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Hydrogen Demand Projections for European Countries applying Econometric Techniques

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Abstract

Climate change, driven by CO_2 emissions, is a global issue threatening the quality of life on Earth. Several international organizations are taking action to prevent a catastrophic future by implementing climate plans to reduce to reduce GHG emissions. More specifically by 2050, the European Union aims to be climate neutral, the International Maritime Organization pursues a 70% GHG reduction compared to 2008 levels and the International Air Transport Association estimates a possible net-zero scenario. Green hydrogen represents an alternative for these ambitious targets, specially for hard-to-abate sectors. Aside from the renewable value of hydrogen, it can also provide energy independence to the EU, shown to be much needed after the Ukraine-Russian political conflict and the natural gas crisis the EU is enduring. Furthermore, hydrogen is an infinite and flexible asset that represents an opportunity for renewable energy storage and transport. However, there is a lot of uncertainty surrounding this commodity; the hydrogen demand depends on the hydrogen availability which depends on the demand.

This report aims to forecast the green hydrogen demand of the EU by 2050. In order to do so, the potential hydrogen applications and their decarbonization alternatives are studied and then, a model is implemented in the software Vensim to calculate the demand. This report estimates hydrogen will penetrate applications like ammonia, steel and olefin production, refineries, industrial heat and the shipping and aviation sector due to the decarbonization targets of the EU. For these applications, it is assumed the gradual implementation of hydrogen into the energy system will mimic the s-shaped growth curve of the bio-fuel share in the road transport sector. The total hydrogen demand will suppose a reduction on the hydrogen price due to economies of scale and learning by doing, implemented using a learning rate. This hydrogen reduction will push the penetration of hydrogen in the road transport sector, where the final consumer can only be encouraged but not forced to switch towards a more sustainable alternative. The total cost of ownership of different vehicles is estimated considering both vehicle and fuel costs and a switch towards the less expensive alternative is expected by the consumer. Finally, a sensitivity analysis based on the variables that might affect the hydrogen price is performed.

As main results this report gives an answer to the demand of green hydrogen divided by sectors by 2050, the future price of green hydrogen and the effects of the hydrogen price on the demand of the road transport sector.

Key words: Hydrogen demand, Green hydrogen, Forecast, Hydrogen price

To my family and friends.

Contents

1 Introduction

1.1 Motivation

Climate change is a worldwide concern which has been gaining importance over the last decades. The Earth's temperature is rising, the glaciers are melting, oceans are increasing in temperature and rising in level and the weather is getting more extreme increasing droughts, severe storms and heat waves. As a consequence, the breeding, development and feeding of wildlife is altered, decreasing the survival rate which is driving some wild species to extinction. As for human life, climate change increases health risks, food crisis and thus, poverty.

According to the European Commission, greenhouse gases (GHG) are the main drivers of climate change and, specifically, carbon dioxide (CO_2) produced by human activities, whose concentration has risen to 48% above its pre-industrial level, is the largest contributor [1]. The European Union (EU) contributed to climate change with more than 3.3 $Mtonnes$ of GHG emissions in 2019 [2], around a 10% of the global GHG amissions [3]. In 2016, the Paris Agreement was signed among others by the EU countries, setting a global framework to fight against climate change and global warming by applying national action plans to decrease emissions. Consequently, in line with the objectives of the Paris Agreement, the European Council, taking note of the European Green Deal, endorsed the objective of achieving a climate-neutral EU by 2050 [4].

Some sectors like international aviation and maritime transport are not part of the Nationally Determined Contribution (NDC) of a country, a climate action plan to reduce emissions and adapt to climate change. The difficulty of allocating these sectors' emissions correctly arises the necessity of a global plan to address a GHG strategy. The International Maritime Organization (IMO), which coordinates 175 member states including all of the EU, expressed its ambition of achieving a 40% reduction of GHG emission levels by 2040 compared to 2008 levels and a 50% reduction by 2050, pursuing efforts towards 70% [5]. On the other hand, the International Civil Aviation Organization (ICAO) and its 193 member states consolidated a statement which reiterated its two global aspiration goals towards a more sustainable international aviation sector: a 2% annual fuel efficiency improvement through 2050 and carbon neutral growth from 2020 onward [6]. Also, the International Air Transport Association (IATA) estimated a net-zero scenario for aviation by 2050 based on sustainable aviation fuels (SAF), new technologies, efficiency improvements and carbon capture [7].

The decarbonization of the energy system is an ambitious target that can not be achieved by maintaining a business as usual scenario; the EU needs a radical change. Although the electrification of the system might contribute to reducing GHG emissions by using sustainable sources, in some sectors it simply can not be applied. Power-to-hydrogen represents an alternative for those hard-to-abate sectors where electrification is not an option, or as a way to store the green electricity produced during strong gusts of wind or elevated solar radiation periods. The EU sees potential in hydrogen and it developed a strategy with an emphasis on the need of an investment agenda, a boost of the demand to scale up the production, the design of a supportive framework and the research and innovation in hydrogen technologies [8]. In parallel, some member states have developed their own national hydrogen strategy as detailed in Table 1.1.

Table 1.1: Hydrogen strategies from EU members

EU member	Document	Release date
Austria	Hydrogen Strategy for Austria	2022
Belgium	Federal Hydrogen Vision and Strategy	2021
Czech Republic	National Hydrogen Strategy of the Czech Republic	2021
Denmark	The Government's Strategy for Power-to-X	2021
Finland	National Hydrogen Roadmap for Finland	2020
France	National Strategy for the Development of Decarbonised and Renewable Hydrogen in France	2020
Germany	The National Hydrogen Strategy	2020
Hungary	National Hydrogen Strategy	2021
Italy	National Hydrogen Strategy Preliminary Guidelines	2020
Netherlands	Government Strategy on Hydrogen	2020
Poland	Polish Hydrogen Strategy until 2030 with an Outlook until 2040	2021
Portugal	Portugal National Hydrogen Strategy	2020
Spain	Hydrogen Roadmap – A Commitment to Renewable Energy	2020
Sweden	Proposal for a national strategy for fossil-free hydrogen, electric fuels and ammonia – Swedish Energy Agency	2021

Refineries (49%), ammonia production (31%) and other chemicals (13%) are the main consumers of hydrogen in Europe nowadays [9]. In the EU, around 5.8 $Mt_{H_2}/year$ are consumed and most of it is grey hydrogen or hydrogen produced using fossil fuels liberating 9-20 kg_{CO_2}/kg_{H_2} [10]. Employing carbon capture in the conventional production process of hydrogen, or blue hydrogen production, could result in the reduction of emissions to 0.18-6.10 kg_{CO_2}/kg_{H_2} assuming a range of 99.8% and 68% capture rate. By switching the production process to electrolysis using renewable electricity, or green hydrogen production, the emissions are eradicated.

Apart from the obvious decarbonization advantages of green hydrogen, another benefit is to be considered: green hydrogen has the potential to reduce the EU imported energy dependency. Currently, the EU is highly dependent on imports of fossil energy. Oil products and natural gas represent around the 45% and 30%, respectively, of the total energy consumption in Europe including electricity and heat production [11]. Europe produces 3,413, consumes 14,896[1], imports 14,867 and exports 3,159 thousand barrels of oil a day. The lack of oil reserves forces Europe to rely on crude oil and refined product imports sourced mainly from Russia (35%), Middle East (19%) and other CIS (10%). Something similar occurs with natural gas, Europe produces 234, consumes 554, imports 353 and exports 8 billion cubic meters of natural gas. Including LNG and pipeline trade movements, 53% of the natural gas is imported from Russia [12]. This

[1] out of which 85% are consumed by the EU

high dependency on imports has negative consequences for the EU like price volatility or scarcity when international events occur. A recent example is the conflict between Russia and Ukraine, where due to political differences Russia is reducing gas deliveries to Europe that might end up with a complete gas supply cut. An alternative energy source is needed in Europe and hydrogen might be the option.

In some reports, the aplications where renewable hydrogen might penetrate are classified in no-regret sectors, no lock-in sectors and game-changing sectors [13]. No-regret sectors represent those alternatives where the decarbonization can not be fully achieved through electrification, and includes ammonia and olefin production, refineries, iron and steel sector, aviation and navigation. No lock-in-sectors include alternatives like heavy duty road transport and high-temperature heat, which can be decarbonized through both electrification or the implementation of hydrogen but it is not clear which alternative is more cost-effective yet. Finally, game-changing sectors include applications that can be decarbonized more effectively through electrification but where hydrogen can not be totally discarded, like light duty road transport and heating in buildings.

The penetration of green hydrogen in the energy system is still uncertain since there have been previous waves of enthusiasm but none of them translated into a scaling up of hydrogen demand [14]. Some reports describe a structural paradox since the consumption of power-to-hydrogen products depends on their availability and their production depends, at the same time, on the demand [15]. However, on this occasion, green hydrogen and derivatives are supported by most of the governments of the EU members (see Table 1.1), industrial and transport companies, engineering and consultancy firms among others. So far, the EU and member states are developing more than 500 green hydroen projects with a total estimated capacity of 30 $Mm^3_{H_2}/h$ [16].

1.2 Goals of the Master Thesis Project

This thesis aims to tackle questions about the green hydrogen demand of the EU. This commodity is surrounded by a huge uncertainty but the decarbonization targets of the EU and international transport associations, as well as the natural gas crisis both clear the pathway for the penetration of green hydrogen. This report focuses on the research of possible applications of hydrogen and different alternatives that can be implemented to decarbonize them. Furthermore, considering hydrogen will penetrate certain sectors in order to fulfill the decarboniztion goals previously mentioned, a model is implemented in the software Vensim to forecast the price of hydrogen and how this will impact on the hydrogen demand from other sectors where citizens can be encouraged but not forced to switch to a more sustainable option. As a summary, these are the project research questions that this report tries to address:

- In which potential applications of green hydrogen will it penetrate? To what extend? In which form?
- How much green hydrogen will be demanded in the future in the EU?
- What will be the green hydrogen price?

- How will the price of green hydrogen affect the hydrogen demand from the road transport?

1.3 Project structure

In order to solve the research questions, this reports focuses on both the demand an production of green hydrogen. The hydrogen demand analysis begins in chapter 2 with the study of the potential applications of hydrogen and the investigation of their decarbonization alternatives. After reviewing the strengths and weaknesses of these alternatives, a critical reflection on the penetration of hydrogen in each sector is presented in chapter 3. Then, in chapter 4, a further analysis the individual sector development is made and model assumptions are established in accordance. Throughout chapter 5 the hydrogen production process is described explaining the different electrolysis technologies. Additionally, potential cost reductions on hydrogen production are defined by a learning rate. Furthermore, model assumptions on hydrogen cost are stated. In chapter 6, the model implementation considering all the previous model assumptions is explained. The important results extracted from the model are presented in chapter 7 and a sensitivity analysis is carried out based on variables that might affect the model outcome. Finally, chapter 8 gives an answer to the previously stated research questions.

2 Decarbonization alternatives for potential hydrogen applications

Hydrogen can be used directly as a fuel for combustion or fuel cells and as a feedstock for synthetic fuels. Furthermore, it is also used for the hydrogenation of fossil and bio-fuels. Across the EU, hydrogen is mainly used as a feedstock in refineries and ammonia production but it is mainly produced using fossil fuels; a switch towards green hydrogen can decarbonize these sectors. Furthermore, renewable hydrogen represents an alternative for a deeper decarbonization of the energy system, specially for hard-to-abate sectors or applications where electrification is not possible.

Throughout this chapter, the main applications where green hydrogen might play a key role in the future are presented. After a brief summary of the applications' current GHG emissions, different alternatives for their decarbonization, including hydrogen and derivatives, are explained. Finally, some facts about the leader companies or organizations of each application and their decarbonization strategy are stated.

2.1 Ammonia production

Ammonia is a chemical compound which is mainly used to produce fertilizers, chemicals and explosives but it can also be potentially used as fuel in the shipping sector. It is obtained through the Harber-Bosch process where hydrogen is manufactured first and then used to synthesize the ammonia. In the EU most of the ammonia is produced by using natural gas as a feedstock (2/3 of the total fuel use) due to its hydrogen content, and as an energy source (1/3 of the total fuel use) [17]. Ammonia production is an energy intensive process that requires 8 MWh per tonne of ammonia, out of which the 90% is used for hydrogen production [18]. In 2019, this process accounted for more than $20Mtonnes$ of GHG emissions in the EU [2]. Given that ammonia production is already a hydrogen-demanding sector, by switching to another route for hydrogen production, its emissions can be neutralized [19].

Copenhaguen Infrastructure Partners (CIP) announced plans to build the biggest green ammonia plant of Europe in Denmark consisting in 1 GW of electrolysers [20].

2.2 Olefin production

Olefins or alkenes are petrochemical derivatives used as solvents, chemical intermediates or as feedstock in the production of plastic. The main olefin products are ethylene, propylene, butadiene and C4 derivatives [21]. These chemicals are produced by hydrocarbon cracking in steam crackers, which use different fossil fuels as feedstock and energy source. Naphtha (67%) and propane (20%) represent the main cracker feedstocks [22]. Europe is said to source around 50% of its naphtha from Russia and, since the Ukraine-Russian conflict began, the purchases have sharply fallen [23]. This clears the way for different alternatives that can help decarbonizing the olefin production process while detaching from the Russian market:

- Decarbonizing the feedstock of the cracking process through biofuels or synthetic fuels can allow business as usual in the sector. Bio-naphtha can be obtained by the Bio-Synfining process [24]. Synthetic- and bio-naphtha are produced during the processing of renewable feedstocks in processes such as Fischer Tropsch fuel production [25][26].

- Electrifying the process heat can, in principle, reduce the total emissions of the cracking process. However, some studies estimate that by using renewable electricity, the total emissions of both conventional steam crackers and fully electric steam crackers are reduced by a 30%, so the electrified steam cracker never results in reduced emissions compared to the conventional process due to the usage of naphtha as a carbon source [27]. Also, since steam crackers are highly integrated, the electrification of the cracking furnaces would reduce the demand of fuel gas on site and, because the fuel gas (methane) is a by-product of the cracking process itself, excess unused fuel gas would be generated loosing the integration value of the process [28].

- The methanol-to-olefin (MTO) method is currently used in many locations in China[1] but it has not been commercially deployed in Europe yet [28]. To reduce the emissions of this process, synthetic methanol from green hydrogen and carbon dioxide, or bio-methanol from waste can be applied. The MTO method yields in efficiencies of 54.3% and 50.3% for bio-methanol and synthetic methanol, respectively, compared to the 56.4% of the conventional steam cracker method [29].

- Chemical recycling consists on the use of plastic solid waste for the production of new polymers (solvent purification), new monomers (chemical depolymerisation) or pyrolisis oil that can be used as a feedstock substitute for naphtha in olefin production (thermal depolymerisation). However, there is still a lack of verified environmental performance for the technologies as well as no robust evidence base that can be used to verify claims around the viability of these technologies [30]. Furthermore, in 2028, 55.4 $Mtonnes$ of plastic were consumed and 29.1 $Mtonnes$ became waste in the EU[2]. Out of that waste, 7.2 $Mtonnes$ ended up being landfill, 12.4 $Mtonnes$ were used for energy recovery and 9.4 $Mtonnes$ were recycled. [31]. It is estimated that the amount of chemically recycled plastics is around the 2% of total plastic waste, limiting the feedstock for chemical recycling [32].

- Carbon capture and storage (CCS) can eliminate the emissions from naphtha used as feedstock and energy source. However, the CO_2 emissions sources usually present a concentration of around 12 vol% and, considering existing pipelines

[1] People's Republic of China
[2] plus Norway and UK

typically operate at 95 vol%, these low concentrations limit the capture efficiency [33].

INEOS, the leading European producer of olefins and polyolefins, is taking action for climate change by developing new recycling technologies to produce polymer products from recycled plastic implementing clean hydrogen as a fuel, bio-based feedstock and the carbon capture technology [34]. Neste, one of the largest plastics, chemicals and refining companies in the world, produces several thousand tonnes of bio-based plastics using its bio-based hydrocarbons [35]. These examples show a variety of alternatives but there is not a clear tendency for the decarbonization of the sector yet.

2.3 Refineries

Refineries currently produce and consume vast quantities of grey hydrogen in different processing units for cracking and treating as detailed in Table 2.1. By switching this grey hydrogen consumption to green hydrogen, refineries can reduce the emissions of these processes. However, the grey hydrogen produced as a bi-product would remain unused.

Table 2.1: Hydrogen production and consumption in refineries [36]

Refinery process	Hydrogen production $m^3 H_2/t\ crude\ oil$
Thermal cracking	3
Catalytic cracking	100
Catalytic reformulation	200
Refinery process	**Hydrogen consumption $m^3 H_2/t\ product$**
Hydrocracking	300
Catalytic cracking	80
Hydration of cokers	50
Gasoline hydrotreating	20
Distilates hydrotreating	35

The REFHYNE project in Germany, funded by the European Commission, will supply clean refinery hydrogen for Europe. The plant, operated by Shell and manufactured by ITM Power, will have a peak capacity of 10 MW and will be able to produce 1300 tonnes of hydrogen per year by the end of 2022 [37]. The REPHYNE II project will expand the REPHYNE's electrolyser capacity from 10 MW to 100 MW [38].

2.4 Iron and steel industry

Steel is a highly demanded material used mainly in construction, transport and machinery production. Currently, steel in the EU is produced by two main routes:

- Primary route, traditionally blast furnace and basic oxygen furnace (BF-BOF), which currently represents 60% of total steel-making, refers to the process that uses iron ore as its main metallic source. Usually, iron ore is reduced in a blast furnace (iron-making) and then the iron is melted into steel in a basic oxygen furnace (steel-making) [39]. In this route, carbon is used as a reducing agent for iron ore, as an ingredient of steel (up to 1% in high-carbon steel) and as an energy source [40].

- Secondary route using electric arc furnace (EAF), which accounts for the other 40%, refers to the process that uses scrap (recycled steel) as its main metallic input. In this process, scrap is collected and melted in an electric air furnace [39].

Even-though the EU steel production technology is the most worldwide emission efficient (less than 2000 $kgCO_2/t_{steel}$ for primary route and less than 500 $kgCO_2/t_{steel}$ for secondary route) [39], steel-making accounted for more than 57 $Mtonnes$ of GHG emissions in the EU in 2019 [2]. In order to achieve the decarbonization goals of the EU, intervention in the steel sector is due now given that, according to the European Commission, 2050 is just one investment cycle away. Three alternatives are proposed for the decarbonization of this sector:

- Increasing the share of secondary route production with renewable electricity and scrap steel. This route is limited by scrap steel availability and thus, it is highly dependent on the circularity of steel.

- Implementing an alternative primary route with direct hydrogen reduction (H-DRI) for iron ore reduction and EAF for steel-making.

- Carbon capture and storage (CCS) as a way to continue using the blast furnaces that are the core of current steel-making. However, the multiple sources of emissions and integrated nature of steel plants means that only a small share of emissions can be addressed if carbon capture is applied to the process as currently configured. To solve this, the heavily reprocess gases from both blast furnace and coke oven can be recycled through a combination of CCU and CCS [40]. This recycle process, known as top gas recycling (TGR), entails modifications in the existing BF to allow the re-usage of the reducing agents contained in the blast furnace top gas. In this process, CO_2 is removed from the top gas leaving the BF to recycle the reducing agents: carbon monoxide and hydrogen. This modification reduces the demand for coke and hence the energy demand for this step and associated emissions from the coking plant [41].

AcelorMittal, the biggest steel producer of the EU, announced its European carbon emissions intensity reduction target of a 35% reduction by 2030 and a net zero by 2050. Implementing DRI technology with natural gas as a precursor to green hydrogen, switching the energy carrier from fossil fuels to green hydrogen, circular forms of carbon and increasing CCUS technologies and the use of scrap are some of its stepping stones to achieve climate neutrality.

2.5 Industrial heat

Heat must be decarbonized in order to decarbonize the industry. After all, in 2020 more than 182 TWh of heat, around the 30% of the total heat consumption in the EU, were used by the industry [42]. This translates to 435 $Mtonnes$ of CO_2 or a 16% of the fuel combustion GHG emissions [2]. Usually, the on site combustion of fossil fuels provides the high-flux heat that the industry needs [43] but different alternatives can be used to decarbonize this sector:

- Electric heating is highly efficient, being the conversion of power to heat nearly 100% efficient, and the cheapest alternative [44]. However, efficiency reduces as requirements for higher temperatures increase, and electric heating may necessitate major adaptations in current production processes [45]. Due to this, electrification can be quite promising for lower temperatures but not for high temperature applications, where technology is still at a rather early stage [46].

- Hydrogen is a promising solution to substitute natural gas-based heating but substantial cost reductions are necessary for it to be competitive [46]. Furthermore, hydrogen is the simplest alternative to apply with minimal retrofit in some systems [44]. The addition of hydrogen to natural gas may result in a simple method for emission reductions and development of hydrogen as a heat source that can lead to hydrogen being the only fuel source for providing medium- and high-grade heat [47]. Gradually replacing existing fuels with hydrogen enables the reuse of current infrastructure, thus making immediate action possible [45]. However, applying hydrogen to produce low-temperature heat would result in a large exergy destruction [47].

- Biomass and derivatives are currently the largest source of non-fossil industrial process heat and, since there are many pathways by which the feedstock can be converted into process heat, in principle, biomass can meet most industrial process heat needs [46]. However, bio-energy is not completely carbon-free and its specific carbon footprint can vary greatly as a function of climate, agricultural practice, regrowth rate, conversion, transportation distance and method and macroeconomic displacement effects [48].

- Carbon capture and storage (CCS) can allow for continued use of existing fossil fuel burning equipment but it is expensive and places high requirements on infrastructure for transport and storage of CO_2 [46]. Also, this alternative has the added benefit of capturing emissions from by-product industrial chemistry, which can represent 20–50 % of the facility emissions and can not be captured through heat substitution alone [44].

- Demand side measures like lowering the demand by increasing the efficiency, or increasing the circularity. Excess heat recovery from various industrial processes, power production and commercial facilities has the potential to support local industries, economies and employment. According to [49], the EU has a potential of 300 $TWh/year$ of waste heat, with one third corresponding to a temperature level below 200 °C, which is often referred to as low-temperature waste heat, another 25% in the range 200–500 °C and the rest above 500 °C[3]. It must be taken into account that heat can not be traded as a commodity and has to be produced and used on site [43] making it difficult to reuse by the industry. However, waste heat can also be utilized in other sectors like district heating where it is easier to implement. Some studies report that waste heat could potentially cover at least 25% of the district heat [50].

Unfortunately, there is not a clear pathway for industrial heat decarbonization. A deeper analysis into the different industries and their processes is indispensable before choosing a decarbonization strategy. Regarding the penetration of hydrogen, some studies estimate that by 2050 around 50% and 30% of the natural gas used to produce high- and medium-temperature heat, respectively, will be substituted by hydrogen by 2050, adding up to 217 TWh of hydrogen [51]. Other reports assume that hydrogen will take over all the oil and 40% of the natural gas used to produce heat in the system and 40% of the coal used in the cement industry, resulting in a hydrogen potential of 514 TWh [47].

2.6 Shipping

With around 80-90% of global trade enabled by maritime shipping, the navigation sector is responsible for around a 3% of the annual GHG emissions, accounting for around 9% of global emissions associated with the transport sector [52]. Three technologies can decarbonize the shipping sector:

- Internal combustion engines. Currently, maritime diesel (MDO) and maritime gasoil (MGO) are the most common fuels but the use of renewable fuels can reduce the emissions of the shipping sector. A technical comparison of the different fuels that might be suitable for such purpose can be found bellow, complemented by Table 2.2.

Table 2.2: Internal combustion engine fuel properties

	LHV (MJ/kg)	Energy density (GJ/m^3)	Storage p. (bar)	Storage temp. (C)	Emissions ($kgCO_2/GJ$)
MGO	42.7	36.6	1	120	87
LNG	50	23.4	1	-162	71
Comp. hydrogen	120	7.5	700	20	0
Liq. hydrogen	120	8.5	1	-253	0
SNG	50	35.8	1	-162	71
Ammonia	18.6	12.7	8.6 1	20 -34	0
Methanol	19.9	15.8	1	20	69
FAME Biodiesel	37.1	33.7	1	120	75
HVO Biodiesel	44.0	33.5	1	120	75

[3]mostly in the range 500–1000 °C

- Synthetic natural gas or methane utilizing green hydrogen and captured carbon. Methane has a medium energy density and given it is the simplest combination of hydrogen and carbon in the hydrocarbon series, it produces a low quantity of CO_2 when burnt as seen in Table 2.2. Appropriately, the last 20 years in engine development have seen a strong trend towards fueling with LNG, which could be a precursor to other sustainable alternatives given that current LNG infrastructure could be used. Methane is a greenhouse gas 28 times more potent than CO2 over a 100 years time span and thus, methane slip must be addressed [53]. Furthermore, the optimisation of the engine performance for NO_x and varying and low engine loads may compromise methane slip and, for safety reasons, the fuel tanks must be placed on deck losing deck space [54].

- Green hydrogen, whose combustion offers the great advantage of only producing water vapor, can reduce shipping emissions. Hydrogen's specific energy value is more than twice as high as conventional fuel oil, however, it has a low volumetric energy density even processed to its liquid form as seen in Table 2.2. Liquefied hydrogen needs to be cooled down to -253°C, and even then it occupies several times the volume of LNG. Moreover, the equipment required to hold the hydrogen in its liquid state is large and complex. A total installation of hydrogen would need 6-7 times more space than a conventional one [53]. Also, hydrogen is highly flammable and when compressed or liquefied to increase its volumetric efficiency, safety concerns might appear related to high pressure volume or evaporation losses [55]. Furthermore, due to their small molecular size, hydrogen diatomic molecules permeate through most steel alloys and aluminium, weakening the mechanical structure of the material. Hydrogen is not only able to occupy the interstitial gaps in metallic structures but it is also able to migrate, leading to a slow, yet dangerous, potential source of explosive atmosphere [54].

- Green ammonia contains no carbon and hence no CO_2 is formed during its combustion. Further advantages are that its storage and handling is relatively simple aboard ships, given that ammonia liquefies at a relatively low pressure or temperature as seen in Table 2.2 and, while with an energy density 3 times lower than liquid diesel fuel, storage will be relatively compact. Also, ammonia is globally traded, but its production is not green yet. The main drawbacks of ammonia are its toxicity, although its pungent smell gives ample warming of its presence, the formation of nitrous oxide or laughing gas, with a factor of 270 compared to CO_2 during its combustion and the lack of bunkering infrastructure [53][54].

- Green methanol synthesised from green hydrogen or biomethanol can lead to carbon neutrality. Methanol has a medium energy density compared to conventional fuels and can be stored as a liquid at ambient temperatures and pressures due to its stability (see Table 2.2, so it comes very close to a drop-in fuel that is compatible with existing infrastructure [56]. Thus, while its production as a green fuel is a complex process, its handling costs are low, reducing the complexity of storage and bunkering infrastructure at ports. Also, it requires little to no engine modification. As a disadvantage, it is quite toxic and presents a corrosive behaviour so fuel storage tanks and distribution system equipment must be corrosion and damage resistant. Furthermore, alcohols burn with a flame that can hardly be seen, so it is important to develop rapidly available and easy-to-use thermal imagery for fire visualisation [54].

  - Biodiesel can be used in current engines with minimal engine modifications and it is a drop-in fuel compatible with existing infrastructure which allows the blending with conventional fossil diesel fuels [57]. If available in sufficient quantities, bio-fuels could thus make a significant contribution to the decarbonization in all engine applications, there is however, considerable doubt regarding the availability of these fuels to satisfy the increasing demand [53]. Indicatively, the production of 300 $Mtoe$ of biodiesel based on today's technology requires about 5 % of the current agricultural land in the world [54].

- Fuel cells combined with renewable fuels like green ammonia or hydrogen can eliminate emissions and noise with benefits like reduced maintenance and modular and flexible design [58]. Fuel cell power generation systems require significant support components and ancillary equipment to produce power, and the energy requirement for the balance of plant can be quite high, typically consuming about 20% of the fuel cell output at full load for high-pressure systems and about 10% for low-pressure systems, in order to drive the fans, pumps and compressors. However, the waste heat from fuel cells can be reused for cogeneration bringing the system efficiency up to 85%. Also, the performance of fuel cells decays with time, however, the latest generations have demonstrated lifetime and operating hours that can meet or exceed the stringent marine requirements [59]. Regarding cost, reflecting their largely experimental nature, the capital cost is still high, especially considering the lower technology readiness level of higher efficiency fuel cells that may be most relevant for shipping [54].

- Battery-electric propulsion systems. Batteries have a high conversion efficiency producing no emissions if renewable electricity is used but they offer a very low energy density which makes direct electrification with batteries only applicable in certain niches like coastal shipping or short-rage ferries. Due to the operating and safety requirements of ocean-going vessels, battery-powered systems cannot meet the demands of larger ships, such as container ships, tankers and bulk carriers [53]. Also, marine batteries are currently designed for a 7-10 year lifetime, and this should be extended to over 15 years in order to match the lifespan of a vessel, which can be a challenge for manufacturers. Furthermore, they can degrade relatively fast as they age, especially with increased usage [59]. Batteries still present issues regarding the self-discharging rates, charging times, charging infrastructure and the cargo space needed for them [54].

MAN energy solutions, one of the world's largest designers and manufacturers of marine propulsion systems as 50% of world trade is being moved by MAN engines, expects ammonia and methanol combustion engines to be the main decarbonization technology in the long term [53]. A.P. Moller-Maersk, the world's largest integrated shipping company, is accelerating its climate ambitions and committing to be net zero by 2040 while scaling green and bio methanol production [60]. Regarding short-distance shipping, Norway's ferry fleet, accounted for its first fully-electric ferry in 2015 and since then is moving closer towards an all-electric fleet adding up the world's largest electric ferry in 2021 [61].

2.7 Aviation

CO_2 emissions from aviation have risen rapidly over the past two decades, reaching nearly 1 Gt in 2019, or about 2.8% of the global CO_2 emissions from fossil fuel combustion [62]. In 2019 only in the EU, national and international aviation accounted for 15 $Mtonnes$ and 132 $Mtonnes$ of CO_2, respectively [2]. Different alternatives can substitute the current fossil fuel combustion of this sector:

- Synthetic kerosene or bio-kerosene can substitute conventional kerosene without requiring changes in the infrastructure or aircraft, however, they offer limited reduction of non-CO_2 effects like NOx [63]. Furthermore, when burnt, they do release CO_2 emissions but, since the carbon source for their production is captured, they can be considered carbon-neutral.
- Battery electric aircraft using renewable electricity would eliminate climate impact in the aviation sector. However, it would require new infrastructure due to fast charging or battery exchange systems. Because of the battery weight and the energy storage, for now they can only substitute conventional fuel in short-range flights [63]. Currently, most of the electric aircraft projects are limited to 2 PAX and very short ranges as pictured in Table 2.3, which includes the technical characteristics of the electric and hybrid aircrafts with the largest passenger occupations and longer ranges to date [64].

Table 2.3: Electric and hybrid aircraft projects [64]

Aircraft	Technology	PAX	Range (km)	Entry into service
Zunum Aero ZA10	Hybrid electric	12	1127	2020
Boeing Sugar VOLT	Hybrid electric	135	6482	2030-2050
Eviation Alice	Electric	9	1046	2021
Wright Electric/Easy Jet	Electric	120	539	2027

- Hydrogen powered aviation has the highest reduction potential of climate impact reducing both CO_2 and NOx but it requires a complete change in the infrastructure. Hydrogen has a low energy density so its storage represents a big issue for aviation and revolutionary technology is needed for longer flight ranges. Table 2.4 includes a forecast of hydrogen aircraft technology including technical characteristics and expected market readiness. In genral, the Cost of Available Seat Kilometer (CASK) of all hydrogen aircraft would increase compared to the conventional ones, specially for longer ranges. Furthermore, although both hydrogen fuel cells and hydrogen propulsion systems would reduce the energy demand compared to conventional kerosene air-crafts in short ranges, it would highly increase for medium to long ranges. Hydrogen is interesting for low ranges where the energy consumption of the aircraft can be reduced in exchange of a slightly higher cost, however the technology will not be available until 2030.

Table 2.4: Hydrogen and hybrid aircraft forecast [63]

Aircraft	Technology	PAX	Range (km)	Entry into service	CASK (%)	Energy (%)
Commuter	Fuelcell	19	500	2030	+0-5	-10
Regional	Fuelcell	80	1000	2030-2035	+5-15	-8
Short-range	Hybrid	165	2000	2035	+20-30	-4
Medium-range	Turbine	250	7000	2040	+30-40	+22
Long-range	Turbine	325	10000	2040-2045	+40-50	+42

ICAO aims for sustainable aviation by introducing sustainable aviation fuels (SAFs) like synthetic or bio- kerosene [6]. IATA, in its net-zero scenario, estimates 65% of the aviation will be powered by SAFs powered and another 13% will be electric or hydrogen based [7].

2.8 Road transport

The road transport sector is a strong fossil fuel consumer that produced almost 800 Mt_{CO_2} across the EU in 2019 [2]. With diesel and gasoline being the main contributors, road freight represents a critically hard-to-abate sector. Blended bio-fuels have served as a renewable alternative in a small scale thanks to the implementation of energy directives. However, bio-fuel scarcity is a concern and different technologies can help to decarbonize this sector:

- Battery electric vehicles (BEV) can potentially reduce GHG emissions depending on the grid electricity mix. They are exponentially growing into the market, specifically in the form of cars and motorcycles, and with them, an infrastructure to support them. However, a further development on the infrastructure is needed if the electrical fleet is scaled up. Direct electrification is the most energy efficient technology, resulting in less energy consumption and thus, reducing the energy costs [65]. Furthermore, the simplicity of the electric powertrain induces lower maintenance costs, up to a 20-30% reduction compared to conventional diesel powered vehicles [66]. Nonetheless, these vehicles are still more expensive than conventional vehicles. The main concern of electric vehicles is the battery, including its longevity due to degradation over time and its size and durability, which limit the range. A bigger battery is needed for long-haul trips reducing the available payload, which is really important for parcel trucks [67]. Many reports focus on different charging methods to avoid huge batteries and long charging times. On the one hand, high power charging can reduce the charging time from 2-4 hours to 20 minutes[4] using direct current and more than 100 kW of power [68]. On the other hand, battery swapping reduces the charging time to minutes but it would not be possible for big batteries due to weight and dimension [69]. Alternatively, electric road systems (ERS) allow vehicle charging while circulating but they require a power transfer infrastructure on the road and vehicle adaptation [70]. Nowadays, urban electric cars are more usual in the automobile market due to current battery technology and charging infrastructure limitations although some companies, listed in Table 2.5, are starting to release electric truck vehicles.

Table 2.5: Technical specifications of BEV tractor trucks in the European market

Vehicle	Autonomy (km)	Capacity (kWh)	GVWR[5] $(tonnes)$	Payload $(tonnes)$	Charging time (min)	Availability $(year)$
Freightliner eCascadia [71]	370	440	37	27	90[6]	Today
Mercedes e-actros [72]	300-400	336-448	19-27	10.6-16.6	105[7]	2024
Nikola tre-bev [73]	560	735	37	16	120[8]	Today
Tesla SEMI [74]	480-800	590-990	N.A	N.A	N.A	2023
Volvo FH [75]	300	540	44	N.A	150[9]	Today

- Hydrogen fuelcell electric vehicles (HFCEV) can achieve zero well-to-wheel GHG emissions when using green hydrogen. They share some characteristics with BEV as they utilize the same powertrain components with the exception of the electrical plug, fuel cell stack and hydrogen storage tank, which leads to an identical engine energy demand. However, the difference in battery size and additional conversion losses when converting the hydrogen in the fuel cell to electricity reduces the overall efficiency of HFCEV [65]. They, however, still offer a higher efficiency when compared to conventional fossil fuel vehicles while preserving a similar refuelling time and longer range availability without compromising the payload [67]. The biggest issue for hydrogen vehicles is green hydrogen availability and the lack of refuelling infrastructure. Some reports estimate the infrastructure cost per vehicle per year to be around 4800€ in 2020, decreasing to 3900€ by 2030, [76]. Hydrogen vehicles are still an emerging technology with high costs compared to conventional vehicles but its decarbonization potential, specially for long-haul transport, has raised interest in different companies which have released the HFCEV models defined in Table 2.6.

The penetration of non-pollutant vehicles in the road transport is due now but it is the

[4]Depending on the battery size and other variables
[5]Gross Vehicle Weight Rating
[6]0-80% at best opportunity
[7]20-80% at best opportunity
[8]10-80% at best opportunity
[9]Full charge at best opportunity
[10]Gross Vehicle Weight Rating

Table 2.6: Technical specifications of HFCEV in the European market

Vehicle	Autonomy (km)	Capacity (kg_{H_2})	GVWR[10] $(tonnes)$	Payload $(tonnes)$	Refuelling time (min)	Availability $(year)$
Hyundai NEXO [77]	600	6.3	2.3	0.5	5	Today
Hyundai xcient [78]	400	31.0	36.0	26.5	20	Today
Mercedes GENH2 [79]	1000	80.0	40.0	25.0	15	2023-2027
Nikola two-fcev [80]	1450	120.2	36.0	18.0	20	2024
Nikola tre-fcev [81]	800	66.3	36.0	18.0	20	2024
Toyota Mirai [82]	650	5.6	2.4	0.5	5	Today

final consumer the one who has the power to decide which alternative yields in a higher utility for them. Investment cost, infrastructure readiness, fuel price and availability, range and payload are some of the characteristics that will differentiate the products but also aesthetics and comfort.

3 Critical reflection on sector decarbonization - the penetration of hydrogen

In a fully developed economy, as is the case for the EU, only regulatory policies, new revolutionary cheaper technologies or surprising events like wars or natural disasters will change the already established energy system. Implementing directives or mandates that force the system to fight climate change can stimulate the penetration of renewable technologies into the energy system, including green hydrogen and derivatives. This can be done in a direct way by forcing the companies or industries to decrease their emissions; or in an indirect way by regulating the emission trading system (ETS) through emission cap and trade and CO_2 price. Setting a price on CO_2 has two main advantages: the externalities or costs of damages due to emissions are internalized and it serves as an incentive for economics actors to reduce their emissions and invest in renewable technologies. According to the European Parliament, by 2020 the emissions covered by the ETS decreased by 41% compared to 2005 levels [83]. However, part of this achievement was due to the financial crisis of 2012 that depressed the demand of emission allowances, reducing the price of CO_2. A readjustment with a reduced emission cap was established in 2019 to achieve further CO_2 reductions. From 2021 to 2022 the price of emissions allowances has increased more than a 130% in the EU reaching more than 80 €$/t_{CO_2}$ [84] and this increase is favorable for the penetration of renewable technologies as they become less expensive compared to business as usual technologies.

Considering the decarbonization targets of the EU and international aviation and shipping organizations seen in chapter 1, a shift towards renewables is expected. Green hydrogen is not the cheapest alternative but it offers a good opportunity for the decarbonization of some applications as studied in chapter 2. For this project, it is assumed that the decarbonization and thus, penetration of green hydrogen in ammonia and olefin production, refineries, steel sector, industrial heat, shipping and aviation sector will be supported by directives and policies. However, citizens are exempt from directives compliance that can not be force but encourage them through policies to switch to a more sustainable option. The penetration of hydrogen in road transport will thus, depend on the individual utility function of private consumers.

This reports assumes a switch to green hydrogen in those applications which are already hydrogen-demanding like ammonia production and refineries. For the potential applications of hydrogen, an individual analysis is done next.

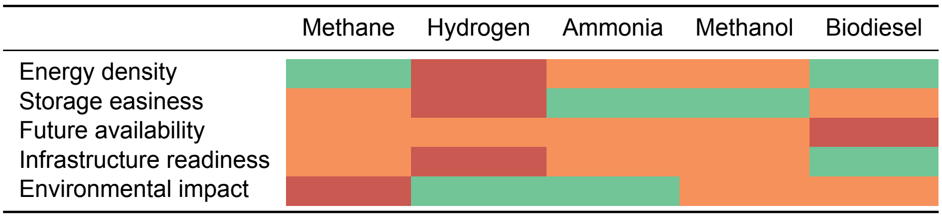
Olefin decarbonization presents different alternatives. However, this report expects the decarbonization of the feedstock to be the decarbonization technique in the long term given that using synthetic or bio- fuels can neutralize the emissions and, in some cases it would allow business as usual with no further investments. The methanol-to-olefin method is promising but it needs a radical change in the production process. On the other hand, electrifying the process heat would require extra investments that would yield the same emission reduction than switching to renewable electricity in conventional steam crackers. Chemical recycling would reinforce the circularity of plastic, but with current plastic recycling rates, the feedstock would not be enough and this route's contribution to the overall olefin production would be negligible. Finally, carbon capture is discarded since its efficiency is reduced at low concentrations, as is the case for olefin production.

In the steel industry, secondary route will experience a growth limited by scrap availability, increasing the sustainability and circularity of steel. Primary route will remain to be one of the main production routes, implementing DRI-EAF technology as a substitute for the conventional BF-BOF. Carbon capture might play a role but given the multiple sources of emission in the steel production process, modifications in the existing BF would be needed.

Industrial heat is a broad application that involves several processes with different characteristics and heat needs. A deeper study into the individual industrial process in suggested to determine which decarbonization alternative would be more suitable for each application. This report expects all the alternatives studied in section 2.5 to penetrate this application. Electrification will play a key role in this sector due to its efficiency and low price, specially for lower heat temperatures. However, given that electric heating efficiency decreases for higher heat temperatures, the combustion of different renewable fuels represents a better alternative for this purpose. Specifically, green hydrogen will play a key role substituting natural gas in high temperature process heating due to high calorific value, the possibility of blending with natural gas and the reuse of current infrastructure.

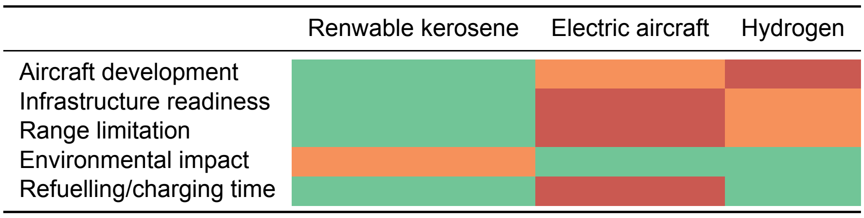
With respect to shipping, fuel cells or battery electric vessels might represent a decarbonization option for short shipping, but this report assumes only electric batteries will take over this small sector. However, long shipping fleet will be dominated by internal combustion engines. Different renewable fuels can be burned in combustion engines to reduce emissions. Biodiesels present the same energy density as conventional fuels and they could use current infrastructure, however they are highly demanded by other sectors and thus, scarce and expensive. SNG or biomethane represent an alternative since LNG is already being used in the shipping sector but there is a risk for methane slip. Green hydrogen most probably wont penetrate the sector due due to its low energy density and storage dificulty. Ammonia and methanol are drop-in fuels with high stability that allow easy storage, both are globally traded so there is an existing transport infrastructure and can neutralize emissions if renewable. After realising a technical comparison between the different renewable fuels, summarized in Table 3.1, this report concludes that green ammonia an renewable methanol will take over the international shipping sector.

Table 3.1: Internal combustion engine fuel technical comparison for the shipping sector



Aviation institutions expect SAFs to be the main decarbonization actors. Synthetic kerosene or bio-kerosene need few retrofit in current infrastructure and aircrafts while offering the same range and refuelling time. It is the addition of all of these characteristics what will push renewable kerosene to have the biggest share in the aviation sector, being specially important for long and medium range aviation. On the other hand, short range aviation can be decarbonized using green hydrogen, which is a drop-in fuel that allows for more autonomy, if not enough renewable fuels are available in the future. Regarding battery electric aircrafts, they will appear in small aircrafts with very short ranges but its contribution to the overall energy consumption will be negligible due to battery limitations and charging constraints. Table 3.2 shows a summary of the main characteristics of the different technologies that lead to the assumptions above.

Table 3.2: Technological comparison for the aviation sector



Regarding the road transport sector, the European Parliament announced their plan to ban internal combustion engines from 2035 eliminating petrol and diesel fuels as alternative for new purchases[1] [85]. The decarbonization alternative, however, still depends on the customer preferences. Given the difficulty of assessing aesthetic inclinations, this report focuses on the technical aspects, presented in Table 3.3.

Urban vehicles are expected to drive less distances and, considering the classification of Table 3.3, both BEV and FCEV represent a good alternative but more infrastructure is needed if their penetration into the market is scaled up. At the same time, heavy duty long haul trucks are expected to drive long distances and thus, require a higher range of autonomy. This is not a problem for HFCEV but represents an issue for BEV. Considering a 800 km autonomy electric truck with an average consumption of 1.15 kWh/km, the battery size needed is around 1150 kWh [76]. In some reports, the battery

[1] with some exceptions

Table 3.3: Technological comparison for the road transport sector

	BEV urban	FCEV urban	BEV truck	FCEV truck
Autonomy				
Refuelling/charging time				
Payload limitation				
Infrastructure availability				
Environmental impact				

density of 250 Wh/kg of the Tesla Model S is used to estimate truk battery weights [86]. Considering this same density, a 1150 kWh battery would need around 4.6 tonnes of battery cells, increasing the vehicle cost and the curb weight and thus, reducing the payload and truck efficiency. As an alternative, the truck autonomy could be reduced but that would mean increasing the refuelling time during the working hours of the drivers. Although it is true that drivers must stop for 45 minutes every 4.5 hours of driving [87], it would take almost 5 hours to fully refuel a truck with the above characteristics using a 240 kW charger. ERS can be a solution, but only for certain applications where routes are predictable. For these reasons, BEV are not contemplated as an alternative for heavy duty road transport.

4 Sector analysis and base model assumptions

Along this chapter a deeper sector analysis of the future applications of hydrogen described in chapter 3 is made. A growth tendency is defined and accordingly, different model assumptions are established to determine the future green hydrogen demand.

4.1 Ammonia

The analysis of the ammonia market is carried out, as a simplification, as the analysis of fertilizer market given that fertilizer production represents more than the 80% of the total ammonia consumption in the EU [17].

Fertilizers are used to provide nutrients for crops but, after applying them to the agricultural soil, ammonia is then released into the atmosphere. By contrasting the total ammonia emissions from agriculture (t_{NH_3}) and the average ammonia emission per area (kg_{NH_3}/ha) obtained from Eurostat [88], the total agricultural area is obtained and displayed in Figure 4.1. There is a strong correlation between the agricultural area and the ammonia emissions from agriculture, which is also linked to the ammonia consumption. It can be assumed that future ammonia consumption mimics the agricultural area growth tendency.

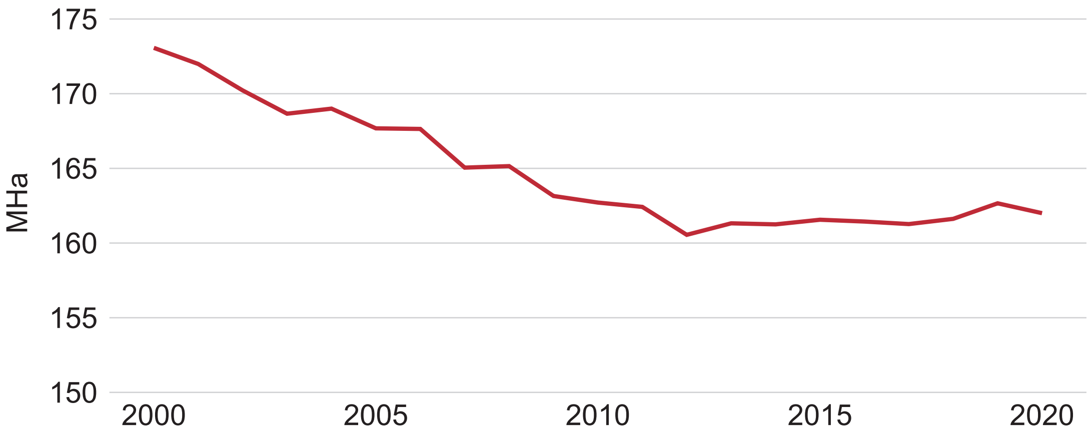


Figure 4.1: Estimated agricultural area based on ammonia emissions

The food industry in the EU is a resilient sector barely impacted by the crisis. While in developing countries like China[1], an increase in GDP would end up triggering food consumption [89], it is not the same case for developed economies. The EU food market highly increased in the past and is now ”stagnated” as seen in fig. 4.1, probably

[1] People’s Republic of China

because it produces more than it consumes and all the population has easy access to crops. Thus, smaller increases in population or GDP will not affect the general crop production and consumption. The European Commission estimates that the growth in the EU production of arable crops is expected to be limited due to land competition; the expansion of forest and pasture areas will limit the available land for arable crops [90]. This lack of growth affects ammonia consumption, which is expected to follow the same trend.

Two events might seem to affect the future of ammonia consumption: the increasing demand for bio-fuels which can be crop-based, and the penetration of ammonia in the shipping sector, which is studied later in section 4.6. Regarding bio-fuels, the EU has limited space for bio-fuel crop production because of indirect land use change (ILUC) limitations, which try to avoid producing bio-fuel crops on existing agricultural land for food supply, as this necessary production would be relocated taking over the space of a former forest for example, leading to a non-CO_2 reduction [91]. Due to this, the increasing demand of bio-fuels will not be covered with more agricultural area and ammonia consumption will not be affected.

Taking all of this into consideration, the following assumptions are implemented into the model:

- Europe has a production capacity of 19.1 $Mt_{NH_3}/year$, mainly dedicated to fertilizer production, that are going to remain constant [51].
- Ammonia demand might increase due to its penetration in the shipping sector but it is not addressed as ammonia production but as shipping demand.
- 177 kg_{H_2} are needed to produce 1000 kg_{NH_3}
- According to chapter 3, green hydrogen will substitute grey hydrogen in ammonia production aiming for its decarbonization by 2050.

4.2 Olefin production

Olefins are used as raw material for plastics, synthetic fibers and rubber so their demand is driven by the consumption of these products. This report focuses on the demand of plastic products to analyse the future demand of olefins.

The plastic consumption is highly correlated with the GDP of a country and, even though its global consumption is far from its maximum, most mature economies appear to be exhibiting some signs of saturation around the 60 kg of plastic per capita, being the EU at around 70 kg of plastic per capita [92]. In fact, besides being the global forecast to double plastic consumption by 2036 and to quadruple it by 2050, some studies expect Europe to reduce its plastic production around a 20% [93][92]. This assumption is in line with the European strategy for plastics, which aims for a circular economy of plastic promoting reusing, recycling and pursuing a lifestyle which minimises the use of plastic reducing its impact on the environment [94].

Currently and according to Petrochemicals Europe, the main olefins produced in Europe are etylene, propylene, butadiene and benzene. As seen in Figure 4.2, olefin production has been quite stable during the last decade with a slightly decreasing tendency accentuated by the COVID-19 pandemic in 2019. This stability could represent and the plastic strategy of the European Union and the consumption saturation some reports talk about.

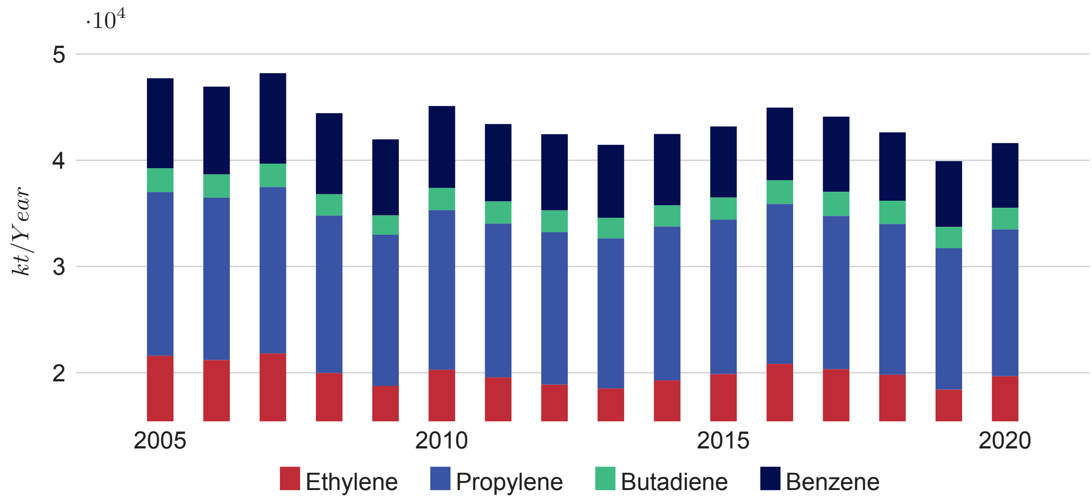


Figure 4.2: EU olefin production by olefin type [95]

The next assumption are considered for the model implementation after analysing the olefin sector:

- The initial value of olefin production is calculated as the average value of the last decade: 41495 $kt/year$.
- Olefin production will decrease a 20% by 2050 in connection with plastic forecasts. A linear progression is assumed.
- As a simplification, all of the fuel used in steam crackers is considered to be naphtha.
- The decarbonization of the sector will be based on bio- and synthetic naphtha with the same share.
- 1.66 t of naphtha are required to produce 1 t of olefins.
- 0.78 and 5.85 MWh of hydrogen are necessary to produce 1 t of bio- and synthetic naphtha, respectively [51].

4.3 Refineries

Refineries transform crude oil into petroleum products through different processes. As seen in Table 2.1, these processes are producers and consumers of hydrogen. However, the net balance of a refinery cannot be calculated from the petroleum product production volumes alone but additional information on process characteristics [36]. Given that current hydrogen consumption from refineries and refinery output data are available, as a simplification, it is considered that there will be a linear correlation between these two parameters in the future.

Knowing this relation, oil products demand is needed as an input to estimate hydrogen demand from refineries. According to IEA, almost a 65% of the oil products are consumed by the transport sector in Europe, but other sectors like industry and residential are also relevant [96]. Considering current decarbonization targets of the EU, fossil fuel demand will suffer a huge impact, decreasing the overall demand of products and thus, the hydrogen demand. However, the estimation of oil product demands in the future would require a rigorous study of all the energy activities of the European energy system which is outside the scope of this project.

As deduced from Table 4.1, the EU imports crude oil that uses as a feedstock in refineries for petroleum derivatives manufacturing which are later mostly exported. This means that the EU covers its demand from petroleum products using the imported final product. As a consequence, the reduction of the petroleum products demand due to the decarbonization can lead to different outcomes: a reduction in crude oil imports or a reduction in the final product imports. Considering the EU current business model, this report assumes a reduction on petroleum products inside the EU will not affect the refinery activity; the EU will remain to import crude oil and export the final petroleum product to third countries.

Table 4.1: Oil balances from the EU in 2019 [97]

	Total (PWh)	Crude oil (PWh)
Oil imports	9.95	5.97
Oil exports	3.82	0.04
Refinery input	6.71	6.11
Refinery output	6.66	-

As a summary, these are the assumptions considered for the model:

- The EU will continue business as usual importing crude oil to export the manufactured petroleum products.
- The reduction on petroleum products demand within the EU will not affect the refinery activity.
- Hydrogen demand from refineries will remain constant throughout the studied period.
- Grey hydrogen demand from refineries is estimated to be 4.8 $Mt/year$ [98].

- As seen in chapter 3, green hydrogen will substitute all the grey hydrogen in the refinery sector.

4.4 Iron and steel

Steel is a crucial material for several applications like construction, automotive and mechanical engineering appliances. Furthermore, steel is a key component to produce the renewable energy technologies required for the energy transition such as wind and solar power. In fact, more than 80% of a wind turbine is made out of steel [99]. Its applications and technical characteristics demonstrate how crucial of a material steel will be in the future. Some reports estimate steel production will increase at a rate of 0.6% per year up to 2040, moment where the production will be stabilized [40].

The EU recycles around the 85% of the end-of-life steel so it is a highly circular material [41]. With an increase on steel production comes an increase on scrap availability which, paired to scrap export reduction, will increase the secondary route share [100].

After analysis the steel sector, these are the assumptions that will be implemented in the model:

- Steel demand in 2019 was about 170 Mt [40].
- Steel demand will increase a 0.6% yearly until 2040, when the demand will saturate [40].
- Secondary route share will increase from 40% to 50%, limited by scrap availability [51].
- According to chapter 3, the decarbonization of the primary route will come with the switch to HDRI-EAF.
- 50 kg_{H_2} are required to produce 1 t of steel by the HDRI-EAF route [101].

4.5 Industrial heat

Industrial heat is a difficult sector to asses due to the high variety of industrial processes. The heat temperature required changes from paper production at 100ºC, to chemical industries that require temperatures over 600ºC, to the cement industry where the heat temperature has to reach 1500ºC [102]. Some studies estimate that 12%, 21% and 67% of the total heat demand in the European Union corresponds to, respectively, low-temperature (<100ºC), medium-temperature (100-500 ºC) and high-temperature heat (>500ºC) based on the heat shares of the German industry [102]. Unfortunately, there is no data set that links the heat temperature with the source used to produce that heat. This lack of information makes it impossible to find the best decarbonization source for heat production in each industrial process. Also, some industries require specific heat sources since they use part of the components as feedstock as well, as is the case for steel production.

Eurostat does offer two data sets containing the total heat consumption by sector and the gross heat production by source in the EU [42][103]. However, there is not a connection between sector and source, so this report relies on the following assumptions and hypothesis for this part:

- The industry sector has been consuming a constant average of 180 TWh of heat [42] and as an hypothesis so will be until 2050.
- Out of the total gross heat production, 36% is produced burning natural gas, resulting in 175 TWh [103].
- As an hypothesis, 50% of the natural gas is dedicated to produce industrial heat that will be substituted by green hydrogen by 2050.

4.6 Shipping

The analysis of the shipping sector is going to be divided in two parts: international navigation, which is going to be represented by the maritime bunkers of the EU, and national navigation.

International shipping is a sector difficult to asses within a country or region. Vessels with one flag might navigate in a different country or even continent, refuelling in their international bunkers, which makes it impossible to allocate their emissions. That is why international navigation is not part of the NDC of a country and its decarbonization is only possible at a global scale. To address international navigation, this report utilizes the energy consumption from the maritime bunkers of the EU provided by Eurostat represented in Figure 4.3. Although this energy consumption is not exclusively from EU vessels, it does represent the fuel supplied to global shipping by the EU, that will follow a similar decarbonization pathway as the rest of the world.

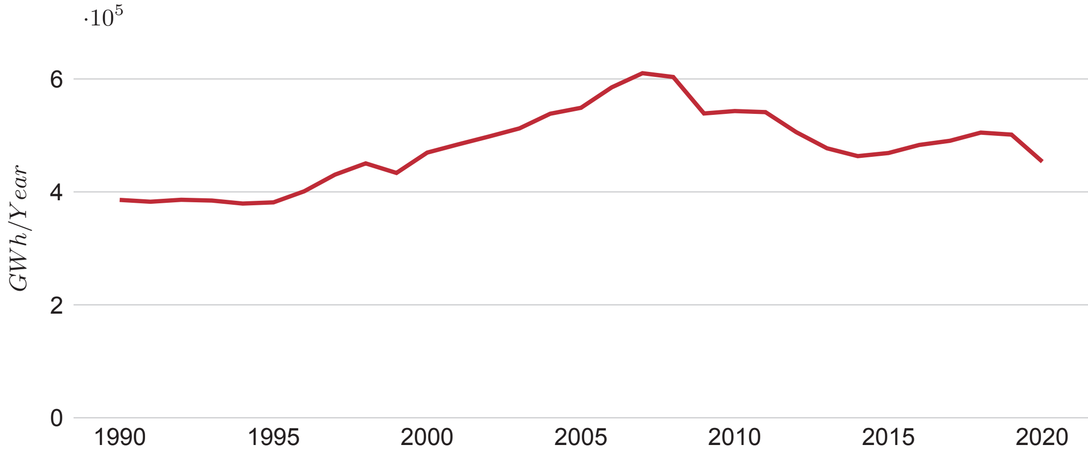


Figure 4.3: Yearly energy consumption from EU maritime bunkers [97]

Three different sections can be differentiated in Figure 4.3: a growing tendency from 1990 to 2009 where international navigation grew highly correlated with the world's GDP, a decreasing tendency from 2009 to 2014, probably because of the global crisis, and a slow recovery from 2014 to 2019 where the COVID-19 hit. Another fact is that while the energy consumption and the number of vessels in the ports was decreasing from 2009, the gross weight of goods handed in all ports increased highly correlated with the gross tonnage of vessels that arrived to port [104][105]. It can be deduced that the energy consumption of a vessel is not linearly correlated with its gross tonnage, and that by increasing the size of vessels, goods can be transported with less energy consumption. This assumption is quite important given that around 75% of EU external trade volumes and 31% of EU internal trade volumes are transported via vessel [106].

Regarding the forecast for 2050, if business as usual is continued and according to IMO, shipping emissions could increase from 90% to as much as 130% of 2008 emissions [107]. However, the organization decarbonization targets aim for a carbon intensity reduction of at least 40% by 2030 and 70% by 2050, relative to the 2008 baseline [5]. This report assumes a linear growth in energy consumption following the tendency from 2014 to 2018 translating into an a 74% increase of energy consumption since 2018 to 2050 paired with a sector decarbonization provided by ammonia and methanol.

A different approach is followed for national navigation, presented in Figure 4.4, which also suffered the consequences of the economic crisis that lead to a reduction in energy consumption. The same recovery period is observed from 2014 to 2018, whose tendency is used to determine the energy forecast for 2050. However, as an assumption, a degrowth coefficient is applied based on a change in the transport system; national navigation passengers will switch to rail or aviation due to faster routes and increased utility. Taking this two aspects into account, the national navigation energy consumption will increase a 98% from 2019 to 2050.

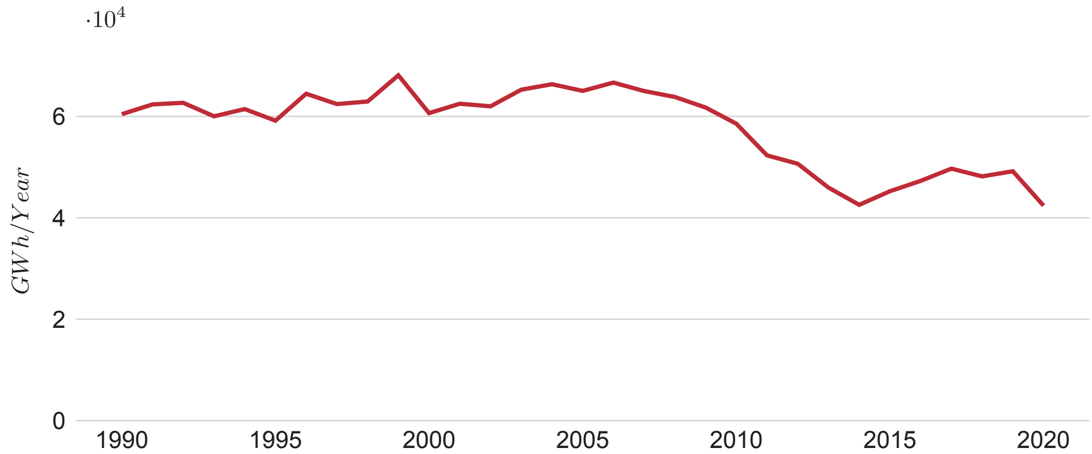


Figure 4.4: Yearly energy consumption from national navigation [97]

Concluding this section, these are the assumption that are going to be implemented in the model:

- International navigation is represented by the maritime bunkers of the EU.
- International navigation energy forecast is to increase 1.79% yearly until 2050.
- International navigation GHG emissions will be reduced by a 70% by 2050.
- National navigation energy consumption will linearly increase until 2050, reaching a 98% growth.
- National navigation will be totally decarbonized by 2050.
- It is assumed that all internal combustion engines (ICE) have an efficiency of 0.45 regardless of the employed fuel [108]
- In accordance with chapter 3, international navigation will be decarbonized employing green ammonia and bio- and synthetic methanol as fuels for internal combustion engines with a share of 50%, 25% and 25% each. National navigation, on the other hand, will be decarbonized through the implementation of electric vessels.
- 2 MWh and 6.3 MWh of hydrogen are necessary to produce 1 t of bio-methanol and synthetic methanol, respectively [51].
- 177 kg_{H_2} are needed to produce 1000 kg_{NH_3}

4.7 Aviation

As it was the case for navigation, aviation is a strong fossil fuel consumer whose decarbonization has to be addressed globally. Eurostat provides data sets about the yearly energy consumption of both domestic and international aviation from the EU, which can be seen in Figure 4.5. The strong development during the last decades, characteristic of this sector, is expected to continue until 2050. Some aviation organizations forecast yearly growing rates from 1.2% (Eurocontrol) to 4.3% (ICAO). This report chooses a conservative side by assuming both national an international aviation will have a yearly growth of 1.2%.

The decarbonization of this growing sector is a concern. However, international aviation organizations like IATA expect a fully decarbonize sector by 2050 while ICAO aims for a sustainability improvement provoked by fuel efficiency and SAFs [6][7]. Considering some European airports already have in view reaching carbon neutrality by 2050, this report will assume a complete decarbonization of the sector by 2050 thanks to the penetration of SAFs and hydrogen.

As a summary, the following assumptions are going to be implemented in the model:

- Aviation energy demand will increase a 1.2% yearly both in the international and domestic levels.
- International aviation will be totally decarbonized by 2050 thanks to the penetration of SAFs.

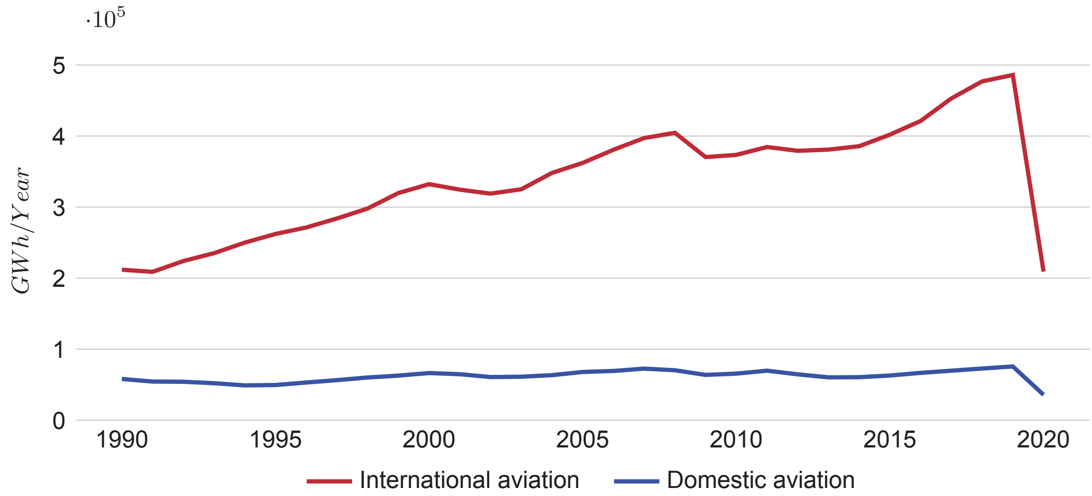


Figure 4.5: Yearly energy consumption from domestic and international aviation in the EU [97]

- Domestic aviation will be totally decarbonized by 2050 thanks to the penetration of hydrogen aircraft from 2030 and SAFs.
- Bio-kerosene and synthetic kerosene production require, respectively, 0.15 and 1.20 MWh of hydrogen to produce 1 MWh of kerosene.

4.8 Road transport

The total energy demanded by this sector can be calculated by multiplying the total energy consumption provided by Eurostat [97] by the tank-to-wheel average efficiency of the vehicles. Natural gas, diesel, gasoline and electric vehicles have, respectively, ranges of efficiency from 14% to 26%, 28% to 42%, 14% to 32% and 50% to 80% [109]. Figure 4.6 shows the total energy demand in the road transport sector divided by energy sources. This energy sector is characterised by an increasing linear tendency only affected by the economic crisis from 2008 to 2013 and the COVID pandemic in 2020, periods where the energy consumption decreases. Given that these events are unpredictable factors, the future yearly growth of the energy demand in this sector can be estimated as the average yearly growth after the crisis.

Since 1990, the GHG emissions by fuel combustion of heavy duty trucks and buses has been approximately a 27% of the total emissions from fuel combustion in road transport [2]. Considering diesel and gasoline, including their bio-equivalents, represent more than the 99% of the total energy demand and assuming a similar distribution of fuels among heavy and light vehicles, it can be stated that the energy demand from heavy duty trucks and buses represents a 27% of the total energy demand.

The cost of ownership of different vehicles is calculated in a simplified manner as the addition of the vehicle cost (CAPEX) and the fuel cost during its whole lifetime (OPEX).

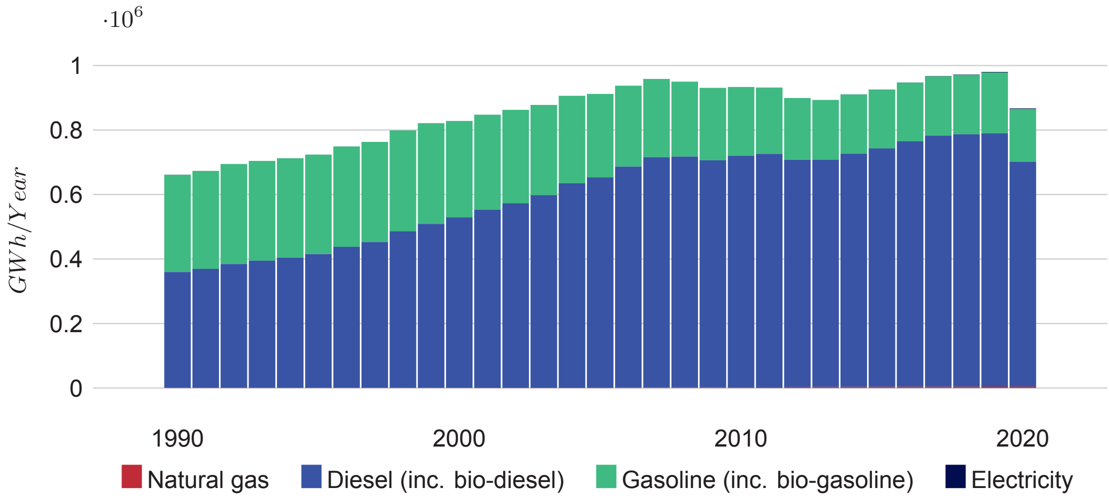


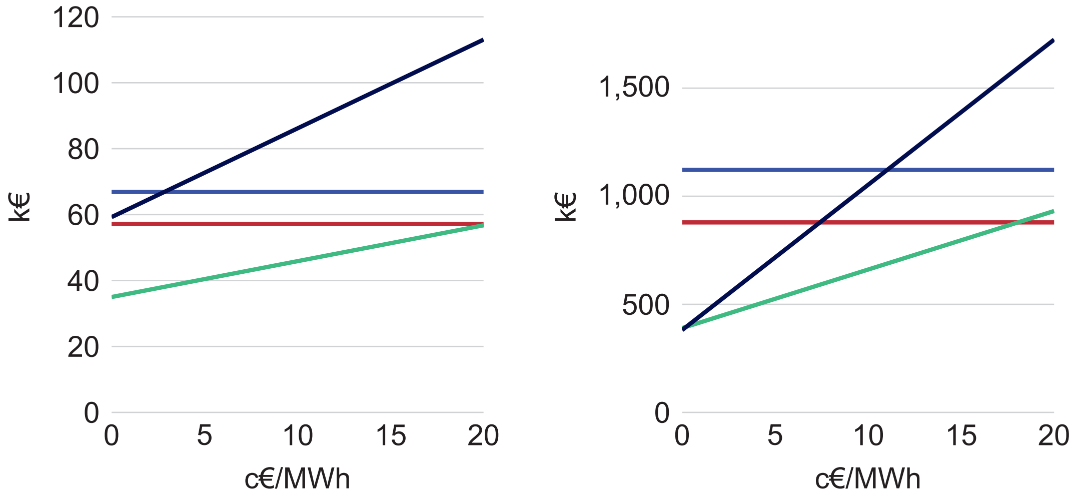
Figure 4.6: EU total energy demand in the road sector divided by source (GWh/year)

The vehicle energy consumption and vehicle costs divided in powertrain, energy storage and rest of the vehicle are obtained from a previous study [110]. Then, considering a km-lifetime of 0.24 Mkm for urban vehicles and 1,2 Mkm for heavy duty long haul trucks, the total cost of ownership of the different vehicles is calculated depending on the fuel price an displayed in fig. 4.7. These figures show the high relevance of the electricity price in the decarbonization of the road transport sector given its influence on both BEV and HFCEV. It is assumed consumers will choose the cheapest alternative when they purchase a new vehicle.

Regarding the rate of new registration of vehicles for heavy and light duty road transport, heavy duty is represented by buses, trolley buses, motor coaches, trailers and semi-trailers, and light duty is represented by the rest of vehicles. Dividing the number of new registrations provided by Eurostat by the total number of vehicles, the rate of new registration is obtained. For light duty, passenger cars are used as reference given that they represent around the 80% of the total number of light duty since 2004 [111]. Assuming the driving range per vehicle is the same among the categories, the rate of potential switch to another energy source is estimated to be the same as the rate of new registrations.

As a summary, these are the assumptions that will be implemented in the model:

- The energy demand of the road transport sector increases a 1.56% yearly until 2050.
- Heavy duty energy demand share is kept as a 27% of the total demand.
- Consumers will have the opportunity to change their vehicle at a rate of change of 0.5% for light duty and 0.6% for heavy duty.



(a) Urban

(b) Heavy duty long haul

Diesel (1.5 €/l) Diesel (2 €/l) BEV FCEV

Figure 4.7: Total cost of ownership of different vehicles depending on electricity price

- Consumers will change their vehicle, when they have the opportunity, to the cheapest option.
- Urban vehicle options include BEVs, HFCEVs and diesel vehicles, however, the high correlation between electricity price and hydrogen price allows to predict that HCEVs will never be less expensive than BEVs until economies of scale reduce their CAPEX. On the contrary, heavy duty does not present the option of BEV as discussed in chapter 3 but it allows FCEVs penetration.
- BEV and HCEV have an energy efficiency of 65% and while diesel vehicles have an efficiency of 35%.
- Diesel price will be fixed at 1.5 €/l.
- Electricity price for BEV charging will have a 100% increase due to taxes.

5 Green hydrogen production

This chapter addresses the production of green hydrogen. First the production technologies are described and compared. Then, the production costs are studied including a learning rate of the potential cost reduction. Finally, the model assumptions regarding hydrogen production are described.

5.1 Electrolysis

Hydrogen can be obtained using electrolysis, a process that decomposes the water into oxygen and hydrogen using electricity; when renewable electricity is used, green hydrogen in obtained. During the process, a DC electrical power source is connected to two electrodes placed in the water and two reactions are produced: a reduction at the cathode producing hydrogen and a oxidation at the anode producing oxygen. The overall reaction of this process, shown in eq. (5.1), produces double the amount of particles of hydrogen than oxygen.

$$2H_2O(l)\rightarrow 2H_2(g) + O_2(g) \tag{5.1}$$

The device used to produce green hydrogen in called electrolyser. A brief description of the main electrolyser technologies is made bellow, complemented with a technical comparison in Table 5.1.

- Electrolysis with alkaline electrolysers is a simple and mature commercial technology. These electrolysers have other applications with existing supply chain so its production can be scaled up, however they offer a slow dynamic response which makes them less suited for variable renewable energy (VRE) support [10]. Due to the avoidance of precious materials and the maturity of the technology, alkaline electrolysis is characterised by relatively low capital costs compared to other electrolyser technologies as seen in Table 5.1 [14].
- Proton exchange membrane (PEM) electrolysers are already commercial and experimenting a fast growth due to their fast dynamic response. Platinum and iridium are required for their production, which expands the overload range to 160% (see Table 5.1) but limits the annual deployment of this technology [10]. They are relatively small, making them more attractive than alkaline electrolysers in dense urban areas [14].
- Solid oxide electrolyser cells (SOEC) electrolysers are not widely commercialized, but they have been tested in laboratory scale and demonstrated to be well suited for constant base load hydrogen production [10]. They use ion-conducting ceramics as the electrolyte, enabling operation at significantly higher temperatures. Further advantages include a high electrical efficiency, low material cost and the

possibility to operate in reverse mode as a fuel cell or in co-electrolysis mode producing syngas (CO + H2) from water steam (H2O) and carbon dioxide (CO2). A key challenge is the severe material degradation as a result of the high operating temperatures, which provokes a shorter lifetime compared to other technologies as seen in Table 5.1. Thus, current research is focused on stabilizing existing component materials, developing new materials, and lowering the operation temperature to 500–700 ºC (from 650 to 1000 ºC) to enable the commercialization of this technology [112].

Table 5.1: Techno-economic characteristics of different electrolyser technologies [14]

	Alkaline	PEM	SOEC
Electrical efficiency (% LHV)	63-70	56-60	74-81
Operating pressure (bar)	1-30	30-80	1
Operating temperature (ºC)	60-80	50-80	650-1000
Stack lifetime (thousand hours)	60-90	30-90	10-30
Load range (%, relative to nominal load)	10-110	0-160	20-100
Plant footprint (m^2/kW_e)	0.095	0.048	-
CAPEX (USD/kW_e)	500-1400	1100-1800	2800-5600

The feedstock for electrolysis production includes only water and electricity. It is estimated that around 9 l of water are needed to produce 1 kgH_2, obtaining 8 kg of oxygen as a by-product [14]. Regarding the electricity consumption, in order to produce 1 kgH_2, around 56 kWh are needed considering an electrolyser efficiency of 70%.

Two alternatives are possible as a source for the electricity supply for hydrogen production: dedicated renewable electricity or direct connection to the grid. A dedicated plant looks like the optimal option since renewable electricity is needed to produce green hydrogen and, considering the electricity mixes among the EU countries, it can not be provided by the grid. Nonetheless, the investment costs of the overall installation increases and potential optimization of the plant operation might lead to selling the electricity to the grid. The increasing share of renewables in the energy system can produce surplus renewable electricity that can be used to obtain and store hydrogen while balancing the system. However, this would result is a less profitable installation decreasing the high full load hours of an electrolyser installation and thus, reducing the hydrogen output. Direct connection to the grid to provide electricity at low prices can be an enabler for green hydrogen production in the future, since the decarbonization of the system also includes electricity production.

5.2 Production cost

Hydrogen price is one of the main drivers of its penetration in the energy system. On the one hand, the CAPEX of hydrogen production includes the electrolyser system, all the neccessary balance of plant including drier, cooling, de-oxo and de-ionisation equipment, the civil work and the electricity grid connection. On the other hand, the variable OPEX costs involve administration costs, insurance, taxes, maintenance, electricity costs and stack replacement costs. The electrolyser costs make up 60% (PEM), 50% (Alkaline), 60% (SOEC) of the plant CAPEX and are assumed to need replacement every 11 (PEM), 9 (Alkaline), 7 (SOEC) years over a 30-year technology technical lifetime [113].

In the future, the electrolyser price can be reduced thanks to technological learning, which might reduce the overall price of electrolysers due to constant design innovation that leads to cheaper materials for their production, efficiency improvements or a longer lifetime, and economies of scale by increasing the module size and plant installation. All of these potential improvements are considered in leaning curves, which show the declining production costs of a technology depending on the total installed capacity. IRENA, after after analysing the possible cost improvements and performing a survey of the studies that have previously estimated learning rates for electrolysers and fuel cells, determines its own learning curve shown in Figure 5.1.

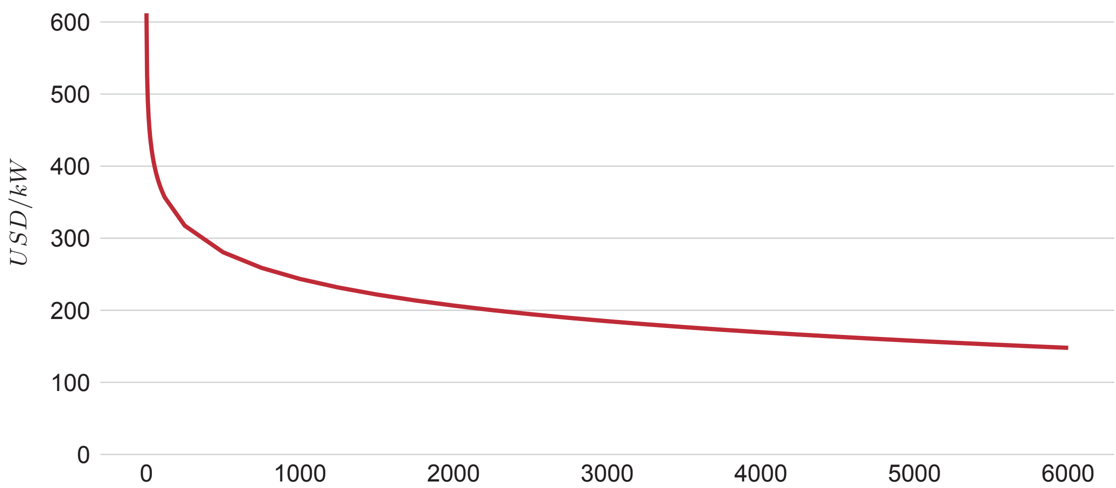


Figure 5.1: Potential cost decrease for electrolysers based on a learning rate [112]

The hydrogen cost is directly correlated to the electricity price. The strong penetration of solar PV and wind energy into the electricity mix can potentially reduce the future electricity prices. Nordic analysis forecast an increase in the electricity price during the first decade due to an increased CO_2 price followed by a decreasing tendency due to renewable penetration [114]. Spanish reports forecast that decarbonization will lead to lower electricity prices due to the fact that although significant investments must be made in emission-free generation power plants and networks, which must be borne by consumers, these costs would be diluted by higher demand resulting in a decrease in the average price per kWh [115]. The results of these two studies are compared in Figure 5.2.

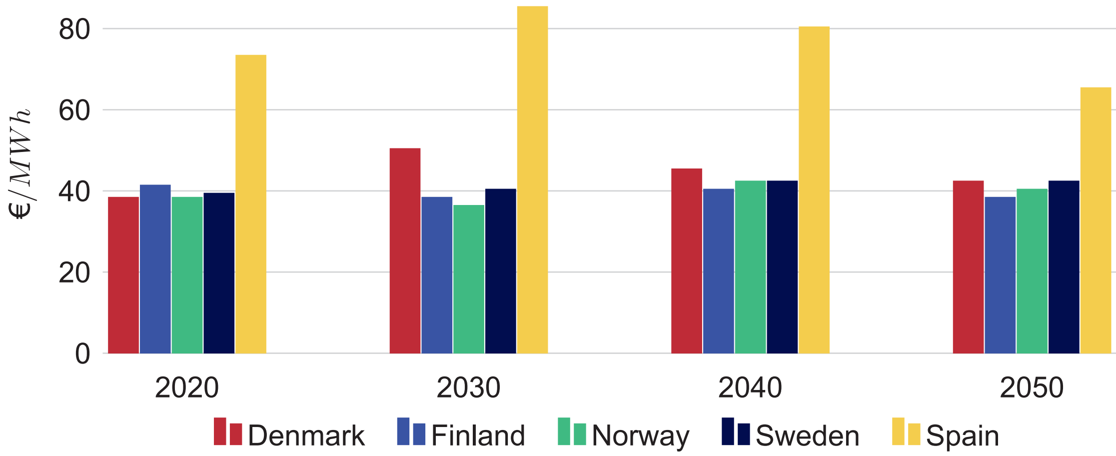


Figure 5.2: Electricity price comparison

5.3 Model assumptions

Based on the last sections, the following assumptions are implemented into the model:

- Hydrogen price will be calculated based on the electrolyser and electricity price as it is done it other reports Equation (6.2),.
- The electrolyser cost will depend on the installed capacity according to Figure 5.1.
- The electrolyser efficiency and stack lifetime in hours are obtained from alkaline electrolysers in Table 5.1.
- The electricity price will follow the tendencies of the Danish market.

6 Base model implementation

Along this chapter, the base model implementation is going to be defined. Firstly, the energy demand or product output of each sector excluding road transport is estimated using the growing rates of chapter 4. Secondly, the hydrogen demand of those applications where decarbonization policies and mandates can force the sector to switch to green hydrogen is calculated using an s-shaped growth curve. Then, the individual demands are added up together obtaining a total green hydrogen demand. Next, the hydrogen price is obtained considering the total green hydrogen demand and possible economies of scale applying a technology learning rate. Afterwards, the demand of those applications where hydrogen penetration depends on the final consumer decision and thus, hydrogen prices, is estimated. Finally, this demand is added up to the total green hydrogen demand creating a loop.

6.1 Initial total hydrogen demand

It is assumed that green hydrogen will penetrate in the following applications due to decarbonization policies or mandates: ammonia and olefin production, refineries, steel production, industrial heat, shipping and aviation sector. This penetration, that can be in the form of direct or indirect hydrogen use, means a switch in the technology already used. This change is implemented by following a Richard's function or s-shaped growth curve that represents, among others, the behaviour of a new technology adoption. As an example, that curve appears in the penetration of bio-fuels in the road transport, represented in Figure 6.1. This curve's behaviour will be mimicked by the penetration of new technologies in the model.

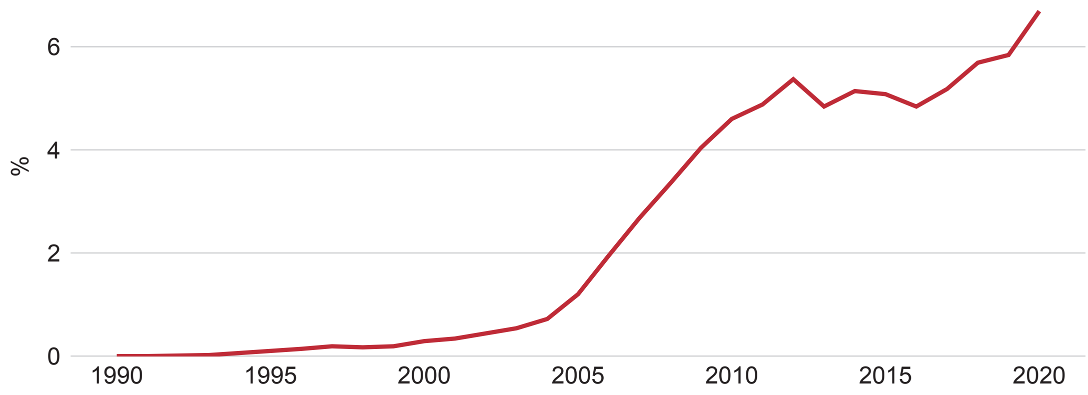


Figure 6.1: Yearly share of biofuels in the road transport sector

An s-shaped curve development is divided in three phases. During the first phase there is a slow positive growth representing the introduction of the new technology into the environment, then the growth increases almost exponentially representing the development phase of the technology, lastly, the technology acquires maturity and starts experimenting a slow negative growth until a saturation level is reached. In the case of Figure 6.1, there is a first curve from 1990 to 2015 and another one starting from 2015 on due to two different policies that stimulated bio-fuel consumption. In 2009, a renewable energy directive (RED) was approved in the EU aiming for a 20% target for the overall share of energy from renewable sources and a 10% target for energy from renewable sources in transport sector by 2020 [116]. It contained a list of national overall targets for the share of energy from renewable sources in the gross final consumption of energy but not for the transport, which caused the under-accomplishment of the second target due to a negligible growth from 2010 on. However, this policy did encourage bio-fuel consumption, increasing its share in the road transport sector since 2004, even before its official approval. Something similar happened with the second policy approved in December 2018, RED II [117], where the overall target for renewable energy consumption by 2030 has been raised to 32% and whose effects are already visible by 2016.

Not all the data available from Figure 6.1 is representative, the low share of biofuels at the beginning of the data set is probably because of the lack of interest in them due to the absence of a policy or mandate, and the exponential growth from 2016 after the previous saturation represents the consequences of a new policy to be approved. Assuming the exponential deployment of green hydrogen will start around 2030 and considering its deployment curve will follow the evolution of bio-fuels in the transport sector, the representative data set includes data from 2000 to 2015, starting the exponential growth in 2005. The resulted curve from this data set is then scaled from 0-100% deployment and adapted to the studied period 2019-2050.

Using the obtained s-shaped growth curve represented by a decarbonization coefficient, the shares of the new decarbonization alternatives described in the model assumptions of chapter 4 are individually implemented in the model with a lookup table. Then, the individual hydrogen demands are calculated by using a $X - to - H_2$ ratio. Finally, all these demands are added up together obtaining a total hydrogen demand represented in the following equation:

$$H_{initial} = H_{amm} + H_{ole} + H_{ref} + H_{steel} + H_{heat} + H_{ship} + H_{av} \tag{6.1}$$

6.2 Hydrogen price

As a simplification, the hydrogen price is calculated as the addition of the electrolyser cost considering the lifespand and efficiency of alkaline electrolysers in Table 5.1, and the electricity price forecast of Denmark from Figure 5.2 considering there are no taxes applied for hydrogen production. The total cost of hydrogen in €$/kg$ is equal to the electrolyser cost (€$/kW$) divided by the lifespand (h) plus the electricity price (€$/kWh$) and everything multiplied by the higher heating value of hydrogen (kWh/kg) divided by the electrolyser efficiency. In addition, cost reduction in the electrolyser due to economies of scale or learning-by-doing is implemented depending on the learning curve from Figure 5.1. This function is applied as a look-up table in the model where the input is initially $H_{initial}$ and the output is the electrolyser cost.

$$C_{H_2} = \left(\frac{c_{electrolyser}}{h} + p_{electricity}\right) * \frac{HVV_{H_2}}{\epsilon_{electrolyser}} \tag{6.2}$$

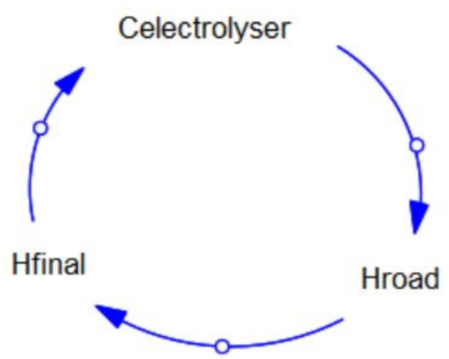
6.3 Definitive hydrogen demand

After estimating the cost of hydrogen, the road sector demand is calculated. As explained in section 4.8, the potential switch to a different vehicle technology in the road sector depends on the individual utility of the alternatives from the point of view of the final consumer. Thus, the hydrogen demand from heavy and light duty road transport depends on the assumptions of chapter 4 and the total cost of ownership of different vehicles depending on the diesel price, the electricity price and hydrogen price described in Figure 4.7. As an input, this part of the model receives the cost of hydrogen, (C_{H_2}), and the electricity price from the Danish market defined in Figure 5.2 with a 100% increase due to taxation which will be applied to electricity used for charging BEV.

After estimating the hydrogen demand from the road sector, the total hydrogen demand is redefined, adding the road transport sector demand as seen in Equation 6.3. This creates a causal loop or reinforcement loop where the total hydrogen demand affects the hydrogen cost, which influences road transport demand and thus, total hydrogen demand. This loop is described in a simplified manner in Section 6.3, however, for a deeper detail of the model see Appendix A.

$$H_{final} = H_{initial} + Hroad \tag{6.3}$$

Figure 6.2: Simplified reinforcement loop on Vensim software



7 Results and sensitivity analysis

The first important result of this report is the total hydrogen demand forecast presented in Figure 7.1, which reaches more than 70 Mt_{h_2} by 2050. In order to satisfy this demand, electrolyser production is scaled up leading to the cost reduction displayed in Figure 7.2 due to the learning rate implemented into the model. Hydrogen price evolution, presented in Figure 7.4, depends on both the electrolyser cost in Figure 7.2 and the electricity prices in Figure 7.3. The steep slope in the early years on the electrolyser cost affects the first years of the hydrogen price. However, as the slope becomes flatter, the effect on the hydrogen price is reduced. It is noteworthy how reaching the lowest electrolyser prices in 2050, the lowest hydrogen price occurs in 2020, manifesting how electricity price is the main driver of hydrogen price.

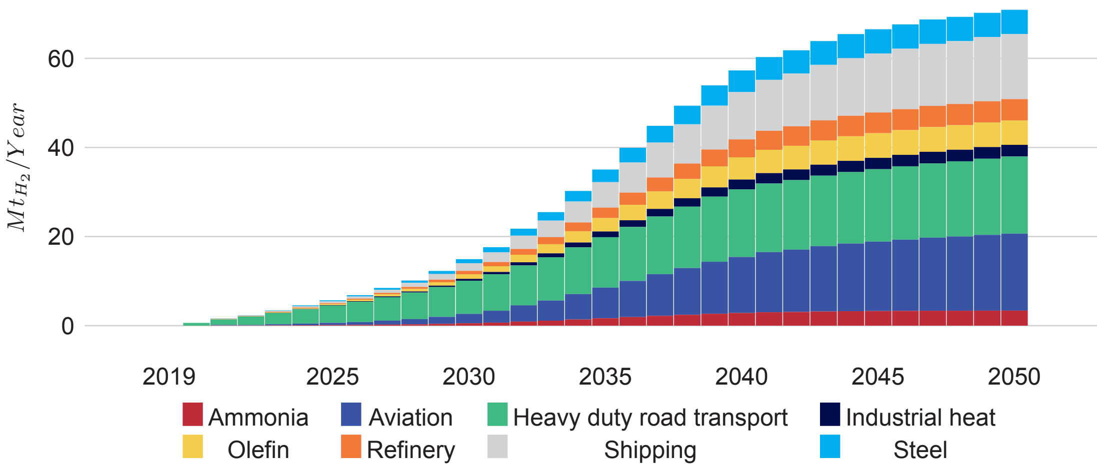


Figure 7.1: EU total hydrogen demand divided by sectors

It is precisely the cost reduction on hydrogen price what allows its penetration in the road sector, where the final consumer has the power to decide. However, as seen on Figure 7.5, FCEV using hydrogen as a fuel are more expensive than the electric alternative for both urban and heavy duty long haul vehicles. For urban applications, FCEV are almost twice as expensive as BEV and given that the hydrogen price strongly depends on the electricity price, further cost reductions in the CAPEX of the vehicle are needed for FCEV to pentrate the urban market. Regarding heavy duty long haul, the CAPEX of FCEV is lower than BEV but the fuel cost increases its overall ownership cost, however the cost of ownership difference is negligible. It is the autonomy of FCEV what increases the utility of the alternative and pushes its penetration into the market. Nevertheless, if battery technology and electric charging infrastructure strongly improves during the following years, hydrogen might lose its opportunity in the long haul sector. In applications were the final consumer makes decissions, if hydrogen is not perceived as the

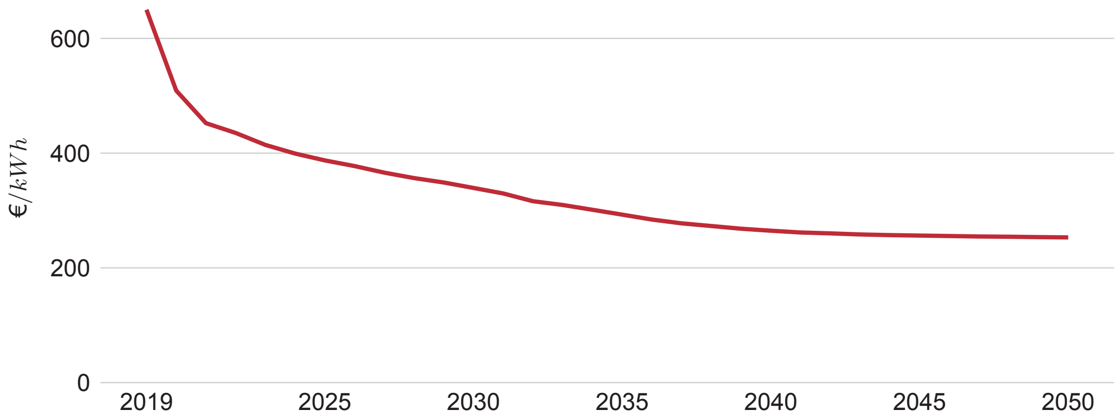


Figure 7.2: Electrolyser cost forecast

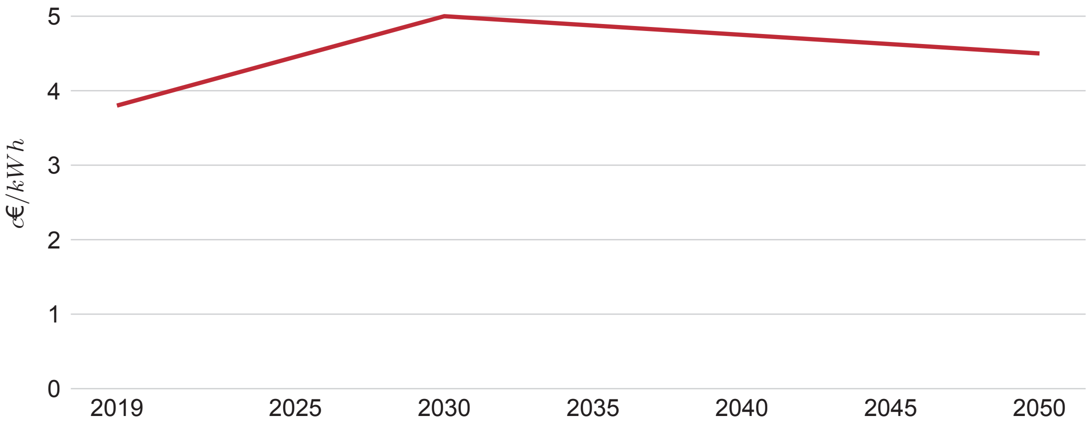


Figure 7.3: Electricity price (taxes not included)

best alternative, it will not penetrate that sector.

Figure 7.1 also shows a breakdown of the different sector contribution to the overall total hydrogen demand. The transport sector is expected to be the biggest hydrogen consumer in the EU, driving the price reductions that push the penetration of hydrogen in other sectors. It can be stated that the hydrogen need of the different fuels used to decarbonise the transport sector are also drivers of the total hydrogen demand and thus, hydrogen price.

Considering the results of the base model, the relations established between the different parameters of the model and the uncertainty of some parameters, two further analysis are carried out base on electricity prices and bio-fuel availability.

Current electricity prices are are far from the expected forecast shown in Figure 7.3 due

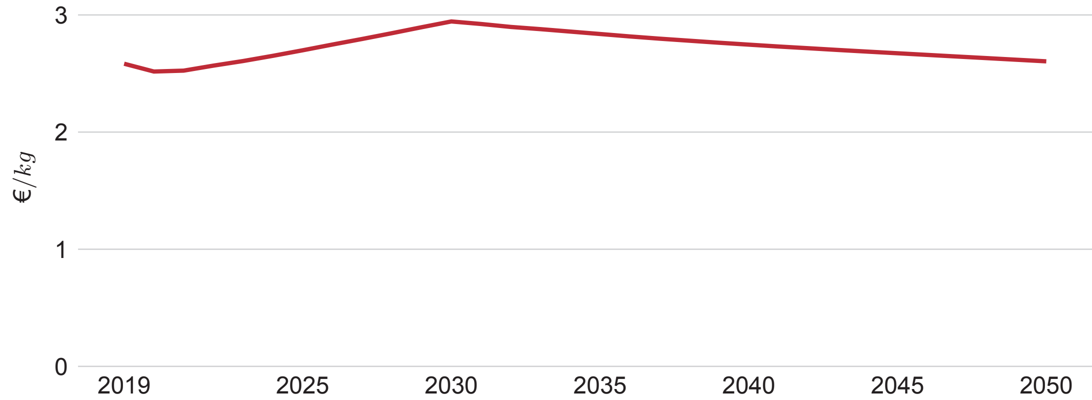
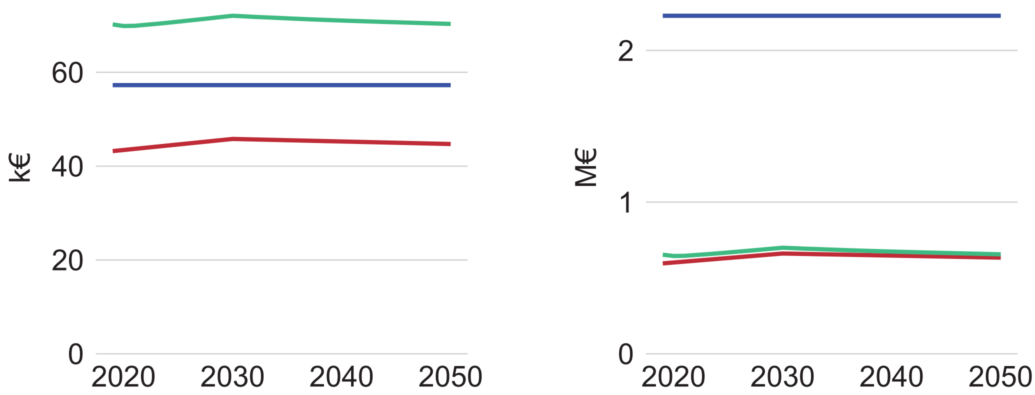


Figure 7.4: Hydrogen cost forecast

to an increased electricity demand paired with the lack of supply because of the gas crisis Europe is facing. During 2021, the yearly average electricity price[1] surpassed the 8 $c€/kWh$ in several EU members reaching its peak at 14 $c€/kWh$ in Ireland, while the lowest price was established at 7 $c€/kWh$ in the Netherlands [118]. A sensitivity analysis is carried out by raising the electricity prices and the results are displayed in Figure 7.6. If the electricity price reaches 20 $c€/kWh$, the hydrogen price will reach more than 10 $€/kg$ which can affect its penetration into the market. However, given that the penetration of hydrogen in all the sectors except road transport depends on the decarbonization targets and not hydrogen price, the demand of these sectors remains the same. Regarding road transport, by comparing the total cost of ownership of the FCEV truck from Figure 7.6 and the diesel truck in Figure 7.5, it can be seen that the hydrogen alternative remains to be cheaper, favoring the penetration of hydrogen into the market even if the electricity prices highly increase. Nonetheless, the ownership cost difference between BEV and FCEV trucks gets bigger as electricity prices increase, which might trigger further investment in this technology leading to a switch towards BEV trucks for certain applications. Another factor to be considered is that if electricity prices increase as much both BEV and FCEV urban vehicles become considerably more expensive than diesel vehicles, delaying the decarbonization of this sector.

Along this report it has been assumed that bio-fuels will cover a large part of the energy demand of the transport sectors studied, increasing the hydrogen demand. However, late directives for bio-fuel production are quite strict, limiting the land use for feedstock growth due to indirect land use and thus, their availability. A sensitivity analysis on bio-fuel availability is performed by decreasing the bio-fuel share in both the shipping and aviation applications and the main results are shown in Figure 7.7. By reducing the bio-fuel share the total hydrogen demand decreases given that synthetic fuels require more hydrogen for their production. However, a reduction on the demand of more than a 30% limited by bio-fuel availability has no effects on hydrogen cost, which will remain

[1] for non-household consumers, does not include taxes



(a) Urban

(b) Heavy duty long haul

Figure 7.5: Total cost of ownership forecast for different vehicles

around 2.6 €$/kg$. This analysis provides robustness to the fact that the main driver of hydrogen cost is electricity price.

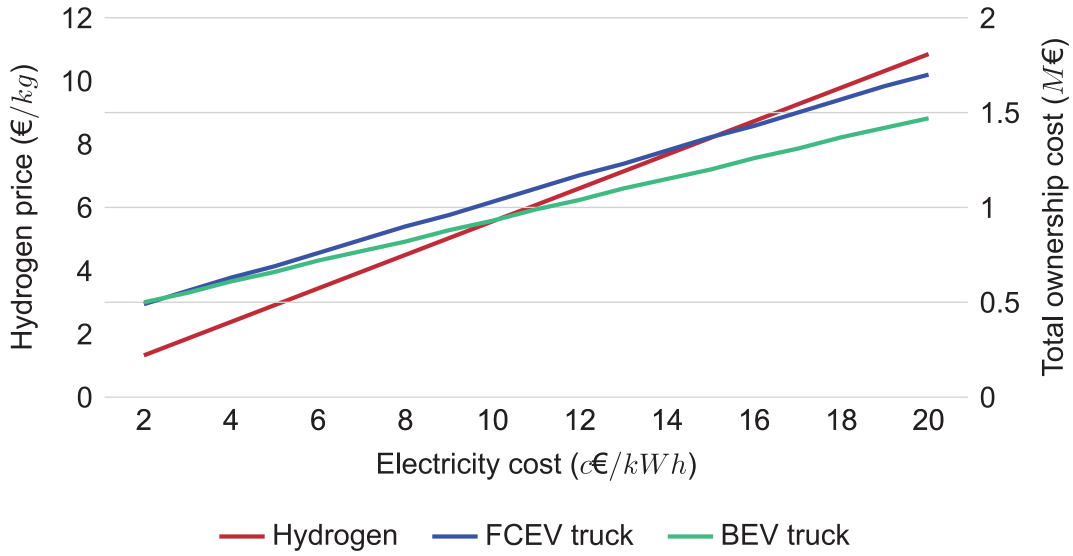


Figure 7.6: Model results of the electricity sensitivity analysis

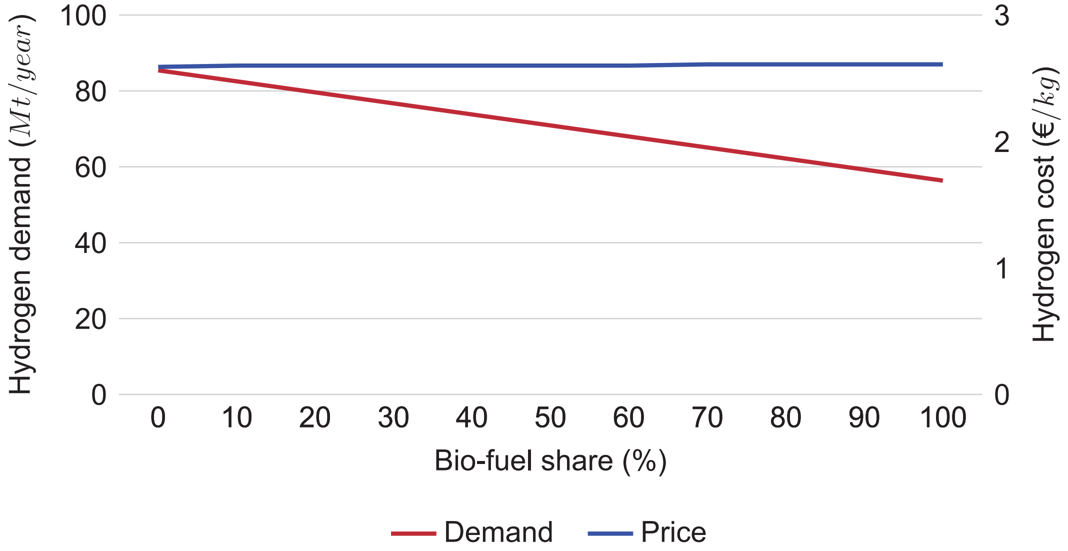


Figure 7.7: Model results of the bio-fuel sensitivity analysis

8 Conclusions

Current decarbonization tagets of the EU and international shipping and aviation associations raise the necessity of a new energy source, specially for those hard-to-abate sectors. Hydrogen represents an alternative for this purpose given that its implementation into the energy system concedes several advantages. No emissions are associated with its direct usage due to its carbon-free chemical formula and, when obtained through electrolysis using renewable electricity, it is called green hydrogen and no emissions are generated during its production process either. Furthermore, apart from the direct uses of hydrogen as a clean fuel for combustion or fuel cells, it can also be used to produce other fuels like ammonia and synthetic fuels and for the hydrogenation or upgrade of fossil and bio- fuels. Synthetic kerosene, diesel or methanol are obtained from hydrogen and captured carbon and they present the exact same characteristics as their conventional fuel equivalent. As a disadvantage, they do have the same environmental impact when combusted too, however given that their carbon source is captured, they can be considered carbon neutral. Further advantages of hydrogen include its contributions to the power sector; the production of hydrogen through electrolysis provides a much needed alternative for energy storage reducing the variable renewable energy curtailment and allowing the transport of renewable power over long distances. Moreover, electrolysers can provide ancillary services to the grid for the electricity system balancing. An opportune benefit from hydrogen is the energy independence it can provide to the EU energy system which is highly dependent on energy imports, specially natural gas and oil. With the recent political conflict between Ukraine and Russia, Europe is enduring a partial cutoff of the natural gas supply and, to face the risk of shortage, Europe needs an alternative energy supply. Under this energy crisis is reflected the necessity of approaching towards an autarchic system energy-wise. It is true that this means leaning towards a more expensive solution but economies of scale can cheapen the costs of this infinite resource in the future while reducing the impact of the volatility of conventional fossil fuel prices.

Green hydrogen will penetrate several applications due to the decarbonization targets of the EU. The ammonia sector and refineries are hydrogen-consumers already and a complete switch towards renewable hydrogen is expected in the following years. Olefin production uses naphtha sourced mainly from Russia as a feedstock and energy carrier; green hydrogen will penetrate this sector too with the production of synthetic naphtha that will decarbonize all the fuel and reduce the import dependency of this sector. Hydrogen will be used for steel production as well, where a switch towards a less carbon intense primary route is forecasted by implementing direct hydrogen reduction of iron ore. Regarding industrial heat, the combustion of hydrogen is expected to substitute part of the natural gas applications due to a compatible infrastructure. Renewable ammonia, bio- and synthetic methanol are expected to decarbonize the 70% of the international shipping sector, represented by the maritime bunkers of the EU, according to the IMO goals. Finally, the aviation sector will account with hydrogen support for SAFs production for national and international aviation and, from 2030, direct hydrogen combustion for national aviation. Due to price reductions, hydrogen will also penetrate the road transport sector in the form of hydrogen fuel cells, specifically in heavy duty long haul applications where the autonomy of the vehicles is indispensable. However, hydrogen will not penetrate urban vehicle applications where electrification is cheaper. Table Table 8.1 shows the specific green hydrogen demand by sector:

Table 8.1: Hydrogen demand projections in the EU divided by application

Base model		2030	2040	2050
Total hydrogen demand	$Mt/year$	14.92	57.29	70.90
Hydrogen demand from ammonia	$Mt/year$	0.54	2.84	3.37
Hydrogen demand from olefin	$Mt/year$	0.77	4.98	5.47
Hydrogen demand from refineries	$Mt/year$	0.77	4.03	4.79
Hydrogen demand from steel	$Mt/year$	0.93	4.88	5.42
Hydrogen demand from industrial heat	$Mt/year$	0.42	2.20	2.62
Hydrogen demand from shipping	$Mt/year$	1.70	10.62	14.63
Hydrogen demand from aviation	$Mt/year$	2.11	12.56	17.28
Hydrogen demand from road transport	$Mt/year$	7.43	15.18	17.31

The green hydrogen price can reach levels around 2.5 €$/kg$, almost regardless of the total hydrogen demand, if the electricity price forecast of around 5 c€$/kWh$ is achieved. However, there is a high correlation between electricity and hydrogen prices and, considering the current electricity prices which can reach the 20 c€$/kWh$, the hydrogen price can increase up to more than 10 €$/kg$. There is still a lot of uncertainty whether or not electricity prices will be low enough for hydrogen to be the best alternative to decarbonize certain sectors. Furthermore, with electrification goals set to highly increase the electricity demand in the future and with, the scaling renewable supply being able to cover only part of that demand, other energy sources like natural gas or oil might be necessary to cover the demand making the EU more vulnerable to the volatility of fossil fuel prices and increasing the electricity prices even more.

It is true that the price of hydrogen might affect its penetration into the energy system; if other alternatives are more attractive economically, the system might lean towards them. However, energy commodities are highly related in price; the natural gas price increases and so does the electricity and so does the green hydrogen price. Furthermore, hydrogen is the only alternative for some application and so, this report assumes it will penetrate the system in those sectors where decarbonization policies or mandates have a direct effect on the consumer. Moreover, even with high electricity prices leading to hydrogen prices of more than 10 €$/kg$, the total cost of ownership of hydrogen FCEV trucks is still less expensive than conventional diesel trucks, favoring the penetration of hydrogen in for heavy duty long haul applications.

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A Vensim model

Figure A.1: Ammonia implementation on Vensim software

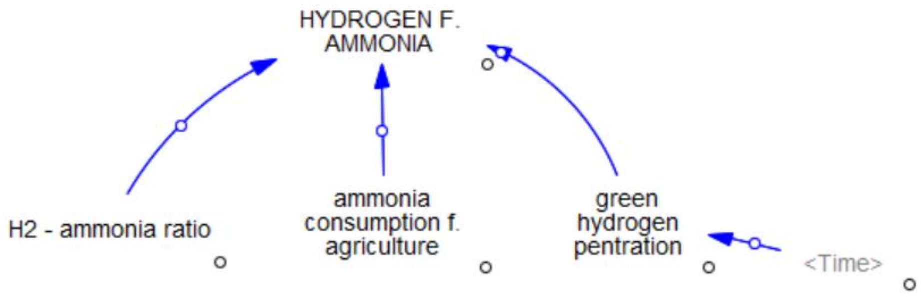


Figure A.2: Olefin implementation on Vensim software

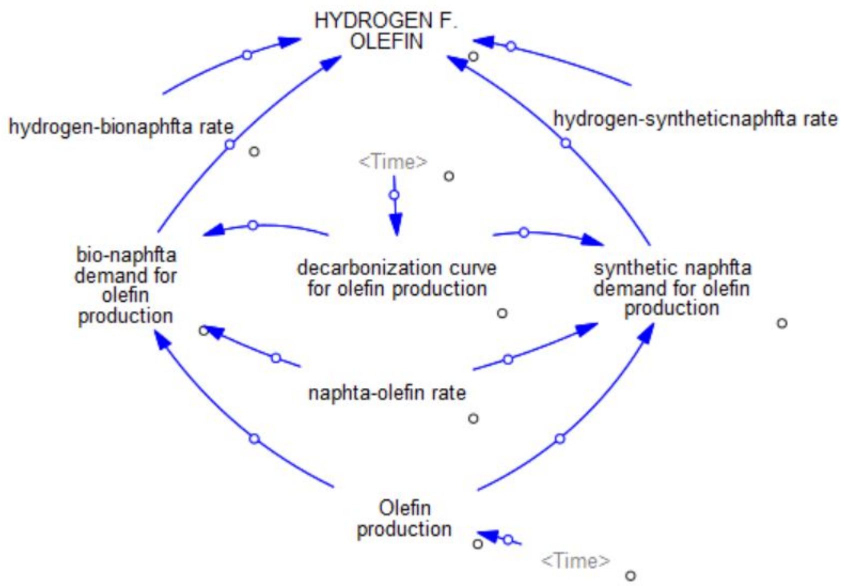


Figure A.3: Refinery implementation on Vensim software

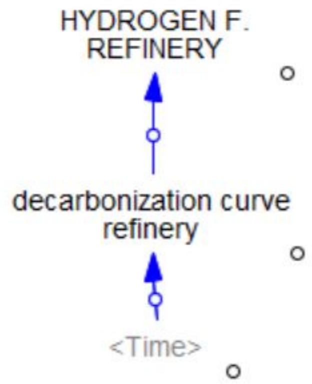


Figure A.4: Steel implementation on Vensim software

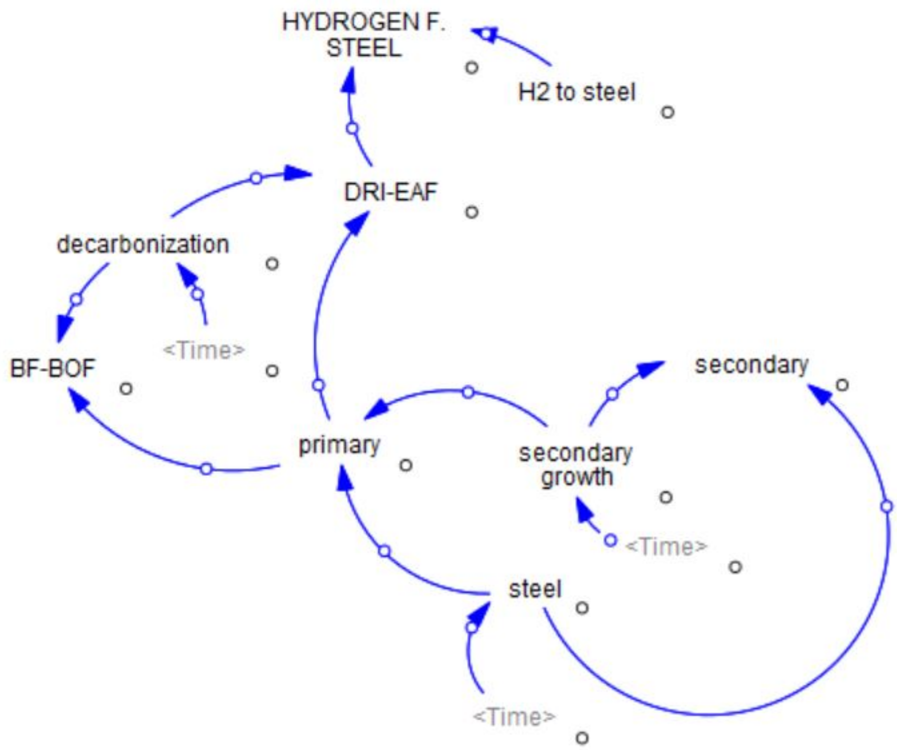


Figure A.5: Industrial heat implementation on Vensim software

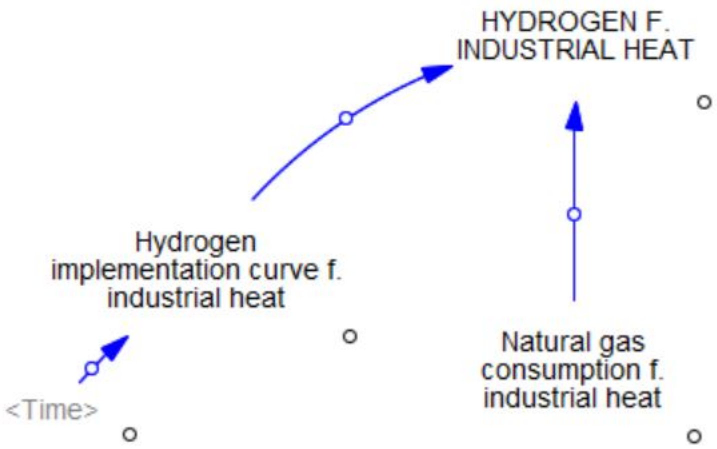


Figure A.6: Shipping implementation on Vensim software

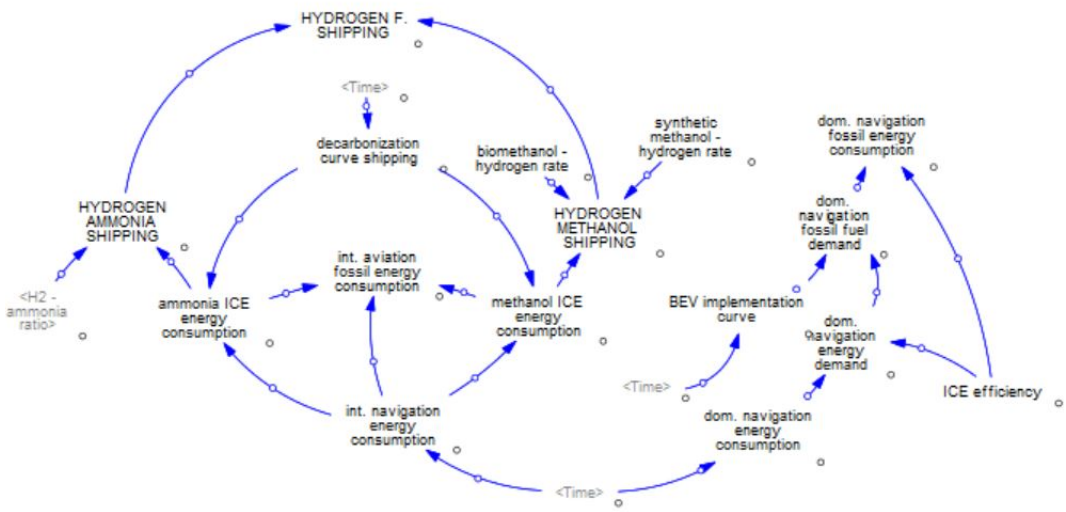


Figure A.7: Aviation implementation on Vensim software

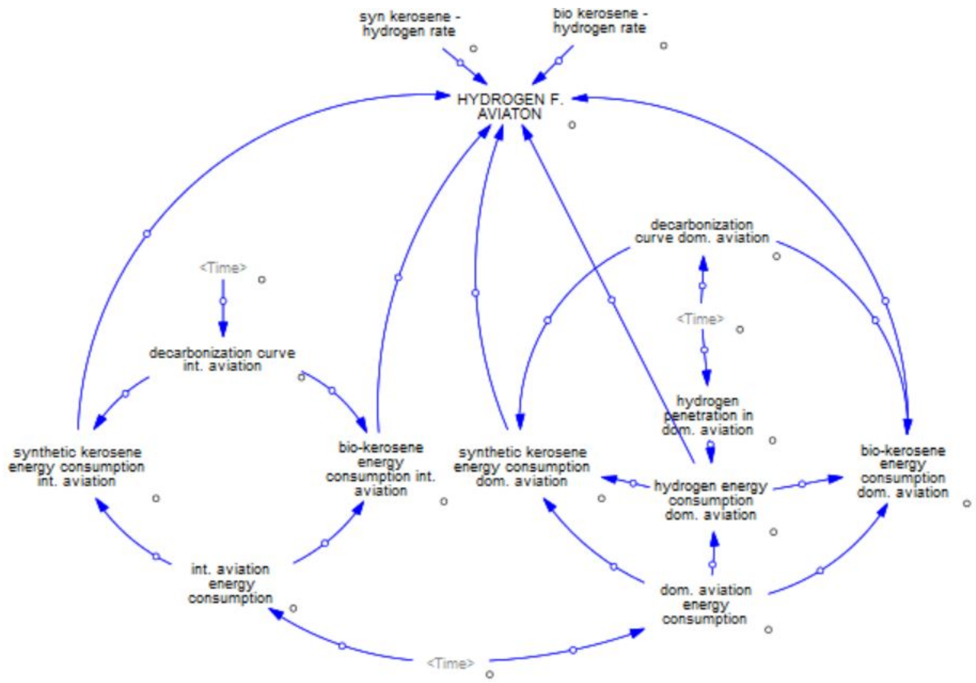


Figure A.8: Road implementation on Vensim software

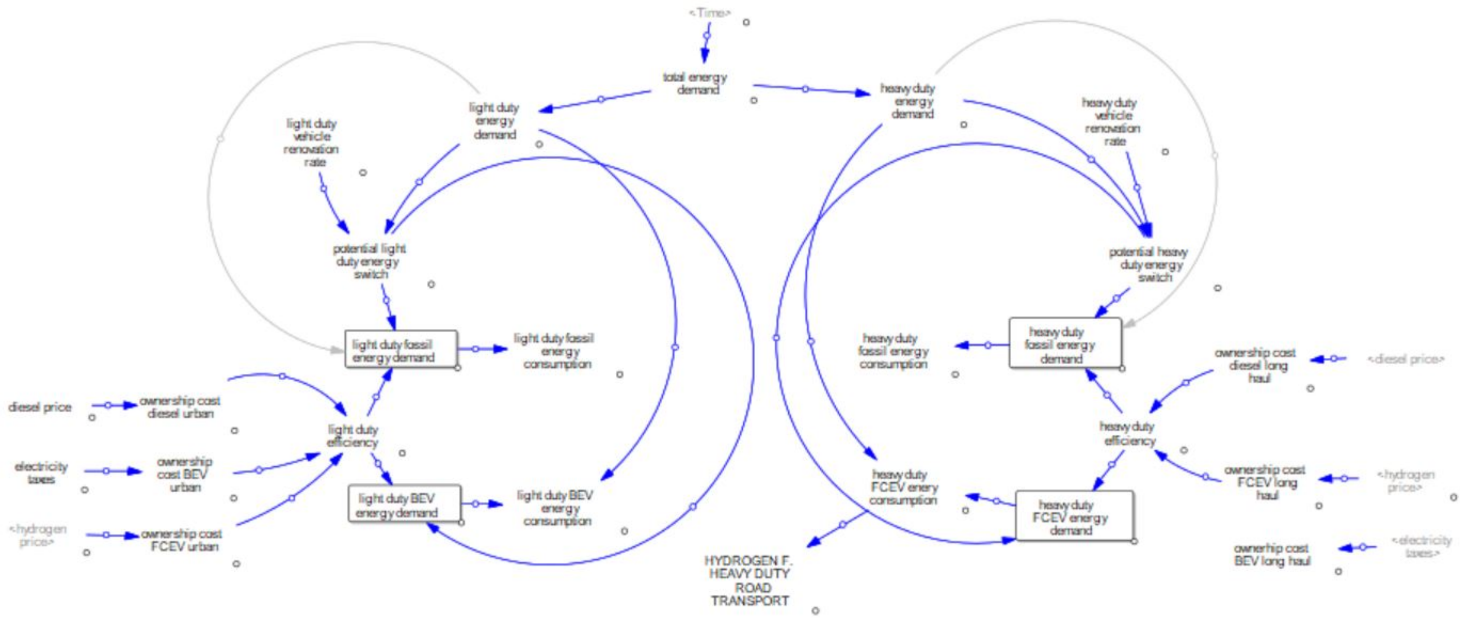
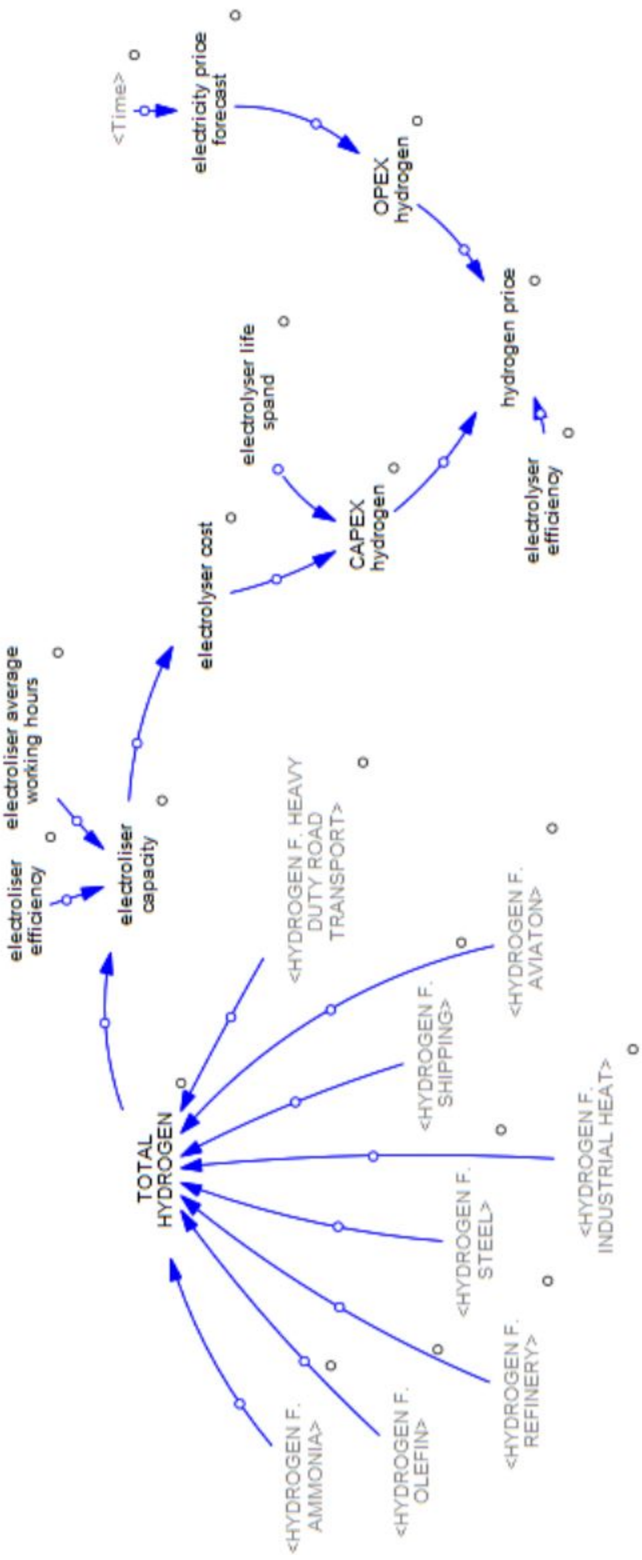


Figure A.9: Hydrogen price implementation on Vensim software



B Model results

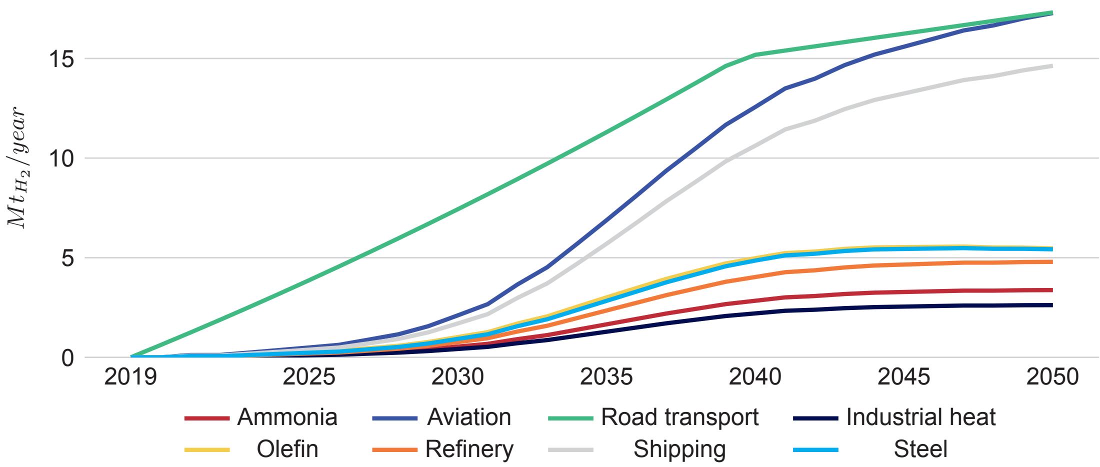


Figure B.1: Hydrogen demand forecast from the different studied sectors

Table B.1: Hydrogen demand projections in the EU divided by application considering a 500% increase in the electricity price

500% increase in electricity price		2030	2040	2050
Total hydrogen demand	$Mt/year$	14.92	57.29	70.90
Hydrogen demand from ammonia	$Mt/year$	0.54	2.84	3.37
Hydrogen demand from olefin	$Mt/year$	0.77	4.98	5.47
Hydrogen demand from refineries	$Mt/year$	0.77	4.03	4.79
Hydrogen demand from steel	$Mt/year$	0.93	4.88	5.42
Hydrogen demand from industrial heat	$Mt/year$	0.42	2.20	2.62
Hydrogen demand from shipping	$Mt/year$	1.70	10.62	14.63
Hydrogen demand from aviation	$Mt/year$	2.11	12.56	17.28
Hydrogen demand from road transport	$Mt/year$	7.43	15.18	17.31
Electrolyser cost	€$/kWh$	339.30	264.76	253.19
Electricity price	c€$/kWh$	25.00	23.75	22.50
Hydrogen price	€$/kg$	13.52	12.79	12.13
BEV urban total ownership cost	k€	89.00	86.30	86.30
Diesel urban total ownership cost	k€	57.27	57.27	57.27
FCEV urban total ownership cost	k€	126.15	122.08	119.00
BEV long-haul total ownership cost	M€	1.75	1.69	1.61
Diesel long-haul total ownership cost	M€	2.22	2.22	2.22
FCEV long-haul total ownership cost	M€	2.04	1.95	1.86

Table B.2: Hydrogen demand projections in the EU divided by application under base case scenario assumptions

Base model results		2030	2040	2050
Total hydrogen demand	$Mt/year$	14.92	57.29	70.90
Hydrogen demand from ammonia	$Mt/year$	0.54	2.84	3.37
Hydrogen demand from olefin	$Mt/year$	0.77	4.98	5.47
Hydrogen demand from refineries	$Mt/year$	0.77	4.03	4.79
Hydrogen demand from steel	$Mt/year$	0.93	4.88	5.42
Hydrogen demand from industrial heat	$Mt/year$	0.42	2.20	2.62
Hydrogen demand from shipping	$Mt/year$	1.70	10.62	14.63
Hydrogen demand from aviation	$Mt/year$	2.11	12.56	17.28
Hydrogen demand from road transport	$Mt/year$	7.43	15.18	17.31
Electrolyser cost	€$/kWh$	339.30	264.76	253.19
Electricity price	c€$/kWh$	5.00	4.75	4.50
Hydrogen price	€$/kg$	2.94	2.74	2.60
BEV urban total ownership cost	k€	45.80	45.26	44.72
Diesel urban total ownership cost	k€	57.27	57.27	57.27
FCEV urban total ownership cost	k€	72.05	70.04	70.31
BEV long-haul total ownership cost	M€	0.66	0.65	0.63
Diesel long-haul total ownership cost	M€	2.22	2.22	2.22
FCEV long-haul total ownership cost	M€	0.70	0.67	0.65