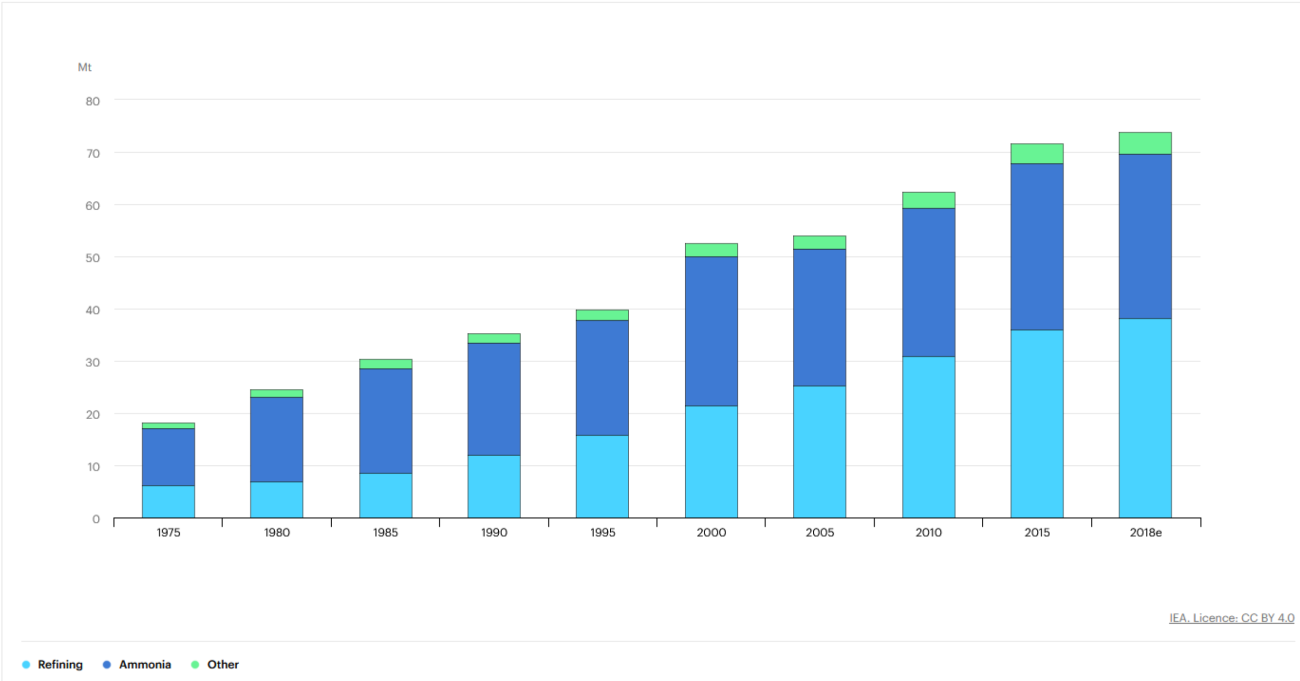


Figure 1. Global demand for pure hydrogen, 1975-2018 (IEA, Global demand for pure hydrogen, 1975-2018, IEA, Paris [https://www.iea.org/data-and-statistics/charts/global-demand-for-pure-hydrogen-1975-2018 , IEA. Licence: CC BY 4.0]

However, it's important to note that currently, the majority of hydrogen production is from natural gas, a process that emits carbon dioxide. The challenge lies in producing hydrogen from water using renewable energy, a process known as electrolysis. This 'green' hydrogen is where the real potential lies in contributing to a sustainable energy transition.

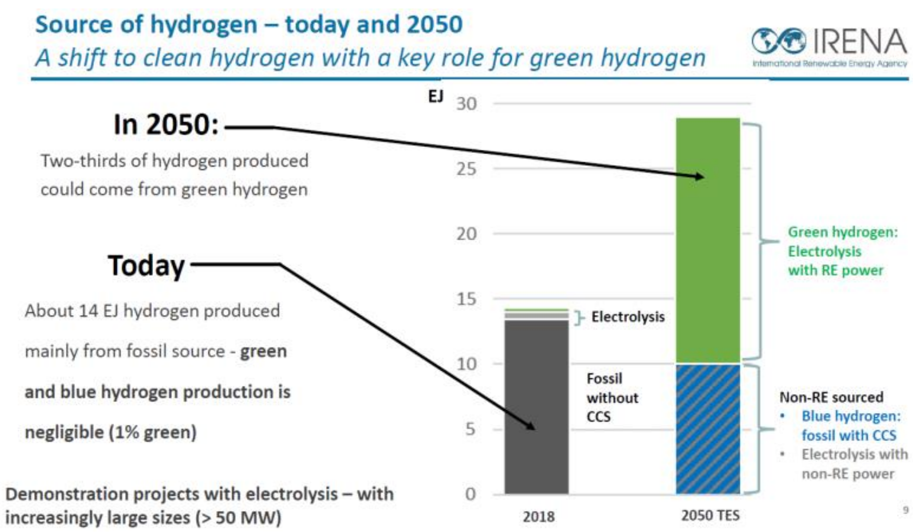


Figure 2. A shift to clean hydrogen with a key role for green hydrogen

[IRENA 2019. Hydrogen: A renewable energy perspective]

The use of hydrogen as an energy source also requires considering the entire supply chain. A robust and optimized hydrogen supply chain is vital to ensure the efficient production, storage, transport, and utilization of hydrogen. As with any energy source, the associated costs, infrastructure requirements, and energy losses are crucial factors that influence its large-scale adoption.

However, it is crucial to remember that hydrogen is not a silver bullet. Its role in the energy transition will be complementary to other solutions, and it will be part of a broader, integrated energy system [E4tech, 2019]. It is within this context that the role of hydrogen in the sustainable energy transition should be understood, and this thesis aims to contribute to this understanding by examining the optimization of the hydrogen supply chain, a critical aspect of realizing the potential of hydrogen as a sustainable energy carrier.

The potential role of hydrogen in the future global energy system cannot be overstated. The International Energy Agency (IEA) has identified hydrogen as a "versatile energy carrier" with a range of potential applications. Moreover, the IEA has highlighted that clean hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly [IEA, 2019].

One critical aspect of hydrogen's role in the sustainable energy transition is its ability to help decarbonize a range of sectors. This potential of hydrogen to serve as a key tool in the global effort to achieve net-zero emissions is central to the discussions and explorations in this thesis.

1.2 European Union's Goals for Hydrogen

1.2.1 Overview of EU's Hydrogen Goals

The European Union (EU) and the United Kingdom (UK) have set ambitious goals for adopting and implementing hydrogen as a key component of their energy strategy. These aims are driven by their commitment to reduce greenhouse gas emissions and achieve climate neutrality by 2050, aligning with the Paris Agreement. The European Hydrogen Backbone study predicts a hydrogen demand of 2,300 TWh (2,150-2,750 TWh) by 2050, equating to 20-25% of the EU and UK's final energy consumption.

Hydrogen is expected to play a critical role in multiple sectors, including industrial applications (e.g., chemicals, iron, steel, and fuel production), dispatchable electricity production, transport, and heating in buildings. The transition from grey to green and blue hydrogen technologies is particularly critical for industrial decarbonization. However, the successful implementation of these goals depends on various factors, including market structures, legislation, technology readiness, and consumer choice.

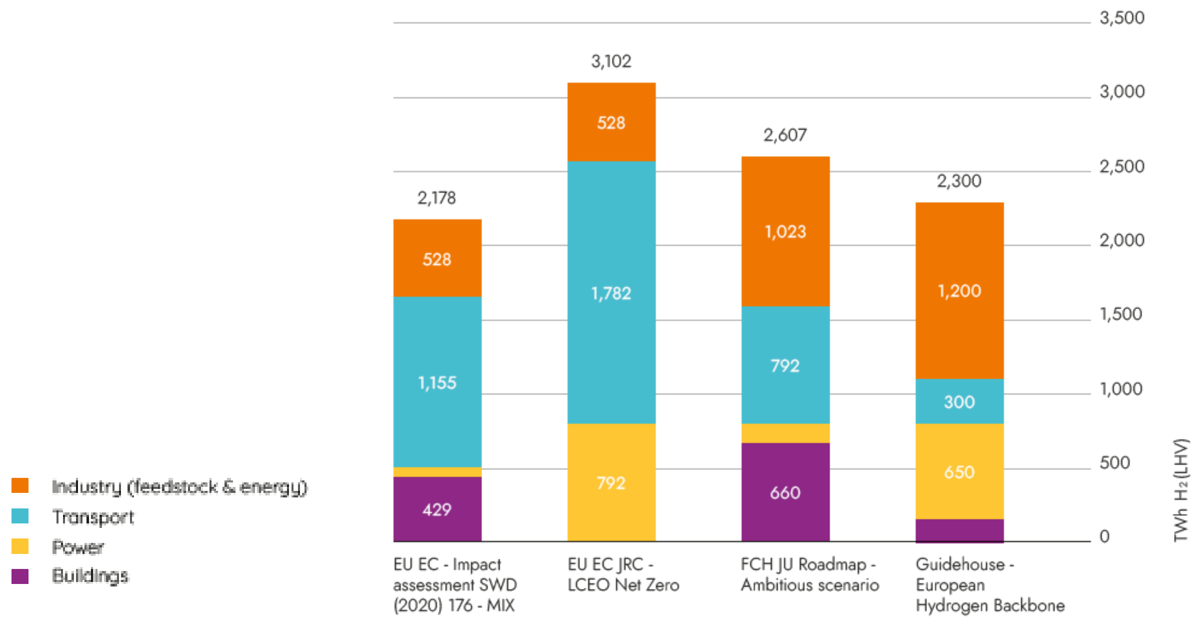


Figure 3. Four scenarios on green and blue hydrogen demand by 2050 according to recent EU decarbonisation studies. Note that this study (Guidehouse – European Hydrogen Backbone) categorizes hydrogen demand for synfuels under 'Industry (feedstock & energy) rather than under transport, as is done in the other scenarios. [EHB,2021]

1.2.2 Domestic Hydrogen Supply Potential

The EU and UK hold vast potential for the domestic production of hydrogen, especially green and blue hydrogen. The potential for green hydrogen production from dedicated renewables is projected to reach up to 4,000 TWh by 2050. Furthermore, the goal is to utilize up to 50% of renewable energy produced for hydrogen production, underscoring the importance of hydrogen in the EU and UK's renewable energy strategy. However, achieving this potential will require a massive expansion of wind and solar capacity, beyond what is needed for direct electricity demand.

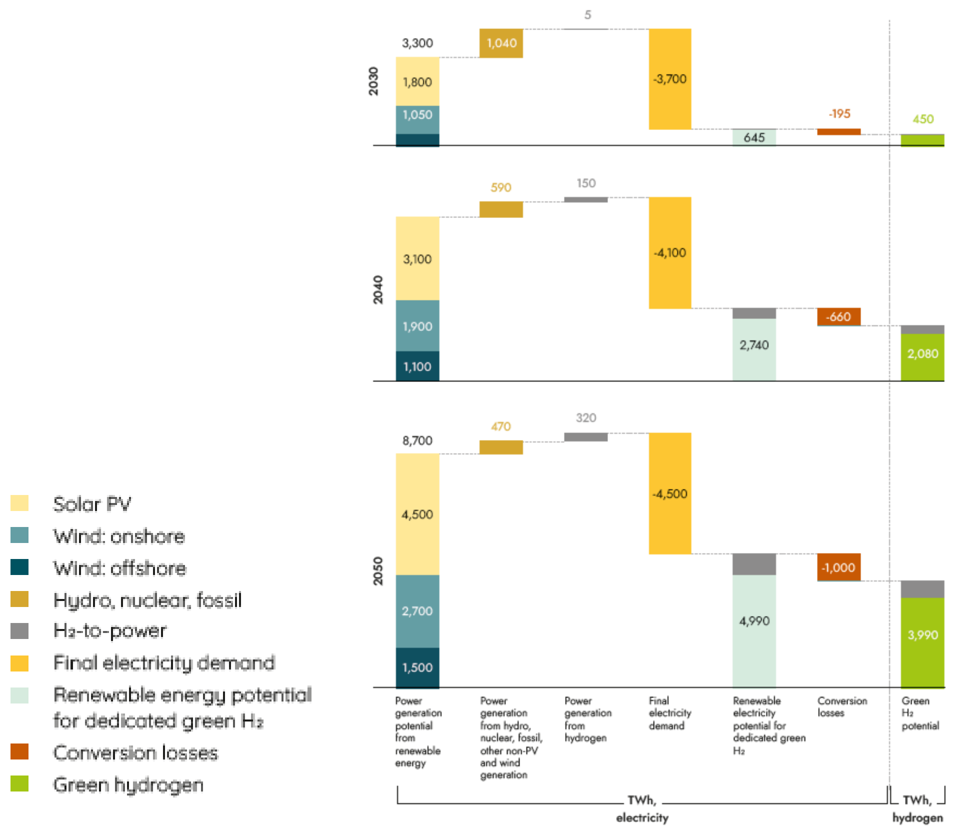


Figure 4. Translating renewable energy supply potential to green hydrogen supply potential – taking into account the needs for electricity and conversion losses – in 2030,2040, and 2050. [Guidehouse analysis based on Gas for Climate and TYNDP future energy scenarios]

In addition to green hydrogen, the EU also has significant potential for blue hydrogen production. The supply is virtually unlimited, given the availability of natural gas and CO2 storage potential. However, producing such quantities of green hydrogen within the EU and UK depends on public acceptance of an accelerated expansion of renewable installed capacity [EHB, June 202].

1.2.3 The European Hydrogen Backbone

Established in 2020, the European Hydrogen Backbone (EHB) initiative has played a pivotal role in the development of a European hydrogen market, primarily through its publication of EHB maps. These maps provide a vision for a Pan-European hydrogen transport infrastructure, which is technically feasible and economically affordable. The EHB maps have aided in the recognition of the significance of hydrogen in achieving climate neutrality and the importance of hydrogen pipeline transport in the future European energy system. This recognition was further endorsed in the European Commission's hydrogen and decarbonised gas package in December 2021.

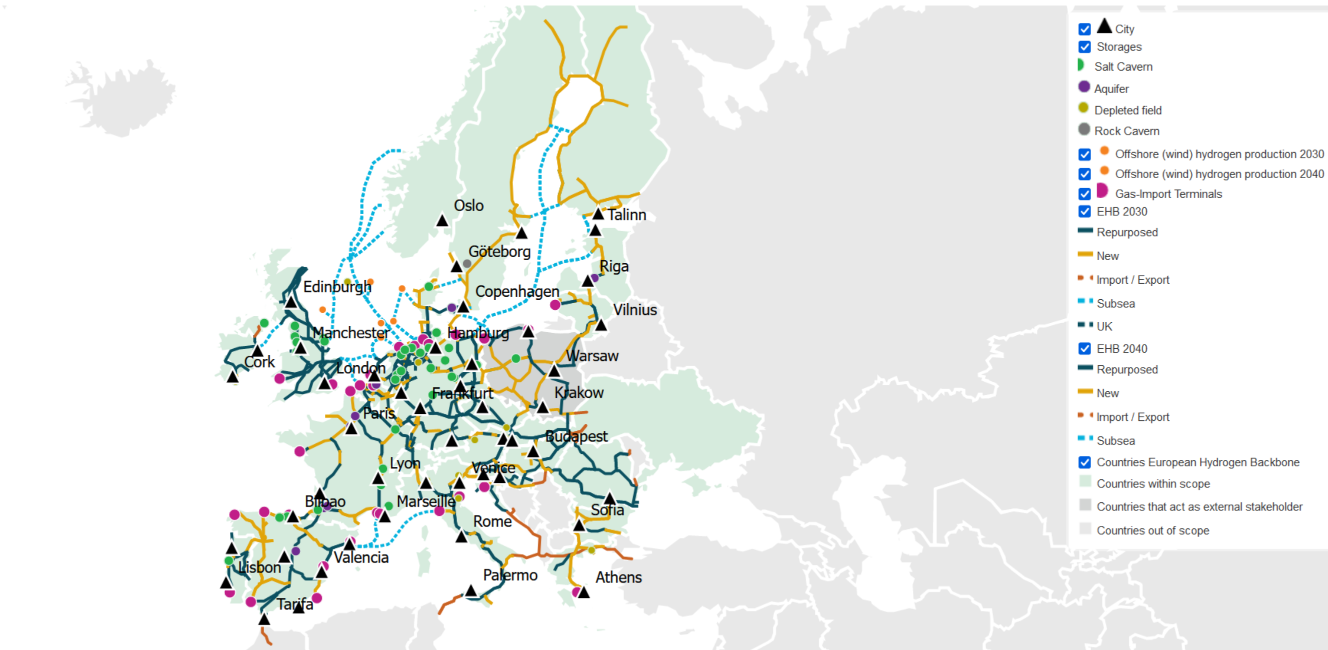


Figure 5. European Hydrogen Backbone Map [https://ehb.eu]

The recent geopolitical events, particularly the invasion of Ukraine by Russia, have intensified the urgency for a swift clean energy transition. The European Commission's REPowerEU proposal, a plan to phase out Europe's dependence on Russian fossil fuels by 2030, and bolster the resilience of the EU-wide energy system, has emphasized this position. The plan includes an ambition to achieve an additional 15 million tonnes (Mt) of renewable hydrogen, exceeding the 5.6 Mt target set under Fit for 55 and the EU's hydrogen strategy [EHB, April 2022] .

In response to the REPowerEU proposal and the accelerating hydrogen market developments, an updated and accelerated EHB vision has been developed, involving 31 energy infrastructure companies across 28 countries. This vision proposes the emergence of five Pan-European hydrogen supply and import corridors by 2030, connecting industrial clusters, ports, and hydrogen valleys to regions with abundant hydrogen supply. This development supports the EC's ambition to create a 20.6 Mt renewable and low-carbon hydrogen market in Europe.

Figure 6. European network operators [https://ehb.eu]

By 2040, the hydrogen infrastructure could evolve into a Pan-European network, stretching nearly 53,000 km, predominantly using repurposed existing natural gas infrastructure. The proposed infrastructure is estimated to require a total investment of €80-143 billion, which is relatively modest in the broader context of the European energy transition. Transporting hydrogen over 1,000 km along the proposed onshore backbone would on average cost €0.11-0.21 per kg of hydrogen, making the EHB the most cost-effective solution for large-scale, long-distance hydrogen transport [https://ehb.eu/newsitems].

The European Hydrogen Backbone presents an opportunity to expedite the decarbonisation of the energy sector, integrate considerable volumes of renewable and low-carbon energy, and connect supply-rich regions with demand centers. It has the potential to rejuvenate Europe's industrial economy while ensuring energy system resilience and security of supply. However, this vision necessitates close collaboration among EU Member States and neighboring countries, along with a stable, supportive, and adaptive regulatory framework.

1.2.4 Role of Imports

Import of hydrogen will play a critical role in the EU's hydrogen strategy. While the EU and UK have significant potential for domestic green and blue hydrogen production, their ability to meet all future demand domestically is subject to public acceptance of an accelerated expansion of renewable installed capacity.

Regions such as North Africa and Ukraine, with abundant natural resources and physical proximity, are attractive partners for future hydrogen trade. Other regions, such as Norway and potentially the Middle East, are also 'priority partners' in the EU Hydrogen Strategy. The sustainability of the imported hydrogen and its contribution to greenhouse gas savings will be a key consideration in the EU's strategy.

Table 1. Renewable energy production and electricity consumption assumptions for Ukraine and North Africa

[EHB, June 2021]

Region	Parameter	Assumptions
Ukraine	Solar PV	– Technical potential: 800 GW [178] – Capacity factor: 19% [179] – Deployment rate: 10% in 2030, 20% in 2040, 50% in 2050[180]
	Onshore wind	– Technical potential: 320 GW [181] – Capacity factor: 35% [179] – Deployment rate: 10% in 2030, 25% in 2040, 60% in 2050[180]
	Final electricity demand	– 170 TWh in 2030, 193 TWh in 2040, 210 TWh in 2050[182]
Morocco & Algeria	Solar PV	– Technical potential: 1000 GW [183] – Capacity factor: 30% [179] – Deployment rate: 10% in 2030, 25% in 2040, 60% in 2050[180]
	Final electricity demand	– 102 TWh in 2030, 134 TWh in 2040, 165 TWh in 2050 [182]

The vast volumes of hydrogen needed to meet the REPowerEU targets necessitate the development of robust and efficient transport infrastructure. Previous analyses by the European Hydrogen Backbone (EHB) suggest that a single hydrogen pipeline can transport around 65 TWh of hydrogen annually. To transport half of the REPowerEU target of 10 Mt, or 330 TWh, approximately five large-scale pipeline corridors would be necessary.

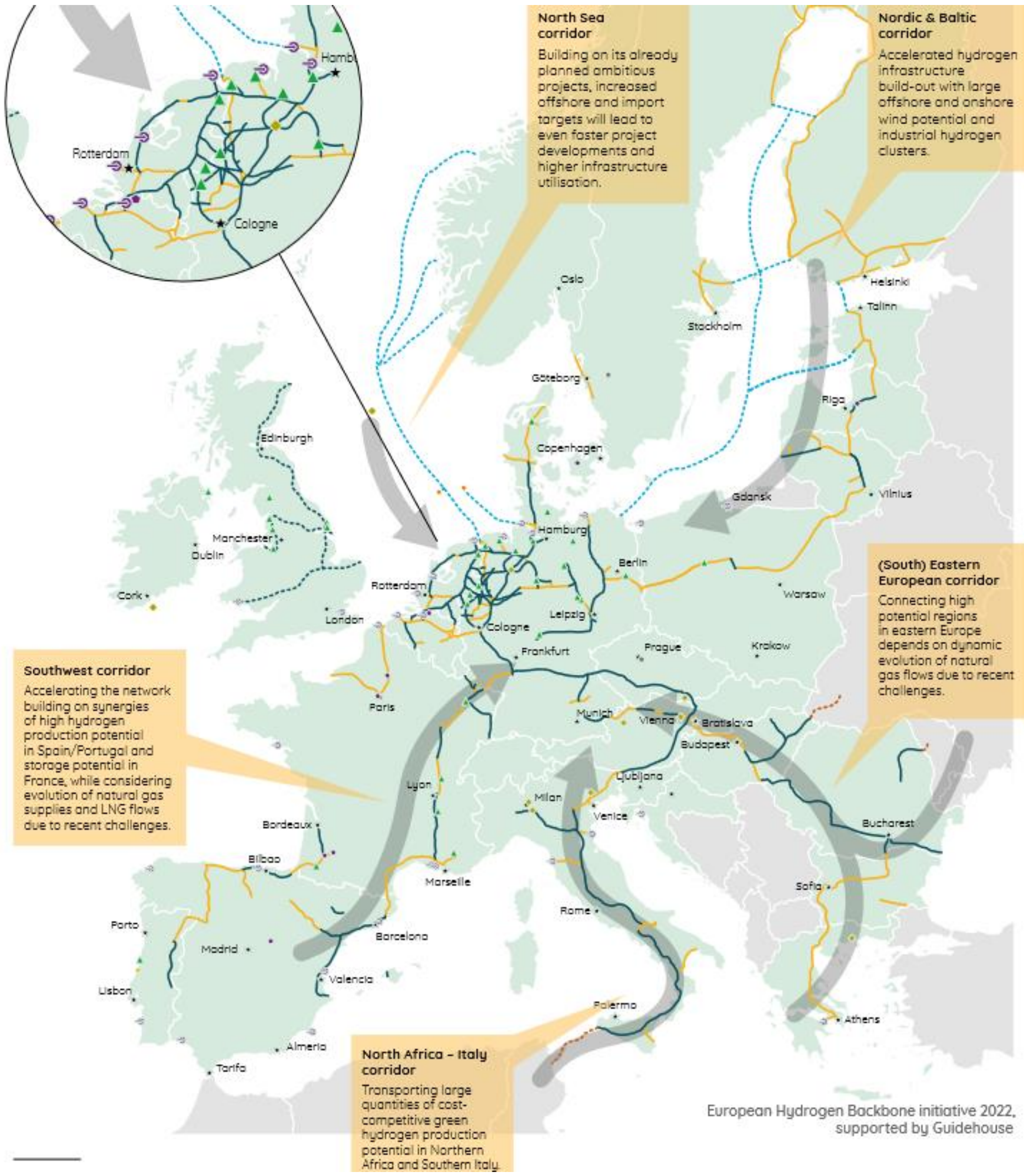


Figure 7. Accelerated and updated 2030 EHB network supports the EC's REPowerEU ambition to create a domestic and import market for hydrogen and increase European energy system resilience[https://ehb.eu]

By 2030, it is anticipated that hydrogen will be imported through both pipelines and import terminals. The balance between pipeline and ship imports will hinge on import terminal strategies, as well as the pace of hydrogen production scale-up in pipeline export regions such as Algeria and Tunisia. For regions where pipeline imports aren't economically viable, hydrogen derivatives could be imported via ship for direct use as methanol or ammonia, or to be reconverted to hydrogen for pipeline transmission in the onshore network.

1.2.5 Greece's Alignment with EU's Goals

Greece, being part of the European Union, aligns with the EU's goals for a climate-neutral future and recognizes the crucial role of hydrogen in achieving this target. Greece's substantial solar power potential could be leveraged for green hydrogen production, contributing to both domestic energy needs and potential exports. Its geographical location could position Greece as a key player in the emerging hydrogen economy.

The National Energy and Climate Plan (NECP) outlines plans to increase installed capacity of Wind Power to 7 GW and Solar PV to nearly 8 GW. Currently, Greece produces 150 thousand tons per year of hydrogen from fossil fuels, meeting a demand of 5 TWh, predominantly from refineries and ammonia production industries. The three main industrial clusters in Athens, Corinth, and Thessaloniki represent potential large demand sources for hydrogen [EHB, April 2022].

The Master Plan for decarbonizing the lignite production area of Western Macedonia reveals substantial potential for hydrogen production in the region, given the expected deployment of large-scale PV plants. There are also plans for a hydrogen-ready pipeline by DESFA in the region for local use or transportation of hydrogen. Several energy entities in Greece are planning for green hydrogen production, contributing to the "greening" of the country's energy sector. Notably, the "White Dragon" cluster project, along with others proposing hydrogen production, is the first step towards realizing hydrogen volumes in the country.

By 2035, Greece plans to have its main industrial clusters in Athens, Corinth, and Thessaloniki interconnected through new dedicated hydrogen pipelines. The potential hydrogen cluster in West Macedonia will also be connected to Thessaloniki via a new hydrogen-ready pipeline [Hydrogen in Greece The state of play, December 2021]. A dedicated hydrogen pipeline will provide access to green hydrogen for large potential consumers across the country, including refineries and chemical industries.

By 2040, the dedicated hydrogen pipeline could be interconnected with adjacent systems, facilitating the flow of hydrogen from Greece towards South-East, South-West, and Central Europe. Interconnectivity with the Italian transmission system and subsequently with Central Europe is anticipated, where significant pure hydrogen demand is foreseen. Also, ports with future import infrastructure for hydrogen could be connected to the pipeline system.

Figure 8. Greece European Hydrogen Backbone Map [https://ehb.eu]

In the case study section of this work, we will delve into Greece's hydrogen strategy in more detail, examining its current hydrogen infrastructure, planned projects, and alignment with EU goals.

1.3 The Importance of Hydrogen Supply Chain Optimization

The optimization of the hydrogen supply chain is crucial for the widespread use of hydrogen globally. It is essential to address various challenges in order to make hydrogen a competitive and sustainable energy solution. The key challenges include cost reduction, reduction of CO_2 emissions, process time reduction, and efficiency improvement.

Cost reduction is a vital aspect of hydrogen supply chain optimization. By identifying cost-effective production methods, improving storage and transportation processes, and leveraging economies of scale, we can make hydrogen more affordable and accessible to a wider range of industries and consumers.

One of the environmental challenges to be addressed is the reduction of CO_2 emissions throughout the hydrogen supply chain. This involves transitioning from gray hydrogen, which is produced from fossil fuels, to green and blue hydrogen, which are produced using renewable energy sources and carbon capture technologies. By minimizing the carbon footprint of hydrogen production and transportation, we can ensure a more sustainable energy system.

Reducing the time of processes is another critical factor in optimizing the hydrogen supply chain. Streamlining production, storage, and transportation processes can improve overall efficiency and responsiveness. This includes advancements in electrolysis technology, hydrogen compression and liquefaction techniques, and the development of efficient logistics and distribution networks.

Improving the efficiency rate is another focus area in hydrogen supply chain optimization. By reducing energy losses during production, storage, and transportation, we can maximize the utilization of renewable energy sources and minimize resource waste. This requires continuous research and development efforts to enhance the efficiency of hydrogen production methods, hydrogen storage technologies, and transportation systems.

These factors - cost reduction, CO_2 emissions reduction, process time reduction, and efficiency improvement - are crucial in making hydrogen a competitive and sustainable energy carrier. By optimizing the hydrogen supply chain, we can unlock the full potential of hydrogen as a clean and efficient energy solution.

Collaborative efforts among industry, academia, and government sectors are essential in driving advancements in hydrogen supply chain management. By fostering partnerships, sharing knowledge and best practices, and aligning policies and regulations, we can accelerate the development and implementation of innovative solutions for hydrogen production, storage, and distribution. This way, we can create a robust and resilient hydrogen supply chain that supports the global transition towards a low-carbon future.

1.4 Objectives and Scope of the Thesis

The primary objective of this thesis is to analyze and optimize the hydrogen supply chain with a focus on transportation methods and associated costs. The specific objectives of this research are as follows:

- Identify key challenges and considerations in the hydrogen supply chain, including cost reduction, CO2 emissions reduction, process efficiency, and competitiveness.
- Evaluate and compare different transport methods for hydrogen distribution, such as trucks, pipelines, and shipping, in terms of their cost-effectiveness and efficiency.
- Develop a comprehensive cost analysis framework that considers various cost components, including fixed costs, variable costs, conversion costs, and reconversion costs.
- Analyze specific supply chain routes and scenarios manually to determine the total amount of hydrogen transported and the associated costs.
- Simulate and analyze different scenarios using the AnyLogic modeling software to further investigate the cost implications of various transport methods and optimize the hydrogen supply chain.
- Provide insights and recommendations for decision-makers in the energy sector regarding the selection of optimal transport methods for hydrogen distribution.

The scope of this thesis encompasses the analysis and optimization of the hydrogen supply chain from the production stage to the final consumption points. The focus is on the transportation methods and associated costs, considering both manual scenario analysis and simulation using the AnyLogic modeling software. The research will examine specific supply chain routes and simulate various scenarios to evaluate the cost-effectiveness and efficiency of different transport methods.

It is important to note that this thesis does not address the detailed technical aspects of hydrogen production or storage but rather concentrates on the transportation component of the supply chain. The analysis will primarily consider the cost implications of different transport methods, while also taking into account factors such as distance, infrastructure requirements, and operational considerations.

2. Background and Literature Review

2.1 Hydrogen as an Energy Carrier

The investigation of hydrogen as an energy carrier necessitates an examination of its unique characteristics and potential advantages in the energy landscape. Hydrogen is an abundant element in the universe, but it does not exist freely in nature on Earth. Therefore, it must be produced from various sources such as water, fossil fuels, or biomass, thereby making it an energy carrier, not a primary energy source [Eberle, Mueller, & Von Helmolt, 2012].

The primary feature that sets hydrogen apart as an energy carrier is its versatility. It can be used in a multitude of sectors - from transportation to electricity to heating - and across different types of energy technologies and applications [Jacobson, Colella, & Golden, 2005]. This makes it a viable option to help decarbonize sectors where reducing emissions is challenging.

Another significant aspect is its high energy content per unit weight, which is nearly three times higher than that of fossil fuels [Santarelli & Cali, 2004]. This characteristic, coupled with its non-polluting combustion products (primarily water), makes it an attractive alternative for a clean, low-carbon energy system. However, hydrogen's low energy density per unit volume poses challenges for storage and transportation, which need to be effectively managed [Ahluwalia, Hua, Peng, & Lasher, 2010].

In terms of environmental impact, the value of hydrogen as an energy carrier is significantly dependent on how it's produced. Green hydrogen, produced through water electrolysis powered by renewable sources, is the most sustainable form of hydrogen, emitting zero greenhouse gases during production [Bertuccioli, Chan, Hart, Lehner, Madden, & Standen, 2014].

Overall, hydrogen, as an energy carrier, has the potential to play a pivotal role in the future energy system, particularly in reaching climate goals. Its versatility across sectors and compatibility with different energy technologies, combined with its potential for low-carbon applications, underpins its significance [Schiebahn, Grube, Robinius, Tietze, Kumar, & Stolten, 2015]. Nonetheless, the technical and economic challenges related to its production, storage, and transportation must be effectively addressed to realize its full potential [Schiebahn et al., 2015]. This analysis sets the stage for subsequent sections, which will delve into the existing hydrogen supply chains, production methods, storage and transportation, and end-use applications, providing a comprehensive overview of the hydrogen ecosystem.

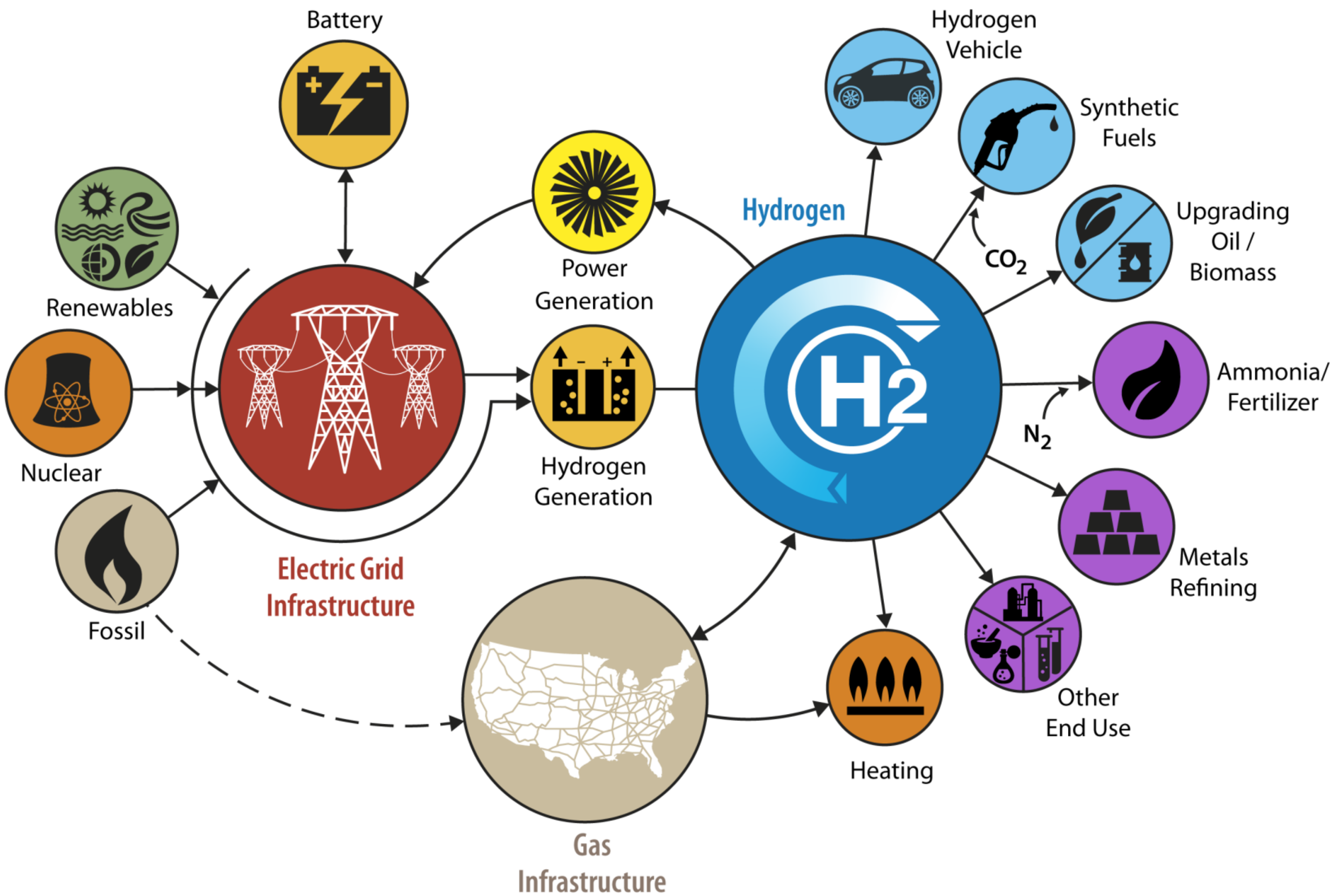


Figure 9. Hydrogen as Energy Carrier

[https://eta.lbl.gov]

2.2 Existing Hydrogen Supply Chains

2.2.1Production of Hydrogen

Hydrogen Production Methods

Hydrogen production is an essential part of the hydrogen supply chain. Currently, hydrogen is produced through a variety of methods, primarily divided into two categories: conventional methods (fossil fuel-based) and sustainable methods (renewable energy-based). Depending on the production method used hydrogen is categorized as grey, blue or green as shown in the table below.

Table 2. Hydrogen types [https://www.materialssquare.com/blog/ai-water-electrolysis-catalyst-en]

Grey Hydrogen	It is hydrogen, largely classified into by-product hydrogen and improved hydrogen, that is gener ated during the production process of a factory. In this process, carbon dioxide is generated.
Blue Hydrogen	It is a method of capturing carbon dioxide generated in the process of gray hydrogen through c arbon capture and storage (CCS) technology while preventing discharge into the atmosphere.
Green Hydrogen	It is a method of producing hydrogen through a hydrolysis reaction using electrical energy obtai ned through renewable energy such as sunlight or wind power.

1. Conventional Methods

a. Steam Methane Reforming (SMR): The most common method of hydrogen production globally is Steam Methane Reforming (SMR). This process involves reacting natural gas with high-pressure steam to produce hydrogen, carbon monoxide, and a small amount of carbon dioxide. The carbon monoxide is then reacted with water to yield additional hydrogen and carbon dioxide. Although SMR is the most cost-effective way to produce hydrogen, it is associated with significant greenhouse gas emissions [Balat & Balat, 2009].

b. Partial Oxidation (POX): In this process, a hydrocarbon fuel like coal, oil, or biomass is partially oxidized to produce hydrogen and carbon monoxide. This method is less efficient than SMR but can utilize a wider variety of feedstocks [Rosen & Koohi-Fayegh, 2017].

c. Autothermal Reforming (ATR): ATR is a process that combines SMR and POX. In ATR, oxygen and steam are combined with a hydrocarbon feedstock (like natural gas) to produce hydrogen and carbon dioxide. The process is called "autothermal" because it is exothermic and does not require an external heat source. ATR can be more efficient than SMR or POX alone and is also capable of processing a wider range of feedstocks [Haryanto, Fernando, Murali, & Adhikari, 2005]

d. Coal Gasification: Coal gasification is another conventional process of hydrogen production where coal is converted into syngas (a mixture of hydrogen and carbon monoxide) through a high-temperature reaction with steam and oxygen. This syngas is then subjected to water-gas shift reaction to produce more hydrogen and carbon dioxide. One of the primary challenges of this method is the high carbon dioxide emissions it produces. Nevertheless, it is widely used in regions with abundant coal resources [Feng, Zhang, & Zheng, 2017].

e. Biomass Gasification: Biomass gasification is a process in which biomass (e.g., wood, agricultural residues) is converted into a gas mixture known as syngas. The syngas predominantly contains hydrogen, carbon monoxide, and carbon dioxide. Like coal gasification, the syngas is processed further to increase hydrogen yield. Biomass gasification is considered a carbon-neutral method of hydrogen production, as the biomass absorbs carbon dioxide from the atmosphere during growth [Basu, 2013].

2. Sustainable Methods:

a. Electrolysis: Electrolysis involves splitting water into hydrogen and oxygen using electricity. When this electricity is sourced from renewable energy, the process results in 'green' hydrogen. Electrolysis is currently more expensive than SMR, but costs are expected to decrease with technological improvements and increased renewable energy availability [Bertuccioli et al., 2014].

b. Thermochemical and Photochemical Processes: These include methods like solar thermochemical water splitting and photocatalytic water splitting, which use heat or light to produce hydrogen from water. These methods are less mature than electrolysis but show promise for the future [Lewis & Nocera, 2006].

c. Biological Processes: Certain microorganisms can produce hydrogen through processes like dark and photo fermentation. While these processes are still in early stages of development, they offer a potential route to sustainable hydrogen production in the future [Vignais & Billoud, 2007].

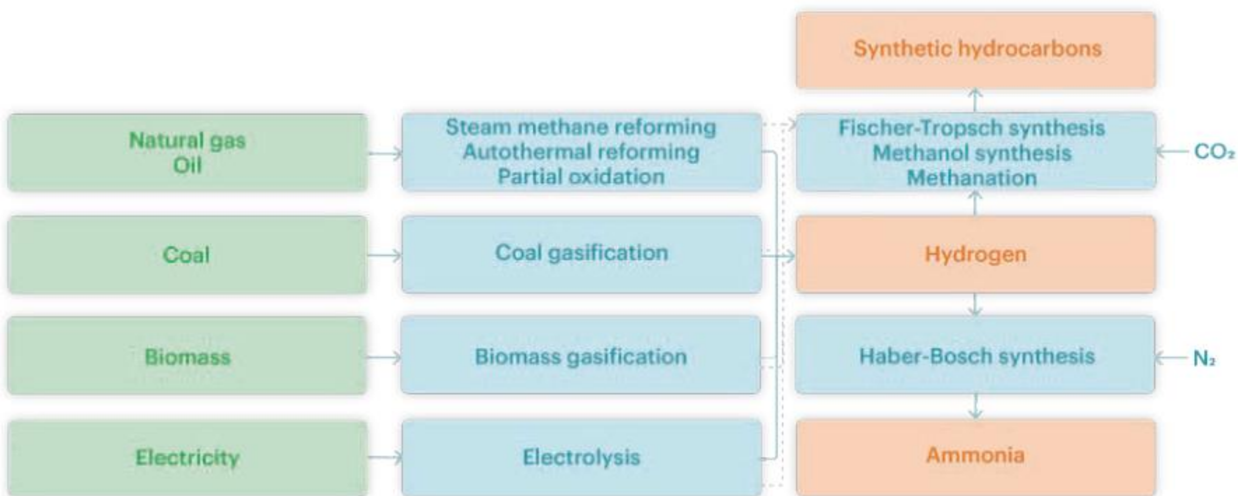


Figure 10. Potential pathways for producing hydrogen and hydrogen-based products

[Source: IEA 2019. All rights reserved]

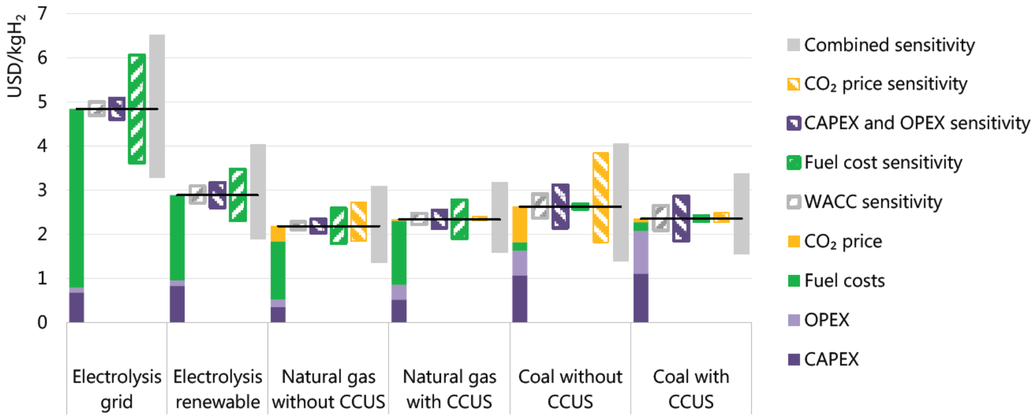
From these methods above that are currently in use for hydrogen production, steam methane reforming, coal gasification, and water electrolysis are standing out as the most dominant techniques in today's energy landscape.

Comparative Analysis of Diverse Hydrogen Production Techniques

1. **Electrolysis:**
    - **Cost:** Electrolysis is generally more expensive than fossil fuel-based methods, largely due to the high cost of electricity. However, costs are decreasing as the technology matures and renewable electricity becomes cheaper.
    - **Efficiency:** Electrolysis is highly efficient, with modern systems achieving around 60-80% efficiency.
    - **Carbon emissions:** When powered by renewable energy, electrolysis results in zero carbon emissions, making it an environmentally friendly method.
    - **Scalability:** Electrolysis plants can be scaled down to suit local needs, making them highly versatile. However, large-scale production is still relatively expensive compared to fossil fuel-based methods.

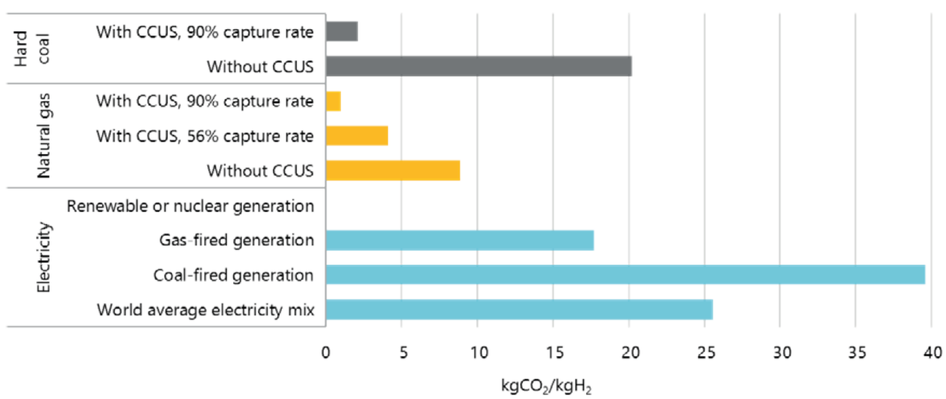
2. **Steam Methane Reforming (SMR) (with and without CCS):**
    - **Cost:** SMR is currently the cheapest method for producing hydrogen, making it the most commonly used method worldwide.
    - **Efficiency:** SMR is relatively efficient, with typical efficiencies of around 70-75%.
    - **Carbon emissions:** SMR produces significant carbon emissions, but these can be greatly reduced if combined with carbon capture and storage (CCS).
    - **Scalability:** SMR plants are typically large-scale, making them less suited to local, small-scale production.

3. **Coal Gasification (with and without CCS):**
    - **Cost:** Coal gasification can be relatively cheap, particularly in regions with abundant coal resources.
    - **Efficiency:** Coal gasification has efficiencies similar to SMR, around 60-70%.
    - **Carbon emissions:** Like SMR, coal gasification produces significant carbon emissions, but these can be reduced if combined with CCS.
    - **Scalability:** Coal gasification plants are typically large-scale and require significant infrastructure, making them less suited to local, small-scale production.



Notes: WACC = weighted average cost of capital. Assumptions refer to Europe in 2030. Renewable electricity price = USD 40/MWh at 4 000 full load hours at best locations; sensitivity analysis based on +/-30% variation in CAPEX, OPEX and fuel costs; +/-3% change in default WACC of 8% and a variation in default CO_2 price of USD 40/tCO_2 to USD 0/tCO_2 and USD 100/tCO_2. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Figure 11. Hydrogen production costs for different technology options, 2030



Notes: Capture rate of 56% for natural gas with CCUS refers to capturing only the feedstock-related CO_2, whereas for 90% capture rate CCUS is also applied to the fuel-related CO_2 emissions; CO_2 intensities of electricity taking into account only direct CO_2 emissions at the electricity generation plant: world average 2017 = 491 gCO_2/kWh, gas-fired power generation = 336 gCO_2/kWh, coal-fired power generation = 760 gCO_2/kWh. The CO_2 intensities for hydrogen also do not include CO_2 emissions linked to the transmission and distribution of hydrogen to the end users, e.g. from grid electricity used for hydrogen compression. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Figure 12. CO2 intensity of hydrogen production

In conclusion, each method has its advantages and drawbacks. Electrolysis has significant environmental advantages but currently suffers from high costs. In contrast, SMR and coal gasification are cheaper but produce significant carbon emissions unless combined with CCS. The choice of method depends on the specific circumstances, including available resources, infrastructure, and environmental priorities.

2.2.2 Storage and Transportation of Hydrogen

Storage Options

Hydrogen, due to its low density, presents unique challenges for storage and transportation. However, multiple storage options have been developed to address these challenges, each with its own advantages and disadvantages:

1. **Compressed Gas:** Hydrogen can be stored as a high-pressure gas in cylinders or tubes. This is the most common method for storing hydrogen, particularly for applications like fuel cell vehicles. However, the energy required for compression and the space needed for storage are significant drawbacks.
2. **Liquid Hydrogen:** Hydrogen can be liquefied by cooling it to extremely low temperatures (-253 degrees Celsius). Liquid hydrogen has a much higher energy density by volume than compressed gas, making it more suitable for some applications. However, the energy required for liquefaction and the need to maintain extremely low temperatures make this method expensive and energy-intensive.
3. **Chemical Carriers:** Hydrogen can be stored in chemical carriers such as ammonia or organic liquids. These carriers can be transported and stored using existing infrastructure and then converted back into hydrogen when needed. This method has significant potential, but the conversion process is currently inefficient and can produce harmful byproducts.
4. **Underground Storage:** Hydrogen can be stored underground in salt caverns, aquifers, or depleted oil and gas fields. This method can store large amounts of hydrogen for long periods, making it ideal for seasonal storage. However, the availability of suitable sites is limited and there can be safety and environmental concerns.

The choice of storage method depends on the specific requirements of the application, including the volume of hydrogen, the duration of storage, the desired energy density, and the available infrastructure and resources.

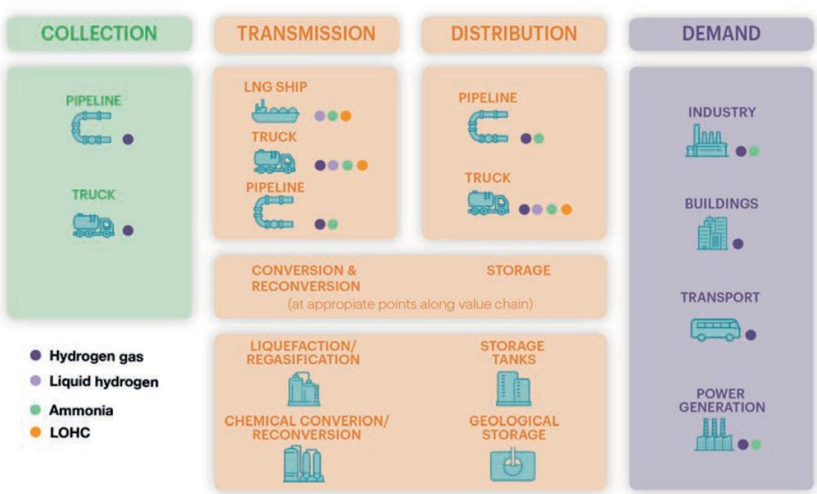


Figure 13. Transmission, distribution and storage elements of hydrogen value chains

[Source: IEA 2019. All rights reserved

Transportation Options

Hydrogen transportation is a critical component of the supply chain, and it can be achieved through a variety of means:

1. **Pipelines:**

   Pipelines are a commonly used method for hydrogen transportation, especially in areas with established industrial hydrogen usage. The main advantage of this method is the ability to provide a continuous flow of hydrogen, making it an ideal choice for large-scale and long-term operations. However, a few challenges exist. One of the primary concerns is hydrogen embrittlement, a phenomenon where hydrogen atoms diffuse into the metal of the pipeline, making it brittle and prone to cracking. This is especially a problem with high-strength steels.

   Furthermore, the initial investment for pipeline infrastructure can be high, particularly if existing natural gas pipelines cannot be repurposed due to compatibility issues.

   Nevertheless, pipeline transportation of hydrogen is a proven technology and continues to be a primary method for the movement of hydrogen, especially in regions with substantial existing infrastructure [Melaina, Antonia, & Penev, 2013].

2. **Trucks:**

   Truck transportation of hydrogen can be accomplished in either gaseous or liquid form. Compressed hydrogen gas is typically transported in high-pressure tubes, while liquid hydrogen requires cryogenic tankers. The versatility of truck transportation allows for the delivery of hydrogen to remote or isolated locations, which would be unreachable via pipelines. However, transportation costs can be quite high, especially for long distances, due to the energy input required for compression or liquefaction and the relatively low amount of hydrogen that can be transported per truck. There are also safety considerations for the transport of highly compressed or cryogenic hydrogen on public roadways.

   Despite these challenges, truck transportation plays a significant role in the current hydrogen supply chain, particularly for small to medium-scale operations and as a flexible, location-independent solution [Saur & Ramsden, 2011].

3. **Ships:**

   The transportation of hydrogen by ship is an emerging area of interest, particularly for the global trade of hydrogen. Hydrogen can be transported as a compressed gas, a cryogenic liquid, or chemically bound in a carrier like ammonia or a liquid organic hydrogen carrier (LOHC). Ship transportation enables long-distance and intercontinental hydrogen transport, potentially linking regions with abundant renewable energy resources (for green hydrogen production) to areas with high hydrogen demand.

Currently, the technology for ship-based hydrogen transport is still in its early stages, and there are challenges to be addressed. These include the need for large-scale liquefaction facilities for liquid hydrogen, the energy requirements for hydrogen compression or liquefaction, and the need for specialized infrastructure at both the shipping and receiving ends. However, significant research and development efforts are underway, and ship-based hydrogen transport is likely to play a significant role in future global hydrogen supply chains [Verbeek, 2020].

Each of these transportation methods has its own advantages and challenges, and the choice of method depends on the specific requirements of the supply chain, including the distance and scale of transportation, the available infrastructure, and the cost.

2.2.3 End-use Applications of Hydrogen

Hydrogen is a versatile energy carrier with a wide range of applications across various sectors. Its usage can be primarily categorized into three segments: industrial applications, energy storage and power generation, and transportation.

1. Industrial Applications:

The largest current use of hydrogen is in oil refining and ammonia production for fertilizers. In oil refining, hydrogen is used to remove impurities such as sulfur from petroleum products in a process called hydrodesulfurization. Ammonia, produced through the Haber-Bosch process, uses hydrogen as a primary input. Hydrogen is also used in the production of methanol and in various other chemical processes.

2. Energy Storage and Power Generation:

Hydrogen can act as a medium for energy storage, effectively enabling the storage of electricity produced from renewable sources. This stored hydrogen can be used to generate electricity during periods of low renewable energy production or peak demand, thus enhancing grid stability. In power generation, hydrogen can be used in fuel cells to produce electricity and heat, or it can be burned in a turbine or internal combustion engine. It can also be combined with carbon dioxide in a process called methanation to produce synthetic methane, which can then be used in all applications where natural gas is used today.

3. Transportation:

Hydrogen is being increasingly recognized as a potential fuel for transportation. Hydrogen fuel cell electric vehicles (FCEVs) utilize hydrogen to generate electricity within a fuel cell; the only byproduct of this process is water, making FCEVs a zero-emission transportation option. Hydrogen can also be used in internal combustion engines or blended with natural gas for use in vehicles.

These applications indicate the potential of hydrogen as a key enabler of a clean, low-carbon economy. However, each of these applications comes with its unique set of challenges and opportunities, which need to be thoroughly understood and addressed for successful implementation.

4. Buildings:

Hydrogen can also play a crucial role in providing heating and cooling solutions for buildings. A large portion of energy consumption in buildings is related to heating, cooling, and providing hot water. Currently, this demand is largely met by burning natural gas or using electricity, which in many places is still predominantly generated from fossil fuels. Hydrogen, when used as a fuel in fuel cells, can provide both heat and electricity for buildings in a highly efficient manner. This combined heat and power (CHP) approach could dramatically reduce carbon emissions from buildings.

In addition, hydrogen can be used in gas-based heating systems. Existing natural gas infrastructure in many regions could be repurposed to deliver hydrogen, or hydrogen-natural gas blends, to consumers. Hydrogen boilers, similar to natural gas boilers, can provide heating by burning hydrogen. Alternatively, hybrid heat pumps, which use a combination of electric heat pumps and hydrogen boilers, could provide a flexible and efficient solution for space heating and hot water in buildings.

Table 3. Summary of hydrogen use in industrial applications and future potential [IEA,2019]

Sector	Current hydrogen role	2030 hydrogen demand	Long-term demand	Low-carbon hydrogen supply	
				Opportunities	Challenges
Oil refining	Used primarily to remove impurities (e.g. sulphur) from crude oil and upgrade heavier crude. Used in smaller volumes for oil sands and biofuels.	7% increase under existing policies. Boosted by tighter pollutant regulations, but moderated by lower oil demand growth.	Highly dependent on future oil demand but likely to remain a large source of demand in 2050, even in a Paris-compatible pathway.	Retrofit natural gas or coal-based hydrogen with CCUS. Replace merchant hydrogen purchases with hydrogen from low-carbon electricity.	Hydrogen production and use is closely integrated within refining operations, making a tough business case for replacing existing capacity. Hydrogen costs strongly influence refining margins.
Chemical production	Central to ammonia and methanol production, and used in several other smaller-scale chemical processes.	31% increase under existing policies for ammonia and methanol due to economic and population growth.	Hydrogen demand for existing uses set to grow despite materials efficiency (including recycling); new ammonia and methanol demand could arise for clean uses as hydrogen-based fuels.	Retrofit or new-build hydrogen with CCUS. Use low-carbon hydrogen for ammonia and methanol production (urea and methanol will still require a source of carbon).	Competitiveness of low-carbon hydrogen supplies depends on gas and electricity prices. CCUS retrofitting is not a universal option.
Iron and steel production	7% of primary steel production takes place via the direct reduction of iron (DRI) route, which requires hydrogen. The blast furnace route produces by-product hydrogen as a mixture of gases, which are often used on site.	A doubling under existing policies as the DRI route is used more, relative to the currently dominant blast furnace route.	Steel demand keeps rising, even after accounting for increased materials efficiency. 100% hydrogen-based production could dramatically increase demand for low-carbon hydrogen in the long term.	Retrofit DRI facilities with CCUS. Around 30% of natural gas can be substituted for electrolytic hydrogen in the current DRI route. Fully convert steel plants to utilise hydrogen as the key reducing agent.	All options require higher production costs and/or changes to processes. Direct applications of CCUS are usually projected to have lower costs, although these are highly uncertain. Long-term competition from direct electrification.
High-temperature heat (excluding chemicals and iron and steel)	Virtually no dedicated hydrogen production for generating heat. Some limited use of hydrogen-containing off-gases from the iron and steel and chemical sectors.	9% increase in high-temperature heat demand under existing policies. No additional hydrogen use without significant policy support.	Heat demand likely to rise further, providing an opportunity for hydrogen if it can compete on cost in the prevailing policy environment.	Hydrogen from any source could replace natural gas, e.g. in industrial clusters or near hydrogen pipelines. Blends with natural gas are more straightforward but less environmentally beneficial.	Hydrogen expected to compete poorly with biomass and direct CCUS in general, but may prove competitive with direct electrification. Full fuel switches, or CCUS, tend to entail significant investment.

Table 4. Potential uses of hydrogen and derived products for transport applications [IEA,2019]

	Current role	Demand perspectives	Future deployment	
			Opportunities	Challenges
Cars and vans (light-duty vehicles)	11 200 vehicles in operation, mostly in California, Europe and Japan	The global car stock is expected to continue to grow; hydrogen could capture a part of this market	**Hydrogen:** Short refuelling time, less weight added for energy stored and zero tailpipe emissions. Fuel cells could have a lower material footprint than lithium batteries	**Hydrogen:** Initial low utilisation of refuelling stations raises fuel cost; reductions in fuel cell and storage costs needed; efficiency losses on a well-to-wheels basis **Power-to-liquid:** Large electricity consumption and high production costs **Ammonia:** Caustic and hazardous substance close to end users mean that use is likely to remain limited to professional operators
Trucks and buses (heavy-duty vehicles)	Demonstration and niche markets: ~25 000 forklifts ~500 buses ~400 trucks ~100 vans. Several thousand buses and trucks expected in China* by end-2019	Strong growth segment; long-haul and heavy-duty applications are attractive for hydrogen	Captive vehicle fleets can help overcome challenges of low utilisation of refuelling stations; long-distance and heavy-duty are attractive options	
Maritime	Limited to demonstration projects for small ships and on-board power supply in larger vessels	Maritime freight activity set to grow by around 45% to 2030. 2020 air pollution targets and 2050 greenhouse gas targets could promote hydrogen-based fuels	**Hydrogen** and **ammonia** are candidates for both national action on domestic shipping decarbonisation, and the IMO Greenhouse Gas Reduction Strategy, given limitations on the use of other fuels	**Hydrogen:** Storage cost higher than other fuels **Hydrogen/ammonia:** cargo volume lost due to storage (lower density than current liquid fuels)
Rail	Two hydrogen trains in Germany	Rail is a mainstay of transport in many countries	**Hydrogen** trains can be most competitive in rail freight (regional lines with low network utilisation, and cross-border freight)	Rail is the most electrified transport mode; **hydrogen** and battery electric trains with partial line electrification are both options to replace non-electrified operations, which are substantial in many regions
Aviation	Limited to small demonstration projects and feasibility studies	Fastest-growing passenger transport mode. Large storage volume and redesign would be needed for pure hydrogen, making **power-to-liquid** and biofuels more attractive for this mode	**Power-to-liquid:** Limited changes to status quo in distribution, operations and facilities; also maximises biomass use by boosting yield **Hydrogen:** Together with batteries, can supply on-board energy supply at ports and during taxiing	**Power-to-liquid:** Currently 4 to 6 times more expensive than kerosene, decreasing to 1.5–2 times in the long-term (Chapter 2), potentially increasing prices and decreasing demand

* China = People's Republic of China.

Table 5. Potential routes to use hydrogen for buildings heat supply [IEA,2019]

Strategy	Advantages	Requirements	Examples
Blending	Low-cost solution compatible with most existing gas infrastructure and equipment	Blending ratios to around 5–20% in most instances. Additional efficiency measures to further abate CO_2	GRHYD project (2017) in France. HyDeploy (2019) in the United Kingdom
Methane produced from clean hydrogen	Full decarbonisation of gas if low-carbon hydrogen and low-carbon CO_2 inputs. Utilisation of existing gas networks and equipment	Investment in methanation plants. R&D to improve the efficiency of methanation. Carbon source, such as CO_2	STORE&GO (2016) European project with catalytic and biological methanation (demonstration projects between 200 kW and 1 MW)
100% hydrogen	Full decarbonisation of gas if low-carbon hydrogen. Lower efficiency losses than synthetic methane	Investment to upgrade gas network and equipment. Co-ordination between gas suppliers and distributors if various networks coexist	The H21 Leeds City Gate (> 2025) and the H21 Network Innovation Competition (NIC-2018) projects in the United Kingdom
Use of fuel cells and co-generation	Multiple energy services (e.g. heat and electricity). Demand-side response potential	Investment in fuel cell or co-generation technology. R&D to improve the efficiency of equipment	ENE-FARM programme in Japan (2009).* Energy Efficiency Incentive Programme in Germany (2016)**

* Current ENE-FARM installations are running on natural gas or liquefied petroleum gas, mainly targeted at cost reduction.

** The programme includes fuel cell applications in buildings.

Table 6. Role of hydrogen and hydrogen-based products in power generation [IEA,2019]

	Current role	Demand perspectives	Future deployment	
			Opportunities	Challenges
Co-firing ammonia in coal power plants	No deployment so far; co-firing has been demonstrated in a commercial coal power plant in Japan	20% co-firing share in global coal power plant fleet could by 2030 lead to an ammonia demand of up to 670 Mt ammonia or a corresponding hydrogen demand of 120 MtH_2	Reducing the carbon impact of existing coal-fired power plants in the near term	CO_2 mitigation costs can be low, but rely on low-cost ammonia supply. Attention has to be paid to NO_x emissions; further NO_x treatment may be needed. Only a transitional measure – still significant remaining CO_2 emissions
Flexible power generation	Few commercial gas turbines using hydrogen-rich gases. 363 000 fuel cell units (1 600 MW) installed	Assuming 1% of global gas-fired power capacity would run on hydrogen by 2030, this would result in a capacity of 25 GW, generating 90 TWh of electricity and consuming 4.5 MtH_2	Supporting the integration of VRE in the power system. Some gas turbine designs already able to run on high hydrogen shares	Availability of low-cost and low-carbon hydrogen and ammonia. Competition with other flexible generation options as well as other flexibility options (e.g. demand response, storage)
Back-up and off-grid power supply	Demonstration projects for electrification of villages. Fuel cell systems in combination with storage	With increasing growth of telecommunications, also growing need for reliable power supply	Fuel cell systems in combination with storage as a cost-effective and less polluting alternative to diesel generators. More robust than battery systems	Often higher initial investment needs compared with diesel generators
Long-term and large-scale energy storage	Three salt cavern storage sites for hydrogen in the United States; another three in the United Kingdom	In the long term, with very high VRE shares, need for large-scale and long-term storage for seasonal imbalances or longer periods with no VRE generation. In combination with long-distance trade, scope to take advantage of seasonal differences in global VRE supply	Due to high energy content of hydrogen, relatively low CAPEX cost for storage itself. Few alternative technologies for long-term and large-scale storage. Conversion losses can be reduced if stored hydrogen or ammonia can be directly used in end-use applications	High conversion losses. Geological availability of salt caverns for hydrogen storage region-specific. Little experience with depleted oil and gas fields or water aquifers for hydrogen storage (e.g. contamination issues)

Note: VRE = variable renewable energy.

2.2.4 SWOT Analysis for the Hydrogen Economy

Strengths:

1. **Decarbonization Potential:** Hydrogen has the potential to contribute significantly to decarbonizing various sectors, offering a cleaner alternative to fossil fuels.

2. **Versatility:** Hydrogen can be used in multiple applications, including transportation, industry, and energy storage, providing flexibility in meeting diverse energy needs.

3. **Energy Security:** Diversifying energy sources through hydrogen production can enhance energy security by reducing dependence on fossil fuels and mitigating geopolitical risks.

4. **Job Creation and Economic Growth:** The development of a hydrogen economy can stimulate economic growth and create job opportunities in various sectors, promoting sustainable economic development.

Weaknesses:

1. **Infrastructure Development:** Establishing the necessary infrastructure for large-scale hydrogen production, storage, and distribution poses a significant challenge and requires substantial investments.

2. **Cost Challenges:** The current high cost of renewable hydrogen production limits its widespread adoption. Cost reduction through technological advancements and economies of scale is necessary.

3. **Energy Intensity:** Hydrogen production processes, particularly electrolysis, require a significant amount of energy, posing a challenge for achieving high energy efficiency.

4. **Public Acceptance:** Public perception, safety concerns, and acceptance of new infrastructure (such as pipelines and fueling stations) can influence the rate of hydrogen technology adoption.

Opportunities:

1. **Sectoral Decarbonization:** Hydrogen presents an opportunity for decarbonizing sectors that are difficult to electrify, such as heavy-duty transport, industry, and heating for buildings, enabling the transition to cleaner energy sources.

2. **Energy Storage:** Hydrogen can serve as an energy storage medium, facilitating the integration of intermittent renewable energy sources and supporting grid balancing.

3. **Technological Advancements:** Continued research and development can lead to technological advancements, improving the efficiency, safety, and cost-effectiveness of hydrogen production and utilization.

4. **Policy Support:** Government support and policies that promote the adoption of hydrogen technologies can create favorable market conditions, accelerate deployment, and drive innovation.

Threats:

1. **Competing Technologies:** Other low-carbon alternatives, such as electrification, biofuels, and synthetic fuels, pose competition to hydrogen technologies, influencing their market penetration.

2. **Regulatory and Policy Barriers:** Inadequate or inconsistent regulations, lack of supportive policies, and limited financial incentives can hinder the growth of the hydrogen economy.

3. **Market Uncertainty:** Volatility in energy markets, geopolitical factors, and changing investor sentiment can impact the viability and investment attractiveness of hydrogen projects.

4. **Technological Limitations**: Ongoing research is needed to overcome technical challenges, such as hydrogen storage, transportation, and infrastructure, to enable wider adoption and utilization of hydrogen.

2.3 Previous Studies on Hydrogen Supply Chain Optimization

The optimization of hydrogen supply chains has gained significant attention in recent years, driven by the growing interest in hydrogen as a sustainable energy carrier. Extensive research has been conducted to explore different aspects of the hydrogen supply chain, including production methods, distribution networks, and end-use applications. In this subsection, we will review some of the key studies in the field and highlight the unique contributions of our study.

Previous studies have focused on diverse aspects of hydrogen supply chain optimization Guannan Heet al. focused on developing a hydrogen supply chain planning model that incorporates the flexibility of various resources to determine the least-cost mix of H2 generation, storage, transmission, and compression facilities. Trucks acting as mobile storage provide additional spatiotemporal flexibility to respond to electricity price variations while meeting H2 demands.

Similarly, Almansoori and Shah conducted a comprehensive review of supply chain optimization models for hydrogen and other energy systems. They emphasized the importance of integrated models that consider the entire supply chain, from production to end-use, in order to achieve efficient and cost-effective outcomes.

Guillén-Gosálbez et al. specifically investigated the optimization of hydrogen supply chains for vehicle refueling. Their study employed a two-stage stochastic programming model to design and plan hydrogen supply chains under uncertain conditions. The model accounted for uncertainties in demand, prices, and technology availability, highlighting the need for robust decision-making in the face of uncertainties.

In the context of green hydrogen, Minsoo Kim and Jiyong Kim integrated various RES technologies for hydrogen production, storage, and transportation, in order to develop a renewable hydrogen supply (IRHS) system. A multi-period deterministic optimization model using mixed integer linear programming (MILP) was employed to optimize the configuration and operational strategy of the IRHS system. The application of the model to the design problem of Korea's future hydrogen economy allowed for an economic evaluation and identification of key parameters influencing the cost of the energy system infrastructure.

While these previous studies have made significant contributions to the field of hydrogen supply chain optimization, our study distinguishes itself by focusing on the specific context of the Greek hydrogen supply chain. We aim to assess the feasibility and optimize the supply chain for meeting the hydrogen demand in various sectors of Greece. Furthermore, our study incorporates specific geographical and operational considerations unique to the Greek energy landscape.

The following subsection will delve into the role of simulation in supply chain optimization, discussing how simulation models can aid in assessing the performance and identifying opportunities for improvement in the hydrogen supply chain.

2.4 The Role of Simulation in Supply Chain Optimization

Simulation plays a pivotal role in the optimization of supply chains, including hydrogen supply chains. It is a powerful tool that allows for the modeling of complex systems, providing insights into system behavior and performance under different conditions and assumptions. This understanding is vital when designing and planning supply chains to ensure efficiency and reliability.

The application of simulation in supply chain optimization can take various forms, including system dynamics, discrete event simulation, and agent-based simulation. System dynamics simulation models the interactions between different components of a supply chain, providing insights into the overall system behavior over time.

Discrete event simulation, on the other hand, models the operation of a supply chain at a granular level, considering individual events such as the arrival of a shipment or the completion of a production process. This type of simulation is particularly useful for analyzing the impact of changes in operational parameters, such as production rates or transportation schedules, on supply chain performance.

Agent-based simulation models the behavior of individual entities, or 'agents', within a supply chain, such as suppliers, manufacturers, and customers. This approach allows for a detailed analysis of the interactions between different agents and the resulting impact on supply chain performance.

In the context of hydrogen supply chains, simulation can be used to model and optimize various aspects, including production processes, transportation networks, storage facilities, and end-use applications. By providing a detailed understanding of system behavior and performance, simulation can support decision-making and strategy development in the design and operation of hydrogen supply chains.

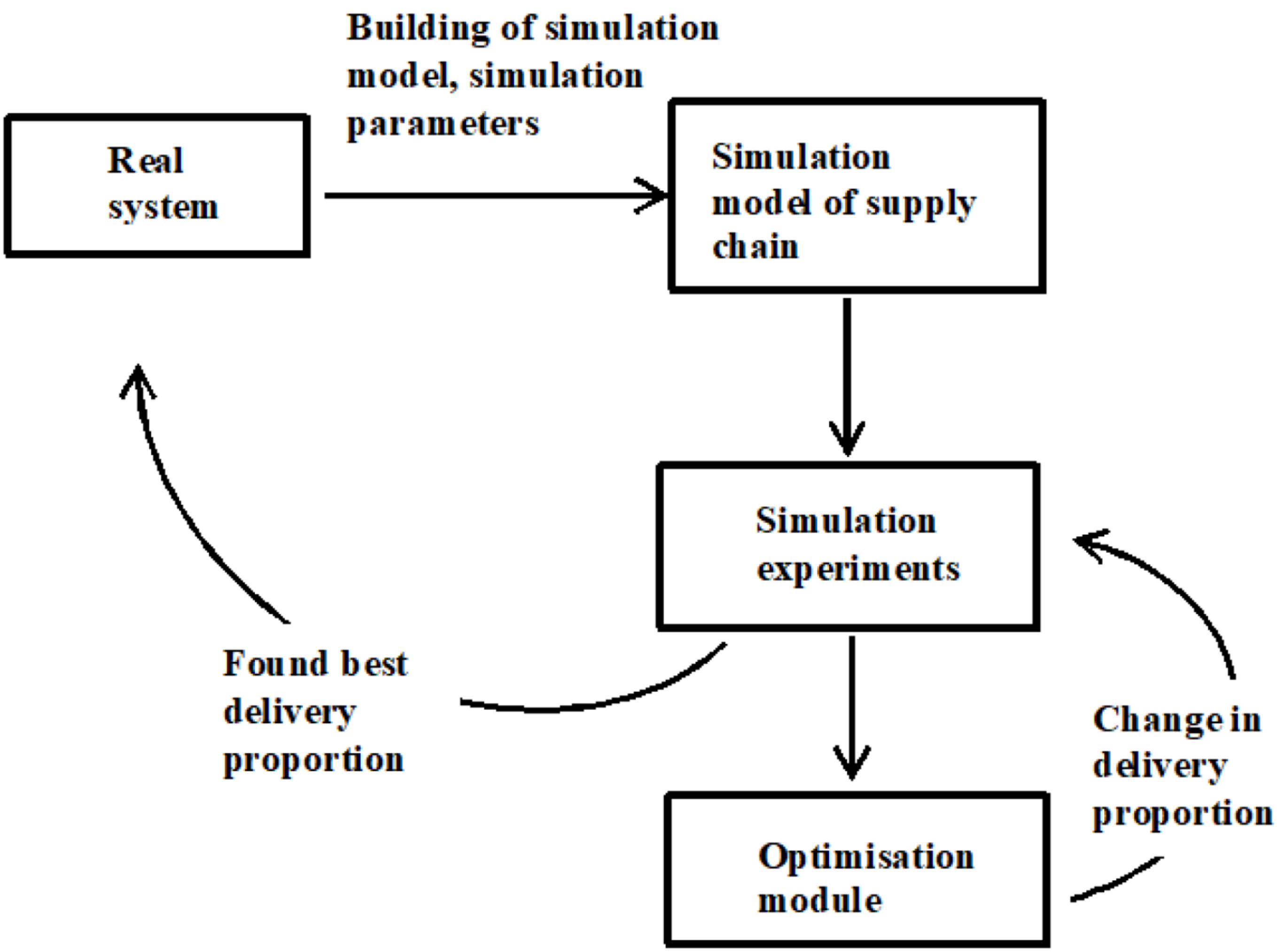


Figure 14. Simulation Modeling Process in Supply Chain Optimization [https://www.mdpi.com/2076-3417/10/8/2783]

3. Methodology

3.1 Introduction to AnyLogic

AnyLogic is a multi-method simulation modeling tool that empowers users to develop detailed, accurate simulations for intricate systems. Uniquely, it integrates various modeling techniques—system dynamics, discrete event, and agent-based modeling—all within a singular model.

Modeling Techniques

1. System Dynamics (SD): Rooted in the feedback control theory of engineering, this modeling technique helps to analyze continuous processes and complex dynamic systems with feedback loops and time delays. In the context of a hydrogen supply chain, this could involve understanding the interaction between hydrogen production and consumption rates over time.

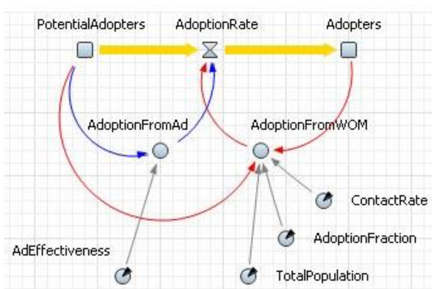


Figure 15. System Dynamics Modeling [https://www.AnyLogic.com]

2. Discrete Event (DE): DE modeling deals with the operations of a system as a sequence of discrete events, each occurring at a specific instant in time. In the hydrogen supply chain, this could mean modeling activities like the loading and unloading of hydrogen, its transport, or any other event-based operations.

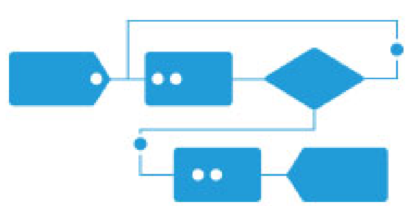


Figure 16. Discrete-event modeling [https://www.AnyLogic.com/]

3. Agent-Based Modeling (ABM): ABM focuses on autonomous agents and observes their interactions to understand the overall behavior of the system. In our context, each entity in the hydrogen supply chain—be it the production facility, storage, transport vehicle, or consumer—can be treated as an agent with its own behaviors and rules of interaction.

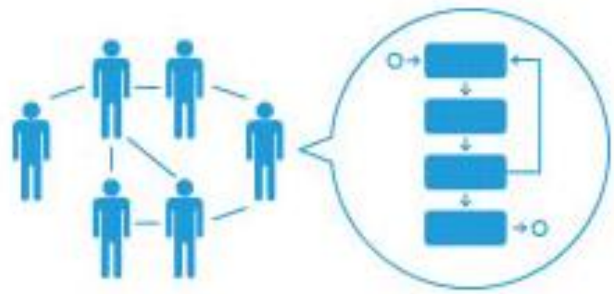


Figure 17. Agent-Based Modeling [https://www.AnyLogic.com]

In the context of this thesis, AnyLogic was chosen for its capabilities to model and optimize complex systems, such as a hydrogen supply chain. This is due to its ability to realistically depict various entities, their behaviors, and interactions. Its integrated development environment is equipped with a comprehensive Java library, graphical and textual editors, tools for debugging, and a platform for visualization of model execution.

The choice of AnyLogic is reinforced by its ability to simulate a wide array of aspects, such as geography, time, process logic, and randomness. This is vital in modeling real-world supply chains as they are influenced by numerous unpredictable factors. Moreover, AnyLogic's GIS (Geographical Information System) features allow users to utilize real-world maps and geographical data, which enhances the accuracy of the model.

In the following sections, we will delve into the specific processes of developing a hydrogen supply chain model in AnyLogic and the optimization methods employed.

3.2 Model Development in AnyLogic

Developing a model in AnyLogic involves a series of stages that include defining the problem, designing the model structure, coding the model, verifying and validating it, conducting experiments, and then analyzing and interpreting the results.

To begin with, a clear understanding of the problem is required. For this thesis, our aim is to optimize the hydrogen supply chain. This entails capturing all the relevant details pertaining to the hydrogen supply chain, including production points, demand points, transportation options and their associated costs and constraints.

Next, we design the structure of the model. Given the complexity and dynamism of a hydrogen supply chain, the model integrates various modeling techniques, as mentioned before, including Discrete Event and Agent-Based Modeling. This multi-method approach allows us to effectively depict the diverse entities and their interactions within the supply chain.

In the coding phase, we utilize AnyLogic's extensive Java library, which provides a wide range of built-in functions and objects. These resources significantly ease the model development process. We also utilize its graphical and textual editors, which allow for visual model construction and detailed scripting respectively. Additionally, AnyLogic provides debugging tools that are essential to identify and correct any errors in the model.

Once the model has been coded, it is important to verify and validate it. Verification ensures that the model accurately represents the developer’s conceptual description and specifications, while validation ensures that it is an accurate representation of the real-world system. In our case, this involves comparing model outputs with empirical data and expert opinion to ensure that the model behaves realistically.

Finally, once the model has been validated, we can conduct experiments using AnyLogic's inbuilt experiment framework. This includes parameter variation, and optimization experiments. The insights from these experiments help us identify key parameters affecting the hydrogen supply chain and the optimal solutions to enhance its efficiency and cost-effectiveness.

3.3 Hydrogen Supply Chain Model in AnyLogic

The hydrogen supply chain model developed in AnyLogic for this thesis integrates the unique features of a hydrogen supply chain. It involves multiple entities such as production sites, transportation systems and demand points, which interact in a complex network. The model integrates various types of modelling techniques – Discrete Event and Agent-Based – to accurately represent the complex and dynamic nature of the supply chain.

Firstly, hydrogen production sites are modeled. They can employ various methods of hydrogen production such as electrolysis, steam methane reforming (SMR), autothermal reforming (ATR), coal gasification, and biomass gasification. Our model focuses in the green hydrogen produced from electrolysis and a small portion of blue hydrogen produced with SMR using CCS methods. Each of these production points are parameterized with their respective name, specific GIS location and production capacities.

Then, the model considers various transportation options, including pipelines and trucks. Each transportation mode is represented with its specific cost structures and transportation capacities.

Lastly, hydrogen demand points are modeled. These points include industrial applications, power generation facilities, transport sector, and buildings sector, each with its unique demand profiles and costs.

The model is designed to simulate the flow of hydrogen over time, capturing the temporal dynamics of hydrogen transportation. AnyLogic's GIS features are utilized to accurately represent the geographic locations of these entities and the transportation routes between them. The model is also capable of conducting "what-if" scenarios to explore the effects of changing various parameters.

In the subsequent sections, we delve into the details of how these components are implemented in the model and how optimization methods are used to identify the most cost-effective and efficient hydrogen supply chain configurations.

3.4 Optimization Methods Used

The optimization methodology utilized in this thesis is distinct in its reliance on manual, iterative user interaction rather than automated optimization techniques.

This approach allows for a custom configuration of the hydrogen supply chain model, attuned to individual requirements or research objectives. As the simulation progresses, users can observe how changes in parameters affect the overall cost in real time. Through this active engagement and modification process, the most cost-effective supply chain setup can be identified.

This interactive method functions in a similar way to a trial-and-error process. Users adjust parameters iteratively and observe how each adjustment impacts the total cost. Each simulation run enhances the user's understanding of the correlations between different parameters and the total cost, allowing for more refined inputs in subsequent simulations.

This user-driven optimization method values flexibility and adaptability. A wide array of scenarios can be accounted for, including potential disruptions that would be challenging to predict or define within a more rigid mathematical model. This strategy capitalizes on the user's judgment and learning capacity for a nuanced exploration of the solution space.

In conjunction with the detailed hydrogen supply chain model developed in AnyLogic, this study offers an engaging and insightful platform for exploring and identifying optimal strategies in hydrogen supply chain management. This approach fosters a better understanding of the interrelationships among various factors and aids in pinpointing potential bottlenecks and opportunities in the hydrogen supply chain.

In the following section, we will dive into the detailed steps of constructing the model and the specific process of implementing this user-driven optimization methodology in the AnyLogic environment.

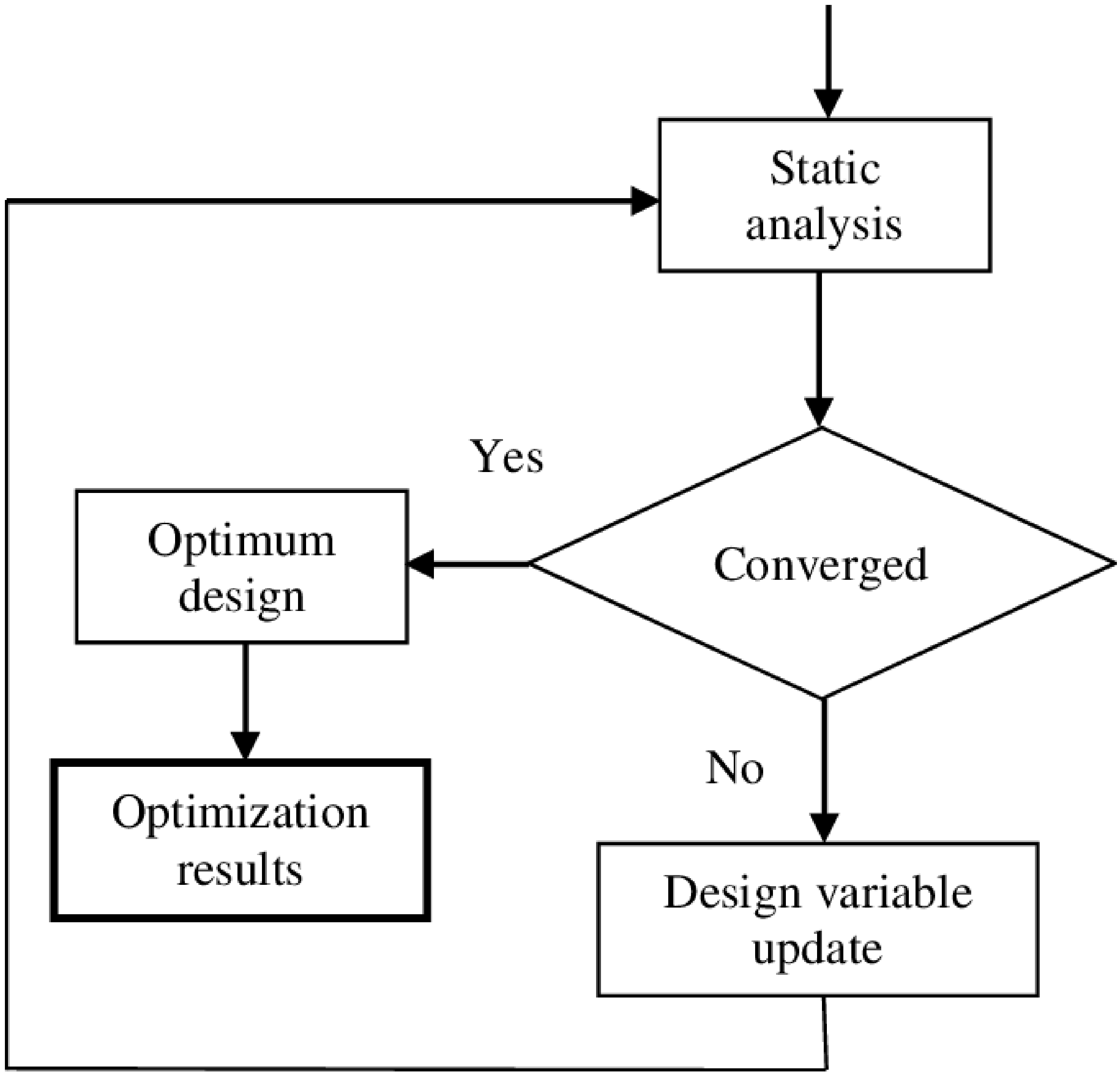


Figure 18. Flowchart of the optimization process.

[https://www.researchgate.net/publication/317042764_OPTIMIZATION_METHODS_APPLIED_IN_CAD_BASED_FURNITURE_DESIGN]

4. Hydrogen Supply Chain Model

4.1 Model Components: Supply Points and Demand Points

4.1.1 Inserting a GIS Map

The first step in the model development was the incorporation of a Geographic Information System (GIS) map, which allowed for a more precise representation of the real-world layout of the hydrogen supply chain. This not only enhanced the visual representation of the supply chain but also allowed for more accurate distance calculations between different entities, such as supply points, transportation routes, and demand points.

The use of a GIS map facilitated the process of positioning the supply and demand points at their actual geographical locations. This is particularly relevant in the context of a hydrogen supply chain, where distances between the various supply and demand points can significantly influence transportation costs and logistics. In the model, these points were represented as agents, each carrying its respective parameters such as production capacity for supply points and consumption rates for demand points.

The inclusion of a GIS map in the model, therefore, provided a more accurate and visually engaging representation of the supply chain's spatial dynamics, aiding in the understanding and optimization of the system. It enabled the simulation to more accurately reflect the real-world geographical constraints and relationships within the hydrogen supply chain.

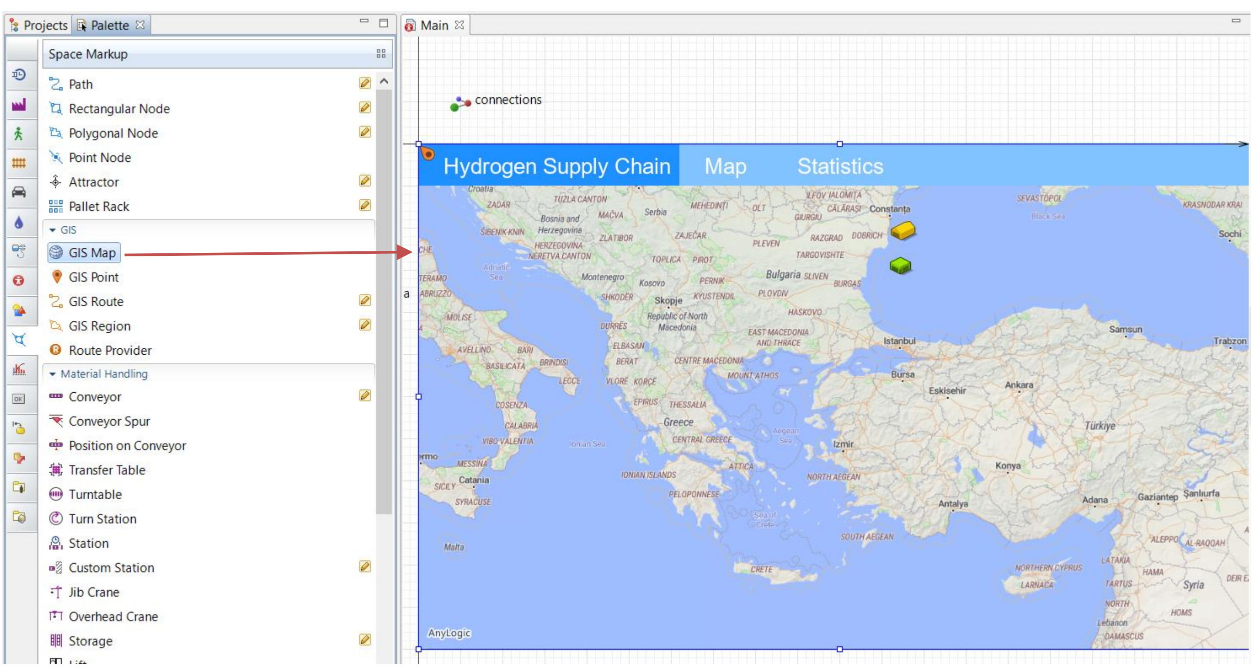


Figure 19. Inserting the GIS Map in our AnyLogic Model

4.1.2 Creation of Supply and Demand Points as Agents

The second stage of model development was the creation of supply and demand points as agents. These agents acted as the fundamental entities in the hydrogen supply chain model, with each representing a unique supply or demand point within the system.

Each agent was linked with a corresponding entry in a database table. This table stored key data for each point, such as geographic longitude and latitude coordinates and the amount of hydrogen supplied or consumed annually. These data served as parameters within each agent, thus individualizing them based on their real-world counterparts.

Once created, the supply and demand point agents were situated on the GIS map according to the longitude and latitude data retrieved from the database. This allowed the accurate geographic representation of the supply chain.

At each supply point agent, a variable called 'hydrogenRemaining' was introduced. This variable represented the remaining amount of hydrogen that was available for supply at each point during the simulation. Initially, it was set equal to the annual production capacity of the respective point (as provided by the database).

Similarly, each demand point agent was equipped with two variables: 'hydrogenRemaining' and 'hydrogenReceived'. The former represented the remaining demand for hydrogen that hadn't yet been satisfied at a particular point in the simulation, while the latter tracked the total amount of hydrogen received at that point. Both were initialized using relevant data from the database: 'hydrogenRemaining' was set equal to the annual hydrogen demand, and 'hydrogenReceived' was set to zero.

By representing supply and demand points as individual agents equipped with specific parameters and variables, the model was able to simulate the dynamics of the hydrogen supply chain with high granularity and accuracy. This approach allowed the model to account for the unique characteristics and requirements of each point, contributing to a more realistic simulation and thereby more reliable outcomes.

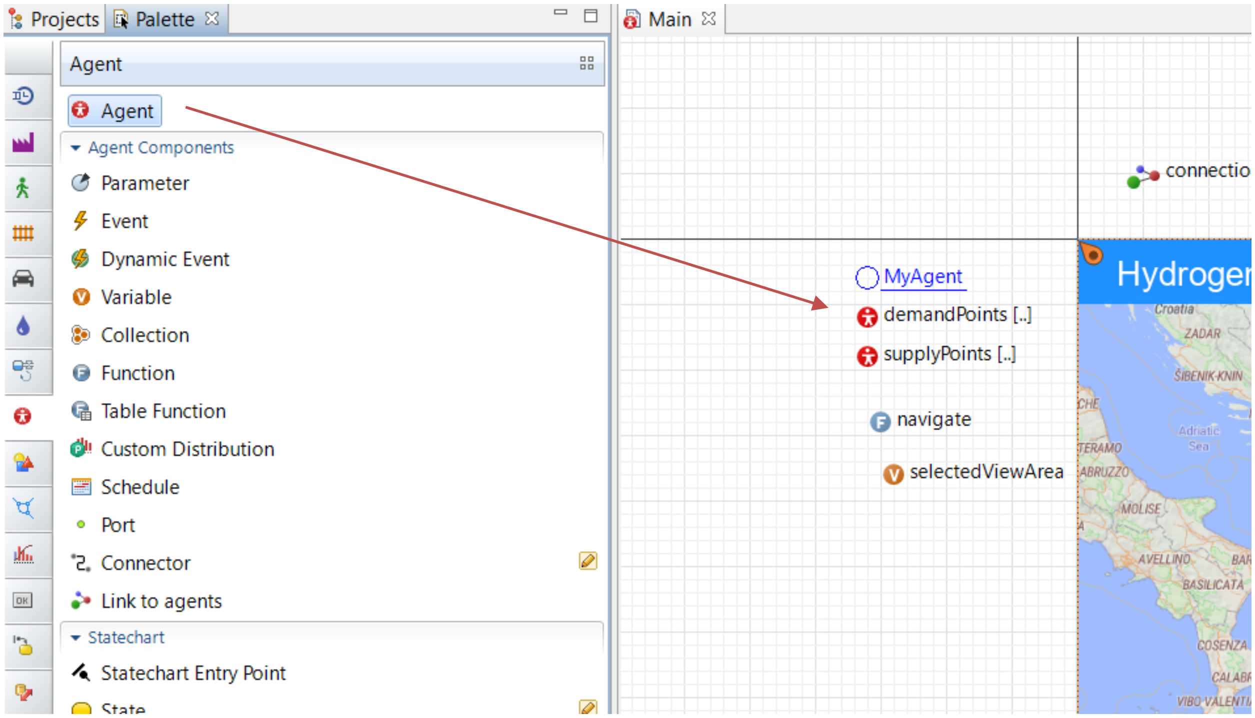


Figure 20. Creation of Supply and Demand Points as Agents

4.2 Implementation of Behaviors

Implementing Supply and Demand Behaviors

This step in the model development involved implementing the behaviors of the supply and demand points, which are primarily related to the supply and consumption of hydrogen, respectively. These behaviors were implemented through methods and actions within the AnyLogic agents using Java code.

4.2.1 Supply Points Behaviors

For supply points, the behavior pattern includes:

1. **Determine Available Hydrogen:**

The supply point checks the 'hydrogenRemaining' variable to ascertain if there is any hydrogen available to supply. If not, the supply point remains idle.

2. **Select a Demand Point:**

The supply point chooses the destination for the hydrogen supply. The selection could be based on several strategies. In our model, two methods were employed: one that targeted the demand point with the highest demand at that moment, and another that selected the nearest demand point.

3. **Send Hydrogen:**

An event called 'SendHydrogen' was created to trigger the process of sending hydrogen to a selected demand point. Upon triggering this event, a 'Transport' agent gets created. The amount of hydrogen sent (defined by the 'amountToSend' variable) and the destination (determined by the 'Select Demand Point' method) are defined at this stage. Once the 'Transport' agent is dispatched, the 'hydrogenRemaining' variable at the supply point gets reduced by the amount being sent.

4. **Calculate Supplied Hydrogen:**

An additional method was defined to aggregate the total hydrogen supplied by each supply point. This information aids in understanding the performance of each supply point and provides valuable insights for optimization.

5. **Calculate Distance:**

Another method was implemented to calculate the distance between the supply point and the destination. This distance is added to a cumulative variable that keeps track of the total distance traveled from each supply point. This is essential for evaluating transportation efficiency and costs associated with the supply chain.

6. Calculate Transport Cost:

Finally, a method to compute the cost for each transport operation is defined. This includes any variable and fixed costs associated with the transport. After each 'SendHydrogen' event, this method is called and the cost is added to a cumulative total, reflecting the total cost of operations for the supply point.

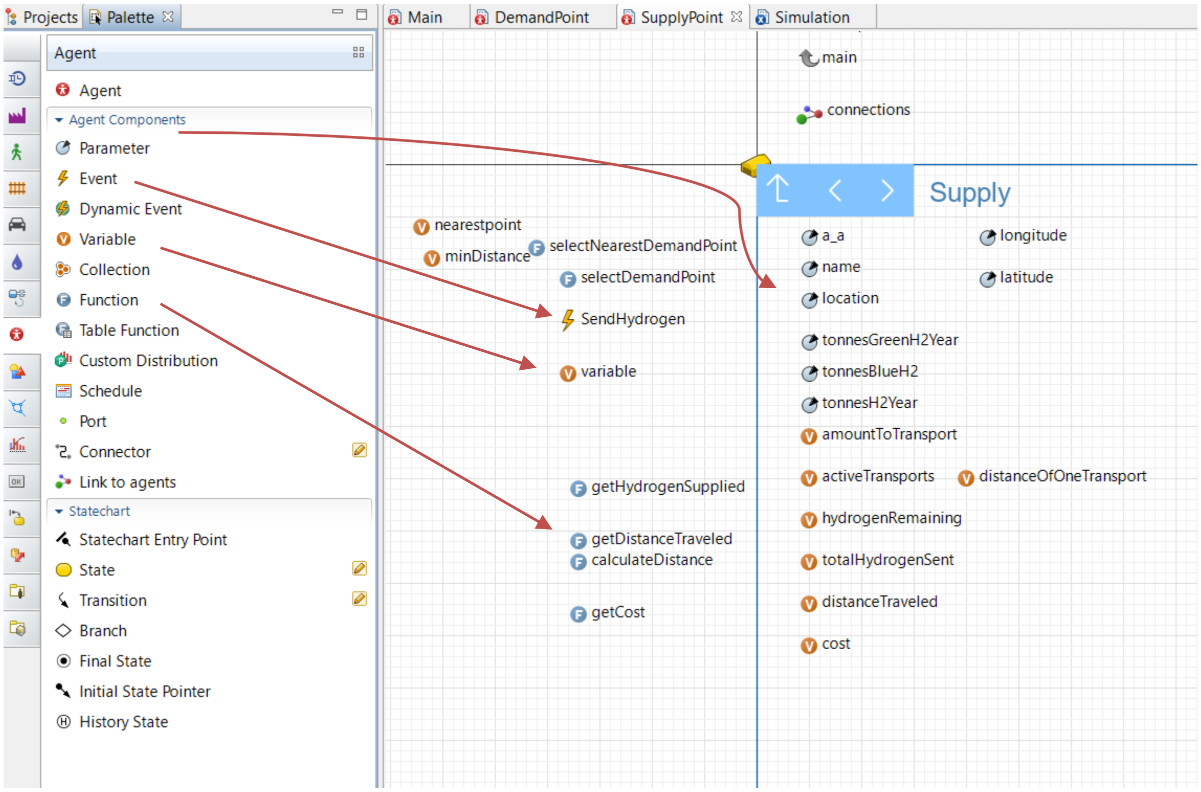


Figure 21. Supply Point Agent with its respective parameters, event, variables and functions.

4.2.2 Demand Points Behaviors

The behavior pattern for demand points includes:

1. **Receive Hydrogen:**

Upon the arrival of a 'Transport' agent at a demand point, the point receives the hydrogen, which involves increasing its 'hydrogenReceived' variable by the amount received and decreasing 'hydrogenRemaining' by the same amount.

2. **Check if Needs are Met:**

The demand point verifies if its hydrogen needs for the year have been met. This involves comparing 'hydrogenReceived' to the annual demand. If the demand is met, no further action is required at the demand point for the rest of the year.

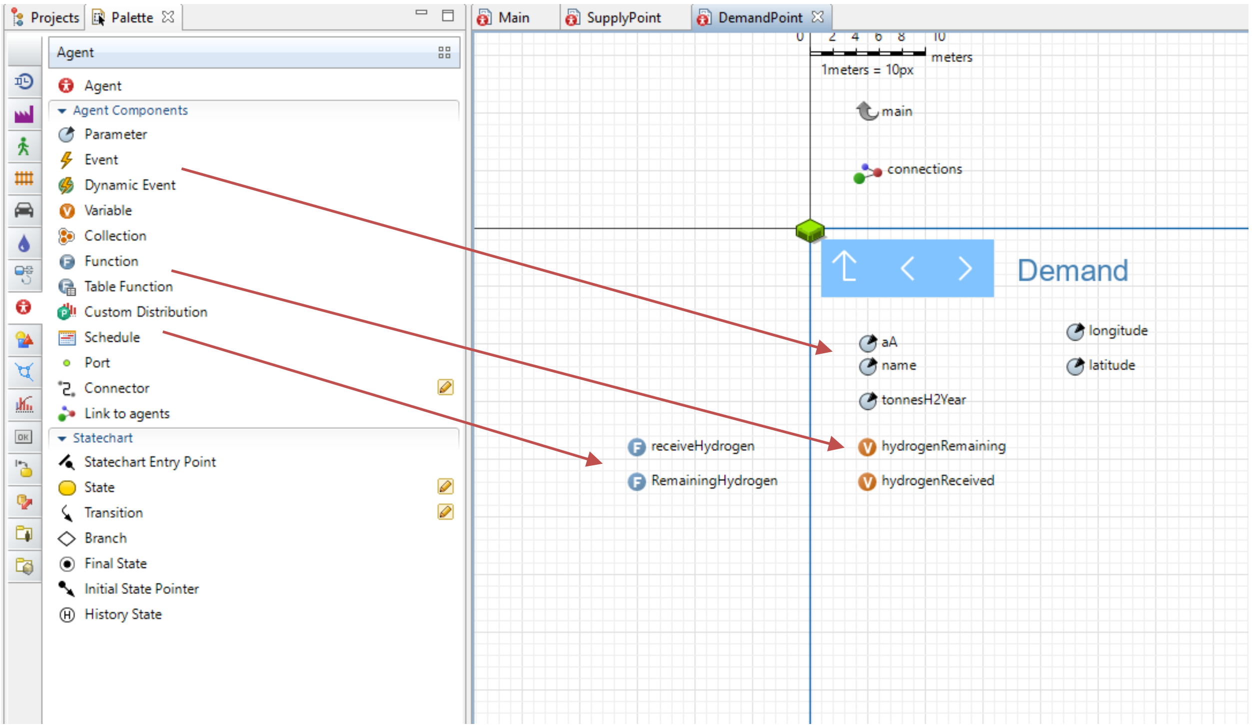


Figure 22. Demand Point Agent with its respective parameters, variables and functions.

4.3 Behaviors and Parameters of the Main Agent

The Main Agent in our model plays a crucial role in controlling and managing the system as a whole. It incorporates two view areas, provides a navigation method, and holds the critical function of calculating the total cost of all the supplied hydrogen.

1. **View Areas:**

The view areas are visual representations of critical elements in the system. The Map view area allows the user to visually track the locations of supply and demand points, giving an intuitive sense of the geographical distribution and scale of the hydrogen supply chain. On the other hand, the Statistics view area serves as an analytical dashboard, showing quantitative data about the performance of the system, including critical parameters and resultant metrics. These two combined provide a holistic and integrated perspective on the model's operation, giving users a clear understanding of the situation.

2. **Navigation:**

The navigation method in the Main Agent is critical for the usability and fluidity of the system. Without it, users would need to manually switch between different views, which could be time-consuming and inconvenient. This user-friendly feature facilitates the ease of use and improves the interactive experience, making the model more accessible to various users, even those who might not be experts in simulation.

3. **New Routes:**

The end goal of this method is to accurately calculate the total distance traveled in a hydrogen supply chain, taking into account the differences between transportation methods. For pipelines, this procedure ensures that each unique pipeline route's distance is only counted once, regardless of how many times hydrogen is sent along that route. This avoids double-counting distance and leads to a more accurate total transportation cost calculation for pipelines. On the other hand, for truck transport, the total distance is calculated in a more straightforward manner. For every trip a truck makes, the distance it travels gets added to the total distance, regardless of whether the truck is traveling a route it has taken before. This reflects the nature of truck transportation, where the costs incurred are directly proportional to the number of trips made.

4. **Total Cost Calculation:**

This method aggregates the cost from each individual supply point to yield the total operational cost of the hydrogen supply chain. Every time hydrogen is dispatched from a supply point, the associated cost is calculated and then added to a running total. This provides a comprehensive economic evaluation of the supply chain's performance, taking into account all contributing factors like distance traveled, quantity of hydrogen supplied, and the specific costs associated with each supply point. It's a crucial tool for decision-making, enabling users to compare and optimize various supply scenarios or strategies.

5. **User-defined Parameters:**

The ability for users to input specific parameters at the beginning of the simulation empowers them to customize the model according to their unique requirements. Whether it's choosing the transportation method, determining the demand point selection strategy, or setting the amount of hydrogen to transport, these inputs add a significant level of flexibility to the model. This feature transforms the model into a versatile tool that can adapt to various scenarios and objectives.

6. **Aggregated Metrics:**

Aggregated metrics like the total distance traveled and the total hydrogen supplied give an overarching view of the supply chain's performance. These metrics, derived from individual supply point data, provide a summary of the entire system's operation and are critical for analyzing the effectiveness and efficiency of the hydrogen supply chain. This high-level overview, combined with the detailed operations at individual supply points, ensures a comprehensive understanding of the system.

In summary, the Main Agent is a pivotal component of the model, playing a central role in controlling and managing the system, providing crucial system-level insights, and offering a user-friendly interface for users to interact with the simulation model.

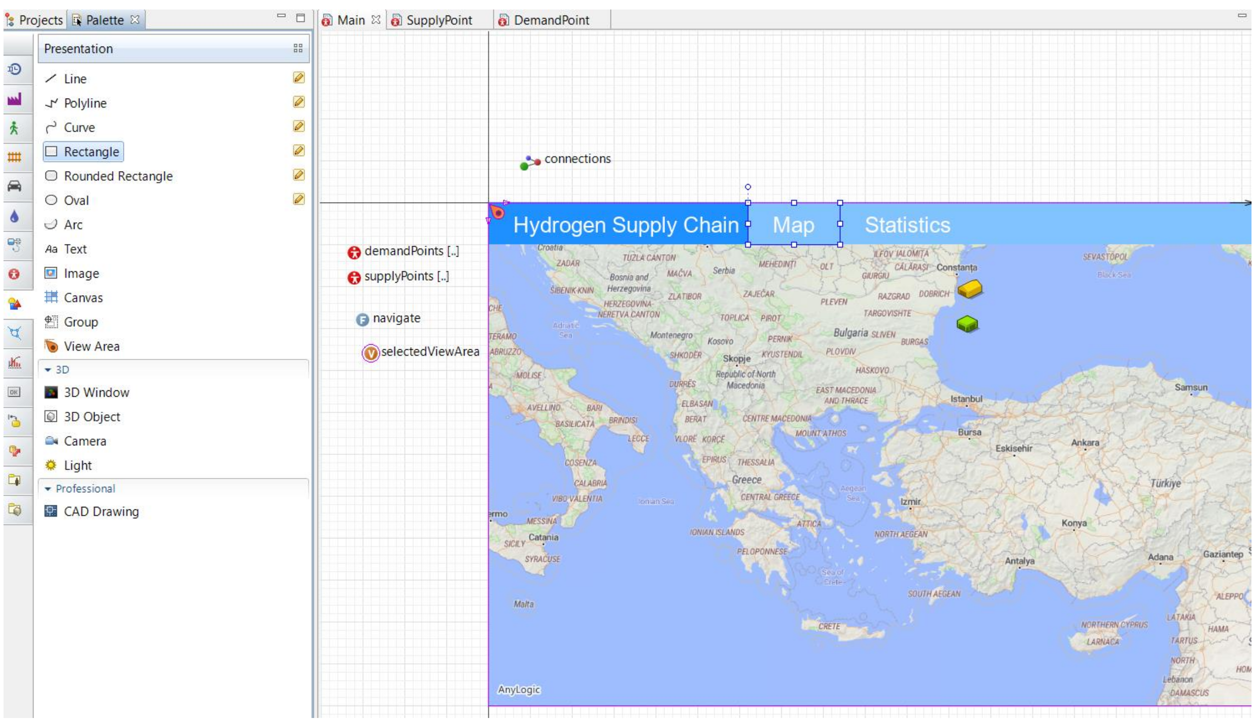


Figure 23. Main Agent Map View Area with its respective agents, variables and functions.

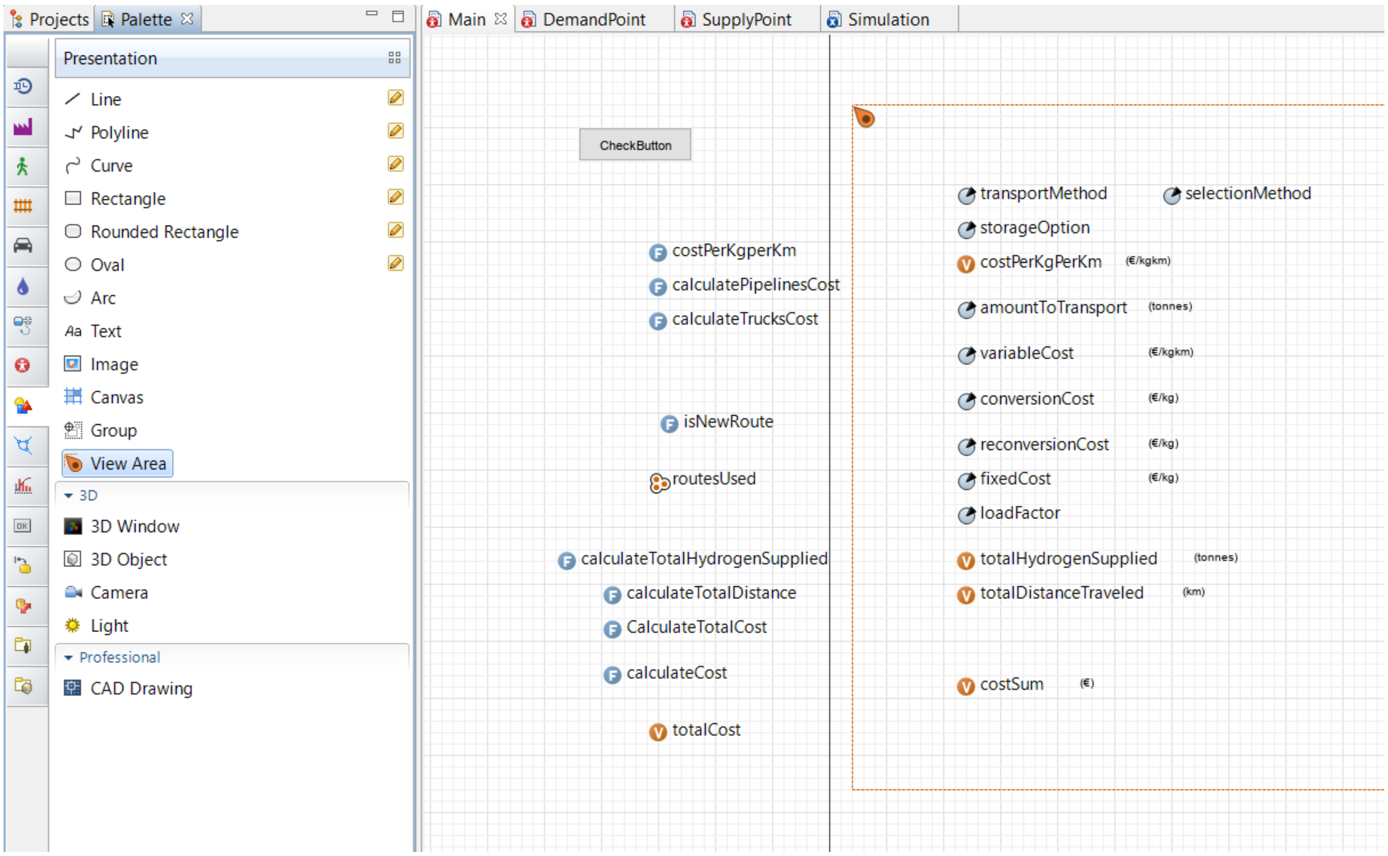


Figure 24. Main Agent Statistics View Area with its respective parameters, variables and functions.

4.4 Implementing Optimization in the Model

1. **Experiment View and User Input:**

The Experiment View serves as the user interface where various parameters are set for the model. This interface is designed for the user to directly manipulate the factors that affect the hydrogen supply chain's total cost, thereby optimizing its performance. These inputs make the model highly adaptable to different scenarios, thus serving as an effective decision support tool.

2. **Transportation Method:**

This parameter influences the method distance is calculated, the cost of hydrogen transportation per kilogram per kilometer and, by extension, the total cost. Pipelines and trucks have different cost structures and capacity limitations. Choosing the transport method determines how the hydrogen is moved from supply to demand points, influencing the efficiency of the supply chain.

3. **Demand Point Selection Method:**

The user can choose between nearest demand point and highest demand strategies. This choice directly affects the total distance traveled. Selecting the nearest demand point may result in lower transportation distances and thus lower costs. However, prioritizing the highest demand could lead to more effective utilization of resources, potentially reducing costs in other areas.

4. **Amount to Transport:**

This parameter is defined by the user within the constraints of each transport method's capacity. It directly influences the number of trips needed to fulfill all hydrogen supplies, impacting the total distance traveled and the total cost. The optimal value for this parameter would strike a balance between maximizing transport capacity and minimizing total trips, thus reducing costs.

5. **Cost Parameters:**

The user inputs specific cost values for different categories. These costs directly influence the calculation of costPerKgPerKm, a critical factor in determining the total cost.

6. **Load Factor (Trucks only):**

The load factor parameter allows the user to specify the proportion of a truck's total capacity that can be loaded with hydrogen. This factor influences the amount transported per trip and, consequently, the total number of trips needed. It ultimately affects the total distance traveled and the total cost.

7. **Running the Simulation:**

After setting all parameters, the user runs the simulation. The model integrates these inputs to simulate the hydrogen supply chain's operation, calculating and presenting the total cost and other important metrics.

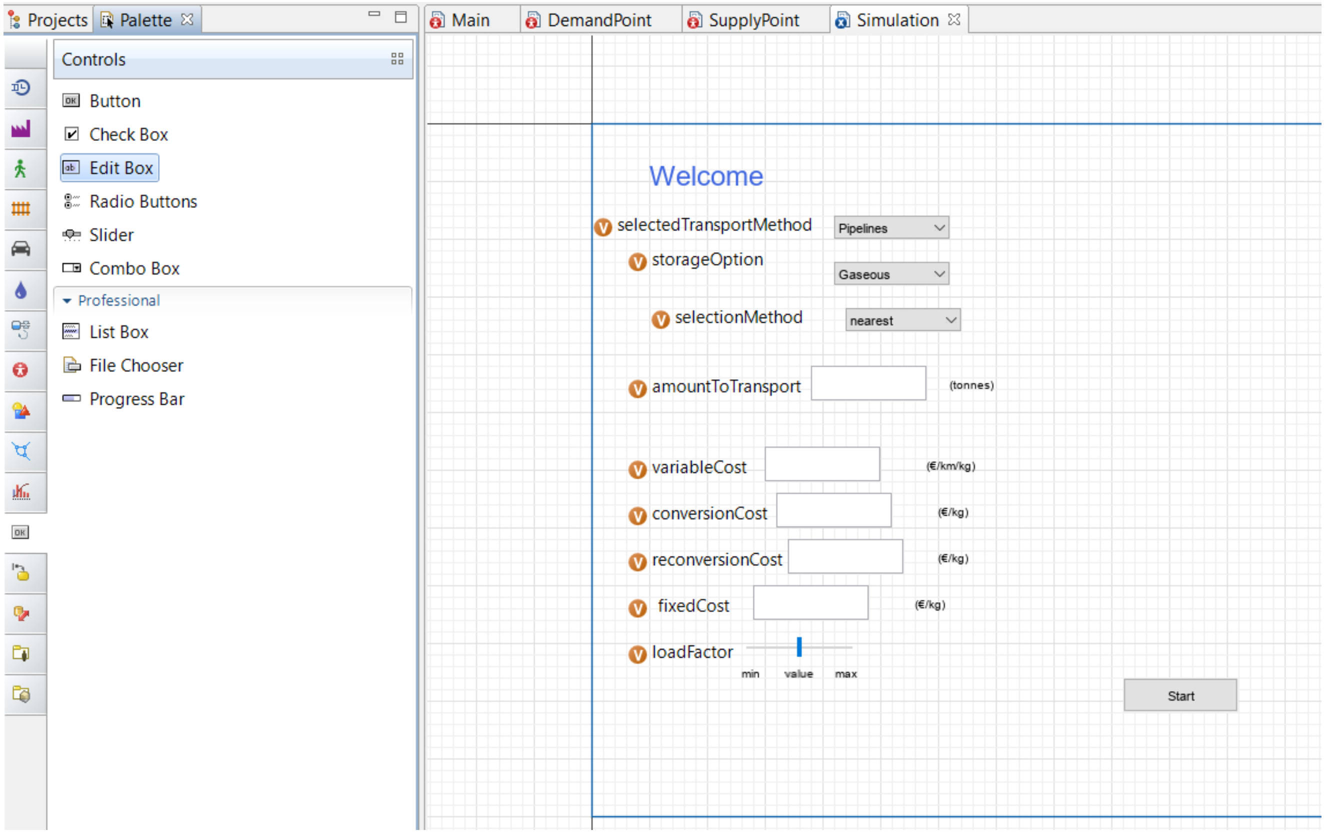


Figure 25. Experiment View with its respective buttons, input fields, combo boxes and variables

Overall, the Experiment View is crucial as it offers users a comprehensive platform to define the model parameters, interact with the model, and visualize the results. Its user-friendly design and flexibility allow for the optimization of the hydrogen supply chain based on different situations and objectives.

5. Case Study – Greece Hydrogen Supply Chain

5.1 Context and Data Source

In the context of this case study, our focus is centered around a potential hydrogen supply in Greece in the estimated future of 2030. To set the foundation of our analysis, the total demand for hydrogen was initially determined by referring to the European Hydrogen Backbone, which outlines the anticipated hydrogen goals in TWh/year for each energy sector within individual countries.

For Greece, the breakdown of the hydrogen demand across various sectors, as provided by the EHB, is as follows:

1. **Industry Sector:**

Expected to demand **9 TWh/year**, predominantly from the Fuel & HVC sector (8.82 TWh/year) by 2030.

Table 7. Overview of expected industrial hydrogen demand per country (in TWh/year)

[https://ehb.eu/]

Country	2030					2040					2050				
	Ammonia	Fuels & HVC	Steel	Industrial heat	Total 2030	Ammonia	Fuels & HVC	Steel	Industrial heat	Total 2040	Ammonia	Fuels & HVC	Steel	Industrial heat	Total 2050
Austria	0.23	2.39	3.30	1.59	**7.51**	1.20	6.74	11.78	4.67	**24.39**	1.50	9.39	11.96	6.16	**29.01**
Belgium	0.95	9.58	4.29	3.04	**17.86**	5.06	27.05	9.10	8.73	**49.94**	6.33	37.71	7.90	11.37	**63.31**
Bulgaria	0.00	2.39	0.00	0.69	**3.07**	0.75	6.74	0.00	1.95	**9.44**	5.03	9.39	0.00	2.52	**16.94**
Croatia	0.00	1.64	0.00	0.25	**1.89**	0.35	4.63	0.00	0.71	**5.69**	2.33	6.45	0.00	0.93	**9.71**
Cyprus	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**
Czech Republic	0.00	2.14	0.22	1.07	**3.44**	0.35	6.05	2.22	3.15	**11.78**	2.37	8.43	3.79	4.16	**18.75**
Denmark	0.00	2.20	0.00	0.38	**2.58**	0.00	6.22	0.00	1.13	**7.35**	0.00	8.67	0.00	1.51	**10.18**
Estonia	0.00	0.00	0.00	0.03	**0.03**	0.00	0.00	0.00	0.11	**0.11**	0.00	0.00	0.00	0.16	**0.16**
Finland	0.00	3.06	2.03	0.14	**5.22**	0.00	8.64	4.05	0.52	**13.20**	0.00	12.04	4.11	0.76	**16.91**
France	1.10	17.71	6.83	5.28	**30.92**	5.87	49.99	15.68	15.55	**87.09**	7.34	69.69	18.72	20.53	**116.28**
Germany	0.93	25.63	17.81	16.60	**60.98**	11.11	72.38	49.59	49.47	**182.55**	18.52	100.90	59.96	65.73	**245.11**
Greece	0.00	8.82	0.00	0.18	**9.00**	0.13	24.91	0.00	0.51	**25.54**	0.85	34.73	0.00	0.66	**36.24**
Hungary	0.00	2.02	0.15	0.76	**2.93**	0.58	5.70	1.53	2.17	**9.98**	3.85	7.95	2.61	2.83	**17.23**
Ireland	0.00	0.87	0.00	0.49	**1.36**	0.00	2.45	0.00	1.44	**3.90**	0.00	3.42	0.00	1.91	**5.33**
Italy	0.31	20.26	4.01	5.76	**30.35**	1.64	57.21	14.62	16.75	**90.22**	2.04	79.76	18.17	21.97	**121.94**
Latvia	0.00	0.00	0.00	0.04	**0.04**	0.00	0.00	0.00	0.12	**0.12**	0.00	0.00	0.00	0.15	**0.15**
Lithuania	0.00	2.32	0.00	0.21	**2.53**	0.89	6.56	0.00	0.58	**8.03**	5.91	9.15	0.00	0.74	**15.81**
Luxembourg	0.00	0.00	0.00	0.26	**0.26**	0.00	0.00	0.00	0.75	**0.75**	0.00	0.00	0.00	0.96	**0.96**
Malta	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**
Netherlands	1.90	16.15	3.21	3.77	**25.03**	10.13	45.61	3.41	10.93	**70.08**	12.66	63.58	11.85	14.33	**102.41**
Poland	0.00	6.99	2.14	2.82	**11.95**	2.24	19.73	5.03	8.20	**35.19**	14.91	27.50	7.90	10.76	**61.07**
Portugal	0.00	5.26	0.00	0.85	**6.11**	0.00	14.86	0.00	2.46	**17.31**	0.00	20.71	0.00	3.22	**23.93**
Romania	0.00	2.91	3.28	1.67	**7.87**	1.79	8.22	4.98	4.65	**19.64**	11.95	11.46	5.05	5.96	**34.42**
Slovakia	0.00	1.52	0.42	0.35	**2.29**	0.47	4.28	4.17	0.97	**9.89**	3.14	5.97	7.11	1.23	**17.45**
Slovenia	0.00	0.00	0.00	0.34	**0.34**	0.00	0.00	0.00	0.99	**0.99**	0.00	0.00	0.00	1.30	**1.30**
Spain	0.25	18.67	3.39	5.34	**27.65**	3.02	52.72	8.40	15.60	**79.74**	5.03	73.50	8.53	20.52	**107.58**
Sweden	0.00	5.10	2.70	0.06	**7.86**	0.00	14.41	6.07	0.17	**20.64**	0.00	20.08	6.16	0.22	**26.47**
UK	1.42	17.79	1.37	4.24	**24.82**	7.55	50.24	2.87	12.42	**73.07**	9.44	70.03	5.05	16.36	**100.88**
Total	**7.07**	**175.43**	**55.17**	**56.20**	**293.87**	**53.13**	**495.34**	**143.50**	**164.68**	**856.65**	**113.19**	**690.53**	**178.86**	**216.97**	**1,199.56**

2. **Transport Sector:**

Expected to demand **0.3 TWh/year** by 2030.

Table 8. Direct Hydrogen demand per country for the transport sector for 2020-2050. (TWh/year)

[https://ehb.eu/]

Country	2020	2025	2030	2035	2040	2045	2050
Austria	0.0	0.0	0.3	0.9	2.1	3.8	5.6
Belgium	0.0	0.0	0.3	1.0	2.1	3.3	4.2
Bulgaria	0.0	0.0	0.3	0.9	1.8	2.6	2.9
Croatia	0.0	0.0	0.1	0.3	0.7	1.0	1.3
Czech Republic	0.0	0.0	0.5	1.6	3.4	4.9	5.7
Cyprus	0.0	0.0	0.0	0.1	0.1	0.2	0.2
Denmark	0.0	0.0	0.3	1.0	2.3	3.7	4.7
Estonia	0.0	0.0	0.1	0.2	0.4	0.6	0.7
Finland	0.0	0.0	0.4	1.3	2.9	4.5	5.8
France	0.0	0.1	3.3	9.8	21.3	33.3	41.5
Germany	0.0	0.1	3.0	9.0	19.8	32.0	41.5
Greece	0.0	0.0	0.3	1.0	2.0	3.0	3.8
Hungary	0.0	0.0	0.4	1.3	2.7	4.5	6.1
Ireland	0.0	0.0	0.2	0.8	2.3	6.0	11.2
Italy	0.0	0.1	2.2	6.7	13.8	20.1	23.4
Latvia	0.0	0.0	0.1	0.3	0.7	1.2	1.5
Lithuania	0.0	0.0	0.2	0.6	1.3	1.9	2.2
Luxembourg	0.0	0.0	0.1	0.2	0.5	1.1	1.9
Malta	0.0	0.0	0.1	0.3	0.6	0.9	1.2
Netherlands	0.0	0.0	0.7	2.1	4.7	8.0	10.8
Poland	0.0	0.0	2.5	7.2	15.5	23.0	26.6
Portugal	0.0	0.0	0.3	0.9	2.0	3.2	4.1
Romania	0.0	0.0	0.4	1.1	2.3	3.4	4.2
Sweden	0.0	0.0	0.7	1.9	4.2	6.5	7.9
Slovenia	0.0	0.0	0.1	0.4	0.9	1.4	1.6
Slovakia	0.0	0.0	0.4	1.1	2.4	3.5	4.1
Spain	0.0	0.1	1.9	5.5	11.9	18.7	23.7
United Kingdom	0.0	0.1	2.4	7.2	16.3	27.3	36.7
EU+UK	0.0	0.7	21.4	64.8	141.1	223.6	285.1

3. **Power Sector:**

The demand is expected to increase gradually, reaching about **1 Twh/year** by 2040.

Table 9. Power sector hydrogen demand per country for 2030, 2040, and 2050 (TWh/year) [https://ehb.eu/]

Country	2020	2040	2050
Austria	0	4	9
Belgium	1	13	27
Bulgaria	0	2	4
Croatia	0	0	1
Czech Republic	0	0	1
Cyprus	0	0	1
Denmark	0	3	7
Estonia	0	1	1
Finland	0	1	4
France	0	9	24
Germany	3	78	183
Greece	0	1	4
Hungary	0	1	2
Ireland	0	7	14
Italy	2	50	92
Latvia	0	0	0
Lithuania	0	2	3
Luxembourg	0	0	0
Malta	0	0	1
Netherlands	1	13	20
Poland	1	37	66
Portugal	0	3	5
Romania	0	2	8
Sweden	0	0	0
Slovenia	0	2	4
Slovakia	0	1	2
Spain	1	15	34
United Kingdom	2	56	106
Total	12	301	625

4. **Buildings Sector:**

The demand is calculated based on the formula:

$\text{Energy} = \text{Floor Area} * Useful\ Energy\ Demand * 5\%$ assuming that hydrogen will be responsible for the heating of the 5% of the total floor area. Leading to an estimated demand of **3.7 TWh/year**.

Table 10. Floor space estimates per country (2020) [https://ehb.eu/]

Country	Residential floor area	Service floor area	Useful energy demand
	million m²	million m²	kWh/m²
Austria	117	459	141.52
Belgium	144	537	167.55
Bulgaria	71	297	53.92
Croatia	35	175	47.66
Czech Republic	105	405	153.41
Cyprus	7	48	48.30
Denmark	121	421	136.50
Estonia	48	98	148.20
Finland	101	303	203.67
France	873	3493	114.65
Germany	1662	5227	164.02
Greece	125	561	107.85
Hungary	104	416	142.22
Ireland	57	222	125.79
Italy	399	3047	101.37
Latvia	18	81	192.26
Lithuania	35	118	139.09
Luxembourg	7	31	200.39
Malta	4	19	26.21
Netherlands	303	955	141.76
Poland	404	1340	115.20
Portugal	100	617	70.82
Romania	78	539	112.57
Slovakia	50	188	105.85
Slovenia	24	93	140.52
Spain	362	2235	58.82
Sweden	167	581	137.54
United Kingdom	728	2907	127.34

Taking into account the anticipated gradual rise in demand for hydrogen, we set the demand parameters for our case study. We envisage the total hydrogen demand in Greece to be around **7.88172 Twh/year** by 2030. We further dissect this total into sector-specific demands as follows:

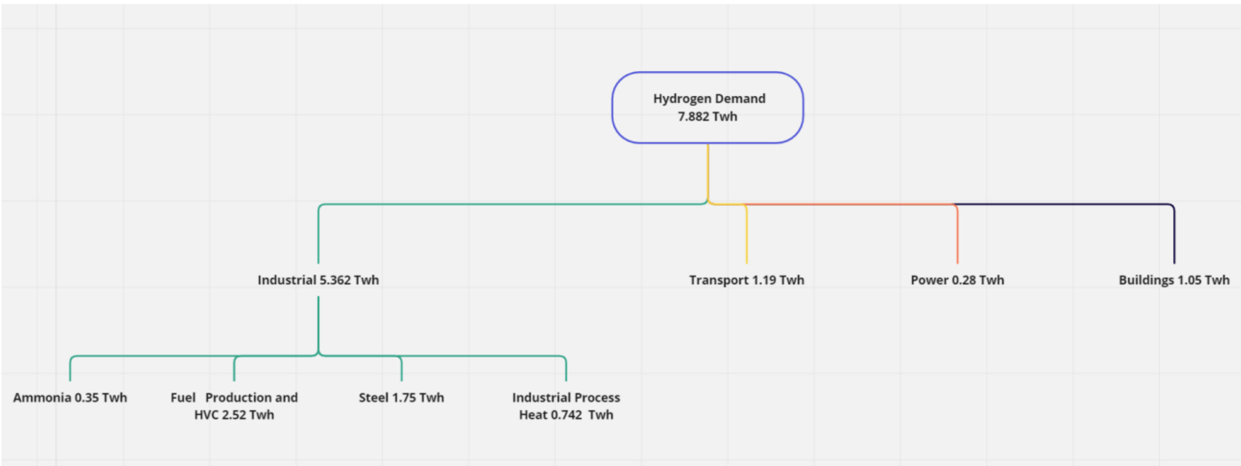


Figure 26.Greece's Hydrogen Demand in our Case Study(Twh/year)

In order to work with these values in a supply chain context, it is crucial to convert them into a more usable unit, in this case, tonnes of hydrogen. We get the energy per unit of mass from the table below, around 120.1 MJ/kg, and convert it into Kwh/kg. So the energy density of hydrogen is approximately 33.6 kwh/kg.

$$Hydrogen\ Energy\ Density = 33.6\frac{kwh}{kg} = 33.6 * \frac{10^{-9}}{10^{-3}}\left(\frac{Twh}{tonne}\right) = 33.6 * 10^{-6}(\frac{Twh}{tonne})$$

Table 11. Physical properties of hydrogen

[The Future of Hydrogen, 2019]

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Using this value to convert the TWh figures to tonnes yields we get a total hydrogen demand for Greece in 2030 of **234,575 tonnes/year**.

$$Hydrogen\ Demand\left(\frac{tonnes}{year}\right) = \frac{Hydrogen\ Demand\left(\frac{Twh}{year}\right)}{Hydrogen\ Energy\ Density\left(\frac{Twh}{tonne}\right)} = \frac{7.88172}{0.0000336} = 234{,}575$$

Continuing from this crucial calculation, the next step in this case study will be to identify the necessary supply points to adequately cover this defined demand. This involves determining the locations and capacity of production sites to supply the required 234,575 tonnes/year of hydrogen. This step is critical, as it outlines the physical infrastructure needed for the hydrogen supply chain in Greece.

Following the identification of supply points, we will also need to define the specific demand points. This step will require a detailed understanding of the energy consumption across various sectors, as outlined earlier (Industry, Transport, Power, and Buildings). Each sector may have numerous potential demand points, each varying in the intensity of hydrogen usage.

The identification and definition of supply and demand points are critical elements in constructing an efficient and reliable hydrogen supply chain. By comprehensively understanding where and how much hydrogen is needed, and where it can be supplied from, we can begin to construct an optimized supply chain model. These crucial steps form the focus of our subsequent sub-sections in this case study.

5.2 Hydrogen Production Points

5.2.1 Introduction to Production Points Selection

Our approach to modeling a hydrogen supply chain in Greece begins with the understanding and calculation of the prospective hydrogen production capacities. To meet the country's hydrogen demand, we have strategized to harness the potential of both electrolysis and blue hydrogen production methods.

Blue hydrogen, which is typically produced in refineries, constitutes a part of our plan. However, we particularly emphasize electrolysis because it offers an environmentally-friendly approach to hydrogen production, harnessing renewable sources like solar energy, onshore wind, and offshore wind.

Table 12. Evolution of installed RES capacity in power generation. [NECP, Greece 2019]

Power generation, installed capacity [GW]	2020	2022	2025	2027	2030
Biomass & biogas	0.1	0.1	0.1	0.2	0.3
Hydro (incl. mixed pumping)	3.4	3.7	3.8	3.9	3.9
Wind farms	3.6	4.2	5.2	6.0	7.0
Photovoltaics	3.0	3.9	5.3	6.3	7.7
Solar thermal	0.0	0.0	0.1	0.1	0.1
Geothermal	0.0	0.0	0.0	0.0	0.1
Total	10.1	11.9	14.6	16.4	19.0

Table 13. Evolution of RES power generation. [NECP, Greece 2019]

Power generation [TWh]	2020	2022	2025	2027	2030
Biomass & biogas	0.4	0.5	0.8	1.0	1.6
Hydro	5.5	6.4	6.5	6.6	6.6
Wind farms	7.3	10.1	12.6	14.4	17.2
Photovoltaics	4.5	6.0	8.2	9.7	11.8
Solar thermal	0.0	0.0	0.3	0.3	0.3
Geothermal	0.0	0.0	0.0	0.3	0.6
Total	**17.7**	**23.0**	**28.4**	**32.2**	**38.1**

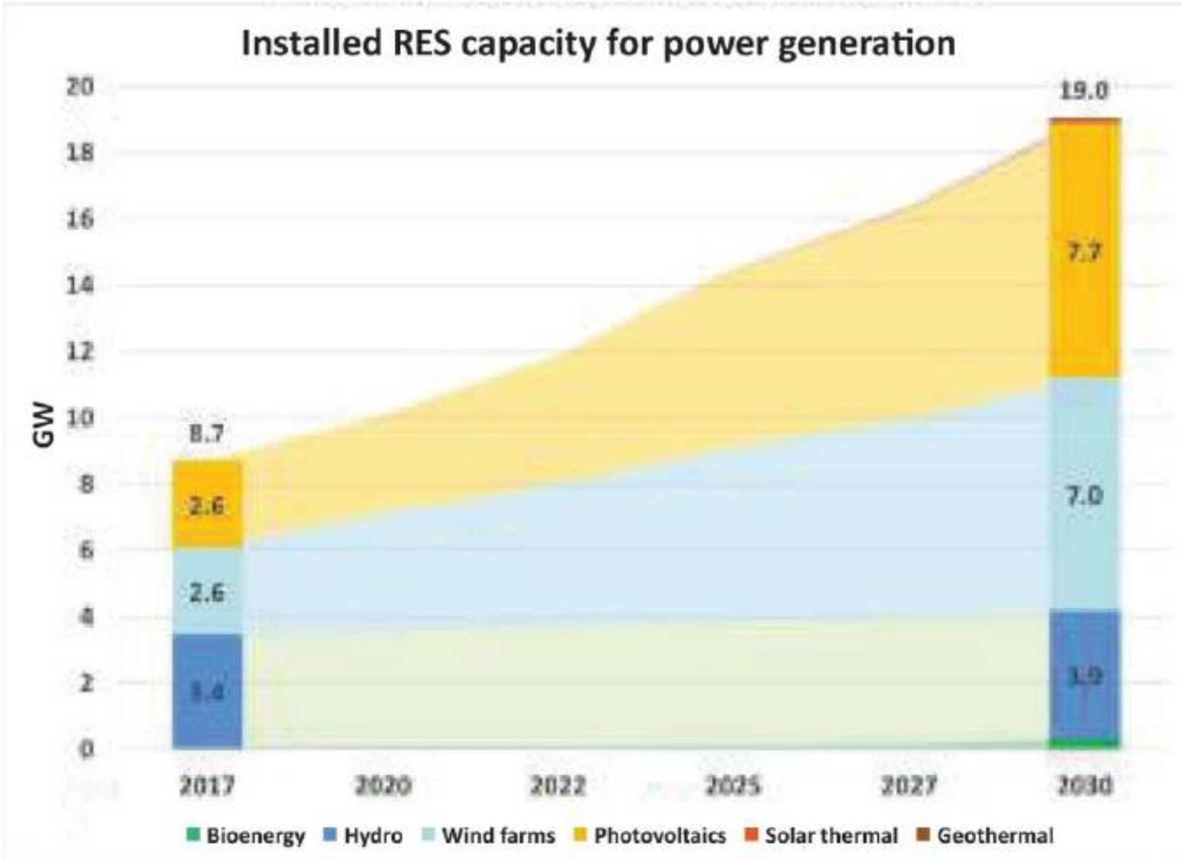


Figure 27. Evolution of installed RES capacity in the period 2017-2030. [NECP, Greece 2019]

We base our estimates on the assumption that around 50% of the power generated from these renewable sources will be used for hydrogen production via electrolysis. This allows us to balance direct electricity usage and the production of hydrogen, adhering to a realistic and sustainable energy strategy.

Identifying the exact locations for hydrogen production is a key aspect of our model. As such, we propose the establishment of renewable energy parks, equipped with the required facilities for hydrogen production. Our choice of these locations as hydrogen supply points is based on several considerations:

1. **Existing Renewable Energy Parks:**

We've identified places that currently have renewable energy facilities. These existing infrastructures can be easily outfitted with electrolysis equipment, which makes them prime candidates for hydrogen production.

2. **Future Projects:**

We've included future renewable energy projects, taking into account the timeline of when these projects are likely to be operational. This forward-thinking approach ensures our model is practical and relevant in the coming years.

3. **Potential Sites:**

We've evaluated locations that don't currently have renewable energy infrastructure but exhibit promising characteristics due to favorable geographical and climatic conditions.

In addition to these factors, there are certain prerequisites that a location must fulfill to be a viable hydrogen production site:

1. **Access to Renewable Energy:**

Since our production relies on solar, wind, and hydroelectric power, the site should be in an area that has access to these renewable energy sources.

2. **Access to Water**:

Electrolysis requires an ample supply of water. Therefore, a viable hydrogen production site must have ready access to a substantial water source.

3. **Infrastructure:**

The site should have the necessary infrastructure for hydrogen production or the potential for such infrastructure to be developed. This includes space for electrolysis equipment and, in the case of blue hydrogen, proximity to refineries.

4. **Proximity to Demand Points:**

Ideally, the site should be close to points of demand to reduce transportation costs and increase efficiency.

5. **Regulatory Compliance:**

The site must comply with all relevant environmental and safety regulations.

By combining existing, future, and potential renewable energy sites, we have drawn up a blueprint that predicts a total hydrogen production of **234,575 tonnes per year**, sufficiently covering Greece's future hydrogen demands.

5.2.2 Solar PVs

Parameters

A key part of understanding the potential of solar energy for hydrogen production lies in calculating the conversion from installed solar capacity to the amount of hydrogen produced. This calculation involves several critical parameters, each of which we'll discuss in turn.

1. **Solar Power Output:**

Solar PV panels produce varying amounts of energy depending on their efficiency and location. According to data from the National Renewable Energy Laboratory (NREL), a rough estimate for the annual energy production of solar panels in a region with Greece's sunlight conditions is about **1,200 kWh per installed kW**.

Table 14. Solar PV power generation of 1Kw installed capacity [https://pvwatts.nrel.gov/pvwatts.php]

RESULTS

1,233 kWh/Year*

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)
January	2.77	61
February	3.43	68
March	4.52	98
April	5.44	112
May	6.23	130
June	7.37	146
July	7.53	153
August	7.00	142
September	6.18	123
October	4.26	90
November	2.70	56
December	2.42	53
Annual	4.99	1,232

Location and Station Identification

Requested Location	athens
Weather Data Source	(INTL) ATHENS, GREECE 5.3 mi
Latitude	37.9° N
Longitude	23.73° E

PV System Specifications

DC System Size	1 kW
Module Type	Standard
Array Type	Fixed (open rack)
System Losses	25%
Array Tilt	20°
Array Azimuth	180°
DC to AC Size Ratio	1.2
Inverter Efficiency	96%
Ground Coverage Ratio	0.4%
Albedo	*From weather file*
Bifacial	No (0)

Monthly Irradiance Loss	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Performance Metrics

DC Capacity Factor	14.1%

2. **Allocation for Hydrogen Production:**

Not all the electricity generated from solar power is directed towards hydrogen production. For this analysis, we assume that approximately **50% of the electricity generated by solar PV systems is used for electrolysis**. This allocation takes into account other uses of solar power and reflects an intent to maintain a balanced energy portfolio.

3. **Electrolysis Efficiency:**

The process of electrolysis—the conversion of electrical energy into chemical energy stored in hydrogen—isn't 100% efficient. Different electrolysis technologies (like Proton Exchange Membrane (PEM) and Alkaline electrolysis) have different efficiencies. For this study, we've assumed an average **efficiency of 70%**, representing a middle-of-the-road value between various types of electrolysis.

Table 15. Techno-economic characteristics of different electrolyser technologies [The Future of Hydrogen, 2019]

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
Operating pressure (bar)	1–30			30–80			1		
Operating temperature (°C)	60–80			50–80			650 – 1 000		
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000	60 000 – 90 000	100 000 – 150 000	10 000 – 30 000	40 000 – 60 000	75 000 – 100 00
Load range (%, relative to nominal load)	10–110			0–160			20–100		
Plant footprint (m^2/kW_e)	0.095			0.048					

4. **Hydrogen Energy Density:**

Hydrogen's energy density is another crucial part of this conversion. This value is generally accepted to be **33.6 kWh per kg** of hydrogen.

Solar PVs Performance Calculations

By considering these parameters, we can calculate the amount of hydrogen produced from solar energy. By multiplying the annual solar power output (in TWh) by the electrolysis efficiency and then by the proportion allocated for hydrogen production, and finally dividing by the energy density of hydrogen, we obtain the annual hydrogen production (in tonnes).

While these are estimations and real-world conditions could lead to variations, this method provides a robust foundation for gauging the potential of solar energy for hydrogen production in Greece. Transparency in these calculations ensures their validity and offers a way forward in comprehending the energy dynamics at play.

$$Power\ Generation(Twh) = Installed\ Capacity(GW) * 1.2$$

$$PowerUsedforElectrolysis(Twh) = 0.5 * PowerGeneration(Twh)$$

$$Hydrogen\ Produced\ (tonnes) = \frac{Power\ Used\ forElectrolysis(Twh)}{Energy\ Density\left(\frac{Twh}{tonne}\right)}$$

Given the foundations of our calculations, we are now ready to embark on the application of these principles within Greece's energy landscape. For this endeavor, we will focus on nine hydrogen production sites that utilize solar energy derived from photovoltaic (PV) parks dispersed across the country. These strategically located sites form a crucial part of our envisioned sustainable Greek energy system, each significantly contributing to the production of green hydrogen via electrolysis. By evaluating each site individually, we will gain insights into the capacity and potential limitations of solar energy in fulfilling Greece's hydrogen requirements. Now, let's delve deeper into these hydrogen production sites powered by solar PV parks and their contributions to the overall hydrogen production framework.

Production Sites using Solar PVs as Energy Source

1. **Ptolemaida:**

Ptolemaida emerges as a vital location for hydrogen production in Greece, given the significant presence of solar PV parks in the region. In alignment with the approach of this case study, Ptolemaida is aimed to harness **2 GW** of solar PV energy for hydrogen production. The White Dragon Project, one of the major initiatives in the region, is committed to green hydrogen production and aims to produce an impressive 16,000 tonnes annually.[1] This green hydrogen will primarily satisfy the district heating needs of Western Macedonia, demonstrating a practical application of hydrogen in supporting local communities.

Additionally, in Kozani, close to Ptolemaida, the Hellenic Petroleum Group (HELPE) has installed the country's largest Solar PV park.[2] This facility, combined with Ptolemaida's existing capacity and future growth, reinforces Ptolemaida's strategic role in Greece's green hydrogen production landscape.

2. **Megalopolis:**

Megalopolis, located in the Peloponnese, is another crucial point for green hydrogen production in Greece. The Public Power Corporation S.A. (PPC) is planning a 340 MW solar PV park in the area,[3]signifying the future significance of Megalopolis in the green hydrogen production landscape. The target for Megalopolis, as per the case study's approach, is to generate **0.8 GW** of solar PV energy.

3. **Drama:**

Drama, in northern Greece, is identified as a potential hydrogen production point due to its favorable solar energy prospects. Drama's geographical positioning and solar irradiance make it an ideal location for harnessing solar power for green hydrogen production. In line with the approach of this case study, the target for Drama is to generate **0.8 GW** of solar PV energy.

4. **Farsala:**

Farsala, situated in the Thessaly region, is a prime candidate for green hydrogen production. Its favorable climatic conditions for solar energy harvesting make it an excellent location for solar PV parks. The goal for Farsala, following the case study's approach, is to establish **0.8 GW** of solar PV energy.

5. **Kalampaka:**

Kalampaka, located in Thessaly, holds significant potential for green hydrogen production. Known for its natural beauty and historical significance, the area also possesses advantageous conditions for

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[1] https://depa.gr/white-dragon-proposal-submitted-for-ipcei-hydrogen-important-projects-of-common-european-interest/?lang=en
[2] https://balkangreenenergynews.com/hellenic-petroleum-completes-biggest-solar-power-plant-in-greece-acquires-303-mw-pv-portfolio-in-florina/
[3] https://www.energyregister.gr/stathmos/%204636

harnessing solar energy. Consistent with the case study's approach, the plan for Kalampaka is to achieve **0.8 GW** of solar PV energy, contributing substantially to Greece's green hydrogen production capabilities.

6. **Aspropyrgos - Hellenic Petroleum (ELPE) Refinery Solar PV Park:**

Aspropyrgos, hosting one of the Hellenic Petroleum (ELPE) refineries, stands as a prominent location for hydrogen production. With the strategic installation of solar PV parks in refinery locations, the approach of this case study is to harness a targeted **0.5 GW** of solar PV energy at Aspropyrgos.

7. **Corinth - Motor Oil Refinery Solar PV Park:**

Corinth, home to the Motor Oil refinery, is another key point for green hydrogen production in Greece. In alignment with the approach of our case study, a solar PV park will be established with a target of generating **0.5 GW** of solar PV energy.

8. **Thessaloniki - Hellenic Petroleum (ELPE) Refinery Solar PV Park:**

Thessaloniki, another location of Hellenic Petroleum (ELPE) refineries, has great potential for hydrogen production. By integrating solar PV parks with refinery operations, the case study envisions Thessaloniki contributing an additional **0.5 GW** of solar PV energy to the national grid.

9. **Eleusis - Hellenic Petroleum (ELPE) Refinery Solar PV Park:**

In Eleusis, where another ELPE refinery is located, the integration of solar PV parks will substantially augment green hydrogen production. Following the approach of our case study, the goal is to generate **0.5 GW** of solar PV energy at this location.

Table 16. Hydrogen Production Points using Solar PVs as Energy Source

No.	Location	Installed Capacity (GW)	Power Generation (TWh/year)	Energy for Hydrogen Production (TWh/year)	Tonnes of Hydrogen per Year (Mt/year)
1	Ptolemaida	2.0	2.4	1.2	25,000
2	Megalopolis	0.8	1	0.5	10,416
3	Drama	0.8	1	0.5	10,416
4	Farsala	0.8	1	0.5	10,416
5	Kalampaka	0.8	1	0.5	10,416
6	Aspropyrgos	0.5	0.6	0.3	6,250
7	Corinth	0.5	0.6	0.3	6,250
8	Thessaloniki	0.5	0.6	0.3	6,250
9	Eleusis	0.5	0.6	0.3	6,250
	Total	7.2	8.8	4.4	91,664

5.2.3 Wind farms

Wind energy, a key renewable resource, plays a crucial role in Greece's energy mix, contributing to a sustainable, green future. With a particular focus on both onshore and offshore wind farms, which harness the power of the wind to generate electricity, wind energy forms a significant part of our case study.

In the context of hydrogen production, wind energy can be used to power electrolysis, the process of splitting water into hydrogen and oxygen. The significant potential of wind power allows for substantial hydrogen production, reducing the reliance on traditional fossil fuels and enabling a transition to a cleaner, greener energy landscape.

In our case study, we will use wind farms, both onshore and offshore, as sources of electricity for hydrogen production. To determine the amount of hydrogen produced, we will employ a series of calculations based on installed capacity, capacity factor, electrolysis efficiency, and the energy density of hydrogen.

Wind Farms Performance Calculations

Firstly, we establish the installed capacity of wind farms. This is the maximum power that the wind turbines can generate under ideal conditions.

Next, we use a capacity factor to account for real-world variations in wind speed and other factors that prevent the turbines from always operating at their maximum potential. Given the variability of wind patterns across the country, and especially the difference between onshore and offshore sites, we take an average capacity factor of **28.5%**, representing a balanced estimation between mainland Greece (25%) and the islands (30%). [Country Overview | Greece Renewable Energy 2020-2030, Greensolver]

We then calculate the power generated by multiplying the installed capacity by the capacity factor and the number of functioning hours in a year. In our approach, we assume that **50%** of this power will be used for hydrogen production through electrolysis.

As with the solar PV calculations, we incorporate the efficiency of electrolysis into our calculations. On average, electrolysis processes (PEM and alkaline) are **around 70% efficient**, so we adjust our energy figures accordingly.

Lastly, we take into consideration the energy density of hydrogen (**33.6 kWh/kg**) to convert the energy used in electrolysis into the amount of hydrogen produced.

By following these calculations, we can estimate the potential hydrogen production from both onshore and offshore wind energy in Greece, thereby demonstrating the significant role of wind power in supporting the development of a robust hydrogen supply chain. In the following sections, we will apply these calculations to specific wind farms across the country.

$$Power\ Generation(Twh) = Installed\ Capacity(GW) * 365 * 24 * 0.285$$

$$PowerUsedforElectrolysis(Twh) = 0.5 * PowerGeneration(Twh)$$

$$Hydrogen\ Produced\ (tonnes) = \frac{Power\ Used\ forElectrolysis(Twh)}{Energy\ Density\left(\frac{Twh}{tonne}\right)}$$

Onshore wind farms

1. **Kilkis:**

Kilkis, a region with an impending Greentop wind farm project,[4] is slated to have an installed capacity of **105.6 MW**. This upcoming project, while enhancing the renewable energy landscape, serves as a crucial pillar for the hydrogen production proposed in our case study.

2. **Western Macedonia:**

In line with the White Dragon Project, Western Macedonia is envisioned to host a wind farm with a capacity of **163.8 MW**. In our case study, this region plays a pivotal role due to its immense potential for green hydrogen production.

3. **Vermio:**

Vermio, with the projected wind farm from ''Aioliki Vermiou''[5] and other farms in the vicinity, could see a combined wind energy capacity of approximately **255 MW**. This accumulated capacity holds the potential to significantly contribute to the hydrogen production through electrolysis, reinforcing Vermio's significance in Greece's hydrogen supply chain as envisioned in our case study.

4. **Anilio:**

Anilio hosts a series of wind farm projects which, when combined, are expected to have an installed capacity of around **144 MW**. Harnessing this capacity for electrolysis is a core part of our case study's hydrogen production strategy.

5. **Karpenisi:**

Though currently without specific wind farm projects, Karpenisi is considered a prospective location for developing new ones in our case study. With a hypothetical goal of reaching an installed capacity of **0.2 GW**, the region demonstrates considerable potential for contributing to future hydrogen production.

6. **Lykouria:**

Like Karpenisi, Lykouria in our case study presents a hypothetical scenario for the development of wind farms, aiming to achieve an installed capacity of **0.2 GW**. This indicative potential enriches Greece's hydrogen production capabilities as envisioned in our case study.

The prospective regions and their individual potential, as analyzed in our case study, mark the future roadmap of green hydrogen production in Greece. By tapping into the power generated by existing and

[4] https://www.energyregister.gr/stathmos/%202491
[5] https://www.energyregister.gr/stathmos/%201691

potential wind farm projects in these regions, our case study envisions a vibrant hydrogen supply chain powered by wind energy.

Table 17.Hydrogen Production Points using Onshore Wind Farms as Energy Source

Location	Installed Capacity (GW)	Power Generation (TWh/year)	Power Used for Hydrogen Production (TWh/year)	Tonnes of Hydrogen per Year
Kilkis	0.1056	0.25	0.125	2,604
Western Macedonia	0.1638	0.42	0.21	2,187
Vermio	0.255	0.64	0.32	3,333
Anilio	0.144	0.36	0.18	1,875
Karpenisi	0.2	0.5	0.25	5,208
Lykouria	0.2	0.5	0.25	5,208
Total	1.0684	2.67	1.335	20,415

Offshore wind farms

Offshore wind farms present a significant opportunity for hydrogen production through electrolysis, given their high capacity and consistent wind speeds. In our case study, we have selected twelve potential locations for offshore wind farms, each with an installed capacity of **0.2 GW**. The selection of these locations was done with meticulous consideration, utilizing valuable information obtained from an online database that provides details on current and upcoming wind farm projects.[6] Additionally, insights from an article published by ekathimerini were taken into account, [7]which highlighted potential sites for offshore wind farms in Greece.

This choice aligns with Greece's strategic goal to install 2 GW of wind farms by 2030,[8]as outlined by its Ministry of Environment and Energy. This goal takes into consideration the potential of the Greek seas for hosting such installations, with the chosen sites demonstrating optimal conditions for harnessing wind power.

In this context, it is essential to underline that this case study focuses on potential future scenarios. We acknowledge that implementing such large-scale infrastructure projects comes with significant economic, environmental, and logistical challenges. However, with the evolving technological advancements and policy support, it is plausible to foresee a more substantial role for offshore wind energy in Greece's hydrogen production landscape.

[6]https://www.4coffshore.com/windfarms/greece/
[7]https://www.ekathimerini.com/economy/1210585/map-of-offshore-wind-farms/
[8]https://windeurope.org/newsroom/news/first-greek-offshore-wind-law-seeks-2-gw-by-2030/

In the following table, we provide a summary of these twelve locations, outlining their installed capacity, the power they could potentially generate, the portion of this power used for hydrogen production, and the resulting hydrogen output in tonnes per year. This summary will underscore the potential role of offshore wind in the transition towards a hydrogen-based energy system in Greece.

Table 18. Hydrogen Production Points using Onshore Wind Farms as Energy Source

Location	Installed Capacity (GW)	Power Generation (TWh/year)	Power Used for Hydrogen Production (TWh/year)	Tonnes of Hydrogen per Year
Agios Efstratios	0.2	0.5	0.25	5,208
Karpathos	0.2	0.5	0.25	5,208
Alexandroupoli	0.2	0.5	0.25	5,208
Igoumenitsa	0.2	0.5	0.25	5,208
Thasos	0.2	0.5	0.25	5,208
Mykonos-Tinos-Syros	0.2	0.5	0.25	5,208
Fanari	0.2	0.5	0.25	5,208
Samothraki	0.2	0.5	0.25	5,208
Petalioi	0.2	0.5	0.25	5,208
Kymi	0.2	0.5	0.25	5,208
Lefkada	0.2	0.5	0.25	5,208
Crete	0.2	0.5	0.25	5,208
Total	2.4	6	3	62,496

Blue Hydrogen Production Sites

Blue hydrogen is produced from natural gas through a process known as steam methane reforming (SMR), which generates hydrogen and carbon dioxide. The process can be further refined with carbon capture and storage (CCS) technologies to reduce the carbon dioxide emissions associated with the process, resulting in what is known as "blue" hydrogen.

Assuming each of the four refineries in Greece could house an SMR facility with CCS, let's evaluate the potential hydrogen production:

Table 19. Blue Hydrogen Production Points

Refinery	Annual Blue Hydrogen Production (Tonnes)
Aspropyrgos - Hellenic Petroleum (ELPE) Refinery	15,000
Corinth - Motor Oil Refinery	15,000
Thessaloniki - Hellenic Petroleum (ELPE) Refinery	15,000
Elefsina - Hellenic Petroleum (ELPE) Refinery	15,000
Total	**60,000**

Therefore, if all four refineries operate under these assumptions, the total production capacity of blue hydrogen in Greece could potentially reach **60,000 tonnes per year**.

Total Hydrogen Supply

Energy Source	Tonnes of Hydrogen per Year
Solar PV Parks	91,664
Onshore Wind Farms	20,415
Offshore Wind Farms	62,496
Refineries (Blue Hydrogen)	60,000
Total	**234,575**

The table provides a comprehensive summary of the hydrogen supply in Greece, categorized by energy sources. It showcases the total tonnes of hydrogen produced annually for each energy source, including solar PV parks, onshore wind farms, offshore wind farms, and refineries producing blue hydrogen. The combined production from these diverse sources yields a total supply of **234,575 tonnes of hydrogen per year**. This balanced supply ensures that the hydrogen demand across various sectors in Greece can be met efficiently, indicating a balanced transport problem where the supply matches the demand.

5.3 Hydrogen Demand Points

As we delve further into our analysis, a thorough understanding of the specific hydrogen demand points within each sector is crucial. This understanding doesn't just illuminate the hydrogen consumption distribution across Greece but also facilitates efficient supply route and logistics planning.

The identification of these demand points was based on sector characteristics and their inherent potential hydrogen applications. For example, the industrial sector might see demand points in heavy industries such as steel production or refineries where hydrogen is used for feedstock or process heat.

Similarly, the transport sector could feature demand points at major transport hubs or refueling stations for hydrogen-powered vehicles.

We allocated a specific amount of hydrogen to each identified demand point, considering the total demand of the corresponding sector as calculated in the previous section.

In the upcoming subsections, we will delve into each sector in detail, pinpointing the specific hydrogen demand points and the associated quantity of hydrogen needed at each point. By doing so, we aim to paint a comprehensive picture of the hydrogen demand landscape in Greece – a key input for effectively designing and executing a well-functioning hydrogen supply chain.

Finally, in this subsection, we will present our findings in the form of table summaries for each sector. These tables will provide a concise and clear overview of the hydrogen demand points, serving as a valuable resource for understanding and interpreting the demand-side dynamics of Greece's hydrogen supply chain.

5.3.1 Industrial Sector Sites

Ammonia

The Kaloudis Chemicals facility, located in Greece, is the sole installation in the country for the production of Ammonia, both Hydrous and Anhydrous, with the highest quality and safety standards. With an annual capacity exceeding 100,000 tonnes, it stands as the largest facility in the Balkans.[9] The demand assumption for hydrogen from Kaloudis Chemicals amounts to 0.350 Twh/year, equivalent to 10,416 tonnes per year. The selection of this demand point was based on its significant production capacity and its critical role in the local and regional market.

Table 20. Demand Points using Hydrogen in Ammonia Production

Demand Point Location	Hydrogen Demand(Twh/year)	Hydrogen Demand (tonnes/year)
Kaloudis Chemicals	0.350	10,416

Fuel Production and HVC

The demand points for hydrogen in the fuel production and heavy vehicles sector were carefully selected based on several key considerations. The primary objective was to include major refineries in Greece that have a significant demand for hydrogen in their fuel production processes. In this case

[9] https://www.kaloudis.com.gr/

study, the selected demand points include the Hellenic Petroleum Aspropyrgos Refinery, Motor Oil (Hellas) Corinth Refineries SA, Hellenic Petroleum Refineries SA in Elefsina, and Hellenic Petroleum in Thessaloniki. These refineries were chosen due to their prominence in the industry and their substantial hydrogen demand. The total hydrogen demand from these refineries is set to 2.52 TWh/year, equivalent to 74,996 tonnes/year. The hydrogen at these demand points is primarily used for fuel production and heavy vehicle applications.

Table 21. Demand Points using Hydrogen for Fuel Production and HVC

Demand Point Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
Hellenic Petroleum Aspropyrgos Refinery	0.630	18,749
Motor Oil (Hellas) Corinth Refineries SA	0.630	18,749
Hellenic Petroleum Refineries SA(Elefsina)	0.630	18,749
Hellenic Petroleum(Thessaloniki)	0.630	18,749
Total	**2.52**	**74,996**

Steel

The demand points for hydrogen in the steel production sector were selected based on the largest steel production factories in Greece. The chosen demand points include Halyvourgiki in Elefsina, Hellenic Halyvourgia in Aspropyrgos, SOVEL SA, SIDENOR SA, and Hellenic Steel SA in Volos. These factories are renowned for their significant contribution to the steel industry in Greece. The total hydrogen demand from these steel production facilities is set to 1.75 TWh/year, equivalent to 52,080 tonnes/year. Hydrogen plays a crucial role in various steel production processes, such as hydrogen reduction of iron ore and hydrogen annealing.

Table 22. Demand Points using Hydrogen in the Steel Industry

Demand Point Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
Halyvourgiki (Elefsina)	0.350	10,416
Hellenic Halyvourgia (Aspropyrgos)	0.350	10,416
SOVEL SA	0.350	10,416
SIDENOR SA	0.350	10,416
Hellenic Steel SA(Volos)	0.350	10,416
Total	**1.75**	**52,080**

Industrial Process Heat

The demand points for hydrogen in the industrial sector were selected based on prominent industries that utilize hydrogen for industrial process heat. The chosen demand points include TITAN Cement Company SA in Elefsina and Thessaloniki, as well as PAKO Vl. Koliopoulos Papermaking SA. These industries have a significant demand for hydrogen in their operations to support various industrial processes. Notably, TITAN Cement Company SA is also involved in a project called H2CEM - TITAN,[10] which aims to produce, store, and utilize green hydrogen for combustion in furnaces to achieve carbonization in the cement plants. The total hydrogen demand from these industrial sectors is set to 0.742 TWh/year, equivalent to 22,092 tonnes/year.

Table 23. Demand Points using Hydrogen for Industrial Process Heat

Demand Point Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
TITAN Cement Company SA (Elefsina)	0.350	10,416
TITAN Cement Company SA (Thessaloniki)	0.350	10,416
PAKO Vl. Koliopoulos Papermaking SA	0.042	1,260
Total	**0.742**	**22,092**

5.3.2 Transport Sector Sites

Marine

The demand points for hydrogen in the maritime sector were selected to cater to the growing demand for hydrogen as a marine fuel. The chosen demand points include Thessaloniki Port, Piraeus Port, and Alexandroupolis Port, which are among the largest ports in Greece. These ports play a vital role in maritime transportation and are strategically important for trade and commerce. By incorporating hydrogen as a marine fuel, these ports aim to reduce emissions and promote sustainable shipping practices. The total hydrogen demand from the maritime sector is set to 0.420 TWh/year, equivalent to 12,498 tonnes/year.

[10] https://www.titan.gr/en/newsroom/news-and-press-releases/new?item=1634

Table 24. Demand Points using Hydrogen as Marine Fuel

Demand Point Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
Thessaloniki Port	0.140	4,166
Piraeus Port	0.140	4,166
Alexandroupolis Port	0.140	4,166
Total	**0.420**	**12,498**

Rail

The demand points for hydrogen in the railway sector were selected to facilitate the adoption of hydrogen as a fuel for trains. The chosen demand points include Alexandroupolis Railway Station, Thessaloniki Railway Station, and Athens Railway Station, which are among the largest and busiest train stations in Greece. By incorporating hydrogen as a fuel for trains, these stations aim to reduce carbon emissions and promote sustainable transportation. The total hydrogen demand from the railway sector is set to 0.420 TWh/year, equivalent to 12,498 tonnes/year.

Table 25. Demand Points using Hydrogen as Train Fuel

Demand Point Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
Alexandroupolis Railway Station	0.140	4,166
Thessaloniki Railway Station	0.140	4,166
Athens Railway Station	0.140	4,166
Total	**0.420**	**12,498**

Road

The demand points for hydrogen in road transport were carefully selected to cater to the growing need for hydrogen refueling infrastructure. In Crete, a region chosen as one of the hydrogen valleys projects by the EU[11], five vehicle refueling stations were strategically placed to support the adoption of hydrogen

[11] https://www.clean-hydrogen.europa.eu/media/news/repowering-eu-hydrogen-valleys-clean-hydrogen-partnership-invests-eur-1054-million-funding-9-2023-01-31_en

as a fuel for vehicles on the island. Additionally, several refueling stations were established in rest areas along major highways across the country. These locations were chosen to ensure convenient access to hydrogen refueling services for road users throughout Greece. The total hydrogen demand from road transport amounts to 0.35 TWh/year, equivalent to 10,416 tonnes/year.

Table 26. Demand Points using Hydrogen as Fuel in Road Transport

Demand Point Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
Vehicle Refueling Station - Chania	0.014	416.8
Vehicle Refueling Station - Rethymno	0.014	416.8
Vehicle Refueling Station - Heraklion	0.014	416.8
Vehicle Refueling Station - Sitia	0.014	416.8
Vehicle Refueling Station - Ierapetra	0.014	416.8
Rest Area Kapandritiou (to Thessaloniki)	0.007	208.3
Rest Area Schimatariou (to Thessaloniki)	0.007	208.3
Rest Area Atalantis (to Thessaloniki)	0.007	208.3
Rest Area Almyrou (to Thessaloniki)	0.007	208.3
Rest Area Nikaia (to Thessaloniki)	0.007	208.3
Rest Area Evangelismos (to Thessaloniki)	0.007	208.3
Rest Area Korinou (to Thessaloniki)	0.007	208.3
Rest Area Korinou (to Athens)	0.007	208.3
Rest Area Evangelismos (to Athens)	0.007	208.3
Rest Area Nikaia (to Athens)	0.007	208.3
Rest Area Almyrou (to Athens)	0.007	208.3
Rest Area Atalantis (to Athens)	0.007	208.3
Rest Area Schimatariou (to Athens)	0.007	208.3
Rest Area Varybobi (to Athens)	0.007	208.3
Rest Area Megara (to Patras)	0.007	208.3
Rest Area Velo (to Patras)	0.007	208.3
Rest Area Aigio (to Patras)	0.007	208.3
Rest Area Psathopyrgos (to Patras)	0.007	208.3
Rest Area Psathopyrgos (to Athens)	0.007	208.3
Rest Area Aigio (to Athens)	0.007	208.3
Rest Area Velo (to Athens)	0.007	208.3
Rest Area Megara (to Athens)	0.007	208.3
Rest Area Evinochoriou (to Ioannina)	0.007	208.3
Rest Area Episkopikou (to Ioannina)	0.007	208.3
Rest Area Filippiada (to Ioannina)	0.007	208.3
Rest Area Filippiada (to Patras)	0.007	208.3
Rest Area Episkopikou (to Patras)	0.007	208.3
Rest Area Evinochoriou (to Patras)	0.007	208.3

Rest Area Grevenon (to Thessaloniki)	0.007	208.3
Rest Area Grevenon (to Ioannina)	0.007	208.3
Rest Area Platanou (to Ioannina)	0.007	208.3
Rest Area Platanou (to Thessaloniki)	0.007	208.3
Rest Area Vaihoriou (to Thessaloniki)	0.007	208.3
Rest Area Analipsi (to Alexandroupoli)	0.007	208.3
Rest Area Spathovouniou (to Kalamata)	0.007	208.3
Rest Area Agios Floros - Arfara (to Kalamata)	0.007	208.3
Rest Area Agios Floros - Arfara (to Athens)	0.007	208.3
Rest Area Spathovouniou (to Athens)	0.007	208.3
Rest Area Pellanas (to Sparta)	0.007	208.3
Rest Area Pellanas (to Athens)	0.007	208.3
Total	**0.35**	**10,415**

5.2.3 Power Sector Sites

At the D.R.H. Atherinolakkos demand point, located in Crete, there is a significant demand for hydrogen in the electricity production facility. To meet this demand and enhance the power generation process, an infrastructure for utilizing hydrogen as a fuel source is proposed. By incorporating hydrogen into the power generation system, the facility can benefit from the advantages of hydrogen as a clean and sustainable energy carrier. The hydrogen demand at D.R.H. Atherinolakkos is set to 0.280 TWh/year, equivalent to 8,332 tonnes/year. This highlights the potential for integrating hydrogen technologies into the electricity sector to promote renewable energy usage and reduce carbon emissions.

Table 27. Demand Point using Hydrogen for Power Generation

Demand Point Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
D.R.H. Atherinolakkos	0.280	8,332

5.2.4 Buildings Sector Sites

The DESFA LNG Terminal, FSRU Agioi Theodoroi, and FSRU Alexandroupoli are identified as demand points for hydrogen in the buildings sector. These locations are strategically chosen to leverage the existing infrastructure of LNG terminals and utilize the pipeline network of natural gas for hydrogen distribution. By integrating hydrogen into the buildings sector, we can harness the benefits of hydrogen as a clean and efficient energy source for heating, cooling, and other energy demands. The total hydrogen demand at these demand points is set to 0.350 TWh/year or 10,416 tonnes/year, highlighting the potential for decarbonizing the buildings sector and reducing reliance on fossil fuels

Table 28. Demand Points supplying Hydrogen to Buildings

Demand Point Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
DESFA LNG Terminal	0.350	10,416
FSRU Agioi Theodoroi	0.350	10,416
FSRU Alexandroupolis	0.350	10,416
Total	1.05	31,248

Total Demand

The following table sums up the hydrogen demand from all the sectors above:

Table 29. Total Hydrogen Demand per Sector

Sector	Hydrogen Demand (tonnes/year)
Ammonia	10,416
Fuel Production and HVC	74,996
Steel Production	52,080
Industrial Process Heat	22,092
Ports	12,498
Railways	12,498
Vehicle Refueling	10,415
Power Generation	8,332
Buildings	31,248
Total	**234,575**

5.4 Mapping the Hydrogen Supply Chain

In this section, we will discuss the process of mapping the hydrogen supply chain, which involves visualizing the demand and supply points identified in the previous section. Mapping plays a crucial role in understanding the spatial distribution of the supply chain components and provides a valuable tool for analysis and decision-making.

5.4.1 Importance of GIS Mapping

Mapping the hydrogen supply chain using Geographic Information System (GIS) technology offers several advantages. Firstly, it allows us to visualize the geographical distribution of the demand and supply points, providing a clear understanding of their spatial relationship. This spatial analysis helps identify potential optimization opportunities and transportation routes for efficient hydrogen distribution. Additionally, GIS mapping enables us to assess the proximity of supply points to demand points, considering factors such as distance, accessibility, and infrastructure connectivity.

5.4.2 Utilizing Google My Maps

For this case study, we chose to use Google My Maps as our mapping tool. Google My Maps offers a user-friendly interface and a wide range of functionalities suitable for our purposes. It allows us to create custom maps, mark specific locations, and add relevant information to each point. Furthermore, Google My Maps provides the ability to share and collaborate on maps, making it a convenient choice to work together in developing and refining the hydrogen supply chain visualization.

5.4.3 Mapping Procedure

To visualize the hydrogen supply chain in Greece, a mapping procedure was implemented using Google My Maps. This section outlines the step-by-step process followed to create a comprehensive map showcasing the supply and demand points.

First, two layers were created in Google My Maps: the Supply Points Layer and the Demand Points Layer. This allowed for a clear distinction between the locations where hydrogen is produced and where it is required.

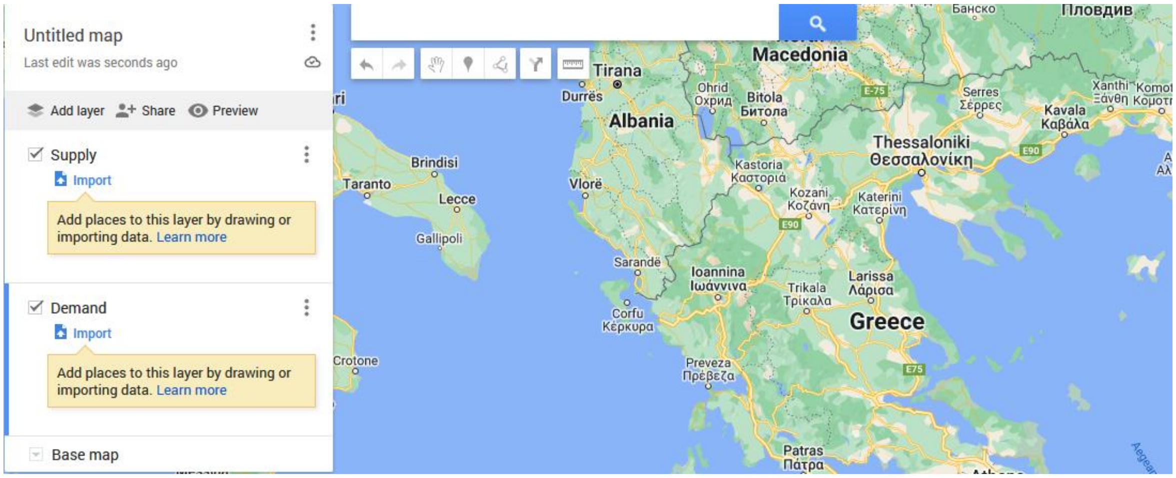


Figure 28. Adding Supply and Demand Layers

Next, all the supply and demand points were pinpointed on the map. By using the search bar or manually navigating to each location in Greece, precise coordinates were marked on the map. Each point was given a name to facilitate identification and organization.

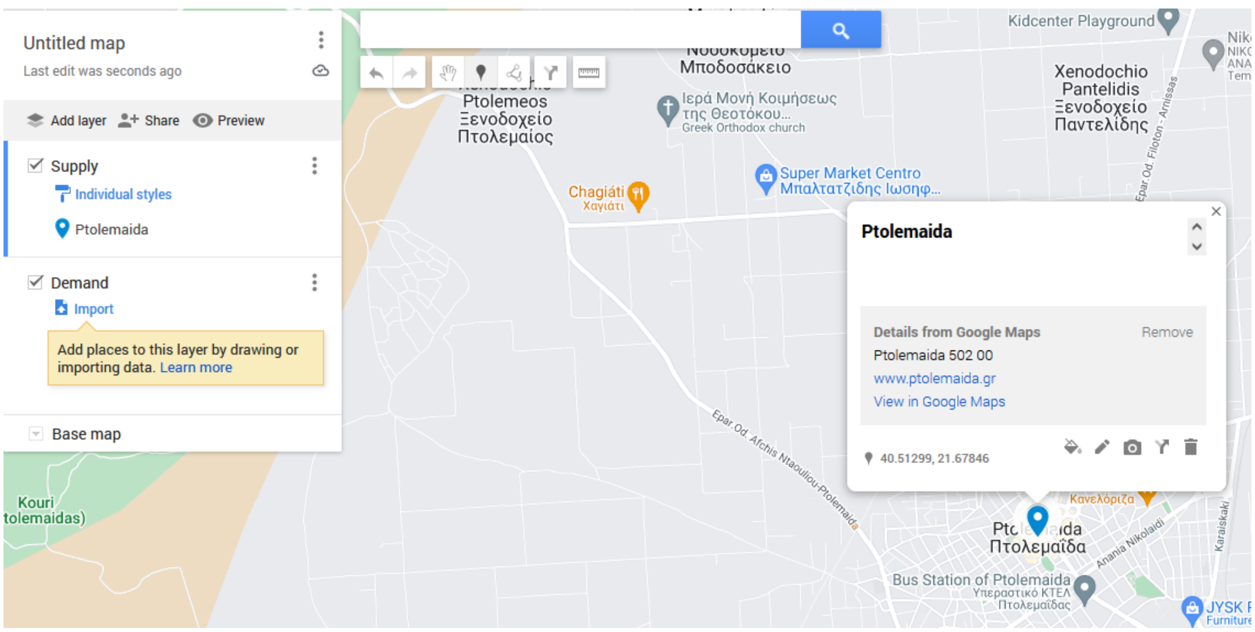


Figure 29. Marking Supply and Demand Points

To export the coordinate data, the map was saved as a CSV file. The resulting files contained the point names, latitude, longitude, and other relevant parameters.

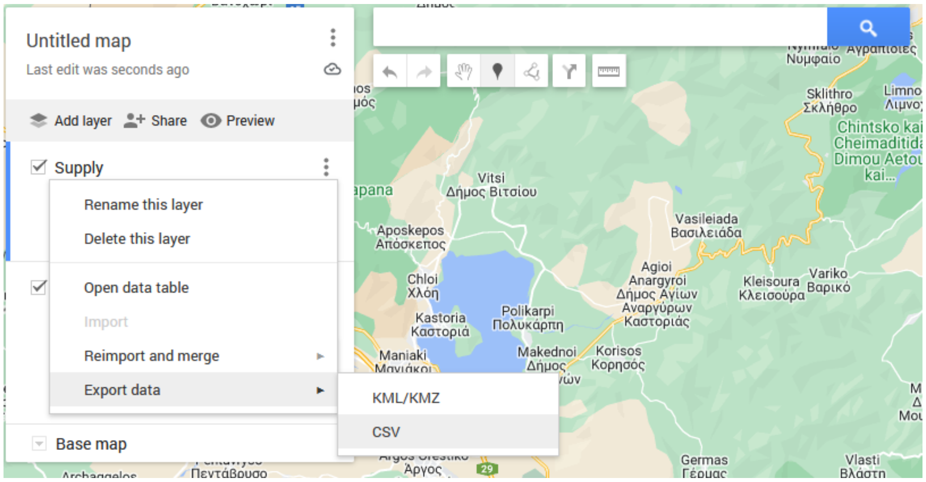


Figure 30. Exporting the CSV file

Modifications were made to the CSV files to include additional columns with the necessary parameters for each point. Parameters include hydrogen production capacity, hydrogen demand, and more. These modified tables are presented below.

Table 30. Summary of the Supply Sites with its respective coordinates

Coordinates	name	Location	Capacity (GW)	Power Generation (TWh/year)	Power Used for Hydrogen Production (TWh/year)	Tonnes of Green Hydrogen per Year	Tonnes of Blue Hydrogen per Year	Total Tonnes of Hydrogen per Year
POINT (25.1000431 39.4862777)	Offshore Wind Farm	Agios Efstratios	0.2	0.5	0.25	5,208		5,208
POINT (27.2149443 35.524899)	Offshore Wind Farm	Karpathos	0.2	0.5	0.25	5,208		5,208
POINT (25.869459 40.807661)	Offshore Wind Farm	Alexandroupoli	0.2	0.5	0.25	5,208		5,208
POINT (19.9223461 39.6249838)	Offshore Wind Farm	Igoumenitsa	0.2	0.5	0.25	5,208		5,208
POINT (24.8104196 40.667841)	Offshore Wind Farm	Thasos	0.2	0.5	0.25	5,208		5,208
POINT (25.1254013 37.3638456)	Offshore Wind Farm	Mykonos-Tinos-Syros	0.2	0.5	0.25	5,208		5,208
POINT (25.132005 40.9604137)	Offshore Wind Farm	Fanari	0.2	0.5	0.25	5,208		5,208

POINT (25.552659 40.5108343)	Offshore Wind Farm	Samothraki	0.2	0.5	0.25	5,208		5,208
POINT (24.2348938 38.0024347)	Offshore Wind Farm	Petalioi	0.2	0.5	0.25	5,208		5,208
POINT (24.1961583 38.6061043)	Offshore Wind Farm	Kymi	0.2	0.5	0.25	5,208		5,208
POINT (20.6231394 38.8237408)	Offshore Wind Farm	Lefkada	0.2	0.5	0.25	5,208		5,208
POINT (26.1536112 34.9815581)	Offshore Wind Farm	Crete	0.2	0.5	0.25	5,208		5,208
POINT (21.6822399 40.508944)	Solar PV Park	Ptolemaida	2	2.4	1.2	25,000		25,000
POINT (24.1186107 41.1969942)	Solar PV Park	Megalopolis	0.8	1	0.5	10,416		10,416
POINT (22.2505995 37.386178)	Solar PV Park	Drama	0.8	1	0.5	10,416		10,416
POINT (21.2511791 39.6752161)	Solar PV Park	Farsala	0.8	1	0.5	10,416		10,416
POINT (22.4431398 39.4154153)	Solar PV Park	Kalampaka	0.8	1	0.5	10,416		10,416
POINT (23.5980559 38.0284189)	Solar PV Park	Aspropyrgos	0.5	0.6	0.3	6,250	15,000	21,250
POINT (23.0725244 37.921188)	Solar PV Park	Corinth	0.5	0.6	0.3	6,250	15,000	21,250
POINT (22.8850279 40.6832467)	Solar PV Park	Thessaloniki	0.5	0.6	0.3	6,250	15,000	21,250
POINT (23.5032101 38.0400967)	Solar PV Park	Eleusis	0.5	0.6	0.3	6,250	15,000	21,250
POINT (22.6629598 41.158199)	Onshore Wind Farm	Kilkis	0.1056	0.25	0.125	2,604		2,604

POINT (21.0818868 40.6303589)	Onshore Wind Farm	Western Macedonia	0.1638	0.42	0.21	2,187		2,187
POINT (21.9201282 40.5213687)	Onshore Wind Farm	Vermio	0.255	0.64	0.32	3,333		3,333
POINT (21.2303603 39.7325865)	Onshore Wind Farm	Anilio	0.144	0.36	0.18	1,875		1,875
POINT (21.7341697 38.8395577)	Onshore Wind Farm	Karpenisi	0.2	0.5	0.25	5,208		5,208
POINT (22.2065818 37.8747014)	Onshore Wind Farm	Lykouria	0.2	0.5	0.25	5,208		5,208

Table 31. Summary of the Demand Sites with its respective coordinates

Coordinates	name	Location	Hydrogen Demand (TWh/year)	Hydrogen Demand (tonnes/year)
POINT (22.8459317 40.7166467)	Ammonia	Kaloudis Chemicals	0.35	10,416
POINT (23.5332536 38.04080539999999)	Industrial Process Heat	TITAN Cement Company SA (Elefsina)	0.35	10,416
POINT (22.8154927 40.70368629999999)	Steel	SIDENOR SA	0.35	10,416
POINT (23.5370375 38.05475769999999)	Steel	Halyvourgiki (Elefsina)	0.35	10,416
POINT (23.5961532 38.0347938)	Steel	Hellenic Halyvourgia (Aspropyrgos)	0.35	10,416
POINT (22.840109 39.1686175)	Steel	SOVEL SA	0.35	10,416
POINT (22.8336419 39.3833867)	Steel	Hellenic Steel SA(Volos)	0.35	10,416
POINT (22.9506064 40.6976363)	Industrial Process Heat	TITAN Cement Company SA (Thessaloniki)	0.35	10,416
POINT (23.4033677 37.95913720000001)	Buildings	DESFA LNG Terminal	0.35	10,416
POINT (23.0870324 37.9163134)	Buildings	FSRU Agioi Theodoroi	0.35	10,416
POINT (25.9069057 40.8489526)	Buildings	FSRU Alexandroupolis	0.35	10,416
POINT (23.5995575 38.03055690000001)	Fuel Production and HVC	Hellenic Petroleum Aspropyrgos Refinery	0.63	18,749
POINT (23.0725244 37.921188)	Fuel Production and HVC	Motor Oil (Hellas) Corinth Refineries SA	0.63	18,749
POINT (23.5028883 38.04018550000001)	Fuel Production and HVC	Hellenic Petroleum Refineries SA(Elefsina)	0.63	18,749
POINT (22.8850279 40.6832467)	Fuel Production and HVC	Hellenic Petroleum(Thessaloniki)	0.63	18,749
POINT (22.9230442 40.6348544)	Marine	Thessaloniki Port	0.14	4,166
POINT (23.6333333 37.9405556)	Marine	Piraeus Port	0.14	4,166
POINT (25.8827468 40.8448799)	Marine	Alexandroupolis Port	0.14	4,166
POINT (25.879006 40.8452197)	Rail	Alexandroupolis Railway Station	0.14	4,166
POINT (22.9291635 40.6444335)	Rail	Thessaloniki Railway Station	0.14	4,166
POINT (23.7208081 37.9922968)	Rail	Athens Railway Station	0.14	4,166
POINT (24.0176235 35.4909961)	Road	Vehicle Refueling Station - Chania	0.014	416.8

POINT (24.4619099 35.36448070000001)	Road	Vehicle Refueling Station - Rethymno	0.014	416.8
POINT (25.14080999999999 35.315105)	Road	Vehicle Refueling Station - Heraklion	0.014	416.8
POINT (26.1042052 35.2000247)	Road	Vehicle Refueling Station - Sitia	0.014	416.8
POINT (25.767087 35.0349444)	Road	Vehicle Refueling Station - Ierapetra	0.014	416.8
POINT (23.8553058 38.2122647)	Road	Rest Area Kapandritiou (to Thessaloniki)	0.007	208.275
POINT (23.5377461 38.367233)	Road	Rest Area Schimatariou (to Thessaloniki)	0.007	208.275
POINT (23.0720614 38.6606389)	Road	Rest Area Atalantis (to Thessaloniki)	0.007	208.275
POINT (22.8888371 39.0629184)	Road	Rest Area Almyrou (to Thessaloniki)	0.007	208.275
POINT (22.4973095 39.54957720000001)	Road	Rest Area Nikaia (to Thessaloniki)	0.007	208.275
POINT (22.5081584 39.81391929999999)	Road	Rest Area Evangelismos (to Thessaloniki)	0.007	208.275
POINT (22.5810897 40.3288099)	Road	Rest Area Korinou (to Thessaloniki)	0.007	208.275
POINT (22.5820609 40.33204529999999)	Road	Rest Area Korinou (to Athens)	0.007	208.275
POINT (22.5073396 39.8147648)	Road	Rest Area Evangelismos (to Athens)	0.007	208.275
POINT (22.4964704 39.54939799999999)	Road	Rest Area Nikaia (to Athens)	0.007	208.275
POINT (22.8881002 39.0629843)	Road	Rest Area Almyrou (to Athens)	0.007	208.275
POINT (23.0720892 38.6590928)	Road	Rest Area Atalantis (to Athens)	0.007	208.275
POINT (23.5369911 38.3670648)	Road	Rest Area Schimatariou (to Athens)	0.007	208.275
POINT (23.8246214 38.1134641)	Road	Rest Area Varybobi (to Athens)	0.007	208.275
POINT (23.3664345 37.99626309999999)	Road	Rest Area Megara (to Patras)	0.007	208.275
POINT (22.74196419999999 37.9744923)	Road	Rest Area Velo (to Patras)	0.007	208.275
POINT (22.0798729 38.23526199999999)	Road	Rest Area Aigio (to Patras)	0.007	208.275
POINT (21.8672982 38.3251915)	Road	Rest Area Psathopyrgos (to Patras)	0.007	208.275
POINT (21.8695994 38.3245779)	Road	Rest Area Psathopyrgos (to Athens)	0.007	208.275

POINT (22.0789496 38.2352094)	Road	Rest Area Aigio (to Athens)	0.007	208.275
POINT (22.7407722 37.9741751)	Road	Rest Area Velo (to Athens)	0.007	208.275
POINT (23.364821 37.9943713)	Road	Rest Area Megara (to Athens)	0.007	208.275
POINT (21.5447222 38.38728950000001)	Road	Rest Area Evinochoriou (to Ioannina)	0.007	208.275
POINT (20.8520231 39.5460554)	Road	Rest Area Episkopikou (to Ioannina)	0.007	208.275
POINT (20.9096003 39.2206778)	Road	Rest Area Filippiada (to Ioannina)	0.007	208.275
POINT (20.9085703 39.2211848)	Road	Rest Area Filippiada (to Patras)	0.007	208.275
POINT (20.8521463 39.545384)	Road	Rest Area Episkopikou (to Patras)	0.007	208.275
POINT (21.5447431 38.3867006)	Road	Rest Area Evinochoriou (to Patras)	0.007	208.275
POINT (21.4385805 40.0648706)	Road	Rest Area Grevenon (to Thessaloniki)	0.007	208.275
POINT (21.39543219999999 40.02549750000001)	Road	Rest Area Grevenon (to Ioannina)	0.007	208.275
POINT (22.5418046 40.5554379)	Road	Rest Area Platanou (to Ioannina)	0.007	208.275
POINT (22.5435093 40.5549801)	Road	Rest Area Platanou (to Thessaloniki)	0.007	208.275
POINT (23.3559251 40.7028463)	Road	Rest Area Vaihoriou (to Thessaloniki)	0.007	208.275
POINT (23.1890916 40.7073196)	Road	Rest Area Analipsi (to Alexandroupoli)	0.007	208.275
POINT (22.8403441 37.8626659)	Road	Rest Area Spathovouniou (to Kalamata)	0.007	208.275
POINT (22.012333 37.1790186)	Road	Rest Area Agios Floros - Arfara (to Kalamata)	0.007	208.275
POINT (22.0129248 37.1783253)	Road	Rest Area Agios Floros - Arfara (to Athens)	0.007	208.275
POINT (22.8410084 37.8624132)	Road	Rest Area Spathovouniou (to Athens)	0.007	208.275
POINT (22.3430189 37.19631979999999)	Road	Rest Area Pellanas (to Sparta)	0.007	208.275
POINT (22.3419332 37.1977396)	Road	Rest Area Pellanas (to Athens)	0.007	208.275
POINT (22.8857154 38.9476924)	Industrial Process Heat	PAKO Vl. Koliopoulos Papermaking SA	0.042	1,260

POINT (26.1410808 35.0038681)	Power	D.R.H. Atherinolakkos	0.28	8,332

The modified CSV files were imported back into Google My Maps. The supply and demand points were added to their respective layers, with the software automatically matching the columns in the CSV files to the appropriate fields.

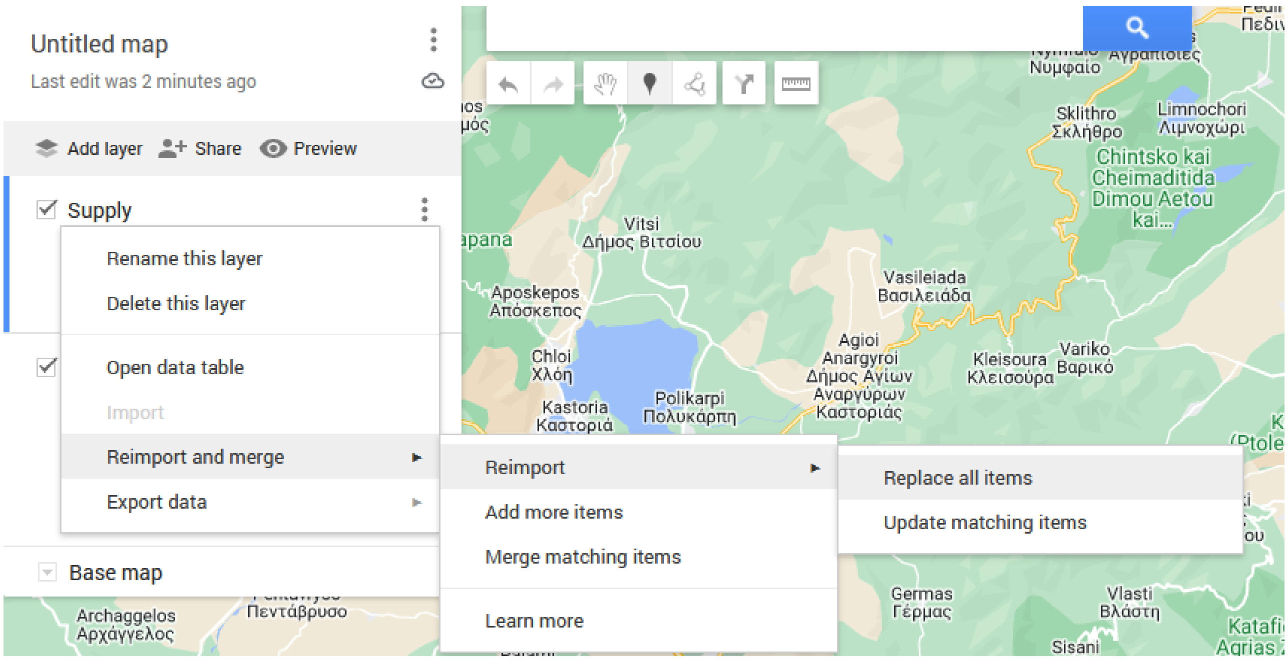


Figure 31. Importing the modified tables

To enhance the visualization of the map, the points were styled by name. Distinctive icons or marker styles were selected for the supply points and the demand points. Different colors or symbols were applied to further categorize the points based on specific parameters, if applicable.

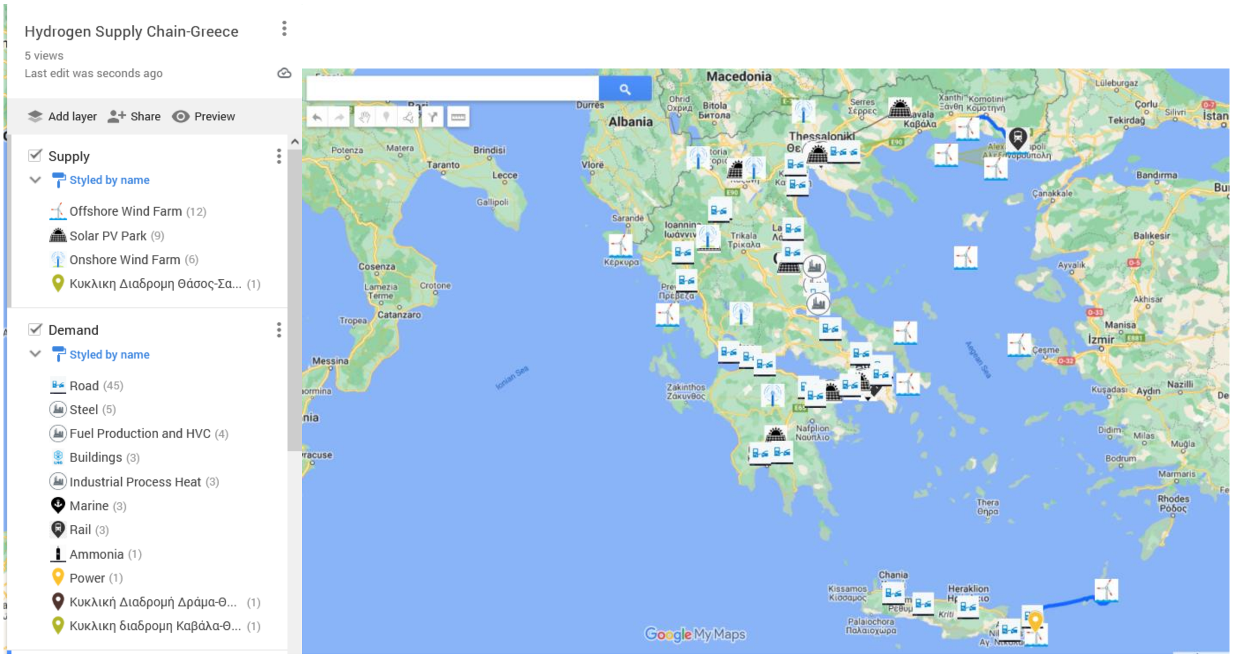


Figure 32. Final Map with its respective styles

By following this mapping procedure, we were able to create a visually appealing and informative map that showcases the hydrogen supply chain in Greece. The map serves as a valuable tool for analysis, decision-making, and communication, enabling stakeholders to better understand and optimize the hydrogen supply chain in the region.

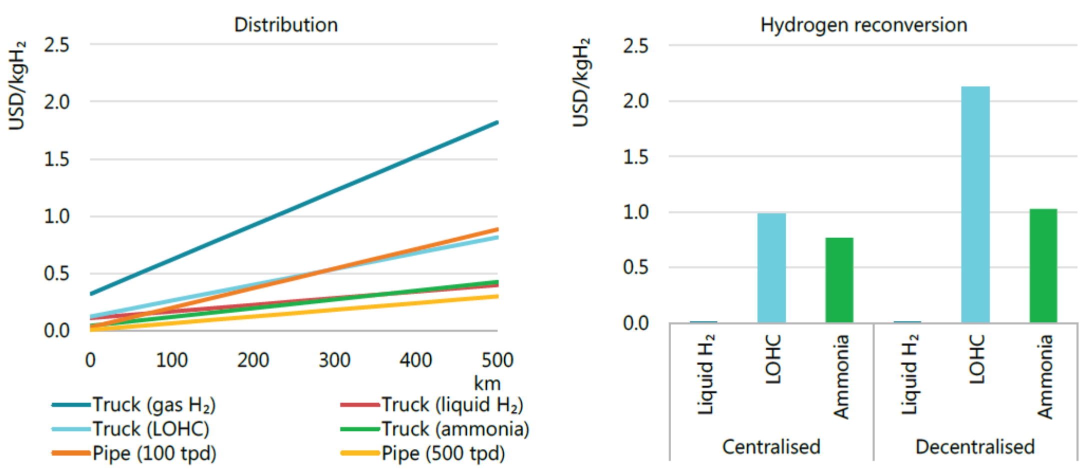
5.5 Cost Data

In order to evaluate the economic feasibility of different transportation methods within the hydrogen supply chain in Greece, a comprehensive analysis of cost data was conducted. This section presents the tables containing the cost data for each transport method, as well as a description of the methodology used to determine these values.

5.5.1 Methodology Used for Cost Analysis:

1. **Data Collection:**

Diagrams representing the cost per kilogram (USD/kg) were obtained for each transportation method (Figure 33). These diagrams displayed a linear relationship between the distance traveled (km) and the corresponding cost per kilogram in the form of y=ax+b, where y is the cost per kg, x is the distance traveled, a is the Variable Cost and b is the Fixed Cost.



Notes: More information on the assumptions is available at www.iea.org/hydrogen2019.

Figure 33. Cost of hydrogen distribution to a large centralised facility and cost of reconversion to gaseous hydrogen.

[The Future of Hydrogen, 2019]

2. **Fixed Cost Determination:**

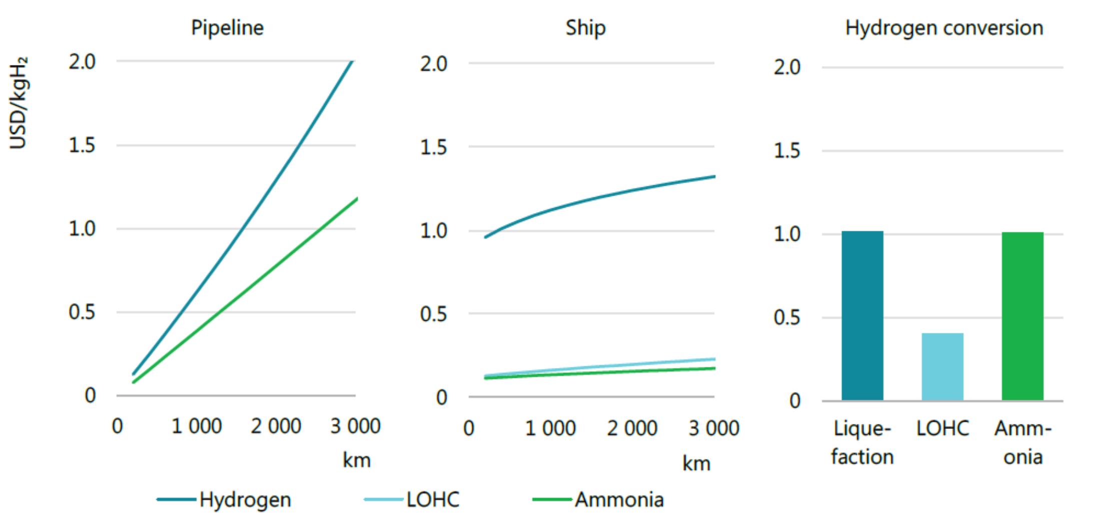
The fixed cost (b) represents the cost per kilogram at 0 km distance. This point is obtained from the diagram and represents the y-intercept of the linear equation. By examining the diagram at 0 km distance, the fixed cost (b) is determined directly.

3. **Variable Cost Determination:**

Two points on the diagram were selected: Point 1 (x1, y1) and Point 2 (x2, y2). These points represent specific distances and the corresponding cost per kilogram at those distances. The variable cost (a) was calculated using the formula: a = (y2 - y1) / (x2 - x1). This determined the rate of cost increase per kilometer traveled.

4. **Conversion and Reconversion Costs:**

For certain transportation methods involving the use of carriers like LOHC (Liquid Organic Hydrogen Carrier), liquid hydrogen, or ammonia, additional conversion and reconversion costs may be incurred. These costs are obtained from a separate diagram that provides the cost per kilogram for the conversion and reconversion processes. It is important to note that for the reconversion cost, we have two separate diagrams: one for the centralized approach and another for the decentralized approach. We used the centralized diagram to calculate the shipping cost since the port terminal is considered centralized. On the other hand, for the cost of pipelines and trucks, we utilized the decentralized value since the reconversion process will take place at the end user location.(Figure 33, Figure 34)



Notes: Hydrogen transported by pipeline is gaseous; hydrogen transported by ship is liquefied. Costs include the cost of transport and any storage that is required; costs of distribution and reconversion are not included. More information on the assumptions is available at www.iea.org/hydrogen2019.

Source: IEA 2019. All rights reserved.

Figure 34. Cost of hydrogen storage and transmission by pipeline and ship, and cost of hydrogen liquefaction and conversion. [The Future of Hydrogen, 2019]

5. **Transport Cost Calculation:**

The cost of one transport for each transportation method is calculated using the following formula:

$$Cost_i(\$) = (\,(\,Variable\ Cost *\ Distance_i) + Fixed\ Cost + Conversion\ Cost + Reconversion\ Cost) *\ Amount_i)$$

- Variable Cost (a): The calculated slope from the diagram.
- $Distance_i$: The distance in kilometers for each hydrogen transportation from a supply to demand point.
- Fixed Cost (b): The determined cost per kilogram at 0 km distance from the diagram.
- Conversion Cost: The cost per kilogram for the conversion process, as obtained from the conversion cost diagram (if applicable).
- Reconversion Cost: The cost per kilogram for the reconversion process, as obtained from the reconversion cost diagram (if applicable).
- $Amount_i$: The amount of hydrogen being transported in each transport.

6. **Total Cost Calculation**

The Total Cost is then calculated by adding up the costs of each transport occurred.

$$Total\ Cost = \sum_{i=1}^{n}(Cost_i)$$

After defining the cost parameters for each transportation method in USD, we convert them to Euros using a conversion ratio of 0.89, which was applicable at the time the study we used for data collection was published [The Future of Hydrogen, 2019]. By applying the appropriate conversion rate, we were able to express the cost function in Euros, providing a standardized currency unit for analysis and comparison.

By applying this methodology, the total cost of hydrogen transportation for each method can be determined, taking into account the fixed cost, variable cost, conversion cost, reconversion cost, total distance, and total amount of hydrogen being transported. This approach allows for a comprehensive analysis of the economic feasibility and cost-effectiveness of different transportation methods within the hydrogen supply chain.

5.5.2 Shipping Cost Parameters

In this case study, three shipping options are commonly considered: Hydrogen Liquefied, LOHC (Liquid Organic Hydrogen Carrier), and Ammonia. Each option has its own cost factors that need to be taken into account. By analyzing these cost factors, it becomes possible to assess the economic feasibility and competitiveness of each shipping option. This analysis helps in determining the most cost-effective and efficient method for transporting hydrogen within a given supply chain.

Table 32. Shipping Cost Parameters

Shipping Cost Parameters			
Transport Method	Hydrogen Liquefied	LOHC	Ammonia
Fixed Cost(€/kg)	0.801	0.089	0.089
Variable Cost (€/kg/km)	0.0001246	3.85667E-05	2.07667E-05
Conversion Cost(€/kg)	0.89	0.356	0.89
Reconversion Cost(€/kg)	0.0089	0.89	0.712

5.5.3 Trucks Cost Parameters

Trucks are another important transportation method within the hydrogen supply chain, offering flexibility and accessibility to various locations. When considering the cost parameters for truck transportation, four options are typically evaluated: Hydrogen Gaseous, Hydrogen Liquefied, LOHC (Liquid Organic Hydrogen Carrier), and Ammonia. Each option is associated with specific cost factors that determine the overall cost efficiency. By evaluating these cost parameters, it becomes possible to determine the most economically viable option for truck transportation within a hydrogen supply chain.

Table 33. Trucks Cost Parameters

Trucks Cost Parameters				
Transport Method	Hydrogen Gaseous	Hydrogen Liquefied	LOHC	Ammonia
Fixed Cost(€/kg)	0.267	0.1068	0.1068	0.0445
Variable Cost (€/kg/km)	0.002848	0.000534	0.0012816	0.0006942
Conversion Cost(€/kg)	0	0.89	0.356	0.89
Reconversion Cost(€/kg)	0	0.0089	1.869	0.89

5.5.4 Pipelines Cost Parameters

Pipelines are an efficient and widely used method for transporting hydrogen within a supply chain. They offer the advantage of continuous and reliable delivery, minimizing the need for intermediate storage and handling. In the case of pipelines, there are no fixed costs associated with the transport method itself, as the infrastructure is established once and maintained over time. Conversion and reconversion costs are also not incurred as hydrogen is transported gaseous. Therefore, the cost per kilogram is calculated by the following function

$$y = ax$$

- y is the cost per kg,
- x is the distance traveled,
- a is the Variable Cost

Data from the International Energy Agency (IEA)[12] were utilized to determine the appropriate parameter "a" for the cost function. This is necessary because the diagram (Figure 33) provides information only for pipelines with specific capacities (100 tpd and 500 tpd)and pipelines capacity is crucial in determining the cost per kilogram. The calculations considered various factors such as the pipeline's capacity, capital expenditure (CAPEX), lifetime, and discount rate. The IEA Database provides also a formula that connects the internal diameter of the pipes directly with the CAPEX. By applying these calculations to the specific amounts per year in our case study, we ensured accurate and tailored cost estimations for the AnyLogic model. To provide a comprehensive understanding of the analytic calculations, detailed information is provided in Appendix A. Pipelines Cost Calculations of this thesis. By analyzing these cost parameters, it becomes possible to assess the economic feasibility of using pipelines for hydrogen transportation in a supply chain.

[12] https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf

6. Application of the Model

6.1 Pre-Optimization Cost Analysis

In order to evaluate the hydrogen supply chain for our case study, we began by analyzing the hydrogen supply and demand in several specific locations. By examining factors such as production capacity, transportation options, and consumption patterns, we aimed to gain a comprehensive understanding of the supply and demand dynamics. These locations included Alexandroupoli, Agios Efstratios, Mykonos-Tinos-Syros and Crete. For each location, we considered the available supply sites, the transportation methods required to distribute hydrogen to demand points, and any special considerations or constraints. These analyses allowed us to make informed decisions and assumptions before integrating the case study into the AnyLogic model.

For each case, we will provide detailed cost calculations, including the total cost and breakdown of various cost components for each transport method. Additionally, we will compare the costs across the different transport methods considered in each case to identify the most cost-effective option based on the initial evaluation. The total cost in each case is calculated by the following formula:

$$Total\ Cost = Trips\ per\ year * Amount\ per\ trip * ((Trip\ Distance * Variable\ Cost) + Fixed\ Cost + Conversion\ Cost + Reconversion\ Cost)$$

6.1.1 Alexandroupolis Case

Description

In Alexandroupoli our supply chain analysis revealed a total hydrogen demand of 18,748 tonnes per year across three key demand sites: Alexandroupoli port, Alexandroupoli train station, and FSRU Alexandroupoli.

To meet this demand, we identified four supply sites in Alexandroupoli, Samothraki, Thasos, and Fanari, with a combined production capacity of 20,832 tonnes per year. Our strategy involved depleting the supply from Samothraki, Thasos, and Alexandroupoli sites and Fanari covering the remaining 3,124 tonnes.

To meet the demand in Alexandroupoli a ship will transport hydrogen in a round-trip route Samothraki-Thasos-Alexandroupoli. Hydrogen produced in Alexandroupolis' supply site will be consumed locally, eliminating the need for transportation. Finally, for the surplus hydrogen in Fanari, the transport method needs to be determined, examining between pipelines and trucks.

Therefore, demand points in Alexandroupoli will be excluded from our AnyLogic model as there is no need for optimization and hydrogen demand is met by the above procedure. In the same way the supply sites Thasos, Samothraki and Alexandroupoli will also be excluded from our model as the hydrogen produced in these points is depleted. However, the supply in Fanari will be adjusted to account for the remaining 2,084 tonnes of hydrogen to be distributed to other demand points.

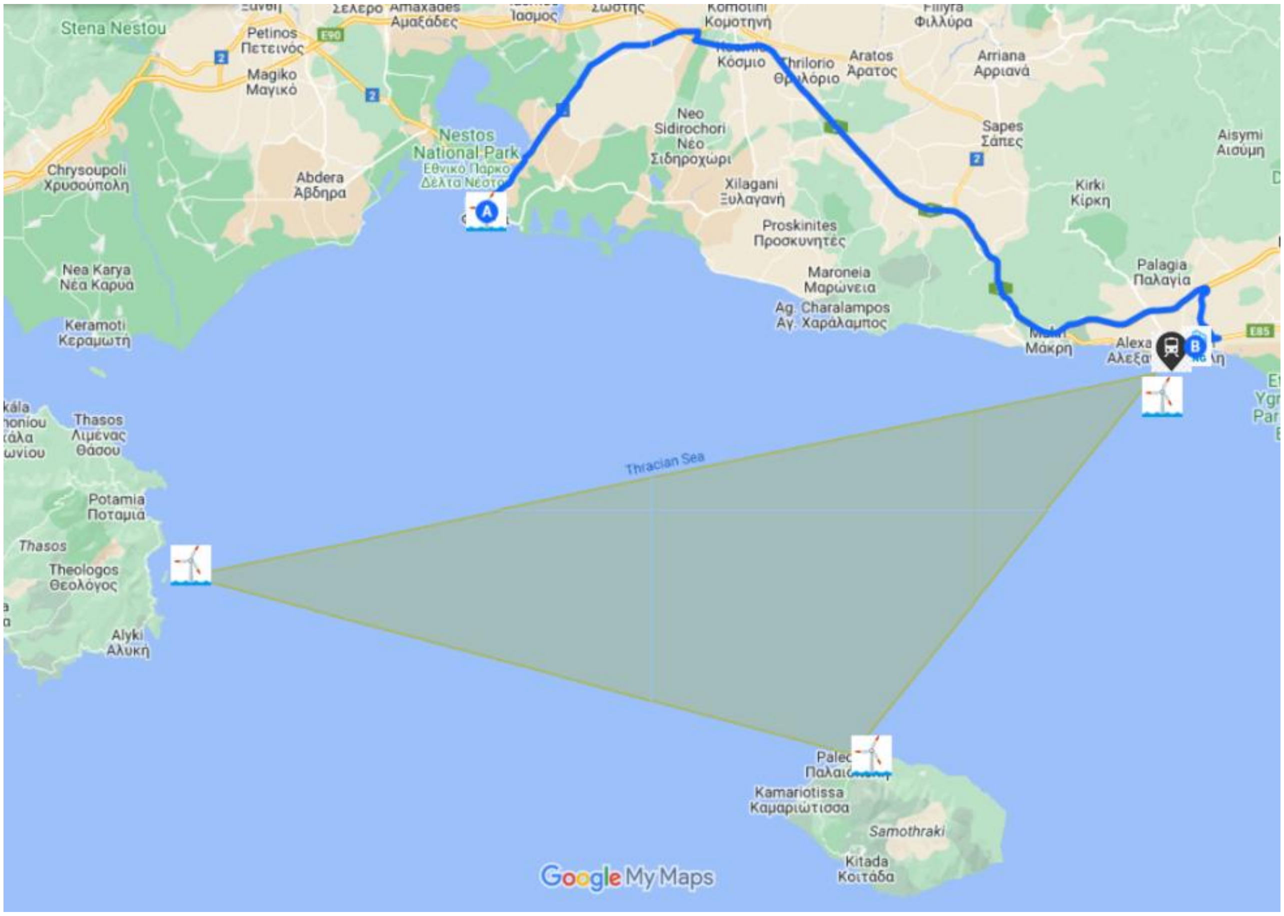


Figure 35. Alexandroupoli Supply Chain

Cost Calculations

The shipping route from Thasos to Samothraki and Alexandroupoli, and back to Thasos, plays a crucial role in our hydrogen supply chain strategy for the Alexandroupoli region. In order to evaluate the feasibility and efficiency of this route, we have analyzed the cost parameters associated with various hydrogen transport methods, namely liquefied hydrogen, LOHC, and ammonia. The cost data used for this analysis were obtained from Table 32 in this thesis, and we have made an assumption that a total of 300 trips per year are made along this route. Our goal is to determine the most cost-effective and practical transport method to meet the annual hydrogen demand of 10,416 tonnes in the region.

Table 34. Thasos-Samothraki-Alexandroupoli-Thasos Route Cost Analysis

Route	Thasos-Samothraki-Alexandroupoli-Thasos		
Shipping			
Transport Form	Hydrogen Liquefied	LOHC	Ammonia
Hydrogen Amount per Year (tonnes)	10,416	10,416	10,416
Trip Distance (km)	200	200	200
Trips per Year	300	300	300
Total Distance per Year (km)	60,000	60,000	60,000
Amount per Trip (tonnes)	34.72	34.72	34.72
Fixed Cost (€/kg)	0.801	0.089	0.089
Variable Cost (€/kg/km)	0.0001246	3.85667E-05	2.07667E-05
Conversion Cost (€/kg)	0.89	0.356	0.89
Reconversion Cost (€/kg)	0.0089	0.89	0.712
Total Cost	17,965,725.12 €	13,985,702.08 €	17,656,717.12 €

After evaluating the cost parameters for the Thasos-Samothraki-Alexandroupoli shipping route using liquefied hydrogen, LOHC, and ammonia, we have determined the most cost-effective option. Based on the analysis, the total cost for the liquefied hydrogen transport method amounts to 17,965,725.12 € per year, while the LOHC method incurs a cost of 13,985,702.08 € annually. The ammonia transport method yields a total cost of 17,656,717.12 € per year.

Considering the goal of minimizing costs, we have determined that the LOHC transport method is the most cost-effective choice for the Thasos-Samothraki-Alexandroupoli shipping route. This selection takes into account the fixed costs, variable costs, conversion costs, and reconversion costs associated with each transport method.

By opting for the LOHC transport method, we can ensure efficient and economical hydrogen delivery along the route, contributing to the overall optimization of our hydrogen supply chain in the Alexandroupoli region.

The transportation of hydrogen from the supply site in Fanari to Alexandroupoli is a critical aspect of our hydrogen supply chain. In order to determine the most cost-effective transport method for this route, we have conducted a comprehensive cost analysis considering various options, including trucks and pipelines. The cost data provided in the table were obtained based on the parameters for gaseous hydrogen, liquefied hydrogen, LOHC, ammonia, and gaseous hydrogen transported via pipelines. Our goal is to identify the transport method that offers the lowest total cost while meeting the annual hydrogen demand of 3,124 tonnes.

Table 35. Fanari-Alexandroupoli Route Cost Analysis

	Fanari-Alexandroupoli				
	Trucks				Pipelines
Transport Form	**Hydrogen Gaseous**	**Hydrogen Liquefied**	**LOHC**	**Ammonia**	**Hydrogen Gaseous**
Hydrogen Amount per Year (tonnes)	3,124	3,124	3,124	3,124	3,124
Trip Distance (km)	99	99	99	99	99
Trips per Year	4,663	727	1,736	1,202	
Total Distance per Year (km)	923,211.9403	143,849.3023	343,640	237,904.6154	99
Amount per Trip (tonnes)	0.67	4.3	1.8	2.6	
Fixed Cost (€/kg)	0.267	0.1068	0.1068	0.0445	0
Variable Cost (€/kg/km)	0.002848	0.000534	0.0012816	0.0006942	0.010102556
Conversion Cost (€/kg)	0	0.89	0.356	0.89	0
Reconversion Cost (€/kg)	0	0.0089	1.869	0.89	0
Total Cost	1,714,926.05 €	3,306,960.18 €	7,680,911.32 €	5,914,437.40 €	3,124,478.22 €

After evaluating the cost parameters for the Fanari-Alexandroupoli transport route using trucks and pipelines, we have determined the most cost-effective option. The total cost for the trucks in gaseous form amounts to 1,714,926.05 € per year, while the pipelines method incurs a cost of 3,306,960.18 € annually. Additionally, we evaluated the cost implications of alternative transport methods, including the use of liquefied hydrogen, LOHC, and ammonia, which result in total costs of 7,680,911.32 €, 5,914,437.40 €, and 7,745,553.07 € per year, respectively.

Considering the goal of minimizing costs, we have determined that the trucks transferring hydrogen gaseous is the most cost-effective choice for the Fanari-Alexandroupoli route. This selection takes into account the fixed costs, variable costs, conversion costs, and reconversion costs associated with each transport method.

6.1.2 Agios Efstratios Case

Description

The supply site in Agios Efstratios produces 5,208 tonnes of hydrogen per year. To efficiently distribute this hydrogen to the demand points, it needs to be transferred to the nearest port terminal. In this case, Kavala Port was chosen as the transfer location.

Considering the specific demand for ammonia in Kaloudis Chemicals in Thessaloniki (10,416 tonnes/year), the hydrogen from Agios Efstratios will be converted into ammonia before transportation. This ammonia will then be directly distributed to Kaloudis Chemicals, satisfying half of their demand for hydrogen. As a result, Kaloudis Chemicals requires an additional 5,208 tonnes of hydrogen supply from other sites.

With this approach, the hydrogen supply from Agios Efstratios is effectively utilized by converting it into ammonia and meeting some of the specific demand at Kaloudis Chemicals in Thessaloniki. This optimization reduces the need for additional hydrogen supply and ensures efficient distribution to the target demand points. From the above we conclude that Agios Efstratios will not be included in our AnyLogic model and Kaloudis Chemicals' demand is going to be reduced accordingly.

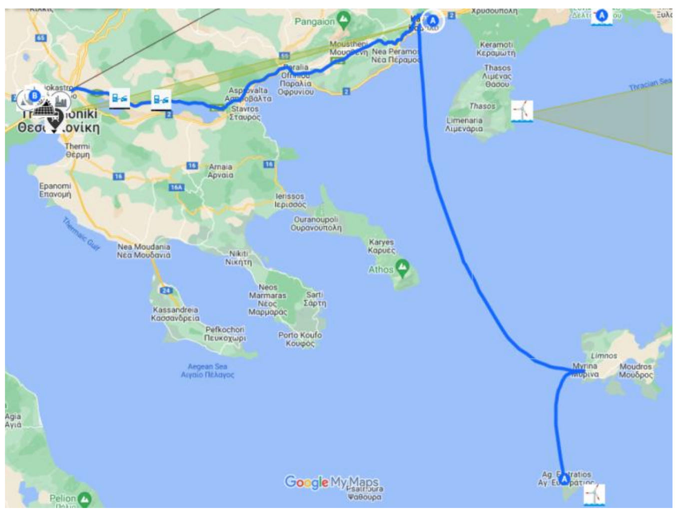


Figure 36. Agios Efstratios-Kavala Port and Kavala Port-Kaloudis Chemicals Routes

Calculations

In the case of Agios Efstratios to Kavala Port route, the transportation method chosen is Ammonia. This involves transporting hydrogen in the form of ammonia from Agios Efstratios to Kavala by ship, and then from Kavala to Kaloudis Chemicals by trucks. This approach optimizes the distribution of hydrogen by converting it into ammonia, meeting the specific demand of Kaloudis Chemicals in Thessaloniki. In this section, we will analyze and compare the total costs associated with transporting 5,208 tonnes of hydrogen per year using these routes. The costs include various factors such as fixed cost, variable cost, conversion cost, and reconversion cost. The tables provided below present a detailed breakdown of the total costs for each transportation route.

Table 36. Agios Efstratios-Kavala Port Route Cost Analysis

Route	Agios Efstratios-Kavala Port
Shipping	
Transport Form	Ammonia
Hydrogen Amount per Year (tonnes)	5,208
Round Trip Distance (km)	194
Round Trips per Year	300
Total Distance per Year (km)	116,400
Amount per Round Trip (tonnes)	17.36
Fixed Cost (€/kg)	0.089
Variable Cost (€/kg/km)	2.07667E-05
Conversion Cost (€/kg)	0.89
Reconversion Cost (€/kg)	0.712
Total Cost	8,827,709.64 €

Table 37. Kavala Port-Kaloudis Chemicals Route Cost Analysis

Route	Kavala Port-Kaloudis Chemicals
Trucks	
Transport Form	Ammonia
Hydrogen Amount per Year (tonnes)	5,208
Round Trip Distance (km)	164
Round Trips per Year	2,003
Total Distance per Year (km)	657,009.2308
Amount per Round Trip (tonnes)	2.6
Fixed Cost (€/kg)	0.0445
Variable Cost (€/kg/km)	0.0006942
Conversion Cost (€/kg)	0
Reconversion Cost (€/kg)	0
Total Cost	824,680.55 €

The total cost of transporting 5,208 tonnes of hydrogen per year from Agios Efstratios to Kaloudis Chemicals via the shipping route from Agios Efstratios to Kavala Port and the truck transportation route from Kavala Port to Kaloudis Chemicals is 9,652,390.19 €. These costs include the expenses associated with both the shipping and truck transportation, taking into account factors such as distance, round trips, and specific cost parameters for ammonia transportation. By optimizing the transportation routes and utilizing ammonia as a transportation form, an efficient and cost-effective supply chain is established to meet the hydrogen demand at Kaloudis Chemicals in Thessaloniki.

6.1.3 Mykonos Case

Description

The supply site in Mykonos-Tinos-Syros generates an annual production of 5,208 tonnes of hydrogen. Similar to the previous case of Agios Efstratios, the hydrogen needs to be transferred to the nearest port terminal for further distribution. In this scenario, the designated port is Piraeus Port.

To determine the most cost-effective transport method from Mykonos-Tinos-Syros to Piraeus Port, a manual cost calculation is conducted. The options considered are ammonia, liquefied hydrogen, and LOHC. By analyzing the cost parameters and distance, the optimal transport method is selected based on the total cost involved. In the AnyLogic model, a supply point will be created at Piraeus Port, with the same quantity as the production from Mykonos-Tinos-Syros.

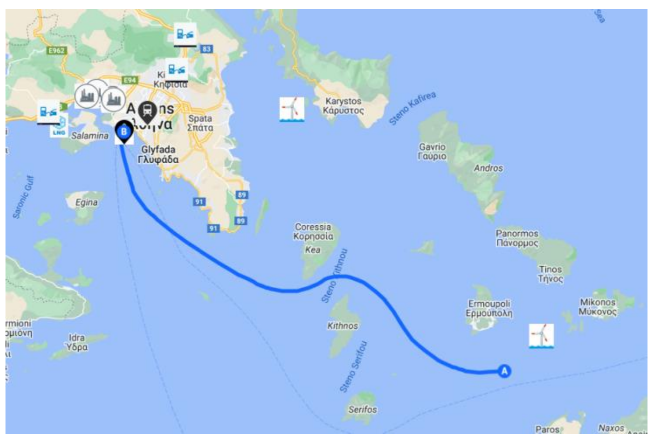


Figure 37. Mykonos-Piraeus Route

Calculations

The table presents the total costs of transporting 5,208 tonnes of hydrogen per year from Mykonos to Piraeus Port via different shipping routes and using various transport forms, including hydrogen liquefied, LOHC, and ammonia. The cost calculations take into account the trip distance, number of trips per year, fixed and variable costs, conversion and reconversion costs, and other relevant parameters.

Table 38. Mykonos-Piraeus Port Route Cost Analysis

Route	Mykonos-Piraeus Port		
Shipping			
Transport Form	**Hydrogen Liquefied**	**LOHC**	**Ammonia**
Hydrogen Amount per Year (tonnes)	5,208	5,208	5,208
Trip Distance (km)	163	163	163
Trips per Year	300	300	300
Total Distance per Year (km)	97,800	97,800	97,800
Amount per Trip (tonnes)	17.36	17.36	17.36
Fixed Cost (€/kg)	0.801	0.089	0.089
Variable Cost (€/kg/km)	0.0001246	3.85667E-05	2.07667E-05
Conversion Cost (€/kg)	0.89	0.356	0.89
Reconversion Cost (€/kg)	0.0089	0.89	0.712
Total Cost	8,958,852.64 €	6,985,419.40 €	8,824,356.91 €

After analyzing the shipping routes from Mykonos to Piraeus Port, it is evident that the most cost-effective option for transporting 5,208 tonnes of hydrogen per year is through LOHC. With a total cost of 6,985,419.40 €, LOHC proves to be the cheapest transport form compared to hydrogen liquefied (8,958,852.64 €) and ammonia (8,824,356.91 €). By selecting LOHC as the preferred transport form, we can optimize the cost of transporting hydrogen while ensuring efficient delivery to Piraeus Port.

6.1.4 Crete Case

Description

In Crete, the total demand for hydrogen is 10,416 tonnes per year, which includes 5 fuel stations and 1 power generation station. This demand will be fulfilled by utilizing two supply points near Crete, namely Atherinolakkos and Karpathos offshore wind farms, with each having a supply capacity of 5,208 tonnes per year.

The hydrogen produced from the production site in Atherinolakkos will be entirely consumed by the power generation station located there, eliminating the need for transportation and associated costs. However, there remains a demand of 3,124 tonnes per year in Atherinolakkos, which needs to be fulfilled. To meet the remaining demand in Atherinolakkos and the fuel stations, the hydrogen produced at the Karpathos offshore wind farm will be transported to Sitia Port. From Sitia port, the hydrogen will be further distributed either by trucks or pipelines to the refueling stations and the Atherinolakkos power station. This transportation method will be employed to fulfill the remaining demand of 5,208 tonnes per year, which includes 3,124 tonnes to Atherinolakkos Power Station and 416.8 tonnes to each of the five fuel stations. By strategically utilizing the supply points and optimizing the distribution network, the hydrogen demand in Crete can be efficiently met, ensuring a reliable and sustainable hydrogen supply for both power generation and transportation purposes.

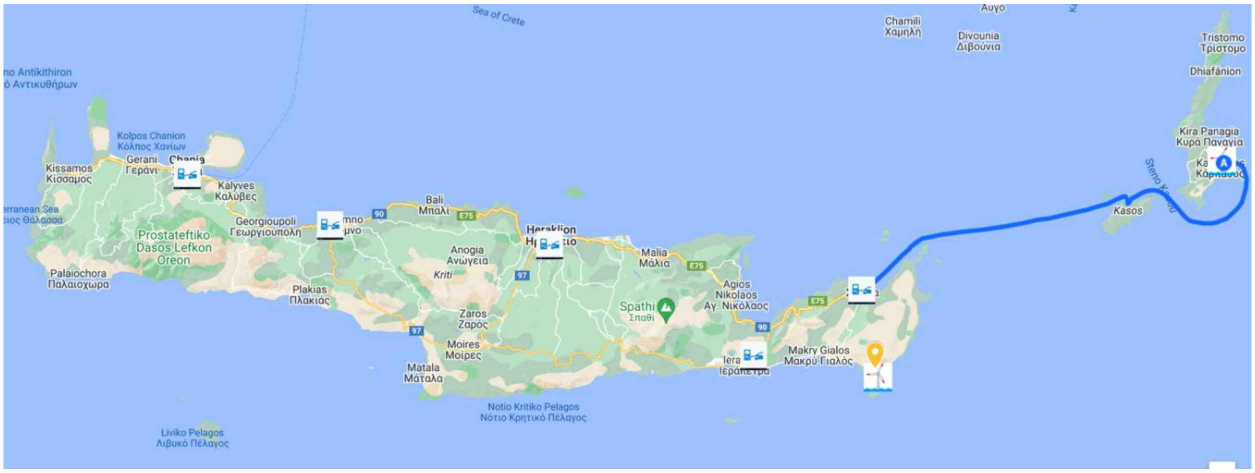


Figure 38. Crete Supply Chain

Calculations

In the case of transporting hydrogen from Karpathos to Sitia Port, we explored three different transport forms: hydrogen liquefied, LOHC, and ammonia. The goal was to identify the most cost-effective option for delivering 5,208 tonnes of hydrogen per year. By analyzing the fixed costs, variable costs, conversion costs, and reconversion costs associated with each transport form, we assessed their overall impact on the total cost. The following table presents the cost analysis for each transport form, allowing us to determine the most economical choice for this specific route.

Table 39. Karpathos-Sitia Port Route Cost Analysis

Route	**Karpathos-Sitia Port**		
	Shipping		
Transport Form	**Hydrogen Liquefied**	**LOHC**	**Ammonia**
Hydrogen Amount per Year (tonnes)	5,208	5,208	5,208
Trip Distance (km)	144	144	144
Trips per Year	300	300	300
Total Distance per Year (km)	86,400	86,400	86,400
Amount per Trip (tonnes)	17.36	17.36	17.36
Fixed Cost (€/kg)	0.801	0.089	0.089
Variable Cost (€/kg/km)	0.0001246	3.85667E-05	2.07667E-05
Conversion Cost (€/kg)	0.89	0.356	0.89
Reconversion Cost (€/kg)	0.0089	0.89	0.712
Total Cost	8,946,523.22 €	6,981,603.15 €	8,822,302.00 €

Upon evaluating the shipping routes from Karpathos to Sitia Port, the analysis reveals that the most cost-effective transport form for delivering 5,208 tonnes of hydrogen per year is LOHC. With a total cost of 6,981,603.15 €, LOHC outperforms hydrogen liquefied (8,946,523.22 €) and ammonia (8,822,302.00 €) in terms of cost efficiency. By selecting LOHC as the preferred transport form, we can optimize the transportation expenses while ensuring a reliable supply of hydrogen to Sitia Port.

6.1.5 Analysis of Pre-Optimization Results

The analysis of pre-optimization results provides valuable insights into the total cost of transport for each route in our hydrogen supply chain. By summing up the individual costs from each route, we obtain a comprehensive overview of the total cost of transport, enabling us to make informed decisions and optimize the entire supply chain. We also calculated the cost per kilogram (kg) for each route (by dividing total cost with total amount), which is a crucial indicator of cost efficiency. It allows for a direct comparison of the cost-effectiveness of different transport methods. Additionally, we determined the cost per kg in the total amount, which considers the combined effect of multiple transport methods within the hydrogen supply chain. This metric provides a comprehensive understanding of the overall cost efficiency and economic viability of the hydrogen supply chain as a whole. By analyzing these metrics, we can make informed decisions to optimize the supply chain and ensure cost-effective transportation of hydrogen.

Table 40. Summary Table of Pre-Optimization Cost Analysis

Route	Transport Method Selected	Cost	Amount (kg)	Cost per kg
Thasos-Samothraki-Alexandroupoli-Thasos	Shipping-LOHC	13,985,702.08 €	10,416,000	1.34 €
Fanari-Alexandroupoli	Trucks-Gaseous Hydrogen	1,714,926.05 €	3,124,000	0.55 €
Agios Efstratios-Kavala Port	Shipping- Ammonia	8,827,709.64 €	5,208,000	1.70 €
Kavala Port-Kaloudis Chemicals	Trucks- Ammonia	824,680.55 €	5,208,000	0.16 €
Mykonos-Piraeus Port	Shipping-LOHC	6,985,419.40 €	5,208,000	1.34 €
Karpathos-Sitia Port	Shipping-LOHC	6,981,603.15 €	5,208,000	1.34 €
Total		39,320,040.87 €	34,372,000	1.14 €

The total cost analysis reveals that different transport methods exhibit varying cost profiles. For ship transport, the Shipping-LOHC method was the most cost-effective option, as demonstrated by the lower total cost for the Thasos-Samothraki-Alexandroupoli-Thasos, Karpathos Sitia Port and Mykonos-Piraeus Port routes. In land transport, Trucks-Gaseous Hydrogen emerged as the most cost-effective method, as evidenced by the lower total cost for the Fanari-Alexandroupoli route. This method offers a cost-efficient solution for transporting hydrogen overland. The Shipping-Ammonia method proved to be a good option for the Agios Efstratios-Kavala Port route, where there was no need for reconversion. This highlights the flexibility and cost-effectiveness of using ammonia for direct distribution to ammonia demand sites.

In conclusion, our analysis indicates that the LOHC method is the most cost-effective for ship transport, while Trucks-Gaseous Hydrogen is the preferred method for land transport with an. The suitability of using ammonia depends on the specific requirements and the absence of reconversion needs. Finally, the combined Cost per Kilogram for all the amount transferred is estimated to be 1.14€/kg.

These findings provide valuable insights for optimizing the hydrogen supply chain, helping us make informed decisions to minimize costs and maximize efficiency.

6.2 Applying our Case Study in the AnyLogic Model

In this section, we will explore the application of our case study in the AnyLogic modeling platform. By leveraging the power of simulation, we can analyze different scenarios and optimize the decision-making process for our hydrogen supply chain. The AnyLogic model serves as a virtual representation of our real-world system, allowing us to evaluate various transport methods, their associated costs, and make data-driven decisions. This section will provide an overview of the final database tables used in the model, the simulation scenarios, and the analysis of the results obtained.

To apply our case study in the AnyLogic model, we have developed a comprehensive framework that incorporates all the key parameters and constraints identified in the previous sections. The model includes information such as hydrogen production sites, demand points, transportation routes, and associated costs. By running different scenarios within the model, we can simulate the transportation process, evaluate the costs involved, and optimize the allocation of hydrogen supply.

6.2.2 Final Database tables for AnyLogic

In the final database tables used for the AnyLogic model, we have included essential information about each location, both supply and demand points, within the hydrogen supply chain. These tables consist of the location name, coordinates (latitude and longitude), and the annual hydrogen supply or consumption for each respective point.

Additionally, we have incorporated a name attribute that refers to the energy source used for electrolysis, specifically indicating whether it is sourced from solar PV, offshore wind, or onshore wind. For demand points, the name attribute categorizes the sector to which the point belongs, providing insights into the specific application or industry associated with the hydrogen demand.

The initial data for these supply and demand tables were exported from the map in Google My Maps as CSV files. Subsequently, the tables were modified to exclude and appropriately adjust the points that were manually examined in the previous subsection of our study. This ensures that the final database tables accurately represent the optimized supply chain configuration for our AnyLogic model.

The inclusion of location information, hydrogen supply/consumption, energy source, and sector categorization in the database tables forms a crucial foundation for the subsequent simulations and analyses conducted within the AnyLogic model.

Table 41. Supply Points Database Table

a/a	longitude	latitude	name	Location	Tonnes of Green Hydrogen per Year	Tonnes of Blue Hydrogen per Year	Total Tonnes of Hydrogen per Year
0	26.1117	35.21299	Offshore Wind Farm	Sitia Port Terminal	5,208		5,208
1	19.9223461	39.6249838	Offshore Wind Farm	Igoumenitsa	5,208		5,208
2	23.63333	37.94055	Offshore Wind Farm	Piraeus Port Terminal	5,208		5,208
3	25.132005	40.9604137	Offshore Wind Farm	Fanari	2,084		2,084
4	24.2348938	38.0024347	Offshore Wind Farm	Petalioi	5,208		5,208
5	24.1961583	38.6061043	Offshore Wind Farm	Kymi	5,208		5,208
6	20.6231394	38.8237408	Offshore Wind Farm	Lefkada	5,208		5,208
7	21.6822399	40.508944	Solar PV Park	Ptolemaida	25,000		25,000
8	24.1186107	41.1969942	Solar PV Park	Megalopolis	10,416		10,416
9	22.2505995	37.386178	Solar PV Park	Drama	10,416		10,416
10	21.2511791	39.6752161	Solar PV Park	Farsala	10,416		10,416
11	22.4431398	39.4154153	Solar PV Park	Kalampaka	10,416		10,416
12	23.5980559	38.0284189	Solar PV	Aspropyrgos	6,250	15,000	21,250

			Park				
13	23.0725244	37.921188	Solar PV Park	Corinth	6,250	15,000	21,250
14	22.8850279	40.6832467	Solar PV Park	Thessaloniki	6,250	15,000	21,250
15	23.5032101	38.0400967	Solar PV Park	Eleusis	6,250	15,000	21,250
16	22.6629598	41.158199	Onshore Wind Farm	Kilkis	2,604		2,604
17	21.0818868	40.6303589	Onshore Wind Farm	Western Macedonia	2,187		2,187
18	21.9201282	40.5213687	Onshore Wind Farm	Vermio	3,333		3,333
19	21.2303603	39.7325865	Onshore Wind Farm	Anilio	1,875		1,875
20	21.7341697	38.8395577	Onshore Wind Farm	Karpenisi	5,208		5,208
21	22.2065818	37.8747014	Onshore Wind Farm	Lykouria	5,208		5,208

Table 42. Demand Points Database Table

a_a	longitude	latitude	name	Location	Hydrogen Demand (tonnes/year)
0	22.8459317	40.7166467	Ammonia	Kaloudis Chemicals	5,208
1	23.5332536	38.0408054	Industrial Process Heat	TITAN Cement Company SA (Elefsina)	10,416
2	22.8154927	40.7036863	Steel	SIDENOR SA	10,416
3	23.5370375	38.0547577	Steel	Halyvourgiki (Elefsina)	10,416
4	23.5961532	38.0347938	Steel	Hellenic Halyvourgia (Aspropyrgos)	10,416
5	22.840109	39.1686175	Steel	SOVEL SA	10,416
6	22.8336419	39.3833867	Steel	Hellenic Steel SA(Volos)	10,416
7	22.9506064	40.6976363	Industrial Process Heat	TITAN Cement Company SA (Thessaloniki)	10,416
8	23.4033677	37.9591372	Buildings	DESFA LNG Terminal	10,416
9	23.0870324	37.9163134	Buildings	FSRU Agioi Theodoroi	10,416
10	23.5995575	38.0305569	Fuel Production and HVC	Hellenic Petroleum Aspropyrgos Refinery	18,749
11	23.0725244	37.921188	Fuel Production and HVC	Motor Oil (Hellas) Corinth Refineries SA	18,749
12	23.5028883	38.0401855	Fuel Production and HVC	Hellenic Petroleum Refineries SA(Elefsina)	18,749
13	22.8850279	40.6832467	Fuel Production and HVC	Hellenic Petroleum(Thessaloniki)	18,749
14	22.9230442	40.6348544	Marine	Thessaloniki Port	4,166
15	23.6333333	37.9405556	Marine	Piraeus Port	4,166
16	22.9291635	40.6444335	Rail	Thessaloniki Railway Station	4,166
17	23.7208081	37.9922968	Rail	Athens Railway Station	4,166
18	24.0176235	35.4909961	Road	Vehicle Refueling Station - Chania	416.8
19	24.4619099	35.3644807	Road	Vehicle Refueling Station - Rethymno	416.8
20	25.14081	35.315105	Road	Vehicle Refueling Station - Heraklion	416.8
21	26.1042052	35.2000247	Road	Vehicle Refueling Station - Sitia	416.8
22	25.767087	35.0349444	Road	Vehicle Refueling Station - Ierapetra	416.8

23	23.8553058	38.2122647	Road	Rest Area Kapandritiou (to Thessaloniki)	208.275
24	23.5377461	38.367233	Road	Rest Area Schimatariou (to Thessaloniki)	208.275
25	23.0720614	38.6606389	Road	Rest Area Atalantis (to Thessaloniki)	208.275
26	22.8888371	39.0629184	Road	Rest Area Almyrou (to Thessaloniki)	208.275
27	22.4973095	39.5495772	Road	Rest Area Nikaia (to Thessaloniki)	208.275
28	22.5081584	39.8139193	Road	Rest Area Evangelismos (to Thessaloniki)	208.275
29	22.5810897	40.3288099	Road	Rest Area Korinou (to Thessaloniki)	208.275
30	22.5820609	40.3320453	Road	Rest Area Korinou (to Athens)	208.275
31	22.5073396	39.8147648	Road	Rest Area Evangelismos (to Athens)	208.275
32	22.4964704	39.549398	Road	Rest Area Nikaia (to Athens)	208.275
33	22.8881002	39.0629843	Road	Rest Area Almyrou (to Athens)	208.275
34	23.0720892	38.6590928	Road	Rest Area Atalantis (to Athens)	208.275
35	23.5369911	38.3670648	Road	Rest Area Schimatariou (to Athens)	208.275
36	23.8246214	38.1134641	Road	Rest Area Varybobi (to Athens)	208.275
37	23.3664345	37.9962631	Road	Rest Area Megara (to Patras)	208.275
38	22.7419642	37.9744923	Road	Rest Area Velo (to Patras)	208.275
39	22.0798729	38.235262	Road	Rest Area Aigio (to Patras)	208.275
40	21.8672982	38.3251915	Road	Rest Area Psathopyrgos (to Patras)	208.275
41	21.8695994	38.3245779	Road	Rest Area Psathopyrgos (to Athens)	208.275
42	22.0789496	38.2352094	Road	Rest Area Aigio (to Athens)	208.275
43	22.7407722	37.9741751	Road	Rest Area Velo (to Athens)	208.275
44	23.364821	37.9943713	Road	Rest Area Megara (to Athens)	208.275
45	21.5447222	38.3872895	Road	Rest Area Evinochoriou (to Ioannina)	208.275

46	20.8520231	39.5460554	Road	Rest Area Episkopikou (to Ioannina)	208.275
47	20.9096003	39.2206778	Road	Rest Area Filippiada (to Ioannina)	208.275
48	20.9085703	39.2211848	Road	Rest Area Filippiada (to Patras)	208.275
49	20.8521463	39.545384	Road	Rest Area Episkopikou (to Patras)	208.275
50	21.5447431	38.3867006	Road	Rest Area Evinochoriou (to Patras)	208.275
51	21.4385805	40.0648706	Road	Rest Area Grevenon (to Thessaloniki)	208.275
52	21.3954322	40.0254975	Road	Rest Area Grevenon (to Ioannina)	208.275
53	22.5418046	40.5554379	Road	Rest Area Platanou (to Ioannina)	208.275
54	22.5435093	40.5549801	Road	Rest Area Platanou (to Thessaloniki)	208.275
55	23.3559251	40.7028463	Road	Rest Area Vaihoriou (to Thessaloniki)	208.275
56	23.1890916	40.7073196	Road	Rest Area Analipsi (to Alexandroupoli)	208.275
57	22.8403441	37.8626659	Road	Rest Area Spathovouniou (to Kalamata)	208.275
58	22.012333	37.1790186	Road	Rest Area Agios Floros - Arfara (to Kalamata)	208.275
59	22.0129248	37.1783253	Road	Rest Area Agios Floros - Arfara (to Athens)	208.275
60	22.8410084	37.8624132	Road	Rest Area Spathovouniou (to Athens)	208.275
61	22.3430189	37.1963198	Road	Rest Area Pellanas (to Sparta)	208.275
62	22.3419332	37.1977396	Road	Rest Area Pellanas (to Athens)	208.275
63	22.8857154	38.9476924	Industrial Process Heat	PAKO Vl. Koliopoulos Papermaking SA	1,260
64	26.1410808	35.0038681	Power	D.R.H. Atherinolakkos	3,124

6.2.3 Simulation Scenarios in AnyLogic

In order to assess the performance and cost implications of different transport methods for hydrogen in our supply chain, we conducted several simulation scenarios using AnyLogic. These scenarios were designed based on two main criteria: the choice of transport method (trucks or pipelines) and the form of hydrogen in the transport.

For the transport method, we excluded shipping transport as it had already been analyzed in the pre-optimization process. Instead, we focused on trucks and pipelines. In the truck scenarios, we considered four options: gaseous, liquefied, LOHC (Liquid Organic Hydrogen Carrier), and ammonia. In the pipeline scenario, gaseous hydrogen was the only available choice.

Another important criterion in our scenarios was the demand point selection method. We had two options: highest demand and nearest. In the highest demand method, the supply point would send hydrogen to the demand point with the highest demand at any given time. However, for our simulations, we chose the nearest method, as it proved to be the most cost-effective approach. By selecting the nearest demand point, we were able to reduce transportation distances and optimize overall costs. The highest demand method can be useful in specific cases where other factors take precedence over cost optimization.

To conduct the simulations, we utilized the cost data and capacity values obtained from the previous section. These parameters were crucial in determining the total cost of each scenario and evaluating their economic viability.

Based on these criteria, we conducted the following simulation scenarios:

Scenario 1:

Trucks transporting hydrogen in gaseous form to the nearest demand point.

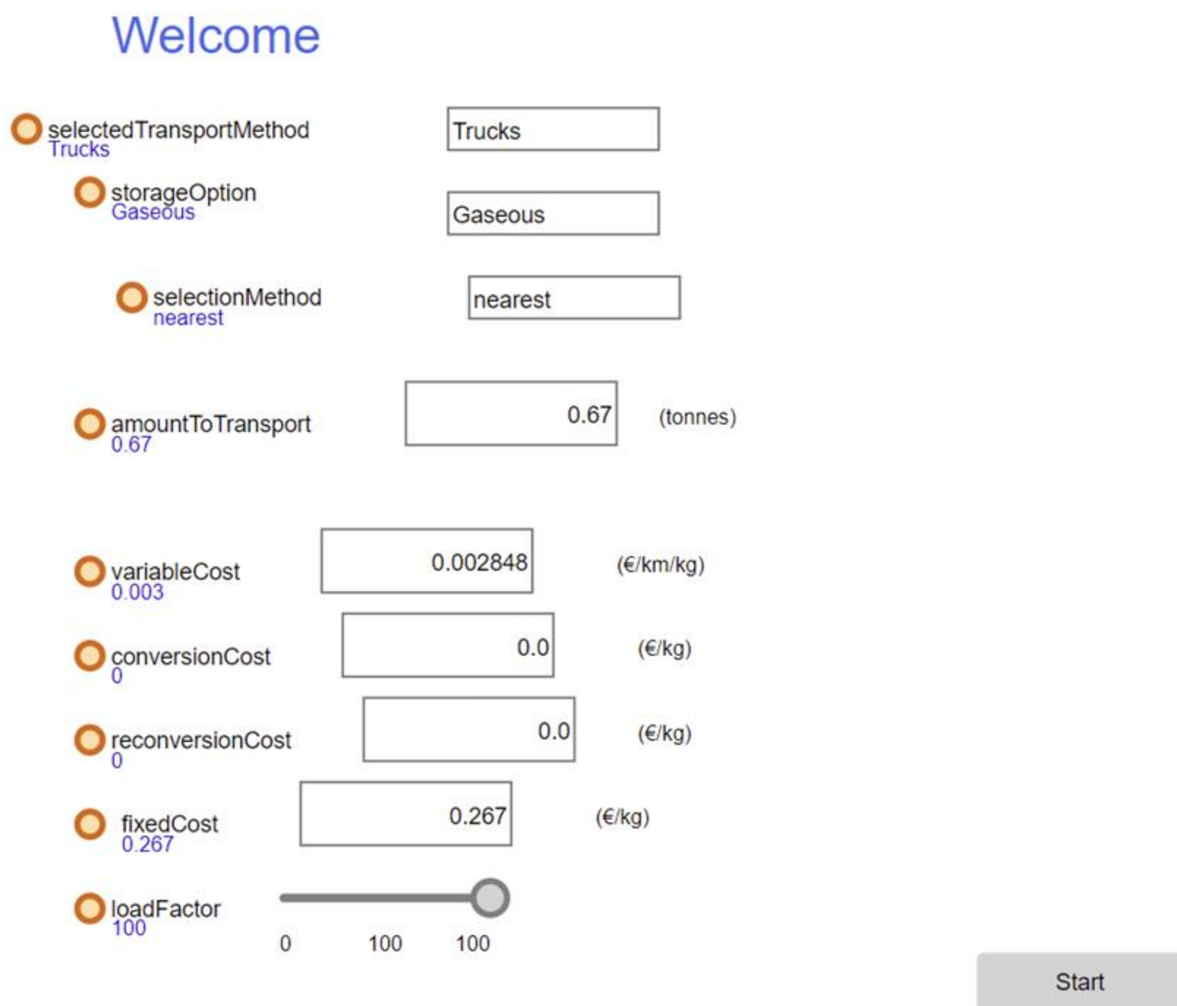


Figure 39. Scenario 1 Parameters

Scenario 2:

Trucks transporting hydrogen in liquefied form to the nearest demand point.

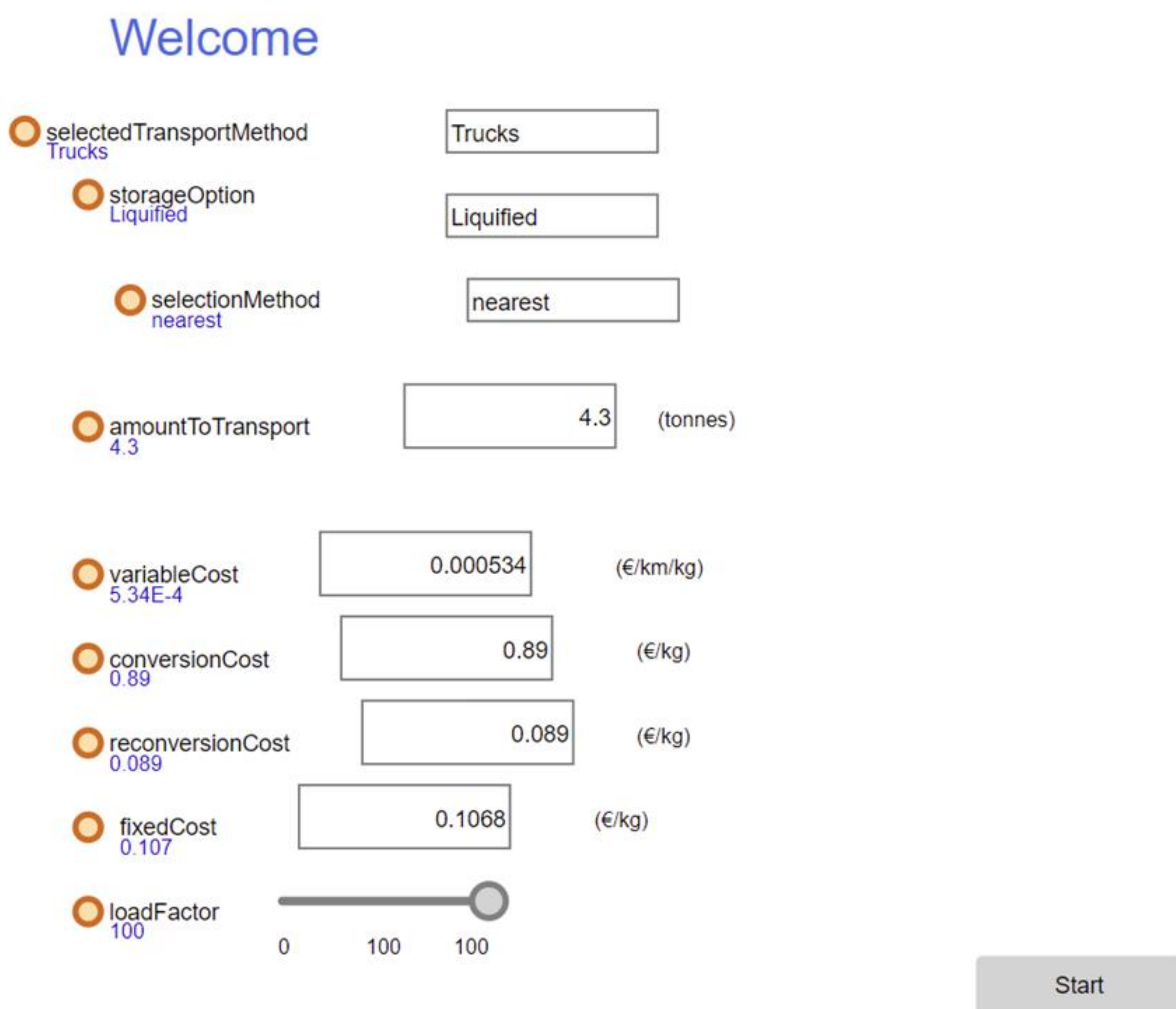


Figure 40. Scenario 2 Parameters

Scenario 3:

Trucks transporting hydrogen as LOHC to the nearest demand point.

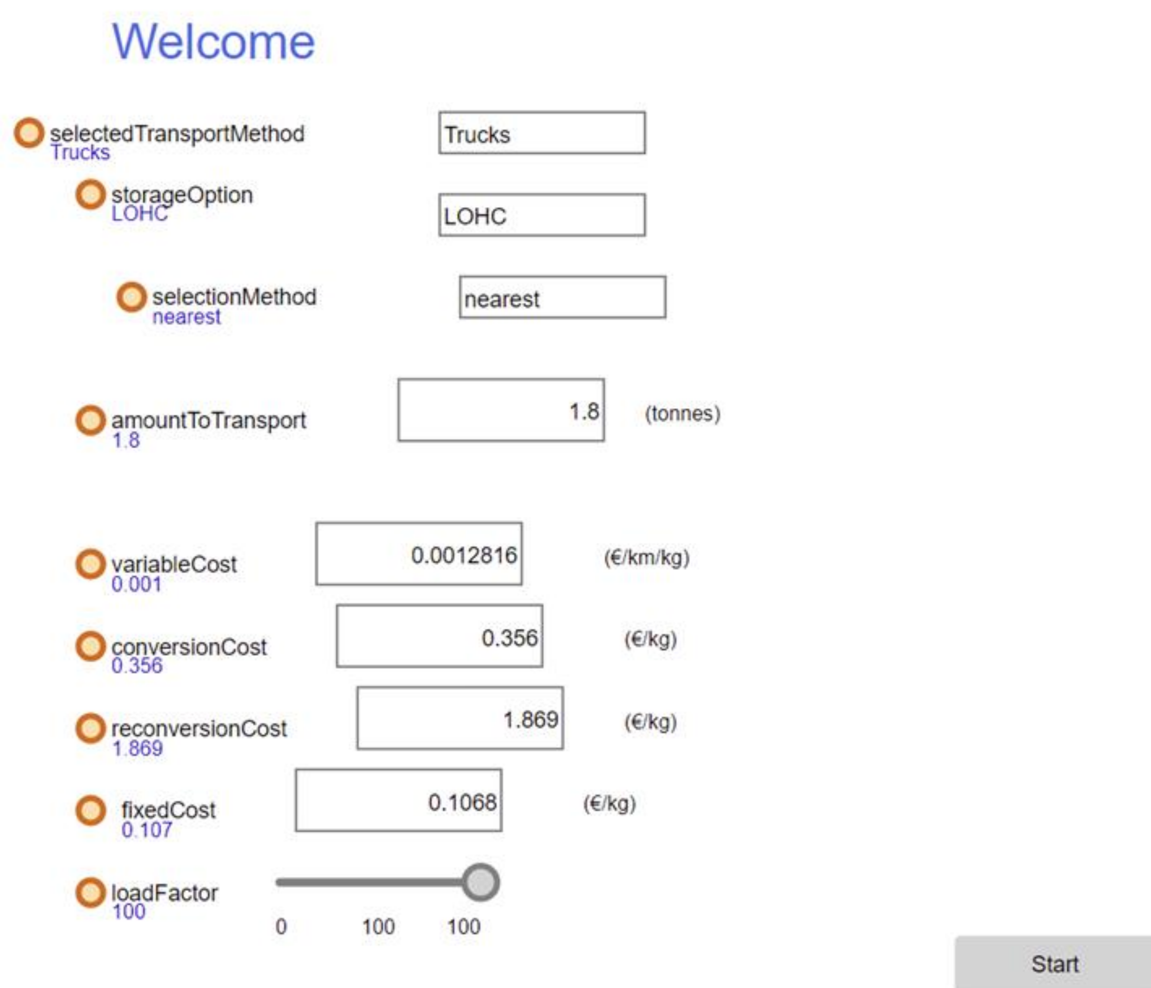


Figure 41. Scenario 3 Parameters

Scenario 4:

Trucks transporting hydrogen as ammonia to the nearest demand point.

Figure 42. Scenario 4 Parameters

Scenario 5:

Pipelines transporting hydrogen in gaseous form to the nearest demand point.

Figure 43. Scenario 5 Parameters

By running these scenarios in AnyLogic, we aimed to analyze the performance, cost, and feasibility of each transport method and form of hydrogen. The simulation results provided valuable insights into the optimal transport strategies and informed our decision-making process.

6.2.4 Results and Analysis

In this section, we will present the results of each simulation scenario conducted in AnyLogic. The simulations were designed to evaluate the performance, cost, and feasibility of different transport methods for hydrogen in our supply chain.

For each scenario, we captured relevant statistics and key performance indicators to assess the efficiency and effectiveness of the transport method. This included metrics such as total cost, transportation distances and total routes required.

Furthermore, we analyzed the impact of different transport forms of hydrogen, such as gaseous, liquefied, LOHC, and ammonia. By comparing the results of these scenarios, we aimed to identify the most suitable form of hydrogen for each transport method, taking into consideration factors such as cost, energy efficiency, and safety.

The following screenshots of the Statistics View Area from AnyLogic, provide a visual representation of the simulation setup and the obtained statistics. These screenshots showcase the associated costs and performance indicators for each scenario.

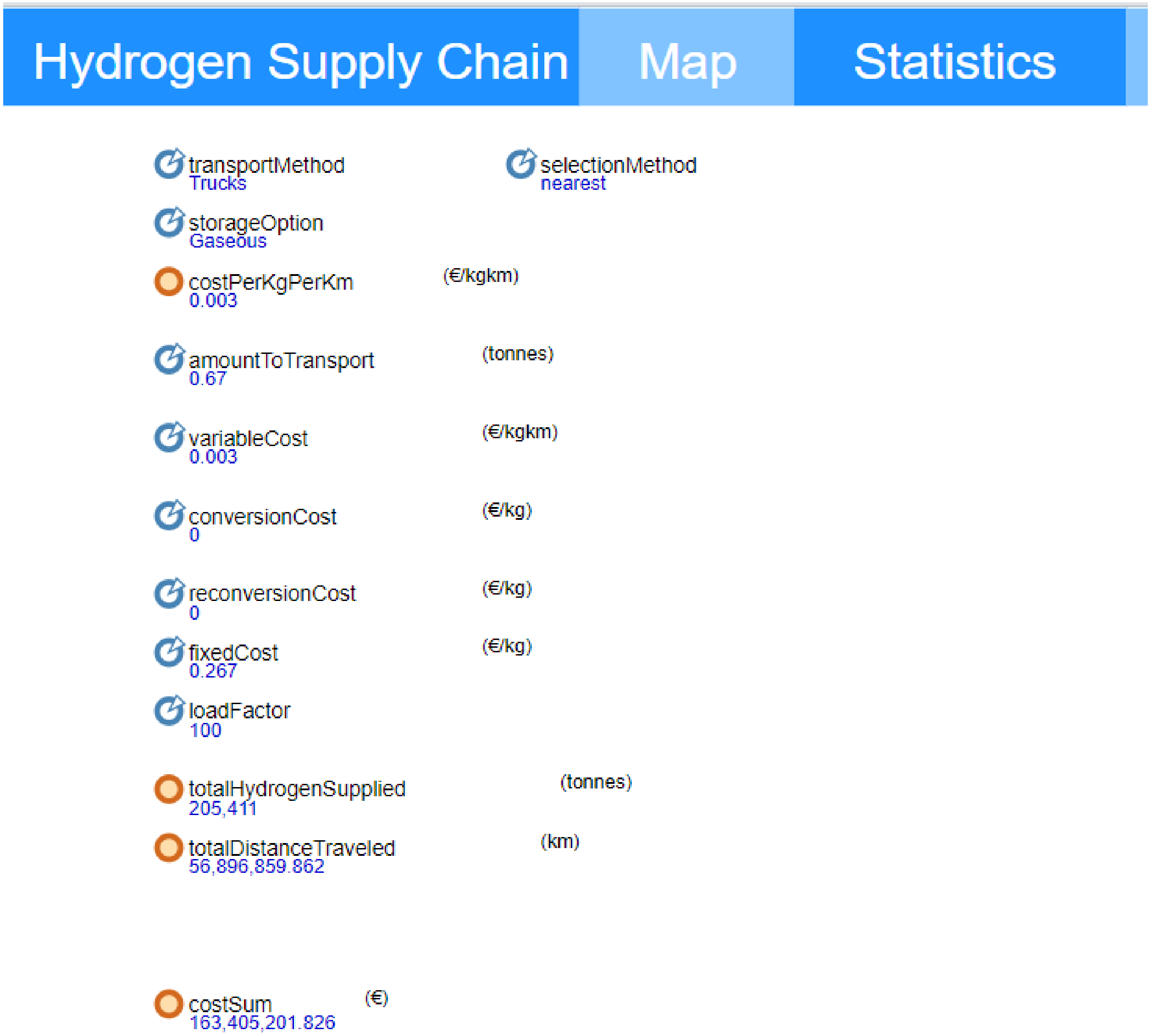


Figure 44. Scenario 1 Results

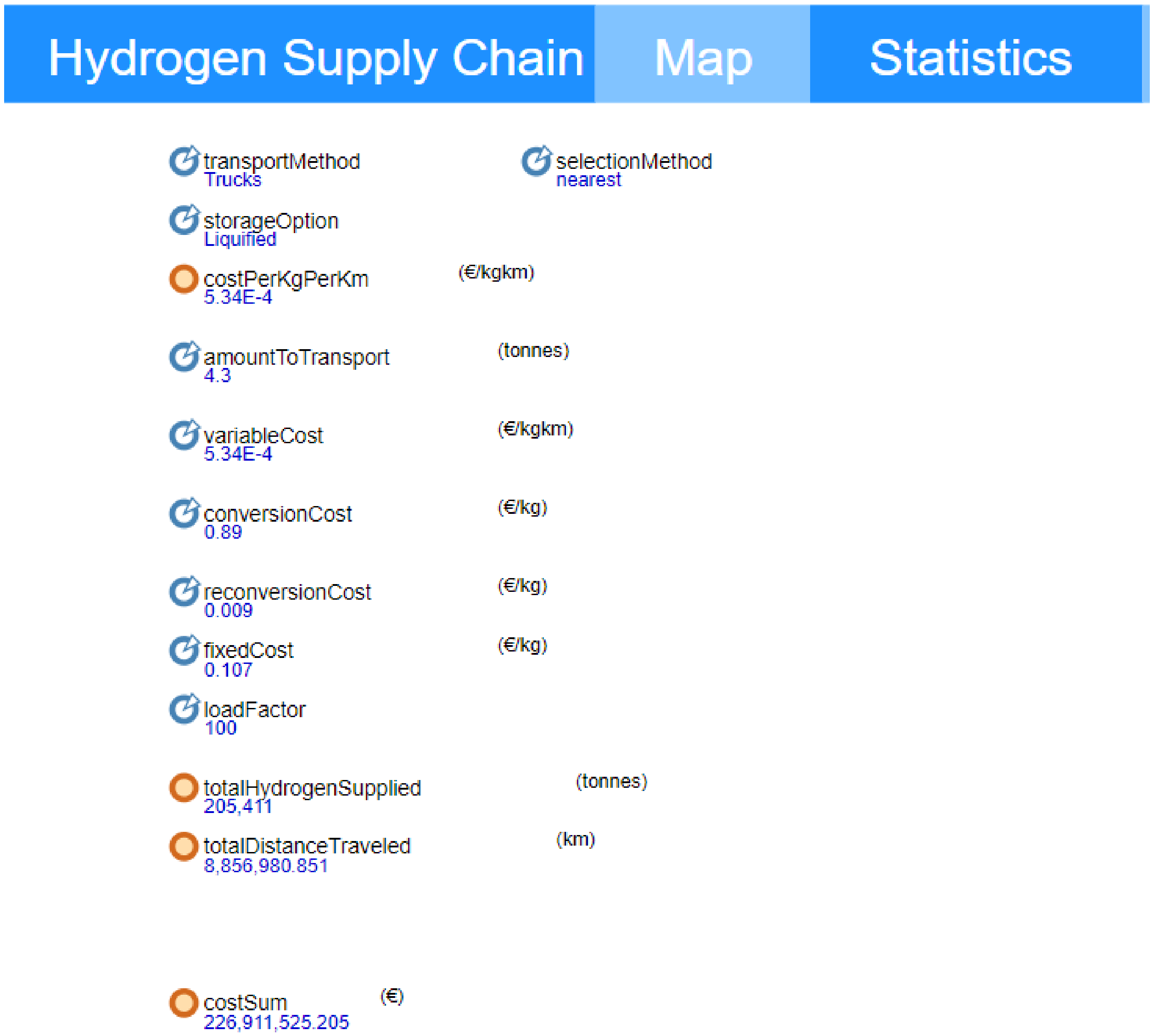


Figure 45. Scenario 2 Results

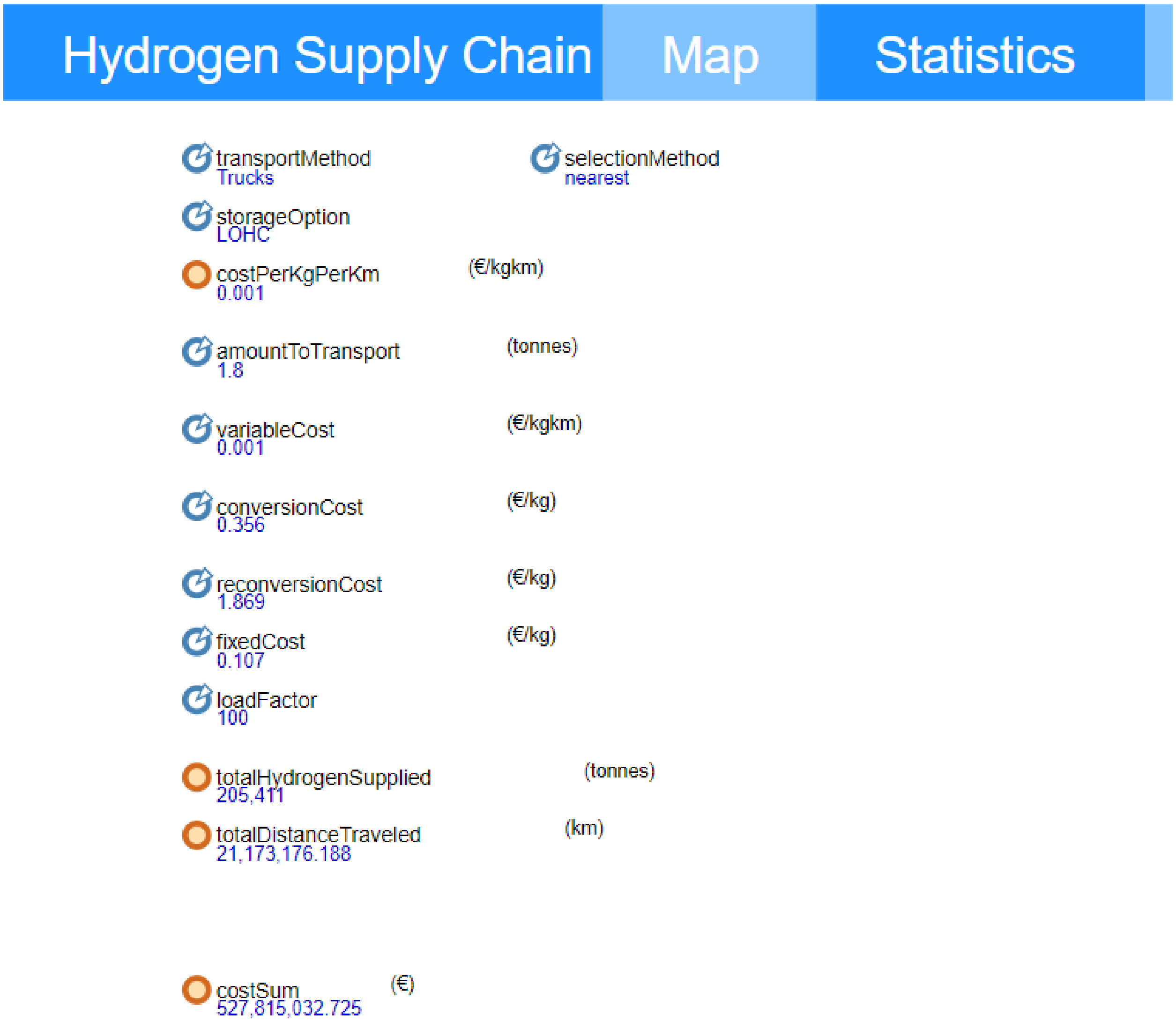


Figure 46. Scenario 3 Results

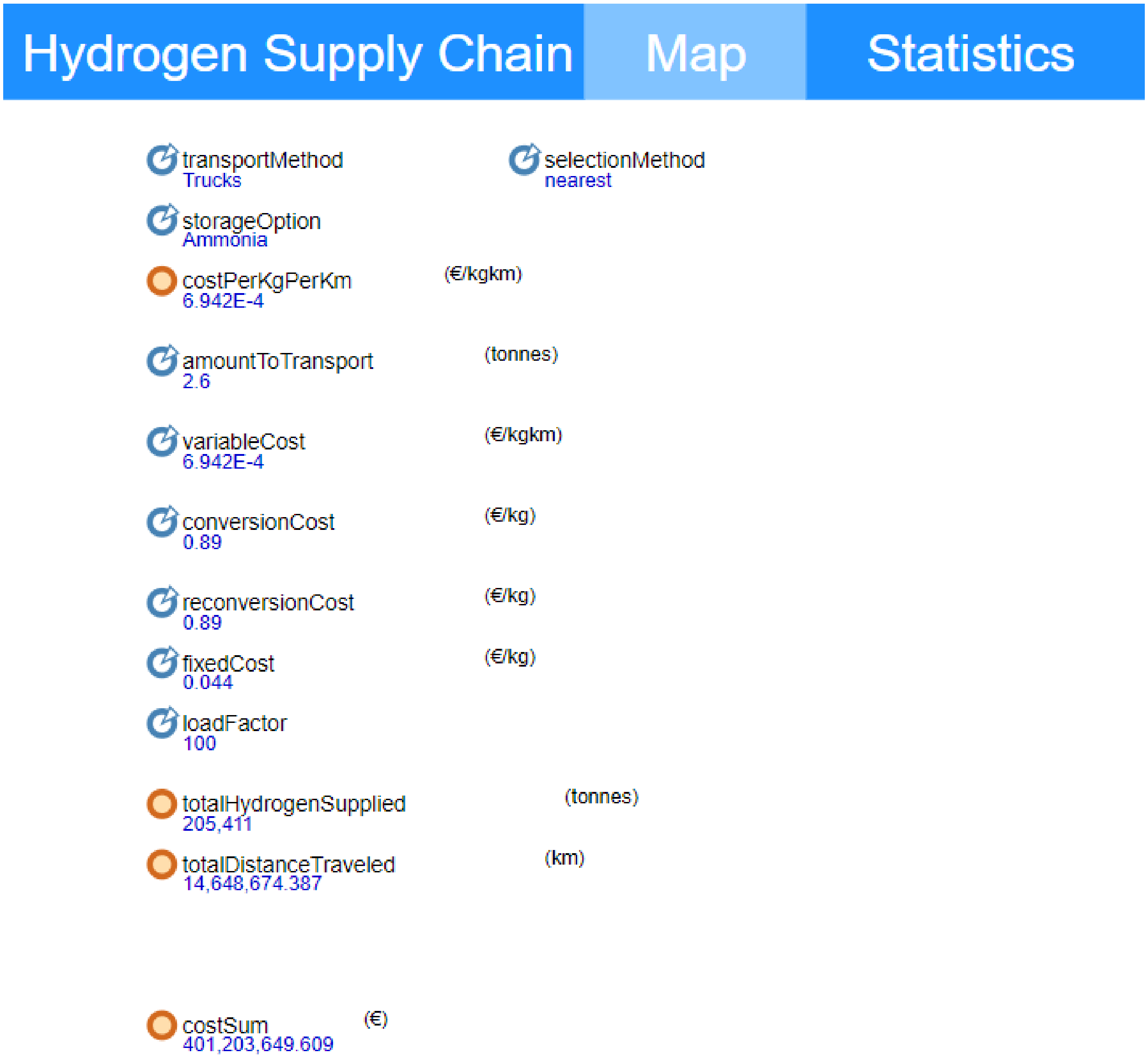


Figure 47. Scenario 4 Results

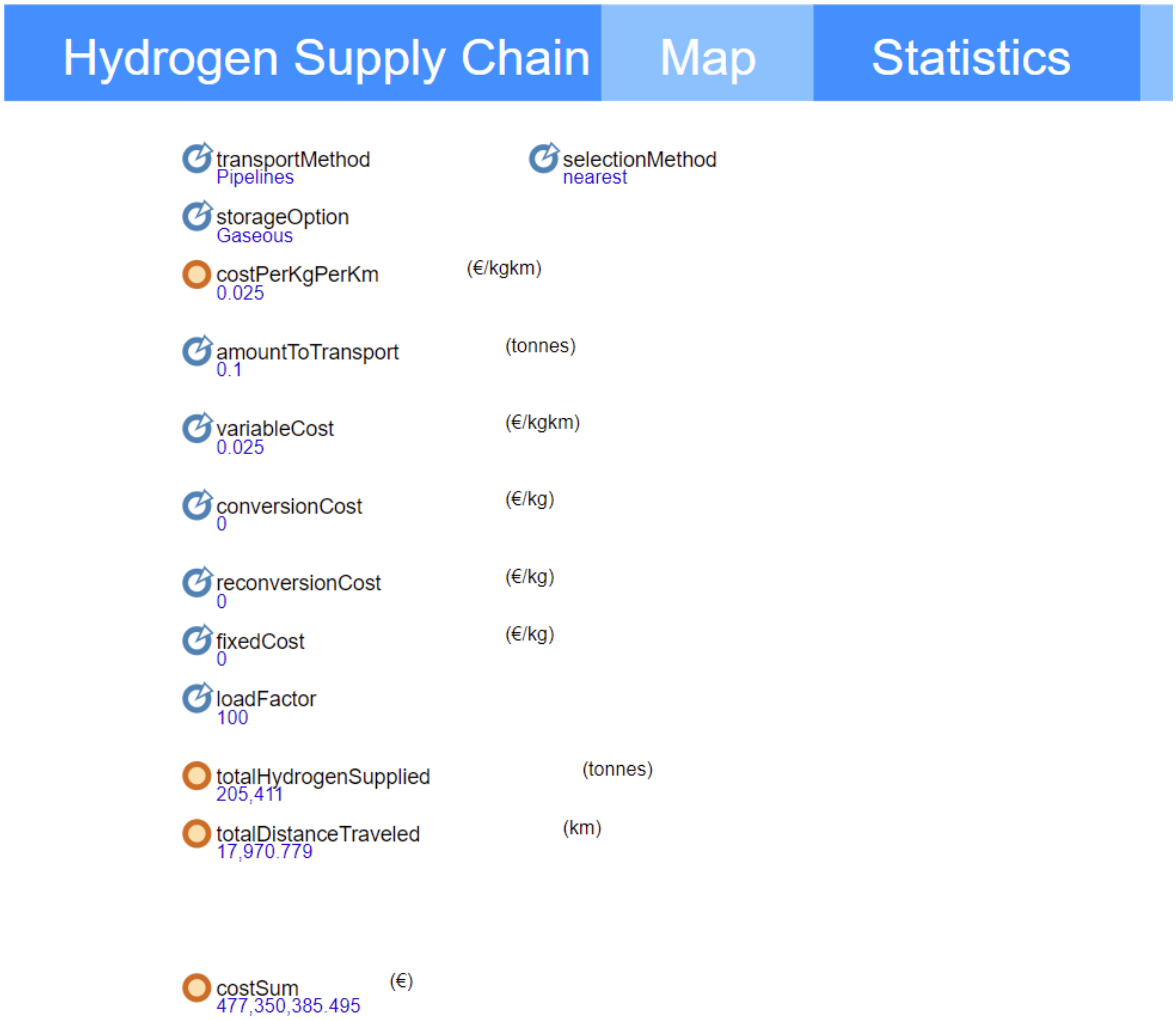


Figure 48. Scenario 5 Results

In addition to the screenshots, we will present a results table summarizing the key findings of each scenario. This table will include important metrics such as total cost, transportation distances, and other relevant performance indicators. We also calculated a key indicator Cost per Kilogram by dividing the Total Cost with the Total Amount. By analyzing this table, we can compare and evaluate the different scenarios, enabling us to make informed decisions regarding the optimal transport method for hydrogen in our supply chain.

Table 43. Simulation Results Table

	Trucks				Pipelines
	Gaseous	Liquefied	LOHC	Ammonia	Gaseous
Selection Method	nearest	nearest	nearest	nearest	nearest
Total Distance/y	56,896,859.86	8,856,980.85	21,173,176.19	14,648,674.39	17,970.78
Total Cost/y	163,405,201.83 €	226,911,525.21 €	527,815,032.73 €	401,203,649.61 €	489,088,802.67 €
Total Amount/y (kg)	205,411,000	205,411,000	205,411,000	205,411,000	205,411,000
Cost per Kg	0.80 €	1.10 €	2.57 €	1.95 €	2.38 €

The results and analysis presented in this section provide valuable insights into the performance and cost implications of various transport methods for hydrogen. These findings will support our decision-making process and help optimize the design and operation of our supply chain in terms of cost-efficiency, reliability, and sustainability.

In order to take into consideration, the pre-optimization analysis for the final cost calculations we have compiled a comprehensive table that combines the results from the pre-optimization cost analysis and the AnyLogic model. This table provides an overview of the total cost and the cost per kilogram (kg) for the entire examined hydrogen supply chain.

Table 44. Summary Table of the Entire Case Study

Transport Method in AnyLogic Model	**Trucks- Gaseous**	**Trucks- Liquefied**	**Trucks- LOHC**	**Trucks-Ammonia**	**Pipelines**
Pre optimization Cost	39,320,040.87 €	39,320,040.87 €	39,320,040.87 €	39,320,040.87 €	39,320,040.87 €
Simulation Cost	163,405,201.83 €	226,911,525.21 €	527,815,032.73 €	401,203,649.61 €	489,088,802.67 €
Total Cost	202,725,242.69 €	266,231,566.07 €	567,135,073.59 €	440,523,690.48 €	528,408,843.53 €
Total Amount(kg)	234,575,000.00	234,575,000.00	234,575,000.00	234,575,000.00	234,575,000.00
Final Cost per kg(€/kg)	0.86	1.13	2.42	1.88	2.25

7. Discussion and Evaluation

7.1 Discussion of Results

In all scenarios, the amount of hydrogen transported per year remained the same at 234,575,000 kg. The selection method for all scenarios was the nearest method, where the supply point sends hydrogen to the nearest demand point.

Now, let's focus on the cost per kilogram of hydrogen for each scenario. This key indicator is calculated by dividing the total cost by the total amount of hydrogen.

In the Trucks-Gaseous scenario, the total cost per year was 202,725,242.69 € , resulting in a cost per kilogram of 0.86 €.In the Trucks-Liquefied scenario, the total cost per year was 266,231,566.07 € resulting in a cost per kilogram of 1.13 €.In the Trucks-LOHC scenario, the total cost per year was 567,135,073.59 € , resulting in a cost per kilogram of 2.42 €.In the Trucks-Ammonia scenario, the total cost per year was 440,523,690.48 € , resulting in a cost per kilogram of 1.88 €.In the Pipelines scenario, the total cost per year was 528,408,843.53 € , resulting in a cost per kilogram of 2.25 €.

These cost per kilogram values indicate the efficiency and cost-effectiveness of each transport scenario. The Trucks-Gaseous scenario had the lowest cost per kilogram, followed by the Trucks-Ammonia scenario, the Trucks-Liquefied scenario, the Pipelines scenario, and the Trucks-LOHC scenario.

It's important to note that while the cost per kilogram is an essential indicator, other factors such as distance, infrastructure requirements, and operational considerations should also be taken into account when determining the optimal transport method for a hydrogen supply chain.

The consistent amount of hydrogen and the selection of the nearest method in all scenarios allowed for a fair comparison of the cost per kilogram and provided insights into the relative cost-effectiveness of each transport scenario. The pre-optimization analysis and the simulation scenarios in the AnyLogic model have provided valuable insights into the cost implications of different transportation methods for hydrogen distribution. Let's delve into what these results reveal for each transport method and their implications for hydrogen supply chain management.

1. **Trucks - Gaseous Hydrogen:**

The cost analysis reveals that transporting hydrogen in gaseous form using trucks has the lowest cost per kilogram compared to other truck-based scenarios. This indicates that using gaseous hydrogen in trucks for transportation is a cost-effective option. However, it's important to note that the capacity limitation of gas trucks, with a maximum of 0.67 tonnes per transport, leads to the need for multiple routes to meet the total demand, which means more trucks to deliver a specific amount of hydrogen and thus less flexibility.

2. **Trucks - Liquefied Hydrogen:**

The cost analysis shows that transporting liquefied hydrogen using trucks has a higher cost per kilogram compared to gaseous hydrogen. This suggests that transporting liquefied hydrogen incurs additional costs associated with the liquefaction process and the need for specialized equipment. Despite the higher cost, the use of liquefied hydrogen in trucks may still be a viable option in specific scenarios where the benefits outweigh the cost implications. One notable advantage of using liquefied hydrogen is its higher capacity of 4.3 tonnes per transport, which reduces the number of required routes and potentially improves operational efficiency.

3. **Trucks - LOHC (Liquid Organic Hydrogen Carrier):**

The analysis indicates that using LOHC for hydrogen transportation using trucks results in the highest cost per kilogram compared to other truck-based scenarios. The additional costs associated with LOHC, such as conversion and reconversion costs, contribute to the overall higher cost. The higher cost of LOHC transportation suggests that alternative transport methods may be more economically favorable in terms of cost-efficiency. Additionally, factors such as LOHC production costs, stability, and handling requirements need to be taken into account when considering this transport method.

4. **Trucks - Ammonia:**

The cost analysis shows that transporting hydrogen as ammonia using trucks has a moderate cost per kilogram compared to other truck-based scenarios. Ammonia has lower conversion and reconversion costs compared to LOHC, which contributes to the lower overall cost. The cost-effectiveness of using ammonia in trucks depends on various factors such as ammonia production costs, storage requirements, and availability of infrastructure. Ammonia offers the advantage of being a well-established and widely-used chemical, which may facilitate its transport and distribution. However, considerations regarding safety, ammonia handling, and potential environmental impacts need to be carefully evaluated.

5. **Pipelines - Gaseous Hydrogen:**

The cost analysis indicates that transporting hydrogen through pipelines in gaseous form has a higher cost per kilogram compared to truck-based scenarios. Despite the potential advantages of pipelines in terms of high capacity and the ability to transport hydrogen over long distances without the need for multiple routes, the initial infrastructure investment and maintenance costs contribute to the overall higher cost per kilogram. While pipelines offer advantages in terms of operational efficiency and reduced handling, the higher initial investment and maintenance costs may affect their cost-effectiveness in certain scenarios.

7.2 Evaluation of the Model

The evaluation of the model involves assessing its effectiveness in capturing the key aspects of the hydrogen supply chain and analyzing the results obtained. This section aims to provide an evaluation of the model's performance and its suitability for addressing the research objectives.

Firstly, the model successfully represents the spatial distribution of supply and demand points, considering their respective capacities and geographical locations. The integration of real-world data, such as hydrogen production sites and demand points, enhances the model's realism and applicability to practical scenarios. Additionally, the selection of different transport methods, including trucks and pipelines, allows for a comprehensive analysis of various transportation options.

The model's optimization capability is a crucial feature for determining the most cost-effective transport method for each scenario. By considering factors such as distance, capacity, and cost parameters, the model provides insights into the optimal allocation of hydrogen supply to meet the demand. The results obtained from the model enable decision-makers to assess the economic feasibility of different transport options and make informed choices.

Furthermore, the model incorporates the concept of selection methods, such as the nearest demand point selection, which adds flexibility in the allocation of hydrogen supply. This allows for the consideration of practical constraints, such as minimizing transportation distances and optimizing resource utilization.

Overall, the model provides a valuable tool for evaluating and optimizing the hydrogen supply chain, taking into account different transport methods and selection criteria. It enables stakeholders to make informed decisions regarding transport options, considering factors such as cost-effectiveness, capacity limitations, and specific requirements of different transport methods.

In the next section, we will discuss the limitations of the model and potential areas for improvement to further enhance its capabilities.

7.3 Limitations and Potential Improvements

While the developed model provides valuable insights into the hydrogen supply chain and transport optimization, it is important to acknowledge its limitations and consider potential areas for improvement. Understanding these limitations helps identify opportunities for future research and refinement of the model.

One limitation of the model is the assumption of fixed cost and variable cost parameters for each transport method. In reality, the costs associated with hydrogen transportation can vary due to market conditions, fuel prices, and other factors. Future improvements could involve incorporating dynamic cost models that consider real-time data and market fluctuations to provide more accurate cost estimations.

Another limitation is the assumption of static demand scenarios. In practice, hydrogen demand can fluctuate over time due to changes in industrial activity, energy requirements, and government policies. Incorporating demand forecasting techniques and considering dynamic demand scenarios would enhance the model's ability to capture real-world variations and provide more accurate results.

Additionally, the model assumes a simplified representation of the hydrogen supply chain, focusing primarily on transport optimization. Future iterations of the model could incorporate other elements of the supply chain, such as hydrogen production technologies, storage facilities, and distribution networks. This would provide a more comprehensive analysis of the entire supply chain and allow for further optimization opportunities

In conclusion, while the developed model offers valuable insights into hydrogen supply chain optimization, it is important to recognize its limitations. By addressing these limitations and considering potential improvements, the model can be further enhanced to provide more accurate, comprehensive, and region-specific analysis of hydrogen transport and supply chain management.

In the final section, we will summarize the key findings of the study, discuss their implications for hydrogen supply chain management, and provide recommendations for future research in this field.

8. Conclusions and Future Work

8.1 Key Findings

Through the evaluation and analysis of the hydrogen supply chain model, several key findings have emerged:

Cost Variation Among Transport Methods:

The analysis of different transport methods, including gaseous hydrogen, liquefied hydrogen, LOHC, ammonia, and pipelines, revealed significant variations in the cost per kilogram of hydrogen transported. Trucks transporting gaseous hydrogen demonstrated the lowest cost per kilogram, followed by ammonia, liquefied hydrogen, and LOHC. Pipelines, on the other hand, generally exhibited higher costs per kilogram compared to most of the truck transport options. These findings highlight the importance of selecting the most cost-effective transport method based on specific requirements and considerations. More specifically we will analyze the key findings for each of the transport methods:

Shipping Transport: Among the shipping transport methods analyzed, LOHC (Liquid Organic Hydrogen Carrier) demonstrated the highest cost efficiency compared to ammonia and liquefied hydrogen. LOHC offers a promising solution for the efficient and cost-effective transportation of hydrogen.

Trucks Transport: Trucks transporting gaseous hydrogen were found to be the most cost-effective option among the truck-based scenarios. However, it is important to consider the limited capacity of gas trucks, which may necessitate multiple routes to meet the total demand. This finding underscores the need to carefully consider the capacity and efficiency of transport vehicles when designing and optimizing hydrogen supply chains.

Pipelines: In the analyzed small-scale hydrogen supply chain, pipelines were not found to be the most cost-effective option. They exhibited higher costs compared to other transport methods, and their upfront infrastructure costs were significant. Pipelines may be more suitable for longer distances or larger-scale hydrogen supply chains.

Importance of Selection Method:

The selection method for matching supply points with demand points significantly impacts the overall cost and efficiency of the hydrogen supply chain. The use of the nearest selection method, where supply points send hydrogen to the nearest demand points, proved to be the most cost-effective approach in the analyzed scenarios. This finding highlights the significance of considering proximity and minimizing transportation distances to optimize the supply chain.

Limitations and Potential Improvements:

The evaluation of the model identified several limitations, such as static demand scenarios, fixed cost assumptions, and the simplified representation of the supply chain. Future research and model enhancements should address these limitations by incorporating dynamic demand scenarios, considering market fluctuations for cost estimations, and expanding the model to capture a more comprehensive representation of the hydrogen supply chain.

Overall, the key findings emphasize the importance of selecting the appropriate transport method, considering capacity limitations, and optimizing the supply chain based on proximity and cost-efficiency. These insights provide valuable guidance for hydrogen supply chain management and inform decision-making processes in the adoption and implementation of hydrogen as a sustainable energy carrier.

8.2 Recommendations for Future Research

Based on our study, several areas for future research in hydrogen supply chain management can be identified. These recommendations aim to further enhance the understanding and optimization of the hydrogen supply chain, taking into account evolving technologies, market dynamics, and sustainability considerations.

Advanced Optimization Models:

Future research could focus on developing advanced optimization models that incorporate multiple objectives, such as cost minimization, carbon footprint reduction, and capacity utilization. These models can consider various factors, including demand variations, transport network design, and the integration of renewable energy sources, to optimize the overall performance of the hydrogen supply chain.

Techno-economic Analysis:

Conducting detailed techno-economic analysis for different transport methods and infrastructure options can provide valuable insights into the cost-effectiveness and feasibility of hydrogen transportation. This analysis should consider factors such as capital costs, operating costs, energy efficiency, and environmental impact to support informed decision-making in supply chain management.

Sustainability Assessment:

Future research should focus on conducting comprehensive sustainability assessments of the hydrogen supply chain. This includes evaluating the life cycle environmental impacts, such as carbon emissions and water usage, associated with different transport methods. Additionally, assessing the social and economic dimensions of the supply chain can provide a holistic understanding of the sustainability implications and inform sustainable supply chain management practices.

Infrastructure Development:

Investigating the infrastructure requirements for hydrogen storage, refueling stations, and transport networks is crucial for the efficient and widespread deployment of hydrogen technologies. Future research should explore the optimal locations for infrastructure development, considering factors such as proximity to demand points, renewable energy sources, and existing infrastructure networks.

Policy and Regulatory Frameworks:

Assessing the role of policy and regulatory frameworks in promoting the development and adoption of hydrogen technologies is essential. Future research should analyze the effectiveness of existing policies and identify areas where supportive regulations can further accelerate the growth of the hydrogen supply chain. This includes exploring mechanisms for incentivizing investment in infrastructure, fostering international collaborations, and addressing safety and certification standards.

Market Dynamics and Business Models:

Studying the market dynamics, including supply and demand fluctuations, pricing mechanisms, and business models, can provide valuable insights into the commercial viability of hydrogen supply chains. Future research should analyze market trends, assess different business models, and explore innovative approaches, such as hydrogen hubs and virtual pipelines, to enhance the efficiency and competitiveness of the hydrogen supply chain.

By addressing these research recommendations, stakeholders can gain a deeper understanding of the hydrogen supply chain and contribute to its further development, efficiency, and sustainability. These research efforts will support the transition to a clean and low-carbon energy future by leveraging the potential of hydrogen as a key energy carrier.

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Appendix A. Pipelines Cost Calculations

In this appendix, we present the methodology used to calculate the cost per kilogram per kilometer for pipelines. This parameter, denoted as 'a' in the cost formula y=ax, is crucial in estimating the cost of transporting hydrogen through pipelines.

To calculate 'a', we utilized data from the International Energy Agency (IEA) and applied the formula that correlates the internal diameter of the pipelines with the capital expenditure (CAPEX). This formula is applicable for a minimum internal diameter of 100mm, which we assumed for our calculations. [Baufumé, 2013]

First, we determined the volumetric flow rate using the equation Volumetric Flow (m3/s) = (D^2 * π * Gas Velocity) / 4, where D is the internal diameter of the pipeline and Gas Velocity is the velocity of hydrogen in meters per second.

$$\text{Volumetric Flow}\left(\frac{\text{m3}}{\text{s}}\right) = \frac{\text{D\^{}2} * \pi * \text{Gas Velocity(m/s)}}{4}$$

Next, we calculated the gas throughput using the equation Gas Throughput (kg/s) = Volumetric Flow (m3/s) * Gas Density (kg/m3), where Gas Density represents the density of hydrogen.

$$\text{Gas Throughput (kg/s)} = \text{Volumetric Flow}\left(\frac{\text{m3}}{\text{s}}\right) * \text{Gas Density (kg/m3)}$$

Finally, we obtained the amount of hydrogen transported per year using the equation Amount per year (kg) = Gas Throughput (kg/s) * Operation hours * 3,600(s).

$$\text{Amount per year(kg)} = \text{Gas Throughput}\left(\frac{\text{kg}}{\text{s}}\right) * \text{Operation hours} * 3{,}600\text{(s)}$$

The resulting amount per year for a 100mm internal diameter was deemed sufficient for our case study, confirming the validity of our assumption to use the minimum internal diameter. It is important to note that this assumption might overestimate the infrastructure requirements, but it ensures that our calculations account for the maximum potential hydrogen throughput.

Additionally, we determined the CAPEX (capital expenditure) using the equation CAPEX (€/km) = 0.89 * (3,400,000 * D^2 + 598,600 * D + 329,000), which considers the internal diameter of the pipeline.

$$CAPEX\left(\frac{€}{km}\right) = 0.89 * (3{,}400{,}000 * D^2 + 598{,}600 * D + 329{,}000)$$

To calculate the present value (PV), we used the equation PV H_2 = A(kg) * (1 - (1 + r) ^(-n)) / r, where A represents the annual throughput of hydrogen in each case, r is the discount rate, and n is the number of years.

$$PV\ H_2 = A(kg) * \frac{1-(1+r)^{-n}}{r}$$

Finally, we obtained the cost per kilogram per kilometer (a) by dividing the CAPEX by the PV value.

$$a(\frac{€}{kgkm}) = \frac{CAPEX}{PV}$$

This methodology allowed us to estimate the cost per kilogram per kilometer for pipelines, taking into account the internal diameter, gas throughput, and capital expenditure. These calculations provide essential inputs for the cost analysis and optimization of the hydrogen supply chain.

We applied the methodology to calculate the cost per kilogram per kilometer for two specific cases. The first case involved the Fanari-Alexandroupoli route, which resulted in an estimated annual throughput of 3,124 tonnes. By utilizing the equations mentioned earlier, we obtained the cost per kilogram per kilometer for this specific route.

Furthermore, in the AnyLogic model, we divided the total amount of hydrogen by the number of routes to estimate the annual throughput in each pipeline route. This approach provided a rough estimate of the tonnes per year for each specific pipeline route, allowing us to incorporate it into the cost analysis and optimization of the hydrogen supply chain.

These calculations for the two cases enabled us to consider the specific characteristics and requirements of different pipeline routes, contributing to a more accurate evaluation of the cost per kilogram per kilometer and overall cost implications for the hydrogen supply chain.

Table 45. Pipelines with 100 mm Internal Diameter Amount per year Calculation

Pipelines Amount Calculation 100mm Internal diameter	
Internal diameter(m)	0.1
Gas Velocity (m/s)	15
volumetric flow (m3/s)	0.117809725
Gas Density (kg/m3)	6.4
gas throughput (kg/s)	0.753982237
Operation time/y (hours)	5,000
Amount per year (kg)	13,571,680.26

Table 46. Pipelines Cost per Kg per Km Calculations

Pipelines Cost Calculation 100mm Internal diameter	3124 tonnes/y	1260.190184 t/y
Amount per year (kg)	3,124,000	1,260,190.184
Internal diameter(m)	0.1	0.1
CAPEX(€/km)	376,345.40 €	376,345.40 €
Lifetime	40	40
Discount Rate	0.080000	0.080000
PV H2	37,252,492.05	15,027,280.67
cost per kg per km	0.010102556	0.025044145