

École polytechnique de Louvain

Electrofuel supply in Belgium towards carbon neutrality

Using EnergyScope TD to study its impact in
2030 and 2050

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Abstract

The European Union aims to be carbon neutral by 2050. In less than 30 years the whole energy system must be reviewed in order to replace the nonrenewable sources and technologies by more sustainable ones. Fossil fuels, such as coal, oil and natural gas, are currently the most important primary energy sources. It has the capacity to provide a huge amount of energy and to be easily transported and stored. An alternative to these are electrofuels, produced from renewable energy sources. The carbon dioxide emitted from their combustion was captured beforehand to produce them, which makes the entire life-cycle carbon neutral. These molecules would maintain the benefits while significantly reducing greenhouse gas emissions, and without having to change all existing fossil fuel based technologies.

Solar and wind energy will be important sources for the electrofuel production. However, their potential is limited and there may be a shortage in several countries of the EU. This is why it is necessary to adopt energy exchanges with countries with sufficient renewable potential, using electrofuels as energy carrier. In this study the particular case of Belgium is analysed through EnergyScope Typical Days, a whole-energy system model. It optimises the total cost based on the emission targets set by the EU for 2030 and 2050. The import of electrofuels from abroad is considered with two approaches : (1) existing agreements and articles that affirm these exchanges, (2) the renewable energy potential of the exporting countries. Different electrofuel supply scenarios are illustrated through case studies. The technologies and the end-use demands that they supply are highlighted to understand their integration in the whole energy system. This is followed by a discussion on the availability of electrofuels and alternative solutions to meet the energy demand.

It results that electrofuels will contribute in large part to the transition towards carbon neutrality. Especially, it will become a main resource for the non-energy demand and the mobility sector by 2030. However, the predicted supply is rather uncertain, which could jeopardise the whole transition.

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List of Acronyms

AAR Acil Allen Report.

AU Australia.

BE Belgium.

BEV battery electric vehicles.

CCGT combined cycle gas turbine.

CCS carbon capture and storage.

CF capacity factor.

CL Chile.

CNG compressed natural gas.

EC exporting countries.

EnergyScope TD EnergyScope Typical Days.

EU European Union.

EUD end use demand.

FC fuel cell.

GHG greenhouse gas.

GWP global warming potential.

HIC Hydrogen Import Coalition.

HVC high-value chemicals.

ID import dependency.

IDF increasing demand factor.

IRENA International Renewable Energy Agency.

LB lower bound.

LCOH levelised cost of hydrogen.

MO Morocco.

NA Namibia.

NDC nationally determined contribution.

NED non-energy demand.

OM Oman.

PV photovoltaic.

R&D research and development.

RWGS reverse water gas shift.

SA Saudi Arabia.

SP Spain.

UB upper bound.

WEC World Energy Council.

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Introduction

According to NASA [1], the earth's temperature has risen by 1°C since the late 19th century. This global warming is mainly due to human activities and its related carbon dioxide emissions. This results in several phenomenons such as the melting of ice (the global sea level has increased by 20 centimetres in the last century), torrential rainfalls, heatwaves, the acidification of oceans and many others. These will become more important and increase in number if global warming does not stop. The 6th and most recent report of the IPCC highlights important risks for Europe [2]. Those include frequent heatwaves, decreases in agricultural yields, water shortages and numerous floods.

The Paris Agreement, adopted in 2015 by 196 Parties, aims to avoid climate disasters by staying well below 2°C of global warming and even trying not to reach 1.5°C compared to the pre-industrial period [3]. The agreement includes a meeting of the Parties every five years to discuss objectives and progress all together by updating and enhancing their nationally determined contributions (NDCs). In its latest NDC dated December 2020, the European Union (EU) affirmed its commitment to reduce its greenhouse gas (GHG) emissions in 2030 by 55% compared to 1990, and to become carbon neutral by 2050.

For more than 150 years, the world's energy system has been built around fossil fuels, which now account for 80% of the supply and about two third of the GHG emissions [4]. The non-energy demand (NED), which includes the energy products used as raw materials and not as fuels [5] (e.g. for the production of plastics and fertilisers), is responsible for about 7% of the worldwide CO_2 emissions. Currently, the main resources of the NED are the fossil fuels [6]. In less than 30 years these fuels need to be replaced by alternative renewable sources, which requires to rethink the entire energy system.

Belgium is a densely populated country with a limited renewable energy potential. According to Limpens et al. [7], Belgium needs at least 401.8 TWh of primary energy annually in 2035, of which 102.3 TWh are used to supply the NED. Moreover the yearly renewable energy potential in Belgium accounts for 126.2 TWh including biomass, wind, solar and hydro [7]. This means that the country will have to rely on imports to achieve its targets, even if all the local potential renewables are used. Importing renewable fuels, such as electrofuels, could become crucial to ensure the energy supply in Belgium.

This master thesis focuses on the supply of electrofuels in Belgium and the influence it will have on the whole energy system. The research question that is covered is stated as follows: *How will the electrofuel supply in Belgium influence its transition towards carbon neutrality?* In particular the years 2030 and 2050, for which the EU has set clear targets, will be analysed.

In Chapter 1, a contextualisation is done about the electrofuels. Topics such as the different types, their importance, advantages and obstacles as well as the demand are discussed. Moreover, an overview of EnergyScope Typical Days (EnergyScope TD), an open-source model that optimises the design of a whole regional energy system, is provided. The model is used in this work to better understand the integration of the electrofuels in the Belgian energy system.

Chapter 2 covers the methodology to predict the supply of electrofuels. It is based on two different approaches. Firstly, agreements and articles that affirm exchanges of electrofuels in the future are taken into account. It can be considered as a lower bound, which will be the minimum available. Then, the share of the renewable energy potential of exporting countries (EC) is considered and seen as the upper bound, what cannot be exceeded and probably never be reached.

In Chapter 3, the impact of the electrofuels is studied using EnergyScope TD. More precisely and for both approaches of the previous chapter, their integration in the whole energy system is described. Technologies that can use them will be highlighted as well as the supplied end use demand (EUD). Furthermore, alternative solutions will be discussed in case of electrofuel shortage. As a first step, solutions are analysed within EnergyScope TD, without changing its current input data. Other resources and technologies can potentially compensate for a lack of electrofuels. As a second step, a further analysis is done beyond the scope of EnergyScope TD. In particular, the impact of the EUD and the nuclear power on the supply of electrofuels is analysed.

Chapter 4 discusses the weaknesses and limitations of this work. It also gives perspectives for further research to improve this master thesis or to follow it up.

Chapter 1

Literature review

1.1 Contextualisation of electrofuels

Why are electrofuels interesting for the future of our energy systems? What are their main advantages? What are the barriers to their current development? How many will be needed globally? And in the case of Belgium, what is the predicted demand for such fuels?

All those questions will be answered in this section to contextualise the research of this report.

As will be seen in Section 1.2, green hydrogen is the basis for the production of electrofuels. During the rest of this section, hydrogen will be used as reference electrofuel, its derivatives having a dependent and thus similar behaviour in most cases.

1.1.1 Advantages of hydrogen

Because of its many advantages, interest in hydrogen has grown in recent years. The main ones [8] are discussed in the following paragraphs.

Firstly, when produced with electrolyzers powered by renewable electricity, it does not emit any GHGs during its production or consumption. Some of its derivatives are however organic molecules (methane, methanol, ...) and will emit CO_2 during their combustion. But, CO_2 is required in their production process and will be obtained by capture technologies or as by-product of other processes [9]. The emitted CO_2 will thus have been previously captured from the atmosphere resulting in a net zero GHG emission cycle.

Secondly, the production of H_2 from electricity provides a partial response to the intermittency of renewable energies, by offering the possibility of long-term storage. This means that the energy does not have to be used directly after its production. Hydrogen can even be used as an energy vector and exported globally to countries with a lack of renewables. This last aspect will be discussed in more details in Section 1.3.

Moreover, hydrogen is versatile. It can be converted into multiple derivatives that can be used in different sectors.

Finally, electrofuels have the potential to defossilise the energy systems. Indeed, they could replace their fossil counterparts without changing drastically the current technologies. This could be useful, especially for the maritime and aviation transport that are difficult to electrify [10].

All these advantages offer convincing arguments to integrate hydrogen in our daily life, especially in this period of climate emergency. This encourages leaders to adapt the energy systems with more environmentally friendly alternatives. Unfortunately, there are also obstacles to the integration of hydrogen. Those are discussed in the following subsection.

1.1.2 Barriers to the development of hydrogen

Sadly, the integration of hydrogen also goes with hurdles that will need to be overcome. Based on reports published by the International Renewable Energy Agency (IRENA) [11] and the World Energy Council (WEC) [12, 13, 14, 15], a set of barriers are discussed below.

First of all, the current technologies are not at their optimal maturity level. "For instance, gas turbines that operate exclusively with hydrogen are not currently available off the shelf, and when it comes to maritime trade, there is only one prototype vessel able to transport liquid hydrogen", as of January 2022 [11].

Furthermore, the current lack of demand means that the private sector is not yet ready to invest in large-scale technologies or infrastructures. On the other hand, without investors, there will be no infrastructures and the demand cannot develop quickly enough. This is referred to as an *egg-and-chicken* problem.

Moreover, the production of hydrogen is energy-intensive, mainly because of the losses that it incurs in the various stages of the production-to-consumption chain [11]. To meet the projected demand in 2050, the renewable energy needed could be 1.9 times the current global electricity production [16]. This requires a massive amount of renewable energy which may become a limiting factor in the future.

Another important constraint to the integration of hydrogen in our day-to-day lives is its social acceptance. To do so, the population will need to understand it, particularly the environmental benefits and safety standards. For example, South Korea introduced a "Hydrogen Day" to raise awareness of hydrogen and include it in the local energy context [13].

Hydrogen is still not considered as a plausible alternative by political and private leaders. The WEC has created a world energy issue monitor where the issues concerning energy transition are placed on an impact-uncertainty graph (see Figure 1.1). This is done "by asking policy makers, CEOs and leading industry experts to assess the level of impact and uncertainty they attribute to pre-identified energy transition issues, ..." [12]. One can see that hydrogen is still perceived to have a limited impact and is thus not seen as a priority in 2022.

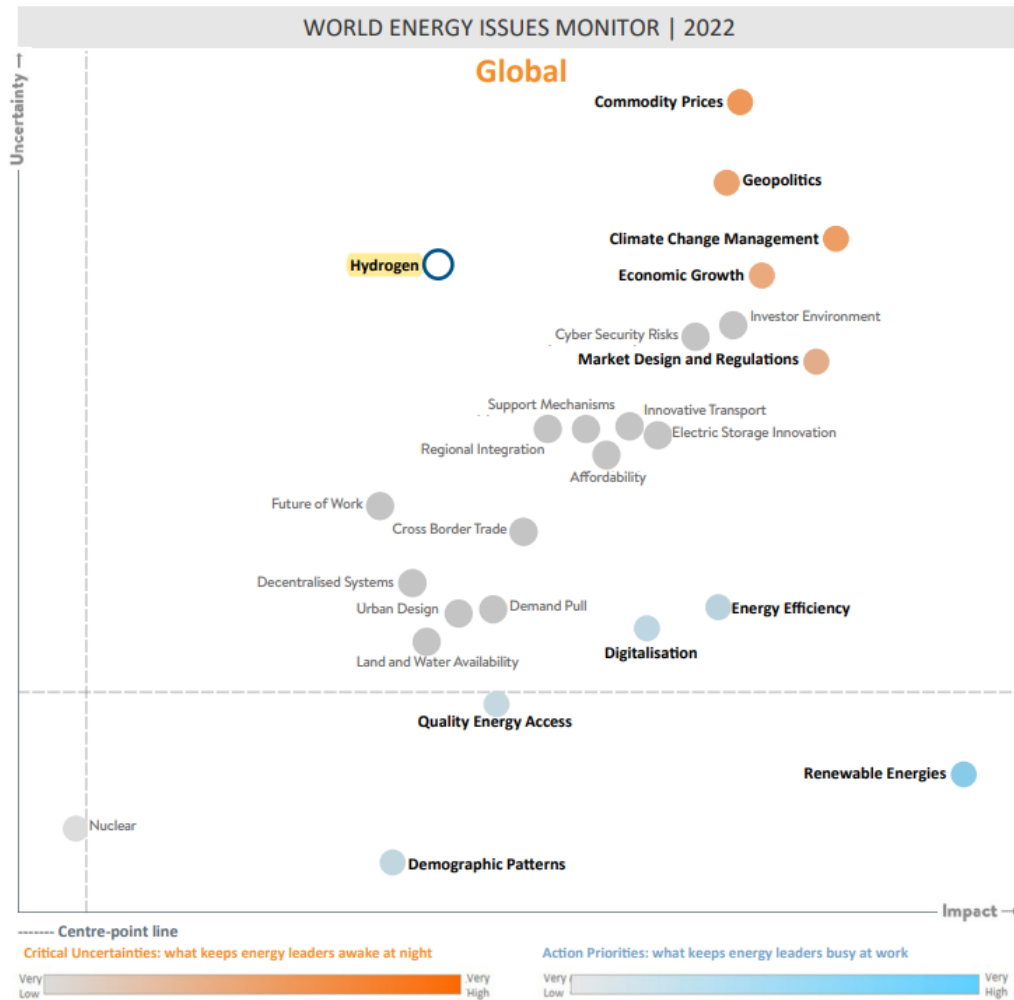


Figure 1.1: The WEC has established a world energy issue monitor [12]. It displays the impact and uncertainty of energy issues on a global scale. It also shows if the issue is being tackled or if it is something the leaders still need to look into.

The hydrogen world needs standardisation of its industrial processes, infrastructures and even definitions. For example, its types, and their corresponding definitions, are not universal. Often, articles make different assumptions on the colours or carbon emissions associated to a certain way of production. The main ones are discussed in Section 1.2.1. A first example is H_2 produced from nuclear power which is sometimes called pink, red, purple or even fluorescent [15, 17]. Another example can be given when comparing the strategies and objectives between different

countries. Some consider clean hydrogen to include only the types that do not emit any GHGs. Others consider that if the amount of carbon captured is above a certain percentage, the production is also considered to be clean. One solution could be to express the produced hydrogen in terms of carbon intensity (amount of CO₂ produced, in kg, for 1 kg of hydrogen), independently of the used technologies.

Finally, an important hurdle to the take-off of green hydrogen is its cost, more specifically for the production and transport. These are the most expensive steps in the production-to-consumption chain. This will be discussed and detailed in Section 2.2.

1.1.3 Demand

The green H_2 production will be limited until 2030. Indeed, the current or in-development plants are in pre-commercial phase and have limited capacities [14]. As of September 2019, around 95% of the hydrogen was produced using fossil fuels [18]. Also, the construction of the infrastructures to transport the hydrogen, such as pipelines and import-export terminals, require a lot of time. Indeed, for a terminal it can take up to ten years and up to twelve years for a pipeline [14].

The supply will increase after 2030, once the required infrastructure will be operational. By 2050, according to a source comparison made by the WEC [14], the global annual hydrogen demand should vary between 200 and 600 Mt_{H₂}, considering the scenarios with high climate ambitions. On the other hand, the IRENA has announced that it could go up to 800 Mt_{H₂} [11]. Taking both sources into account, this corresponds to a range going from 6500 to 26500 TWh_{H₂} approximately. The first message that can be drawn from this is that the future demand of hydrogen is currently uncertain. Secondly, by 2050 there will be a need for huge amounts of renewable electricity, going up to 1.9 times the actual electricity demand in the highest case, as was mentioned in the previous subsection.

Considering only Belgium, the demand is expected to be about 20.5 TWh_{H₂} in 2030 and about 100 TWh_{H₂} in 2050 [19]. Given the ranges of uncertainty at global level, these values need to be taken with caution as they are likely to vary over time. On the other hand, it is anticipated that the country will install 1.4 GW of electrolyzers by 2030 [20]. This corresponds to an annual production of ± 2.6 TWh_{H₂}. In 2050, this production could be multiplied by a factor 10 [21].

The difference between the demand and the local production has to be met by imports, which is discussed in Chapter 2.

1.2 Types of electrofuels

During the course of this work four different electrofuels are considered: hydrogen (H_2), methane (CH_4), ammonia (NH_3) and methanol (CH_3OH). These are the most common electrofuels and are at the basis of more complex ones that are briefly discussed at the end of this section. For each of these electrofuels, the production and main uses are described.

1.2.1 Hydrogen

This molecule is at the basis of the production of any other electrofuel. This is why most articles, including this report, mainly consider H_2 and estimate quantities in hydrogen equivalents ($H_{2,eq}$).

Production

Hydrogen can be produced in different ways but only one of them is considered as an electrofuel. The main types are the following [22]:

- **Black or brown H_2 :** The hydrogen is produced through burning coal or lignite, which emits 10 to 12 $\text{kg}_{CO_2,eq}/\text{kg}_{H_2}$. It is considered as the least environmentally friendly H_2 since it emits the most GHGs out of all the types.
- **Grey H_2 :** Constitutes currently almost all the hydrogen for industrial use. It is produced with natural gas via the steam reforming process ¹. It emits about 9 $\text{kg}_{CO_2,eq}/\text{kg}_{H_2}$, which is still not an environmentally friendly way of producing H_2 .
- **Blue H_2 :** The process is the same as for grey hydrogen, but with a carbon capture and storage (CCS) step added. Even with the capture of CO_2 the process still emits GHGs (about 4 $\text{kg}_{CO_2,eq}/\text{kg}_{H_2}$ with a 56% capture rate and 1 $\text{kg}_{CO_2,eq}/\text{kg}_{H_2}$ with a 90% capture rate [23]). Therefore, it is not the optimal solution towards carbon neutrality.
- **Green H_2 :** This form of hydrogen is produced by electrolysis powered by renewable electricity. It does not add any GHGs and represents the most eco-friendly way of producing H_2 . This form is considered as an electrofuel.

In this report mainly green, carbon-free hydrogen is considered to supply the Belgian energy system. In some cases, exceptions are made and the import and use of blue hydrogen is tolerated.

¹Combines CH_4 with water, as steam, to produce H_2 .

Usage

It is predicted that hydrogen will be used in the following sectors [19]:

- Industry :
 - As feedstock for the production of ammonia and other fuels, as well as high value chemicals (HVC).
 - As reducer in the steel-making process.
 - As source to produce industrial process heat.
- Transport : In the form of hydrogen fuel cells, mainly in heavy-duty vehicles.
- Power : Used in gas fired turbines and in fuel cells.
- Buildings : To replace the natural gas as heating source.

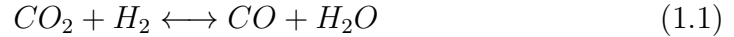
Europe will focus on the two first sectors in priority [12].

1.2.2 Methane

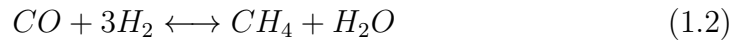
Production

The process to produce methane, or CH_4 , with green H_2 and CO_2 is called the CO_2 methanation process (see Figure 1.2). The required CO_2 can be obtained by capture in the atmosphere, in highly concentrated flue gasses in industry, via purification of biogas [9] or other numerous paths. CO_2 methanation is divided in two steps [24] :

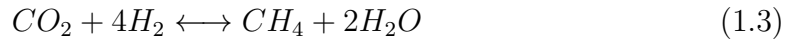
1. The endothermic reverse water gas shift (RWGS) reaction, where the CO_2 is converted into CO :



2. The exothermic CO methanation:



Altogether, the exothermic CO_2 methanation can be written as:



Usage

Similarly to hydrogen, the demand for methane is subdivided into several sectors [25]:

- Industry: As a fuel for process heating and as feedstock to produce chemicals or fertilisers.
- Residential: As feedstock to heat buildings and water.
- Power: As a feedstock to generate electricity or to produce useful thermal output.

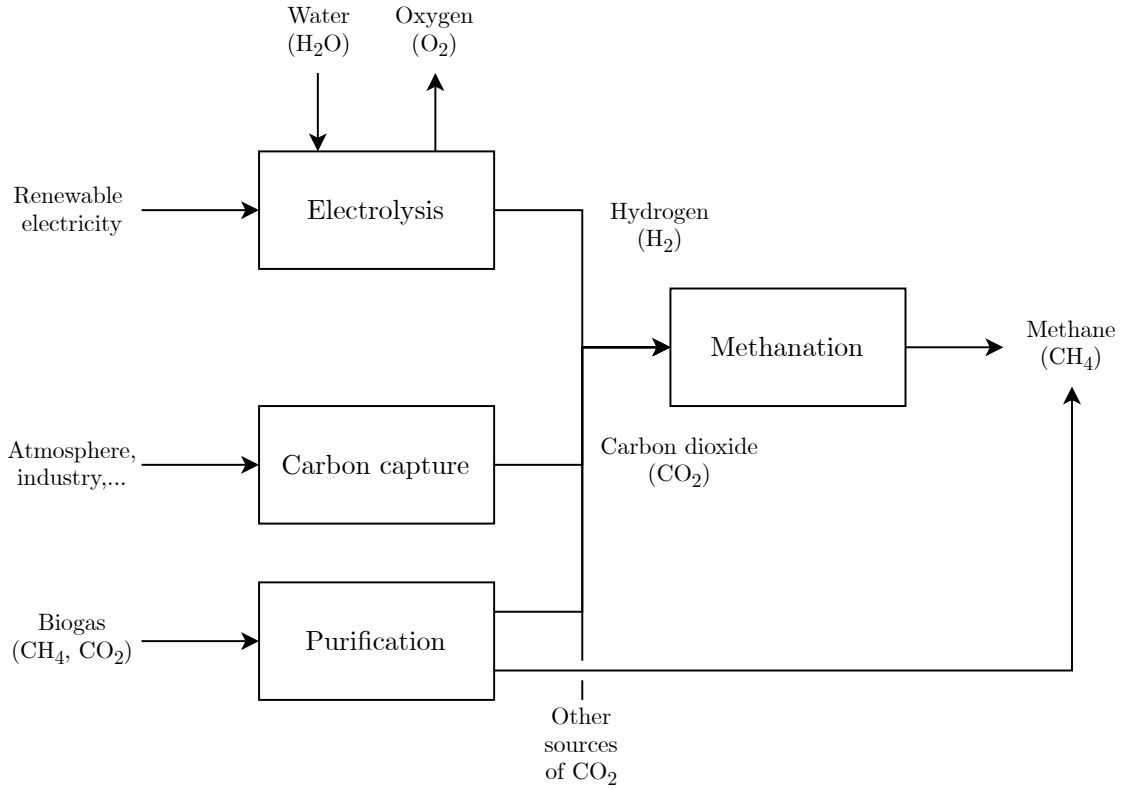


Figure 1.2: Simple schematic representation of green methane production. Renewable electricity is used to split water into hydrogen and oxygen. Carbon dioxide is obtained in numerous ways (capture, byproduct, ...). Hydrogen and CO_2 are then combined with each other via the methanation process to produce methane.

1.2.3 Ammonia

Production

The main way to produce green ammonia is by using the Haber-Bosch process. It converts H_2 , produced by electrolysis, and N_2 , obtained using an air separation unit, into NH_3 .



This equilibrium reaction is used for its synthesis (exothermic) and its decomposition (endothermic) [26]. Figure 1.3 gives a schematic representation of the production process of green NH_3 .

Usage

Ammonia has two main ways that it can be used to meet the demand of our society. First and foremost in the energy sector. Indeed, NH_3 can be used as fuel in internal combustion engines, gas turbines, furnaces and in fuel cells. It can also act as a hydrogen carrier, mostly during shipping, since NH_3 can more easily be compressed into a liquid than H_2 [28].

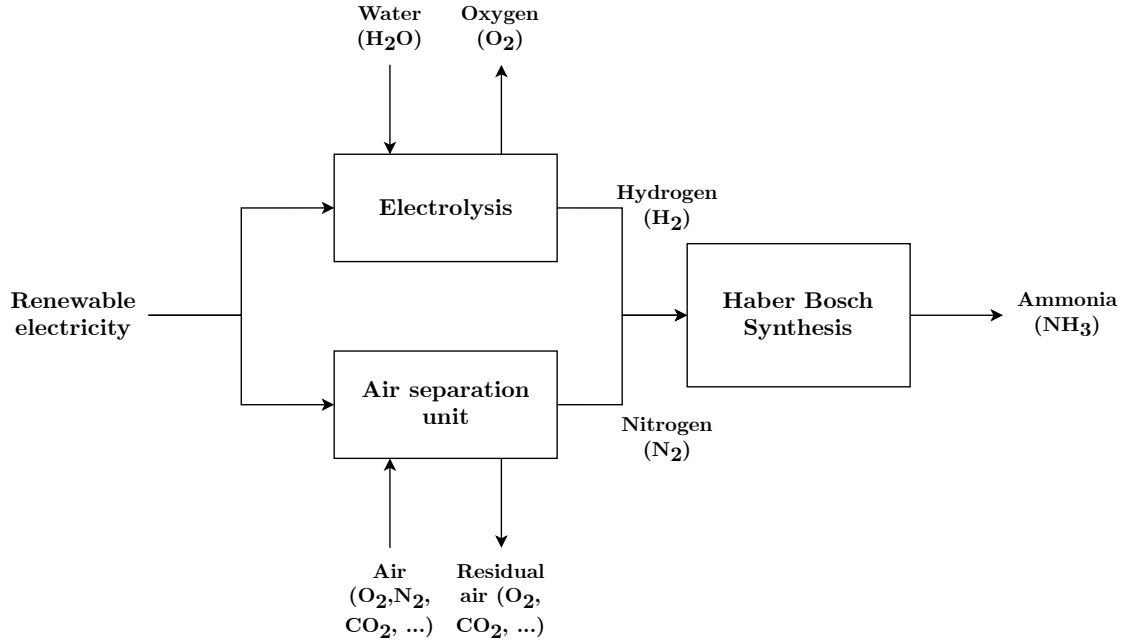


Figure 1.3: Simple schematic representation of green ammonia production, based on a figure given in [27]. Renewable electricity is used to isolate nitrogen from the air and to split water into hydrogen and oxygen. Hydrogen and nitrogen are then combined with each other, via the Haber Bosch Synthesis process, to produce ammonia.

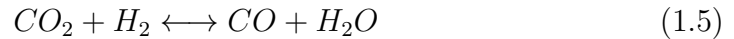
Secondly, there is a significant demand of ammonia for the NED. It is used for the production of fertilisers, but also for the synthesis of chemicals and plastics. Finally, NH_3 can also be used as a cleaning agent or in pharmaceuticals.

1.2.4 Methanol

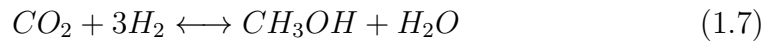
Production

Methanol is produced by CO_2 hydrogenation from green H_2 and CO_2 . The CO_2 is obtained in the same ways as for the synthesis of methane. The hydrogenation process is divided two steps [29]:

1. H_2 first reacts with CO_2 via an endothermic RWGS reaction to produce CO :



2. Then, the obtained carbon monoxide and the rest of the carbon dioxide reacts with hydrogen to produce methanol:



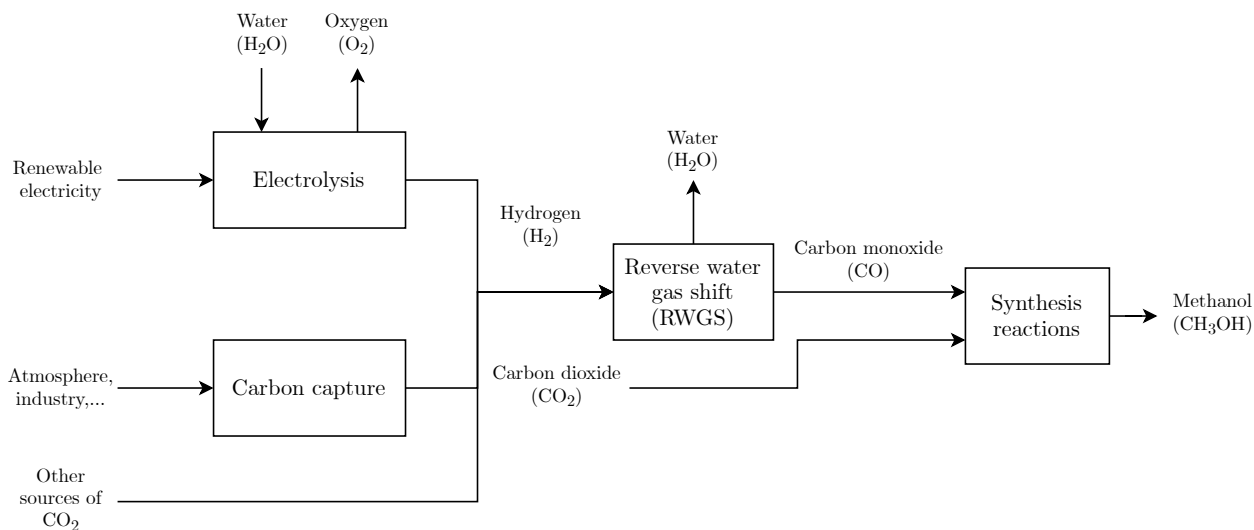


Figure 1.4: Simple schematic representation of green methanol production. Renewable electricity is used to isolate split water into hydrogen and oxygen. Hydrogen and captured CO_2 are then combined with each other, via a RWGS and synthesis reactions, to produce methanol.

Usage

Similarly to ammonia, it can be used as a fuel but mainly in the transport sector. Methanol can also be used to respond to the NED as a feedstock for the production of chemicals and plastics [30].

1.2.5 Other electrofuels

As mentioned before, other, more complex derivatives also exist. The main ones are represented in the blue rectangles of Figure 1.5. They are briefly discussed below.

Higher hydrocarbons, as e-kerosene, e-diesel or e-gasoline, can be produced with syn-gas (H_2 and CO) via the Fisher-Tropsch or methanol-to-hydrocarbons (ex. methanol-to-gasoline) processes. As their fossil counterparts, they could be used in, mainly, the mobility sector [31].

Another family, the ethers, is mainly constituted of DME (Dimethyl ether, CH_3OCH_3) and OME ($CH_3O(CH_2O)_nCH_3$). They are produced from methanol and have, also, potential use as automotive fuels [32, 33].

Finally, higher alcohols, as ethanol or butanol, are mainly used in the non-energy sector as solvents or to produce plastics [34].

3. By ship : The shipping process can be broken into different steps [19] (see Figure 1.6):

- (a) Transport by pipeline from the production to the export terminal.
- (b) Liquefaction or conversion into a carrier. Transporting hydrogen by ship costs a lot because it has a low density in gaseous form, thus it needs to be liquefied. Unfortunately, the liquefaction of hydrogen is an expensive process [36]. Another possibility, which is more commonly used, is to convert it into NH_3 or other energy carriers that can more easily be liquefied.
- (c) Storage at the export terminal.
- (d) Shipping via tanker ship.
- (e) Storage at the import terminal.
- (f) Gasification of liquid into gaseous H_2 or re-conversion by cracking the NH_3 into H_2 .
- (g) Transport by pipeline from the export terminal to the final destination.

This form of transport is mainly used for long distances, above $\pm 4000\text{km}$, and for all types of volumes.

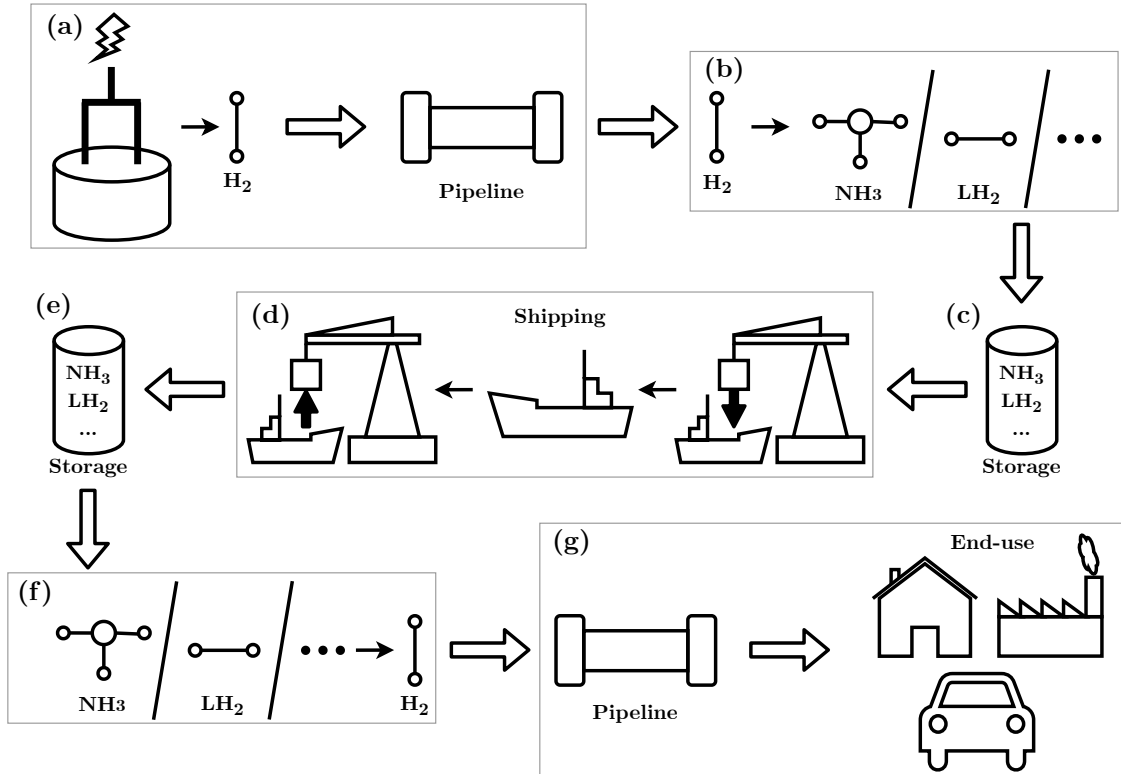


Figure 1.6: Schematic representation of the shipping process of hydrogen starting from its production to its end-use.

1.4 Description of EnergyScope TD

EnergyScope Typical Days is a cost-optimising model representing the whole energy system of a specific region for one year. Based on several input data, such as the weather conditions of the region, its EUD, the resources and the technologies, it aims to minimise the total cost of the system considering a global warming potential (GWP) limit. A wider description of the model is available in [37].

Model structure The model has several input data that interact together. First there is a *hourly weather database* to implement the Typical Days, which is explained later. Then, there are the *resources* that can be considered as the primary resources of the system. They can either come from the territory itself, such as solar energy, wet biomass and others, or be imported from abroad, such as imported electricity, electrofuels and others. They are characterised by their annual availability, cost and GWP. Those resources can be seen as the starting point of the model. The arrival point is given by the EUD, which is the predicted annual final energy demand. It is separated in different categories such as electricity, high and low temperature heat, freight and passenger mobility and the NED. *Technologies* take resources as input and convert them into other resources or into an EUD. The technologies are characterised by their investment and operating & maintenance cost, GWP of their construction and dismantling, lifetime, capacity factor and minimum and maximum installed capacity. Moreover, resources can be stored with *storage technologies*. These are characterised by their charge and discharge time, availability and losses.

The process of the model is divided into two main steps: the selection of the typical days, followed by the optimisation itself [37]. A schematic representation of the whole model is given in Figure 1.7.

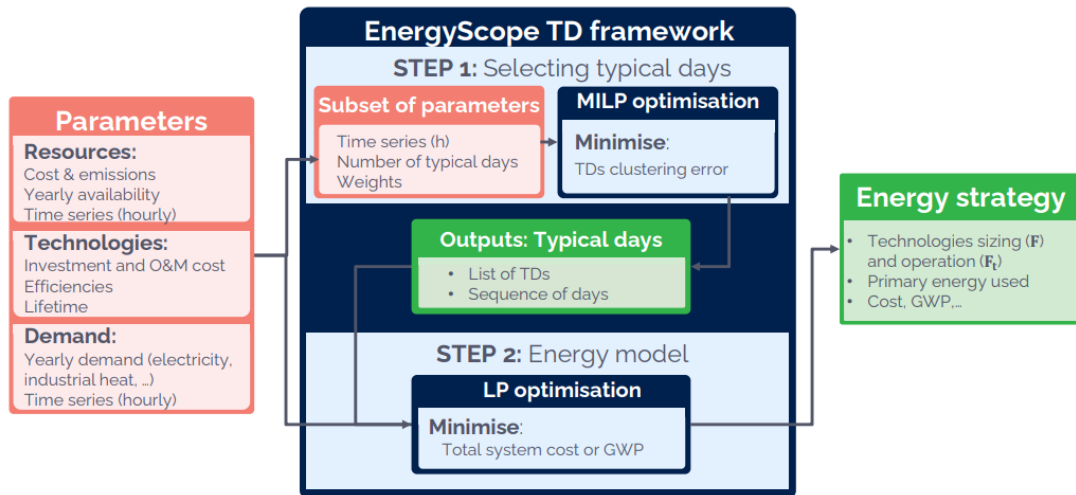


Figure 1.7: Schematic representation of EnergyScope TD [38].

Step 1: Selecting Typical Days The computational time to consider each minute, hour or even day in one year separately would be too important. Therefore, before the optimisation, 12 "typical" days are selected. This is done based on the hourly regional weather data of a specific year. Then, the typical days are assigned to each day of that year by similarity. The number of typical days (12) was chosen as a trade-off between having a relatively low computational time and a small error that appears due to this approximation.

Step 2: Energy model The second step of the model is the optimisation of the total annual cost. The objective function, that must be minimised, is given as follows:

$$\min C_{tot} = \sum_{j \in TECH} (\tau_j C_{inv}(j) + C_{maint}(j)) + \sum_{i \in RES} C_{op}(i) \quad (1.8)$$

where:

- $TECH$ and RES are sets including respectively the conversion technologies and resources,
- $\tau_j C_{inv}(j)$ is the annualised investment cost of technology j expressed in [M€],
- $C_{maint}(j)$ is the operating and maintenance cost of technology j expressed in [M€],
- $C_{op}(i)$ is the operating cost of resource i expressed in [M€].

The function is constrained by a GWP limit of the whole system that cannot be exceeded:

$$gwp_{limit} \geq \sum_{j \in TECH} \frac{GWP_{constr}(j)}{lifetime(j)} + \sum_{i \in RES} GWP_{op}(i) \quad (1.9)$$

where:

- gwp_{limit} is the maximum allowed amount of yearly emissions expressed in [ktonCO₂ – eq./year],
- $GWP_{constr}(j)$ is the amount of emissions due to the construction and dismantling of technology j expressed in [ktonCO₂ – eq.],
- $lifetime(j)$ is the lifetime of technology j expressed in [years],
- $GWP_{op}(i)$ is the amount of emissions due to resource i expressed in [ktonCO₂ – eq./year].

The model is built according to linear programming and ends up finding the cost-optimal design of the whole energy system.

1.4.1 Limitations of EnergyScope TD

According to [37], EnergyScope TD has different objectives: *"to be representative of a multi-sector urban or regional energy system accounting for all the energy demand and carriers; to allow the implementation of energy storage at different time scales; to facilitate the integration of new branches or promising technologies into the energy system; to allow high shares of intermittent renewable energies with an hourly time resolution and thus understand how the system deals with their intermittency; to have an acceptable computational time for uncertainty applications and interactive what-if analyses; to have a free and open-source code with a simple formulation to make it accessible to all and support education"*.

It is an optimisation model and not a predictive model. It gives the optimal energy system design with constraints assigned to it. The model focuses to minimise the system cost, without taking into account some parameters such as risk and failure, geopolitics and other environmental impacts. Policymakers can build on this type of model while adding other constraints beyond its scope. It should not be seen as a predictive model, but used for possible strategies concerning the investment in the design of future energy systems. Moreover, EnergyScope TD takes into account on an equal footing the different EUDs: the mobility, the power sector, the heating sector and the NED. Focusing more on one sector would increase the complexity and the computational time of the model. Then, the model was developed for high scale periods of time (annual scale) and spaces (national scale), which results sometimes in lack of precision. This makes it difficult to analyse at smaller scales such as the hourly variability of the market price and the focus on single buildings.

Chapter 2

Import analysis

As mentioned in the introduction, Belgium has a limited renewable energy capacity and will not produce electrofuels in sufficient quantities to supply its own demand. Importing electrofuels from countries with sufficient renewable resources is the most credible scenario for ensuring Belgium’s energy supply and is therefore the main subject of this study.

To include this scenario in EnergyScope TD, the cost and availability of the different electrofuels from the EC must be estimated. As mentioned earlier, the study focuses on the years 2030 and 2050, for which clear targets are set. To implement those years in EnergyScope TD annual values will be used.

2.1 Exporting countries

A previous study, made by the Hydrogen Import Coalition (HIC)¹ [39], has selected EC based on different criteria: a high capacity of low-cost renewable energy thanks to good solar irradiation and high wind potential, political stability and access to multiple seaports. Based on these considerations, five countries have been selected for Belgium: Spain (SP), Morocco (MO), Chile (CL), Oman (OM) and Australia (AU). In addition, Saudi Arabia (SA) [40] and Namibia (NA) [41] are also considered as Belgium has entered into MoUs (Memorandum of Understanding) with these countries for the supply of electrofuels. Not all of these countries will necessarily export to Belgium, but they constitute a representative sample on which the rest of the analysis can be based. It is important to keep in mind that the set of EC could include more and/or different countries depending on the political agreements that will be made in the following years.

¹Group of Belgian companies that have a focus on import and/or hydrogen.

2.2 Cost of importing electrofuels

Also based on the article published by the HIC, the types of electrofuels that can be imported are: hydrogen², methane, methanol and ammonia. The article estimates the cost for each of those electrofuels for the 5 selected EC in 2030 and 2050. The values are graphically displayed and expressed in terms of levelised cost of hydrogen (LCOH) in $\text{€}_{2020}/\text{MWh}_{H_2}$ in Appendix A.1. These graphics were used to extract³ the data of Table 2.1. The LCOH includes the costs due to the efficiency, CAPEX and OPEX of the electrofuels synthesis, shipping, local and remote conversions and storage.

For CH_4 and CH_3OH , the costs are given in a range of values since they depend on the cost of CO_2 required for their production. The latter can vary between $80 \text{ €}_{2020}/\text{t}$ and $160 \text{ €}_{2020}/\text{t}$.

Since Namibia and Saudi Arabia were not analysed by the HIC, their LCOH is found elsewhere. The African Climate Foundation [42] gives an estimation on the cost of 1 ton of NH_3 in 2030. The LCOH can then be deduced by converting the values into $\text{€}_{2020}/\text{MWh}_{H_2}$ (see Appendix A.2). The values of 2050 for Namibia and Saudi Arabia are estimated based on the relationships between the already known LCOHs of the other EC in 2030 and 2050 (see Appendix A.3).

Renewable electricity accounts for a significant proportion of these costs. Increasing the number of renewable electricity plants would, over time, reduce the LCOH.

Another main driver of these costs is the transport and storage. As mentioned in Section 1.3, repurposing natural gas pipelines for hydrogen distribution or oil infrastructures for the distribution of ammonia could reduce transport and storage costs. Further, over time, the electrolyser cost dynamics will also drop, making low carbon hydrogen production even more attractive [14]. This should be made possible by, first of all, the standardisation of electrolysers and other technologies, such as carbon capture. Secondly, the mass production of these technologies will help to reduce costs [14].

Moreover, it is interesting to note that as the costs of green H_2 will decrease over time, the ones of low-carbon hydrogen from natural gas with CCS are expected to increase in the future [12]. This suggests that from 2030 onward, the proportion of green and carbon-free H_2 in the market should increase.

²According to the HIC, hydrogen is assumed to be transported in liquid state except from Morocco and Spain, transported in gaseous state through pipelines.

³Using a WebPlotDigitizer : <https://apps.automeris.io/wpd/>

Table 2.1: LCOH of electrofuels that can be exported to Belgium, expressed in [$\text{€}_{2020}/MWh_{H_2}$]. Hydrogen can be transported in liquid form, $H_{2,l}$, by ship or in gaseous form, $H_{2,g}$, exclusively by pipeline (when possible). For the organic molecules, a range is given due to the possible variation of the cost of CO_2 required in their production.

	$H_{2,l}$	$H_{2,g}$	CH_4	CH_3OH	NH_3
2030					
Australia	125	/	95 - 110	80 - 98	73
Chile	101	/	89 - 104	75 - 93	66
Oman	92	/	85 - 100	75 - 93	69
Namibia	/	/	/	/	60
Morocco	90	80	85 - 100	77 - 95	63
Saudi Arabia	/	/	/	/	58
Spain	104	93	99 - 114	87 - 105	77
2050					
Australia	108	/	84 - 99	74 - 92	61
Chile	81	/	80 - 95	68 - 86	56
Oman	80	/	73 - 88	66 - 84	60
Namibia	/	/	/	/	52
Morocco	77	75	73 - 88	68 - 86	57
Saudi Arabia	/	/	/	/	48
Spain	82	78	86 - 101	79 - 97	65

2.3 Availability of exportable electrofuels

To date, electrofuels are only slightly present on the market. Indeed, as mentioned in Section 1.1.3, in 2019 95% of the global hydrogen was produced from fossil fuels. However, the demand for electrofuels will increase over the years [19], which means that the production capacities in the EC will have to increase as well. One must therefore rely on predictions, which are rather uncertain, to have an idea of their availability in the future. Moreover, Belgium, and more widely the EU, is not the only interested importer. It is thus necessary to estimate the fraction of the availability in the EC that could go to the EU and ultimately to Belgium.

This section covers two different methodologies to find availability values.

In a first instance, it is necessary to examine the announcements made by the EC as well as the existing or future agreements between Belgium, or the EU, and these EC. This can be considered as the **lower bound (LB)**, the minimum available quantity that can be imported from abroad. If there is a lack of information concerning the data, assumptions are made by considering more pessimistic or conservative values to respect the idea of the LB.

In a second instance, as the number of agreements is likely to increase in the next few years to meet greater demand [11], one should analyse the maximal availability in the EC. This value is obtained by considering their theoretical solar and wind potential. In the analysis this renewable potential is used as starting point, the final step being its fraction available for Belgium (expressed in $\text{TWh}_{H_2,eq}$). Based on the approach of the maximum amount importable, the **upper bound (UB)** can be defined, which cannot be exceeded and will likely never be reached. The reason why is detailed in Section 2.3.3.

2.3.1 Belgian share of the exports

A case-by-case study must be considered for each exporting country based on existing agreements or predictions. However, two steps are common for several cases, which are discussed before having a deeper look into each country. First, an assumption is made about the EU's share of the total quantity that can be exported from a country. Indeed, it is firstly considered that the import will be delivered to Europe as a whole. This is done because European countries will probably have similar hydrogen strategies in the future. For instance, the European commission has developed a plan to install and import green H_2 on the EU scale [23].

Then, the fraction from the EU available for Belgium is determined depending on the hydrogen import dependency of each European country, i.e. the fraction of the H_2 demand that needs to be met by imports.

The countries in competition with Europe to import electrofuels are considered in Table 2.2, issued by the IRENA. It represents the current, the predicted and the potential green hydrogen routes between exporters and importers, based on published strategies. For example : Australia has hydrogen routes connected with South Korea, Japan, Singapore and Europe.

Table 2.2: Current, planned or potential hydrogen routes [11], where China (CH), Korea (KR), Japan (JP), United States of America (USA) and Latin America (LATAM) are competitors of Europe (EU) on the global export market of electrofuels for the considered set of EC.

Exporter \ Importer	EU	CH	KR	JP	USA	LATAM	Only BE
Australia	X	X	X	X			
Chile	X	X	X	X	X	X	
Oman	X						
Namibia							X
Morocco	X						
Saudi Arabia	X	X	X	X			
Spain	X						

Now that the quantity of available exports to the EU can be estimated, there is a specific fraction γ_{BE} that is destined for Belgium. It is supposed that the fraction of H_2 imports of each European country is proportional to its hydrogen import dependency (ID) in 2030. This is defined as the difference between the total H_2 demand and the local H_2 production of each European country, given by Equation 2.1. In other words, it gives an idea of the green hydrogen importing demand of each country.

$$ID = E_{H_2, Loc. Demand} - E_{H_2, Loc. Prod.} \quad [TWh_{H_2}] \quad (2.1)$$

All the results of the hereunder mentioned computations are detailed in Appendix A.4. It gives a more detailed overview of the values of production, demand and ID of each European country.

Local demand The estimated demand takes into account the industry, transport, power and buildings sectors [19]. The values of H_2 demand for buildings are not directly specified in the above mentioned source, but a webinar [43] about that source indicates that buildings will be responsible for about 6,5% of the future H_2 demand.

Local production Equation 2.2 indicates how much hydrogen is produced by a certain country :

$$E_{electro} = \eta_{electro} \cdot P_{electro} \cdot CF \cdot 8760h \quad (2.2)$$

where :

- $E_{electro}$ represents the total H_2 production of a country in one year, expressed in TWh_{H_2} .
- $\eta_{electro}$ represents the efficiency of the electrolyzers. To simplify our model, only alkaline electrolyzers are considered. Their efficiency is set at 73% [44].
- $P_{electro}$ represents the installed power of electrolyzers in the considered country, expressed in GW_{H_2} .
- CF represents the capacity factor of the electrolyser. Electrolyzers are the most cost effective at a capacity factor of 35% [18]. Thus, it is assumed that the countries would only install electrolyzers if they can feed them with enough renewable energy to be able to reach a capacity factor of 35%.

The demand and local production being known, the ID, given by Equation 2.1, can be computed for each country of the EU⁴.

⁴Note : Spain is announced to produce 6.4 GW by 2030, but will export 4 GW to other European countries (more information about that in Section 2.3.2), thus only 2.4 GW will be available for local use.

Belgian share γ_{BE} From the total European imports, a small share will go to Belgium. This fraction is estimated as follows:

$$\gamma_{BE} = \frac{ID_{BE}}{\sum_X ID_X} = 6.6\% \quad (2.3)$$

where the denominator represents the sum of the ID of all European countries. This fraction, computed with predictive values of 2030, is also assumed to remain the same in 2050. Figure 2.1 shows the total demand for hydrogen in each EU country and identifies the share that is met by local production and that needs to be imported.

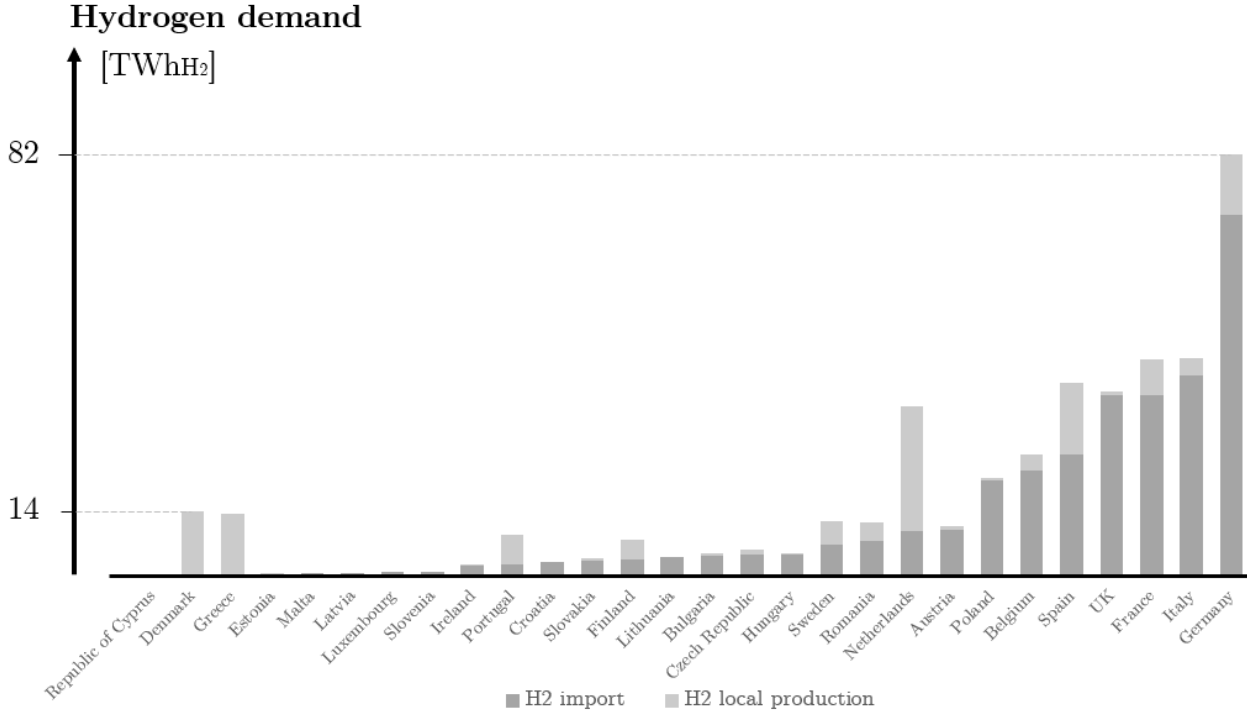


Figure 2.1: Total H_2 demand of each EU country + UK and the part that is met by the local production and by the imports in 2030.

2.3.2 Lower bound - Availability based on current announced political ambitions

Australia

The availability of electrofuels imported from Australia is based on a research done in the Acil Allen Report (AAR) [45] to inform the Australian government. It gives the predicted quantity of green hydrogen that will be exported in 2030 and 2040 to different parts of the world. The AAR predicts that Australia will mainly export to China, Japan, Singapore and Korea. A small part will also go to what is called "The Rest of the World". According to Table 2.2, that part will be destined to EU only. Three scenarios are mentioned in the report: a pessimistic one, a reference one and an optimistic one. To respect the idea of the LB, the pessimistic scenario is chosen for this study. However, the AAR gives no information about 2050. A study

made by PWC Australia [46] shows that the quantity of green hydrogen available for export will increase by a factor of ± 5.3 between 2040 and 2050. This factor is used, combined with data previously found in the AAR, to obtain the availability for the EU in 2050. Finally, the fraction γ_{BE} allows to determine the availability for Belgium. Table 2.3 shows these values.

Table 2.3: Australia export availability.

		2030	2050
Green H_2 [TWh $_{H_2}$]	EU	0.139	3.53
	BE	0.009	0.234

Chile

The Ministry of Energy of Chile has published an article about its strategy to export green hydrogen and green ammonia globally [47]. It contains the total revenues obtained with the exports to the different continents for several years until 2050. The total availability of electrofuels is computed with Equation 2.4.

$$E_{H_2,eq} [TWh] = \frac{R_{EU}}{P_C} \cdot LHV \quad (2.4)$$

where:

- R_{EU} represents the revenues thanks to exports to Europe [USD].
- P_C is the production cost, announced by the Ministry of Energy of Chile to be 1.5 [USD/kg $_{H_2}$] by 2030. According to the HIC, the production costs of H_2 and NH_3 in Chile are very similar, both in 2030 and 2050. The production cost of NH_3 is thus assumed to be 1.5 [USD/kg $_{NH_3}$] as well.
- $LHV_{H_2} = 33.33 \cdot 10^{-9}$ [TWh $_{H_2}$ /kg $_{H_2}$] and $LHV_{NH_3} = 5.25 \cdot 10^{-9}$ [TWh $_{NH_3}$ /kg $_{NH_3}$] are factors that ensure the conversion from kg to TWh for each fuel [48].

To express quantity into a reference unit, the TWh $_{NH_3}$ are converted into TWh $_{H_2,eq}$ according to the conversion factors given in Appendix A.2. The final values are summarised in Table 2.4.

Table 2.4: Chile export availability.

		2030	2050
Green NH_3 [TWh $_{NH_3}$]	EU	3.93	9.32
	BE	0.26	0.62
Green H_2 [TWh $_{H_2}$]	EU	3.06	149.90
	BE	0.2	9.94
$H_{2,eq}$ [TWh $_{H_2,eq}$]	EU	7.49	160.44
	BE	0.5	10.64

Oman

Oman announced a capacity of electrolyzers of 1GW by 2025, 10GW by 2030 and 30GW by 2040 [49]. Due to lack of information and to respect the idea of the LB, it is assumed that the production will not increase between 2040 and 2050.

The predictions concern blue and green H_2 . Unfortunately, no distinction is made on the total production, so it is not possible to know what share of the hydrogen production will be green. In this case, a first exception is made and importing blue hydrogen is tolerated and assumed to be carbon neutral.

According to Table 2.2, Oman only delivers to Europe.

By considering the same capacity factor ($CF_{elec} = 35\%$) and efficiency ($\eta_{elec} = 73\%$) of the electrolyzers as mentioned before, and using Equation 2.2, the total exports from Oman to Europe can be derived. Table 2.5 gives an overview of the availability for respectively the EU and Belgium, in 2030 and 2050.

Table 2.5: Oman export availability.

		2030	2050
Green and blue H_2 [TWh $_{H_2}$]	EU	13.5	40.51
	BE	0.9	2.69

Spain

By 2030, Spain aims to install 6.4 GW of electrolyzers to produce green hydrogen [19], 4 GW being fully provided to Europe [50]. As is done for Oman, the CF and η_{elec} are taken into account to obtain the total importable electrofuels (see Equation 2.2). Spain will not be able to export anymore in 2040 since its green hydrogen production will be insufficient for its auto-supply [11]. The final green hydrogen available from Spain for Europe and Belgium is summarised in Table 2.6.

Table 2.6: Spain export availability.

		2030	2050
Green H_2 [TWh $_{H_2}$]	EU	8.95	0
	BE	0.59	0

Morocco

An article published by the government of Morocco [51] estimates the total green hydrogen exports for the coming years. It makes a distinction between a reference case and an optimistic case. To stay conservative, the reference case is selected for this study. According to Table 2.2, it can be assumed that Morocco will only export to Europe. The final availabilities are represented in Table 2.7.

Table 2.7: Morocco export availability.

		2030	2050
Green H_2 [TWh $_{H_2}$]	EU	10.3	114.7
	BE	0.68	7.6

Namibia

An agreement has been made between the governments of Namibia and Belgium on the production and export of green ammonia [41]. By 2026, Namibia should be able to produce annually 1 million tons of green ammonia⁵. Half of this will be exported to Belgium only (it is supposed that it will not be redistributed among the other EU countries). Since no further information has been found, it is assumed that the availability will be the same in 2050 to respect the LB as such. The quantities are represented in Table 2.8.

Table 2.8: Namibia export availability.

		2030	2050
Green NH_3 [TWh $_{H_2,eq}$]	BE	3	3

Saudi Arabia

Being currently one of the main exporters of crude oil [52], Saudi Arabia will export a mix of green and blue hydrogen in the future [53]. The country announces that it could export 2.9 and 4 million tons of H_2 by 2030 and 2035 respectively. There are no details on the part of green H_2 in this mix. Thus, a second and last exception is made and the supply of blue hydrogen from Saudi Arabia is assumed to be carbon neutral. Again, due to lack of information, the quantity in 2050 is assumed to be the one in 2035.

Saudi Arabia will mainly export to Asian countries as Japan and South Korea but also to Europe. Since no clear subdivision of the destination of the exports is made, a 50/50 split is assumed.

⁵An employee of the company in charge of the project, CMB, has highlighted an error in the source. Indeed, Namibia will produce 1 million tons of ammonia instead of hydrogen, as was announced by the press article.

As shown in Table 2.1, only the LCOH of NH_3 is known. Thus, one assume that only ammonia will be imported from Saudi Arabia. Table 2.9 summarises the final availabilities.

Table 2.9: Saudi Arabia export availability.

		2030	2050
Green and blue NH_3 [TWh $_{H_2,eq}$]	EU	48.33	66.66
	BE	3.2	4.42

Overview

Figures 2.2 and 2.3 display the LCOH and availability of each country ranked by cost. Since the LCOH of NH_3 is the only one known for all EC, that case is considered. As a reminder, Namibia and Saudi Arabia will only export in the form of ammonia. The figures show that Belgium will primarily import NH_3 from Saudi Arabia (cheapest) and lastly from Spain or Australia (most expensive), depending on the year. A maximum of 8.85 and 28.55 TWh $_{H_2,eq}$ can be imported in 2030 and 2050 respectively. Those values are well under the predicted demands for Belgium (see Section 1.1.3): 20.5 and 100 TWh $_{H_2,eq}$ for 2030 and 2050 respectively. The first and most obvious conclusion that can be taken is that, at this point, Belgium will not import enough electrofuels to meet its demand. To solve that, solutions will be discussed in Section 3.5, such as considering more EC or decreasing the EUD.

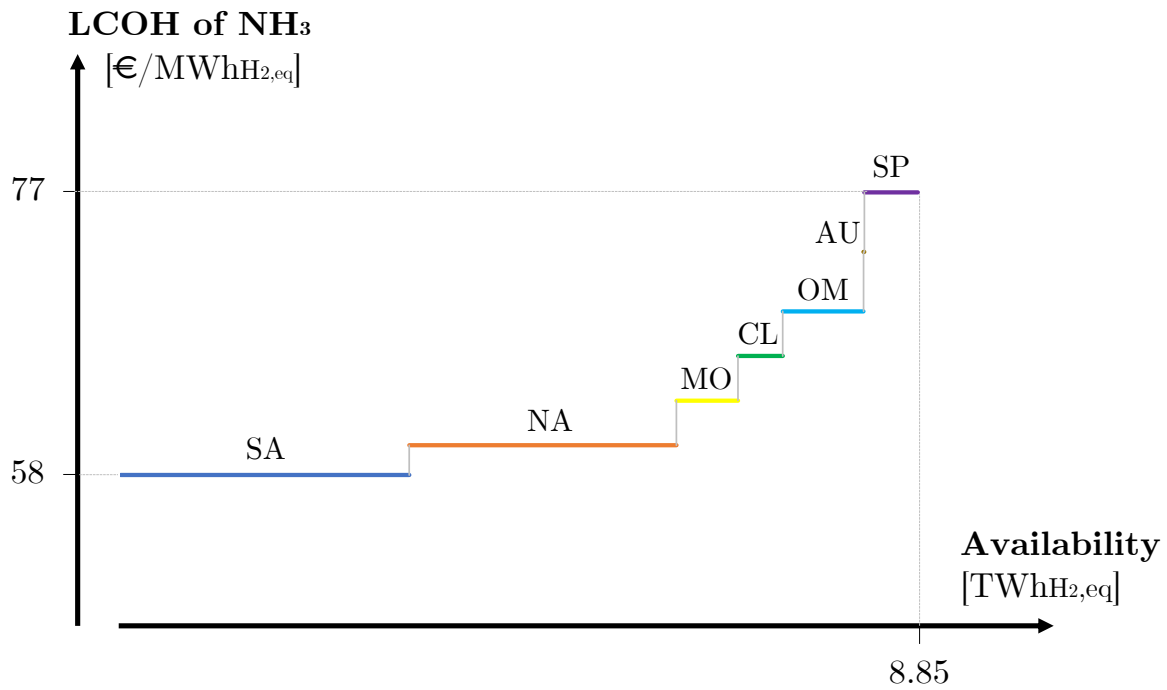


Figure 2.2: LCOH of NH_3 and share of the availability from the EC to Belgium in 2030, expressed in $H_{2,eq}$. Belgium will firstly import NH_3 from Saudi Arabia, cheapest, and lastly from Spain, most expensive.

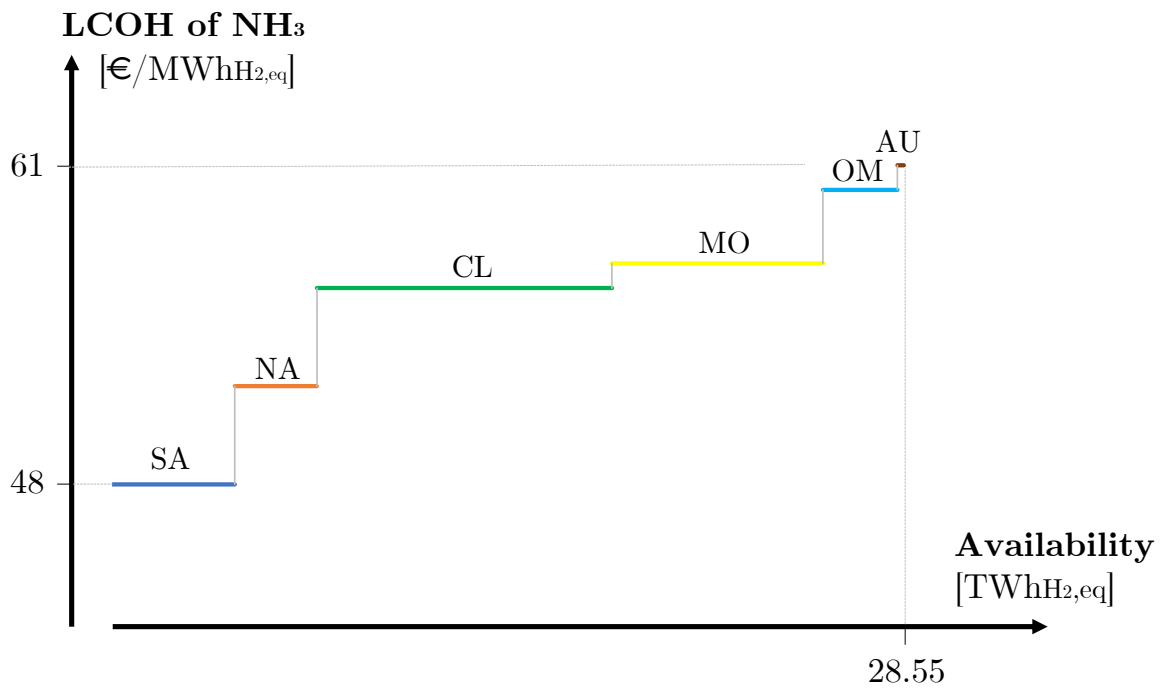


Figure 2.3: LCOH of NH_3 and share of the availability from the EC to Belgium in 2050, expressed in $H_{2,eq}$. Belgium will firstly import NH_3 from Saudi Arabia, cheapest, and lastly from Australia, most expensive.

2.3.3 Upper bound - Availability based on the renewable energy potential

This section describes the maximum importable electrofuels assuming that all the renewable potential of each exporting country is used. It constitutes the UB on the quantity of imports of electrofuels and cannot be exceeded.

Before getting to the heart of the matter, it is important to bear in mind the following : the values in question represent a maximum capacity for renewable energy production and will most likely never be reached. This is explained by the fact that it is physically not possible to install all those windmills, PV panels and CSPs needed to reach the potential by 2030 or even 2050. For example, in 2020 Australia generated about 65 TWh of renewables and its yearly increase is about 5 to 10 TWh [54]. This means that to reach its potential it would have to multiply its annual growth by a factor of approximately 180. This can clearly not be considered.

In addition to that, the countries decide at what pace they want to increase their renewable production, the reachability of the UB thus depends on the decisions made by the EC. Hence, it can be concluded that the UB is a theoretical state that will not be reached in the near future, and even not in 2050.

Hypotheses on the renewable potential

The values of renewable potentials used were determined by Dupont et al. [55, 56]. The main constraints and assumptions made in the paper are listed below:

- Onshore and offshore wind, and solar energy are considered
- Wind potential [55]:
 - A suitability factor is considered: it takes into account the technical and geographical constraints.
 - A minimal EROI (Energy Return On Investment) is imposed on the installed capacity.
 - The potential is computed considering a local CF and taking wake effects of multiple turbines into account.
- Solar potential [56]:
 - A suitability factor is considered: it takes into account geographical constraints.
 - PV and CSP (Concentrated Solar Power) technologies are considered.
 - A minimal EROI is imposed on the installed capacity.

From abroad renewables to Belgian electrofuel imports

Local demand By definition of the UB, it is assumed that all the EC will attain their renewable potential. In this scenario, it is assumed that the local demand of these countries is met by their renewables. This local demand is expected to increase in the coming years, but not at the same rhythm in every part of the globe. The WEC [57] estimated these increases between 2010 and 2050 considering different areas of the world. The increasing demand factor (IDF) is defined as follows:

$$\text{IDF} = \frac{CD_{2050}}{CD_{2010}} \quad (2.5)$$

where CD_{2010} and CD_{2050} correspond to the demand of the area in 2010 and 2050 respectively. Table 2.10 displays these values for the areas that include the EC. Two scenarios were assumed in the study: the first one, called Jazz, where the goal is to achieve individual access and affordability of energy, and the second one, called Symphony, where the focus is set on achieving environmental sustainability. Since both are plausible, the mean of the projected values of those scenarios is chosen. Once the primary energy demand of the countries of interest for 2010 is determined [58], it is multiplied by its corresponding IDF to obtain the local demand for 2050. The 2030 demand is then interpolated (linearly) between those 2 values. The EC have a higher renewable potential than their local energy demand, except for Spain. This excess in renewables is obtained by subtracting the total energy demand from the renewable potential. Since Spain will not have a surplus of renewables to export, the value of its UB is assumed to be the same as the one given in the LB. Indeed, it would be contradictory to have a greater value in the LB than in the UB. Furthermore, Spain has announced that it will export electrofuels in 2030 which cannot be denied.

Table 2.10: Increasing demand factor of the areas of interest that include at least one of the selected EC. The areas considered are the following: Europe (EU), Oceania (OCE), Latin America (LATAM), North Africa (N. AFR) and South Africa (S.AFR).

	EU	OCE	LATAM	N. AFR	S. AFR
Countries of interest	SP	AU	CL	MO, OM & SA	NA
IDF	1.03	1.95	2.03	1.97	2.09

Conversion into electrofuels All the excess of renewable energy is assumed to be completely converted into electrofuels, expressed in $H_{2,eq}$. It is considered that the countries will be able to undertake the conversions via electrolyzers locally. The efficiency of these electrolyzers is still considered to be 73%.

Share available to Belgium To determine the Belgian share of these exports, the European share must be defined first. This fraction is assumed to be the same as for the LB analysis. In the case of Namibia and according to The African Climate Foundation [42], this share corresponds to 25% of the total electrofuel exports.

Similarly as for the LB, the Belgian share of the EU imports is found by multiplying the latter by γ_{BE} , defined in Subsection 2.3.1.

Overview Table 2.11 displays the final Belgian shares of the total abroad potential of the selected EC. An extended version of this table, with values of demand, $H_{2,eq}$ production potential and European shares of exports, is given in Appendix A.5. Figure 2.4 shows a schematic overview starting from the initial renewable potential of the EC, to the final available electrofuels for Belgium.

Table 2.11: For each exporting country the following elements are quantified for the years 2030 and 2050: The total renewable potential [TWh_{elec}], including solar as well as on- and offshore wind, and the Belgian share of the associated potential exports of electrofuels expressed in [$TWh_{H_{2,eq}}$]. An extended version of this table is given in Appendix A.5.

	AU	CL	OM	SP	MO	NA	SA	TOT
Potential renew.	53,820	2,520	2,860	1,680	1,700	4,970	12,540	80,090
2030 BE share	50	50	120	0.6	70	60	215	565
2050 BE share	125	35	115	0	65	60	185	585

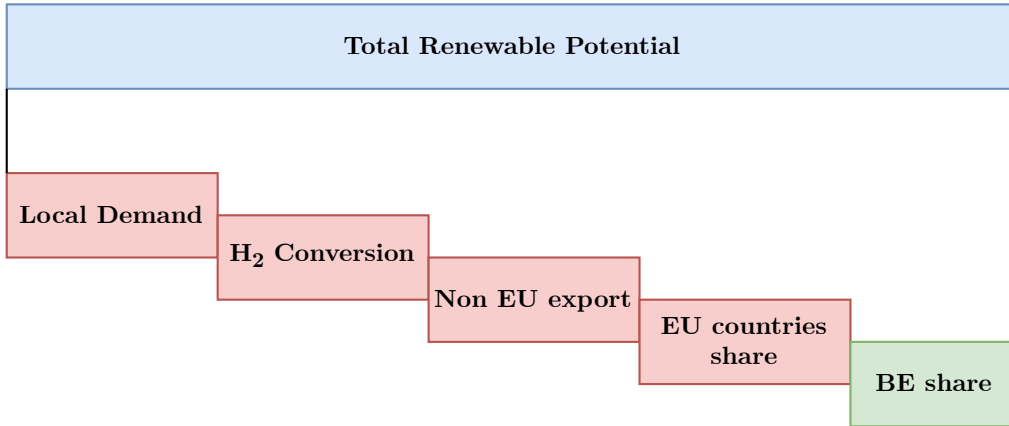


Figure 2.4: Schematic overview on the subdivision of the total renewable potential of an EC. From the total renewable potential, a first part is supposed to be used by the country itself to satisfy its local demand. Then, a part of it will be lost in the electrolyzers to convert the electricity into hydrogen. All this surplus will be exported and sometimes only a part of it will go to Europe. Finally, from that share, only a small part will go to Belgium.

As mentioned at the start of this analysis, it is wrong to conclude that there will be much more electrofuels available than in the lower limit scenario. The UB will probably never be reached and if it is, it will not happen by 2050.

Now that the costs and the LB and UB availabilities of each EC are determined for the years 2030 and 2050, case studies can be carried out. The next section will describe those and discuss the results.

Chapter 3

Case studies

This chapter covers different scenarios based on the electrofuels availability intended for Belgium in the EC previously identified. EnergyScope TD was used to compute the cost-optimal outcomes for the different input data such as GHG emission limits (cfr. 2030 and 2050 targets), and the cost and availability of the electrofuels. Changes to EnergyScope TD are detailed in Appendix C.

First, a global idea of the electrofuel demand in 2030 and 2050 is studied. This is done by considering, in EnergyScope TD, an infinite amount of electrofuels available at costs of the same order of magnitude as found in Section 2.2. Then, case studies are made for 2030 and 2050 respectively, comparing availabilities based on the LB and UB methodologies. Finally, possible alternatives are discussed in case of lack of electrofuel supply.

3.1 Predicted electrofuel demand

The approach estimates how much electrofuels Belgium would use if it was not limited in its supply. To do so, EnergyScope TD does not constrain the availability of electrofuels, and considers their cost to be of the same order of magnitude as in Section 2.2. At this stage no distinction is made between the different EC.

Figure 3.1 shows an increase of the demand expected between 2030 and 2050, with $65 \text{ TWh}_{H_2,eq}$ and $204 \text{ TWh}_{H_2,eq}$ annual import respectively. These quantities are well below the $565\text{--}585 \text{ TWh}_{H_2,eq}$ available thanks to the renewable potential (UB) in the EC. However, they are well above the $8.8 \text{ TWh}_{H_2,eq}$ and $28.5 \text{ TWh}_{H_2,eq}$ available in the LB in 2030 and 2050 respectively. Following sections will discuss the EnergyScope TD response facing this shortage. However, in some cases there may be no alternatives to electrofuels for the model to converge towards its GHG targets. Sometimes electrofuels are the only green solution to meet a given demand. For this reason, expensive virtual electrofuels, in infinite quantities, are added to what is available in each exporting country. They are implemented with the sole aim that EnergyScope TD uses them in case of absolute necessity, to be able to converge

to a solution. Their cost is set higher than that of other resources, with a factor of three over the highest cost of the available electrofuels (all EC considered). Also, it is important to note that the costs of the electrofuels (the available and the virtual) do not change between the LB and UB simulations of a same year.

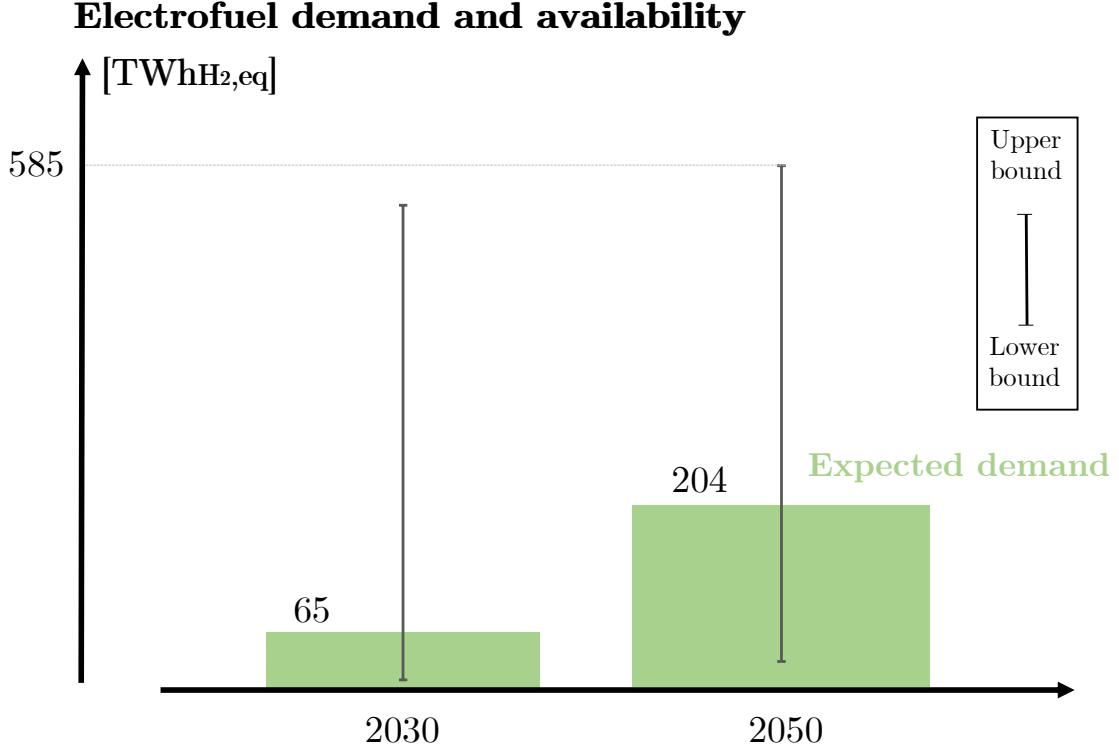


Figure 3.1: Predicted electrofuel demand of Belgium in 2030 and 2050. 65 TWh_{H₂,eq} are expected in 2030 and 204 TWh_{H₂,eq} in 2050, which is much more than what is available according to the LB.

3.2 2030, a first step in the transition

As a reminder, the EU has a target in 2030 to reduce its emissions by 55% compared to 1990 (47.45 MtCO₂-eq./year). The Belgian government has taken the decision in March 2022 to extend by 10 years Doel 4 and Tihange 3, for a total of 2.1 GW [59]. This has been integrated in the model.

Two case studies are made: one on the LB and another on the UB. This makes it possible to study the two extreme cases. All data concerning the simulations were defined in Chapter 2.

3.2.1 Lower bound (LB)

As expected, all the electrofuels available from the EC, which corresponds to a total of $8.8 \text{ TWh}_{H_2,eq}$, are imported in this case. Furthermore, as shown in Figure 3.2, $2 \text{ TWh}_{H_2,eq}$ of virtual electrofuels (indicated as "Extra") are used. This means that, to converge, the model needs to pay more to have enough electrofuels. All imports are in the form of ammonia. The whole ammonia imported in this case is to supply the NED.

The overall cost of the system is about 51 b€. To give an idea of this order of magnitude, the GDP (gross domestic product) of Belgium was estimated at 515 b€ in 2020 [60]. The whole energy system cost is in this case influenced by the cost of the expensive virtual electrofuels, which was assumed arbitrarily (cfr. Section 3.1). However, only $2 \text{ TWh}_{H_2,eq}$ of the virtual electrofuels are imported. This corresponds to an increase of 0.5 b€ compared to the case if the $2 \text{ TWh}_{H_2,eq}$ were imported at a cost of the "less expensive" ones. Therefore, the cost of the expensive virtual electrofuels does not affect significantly the total cost, and 51 b€ is kept as reference. A cost comparison is discussed in Subsection 3.2.3.

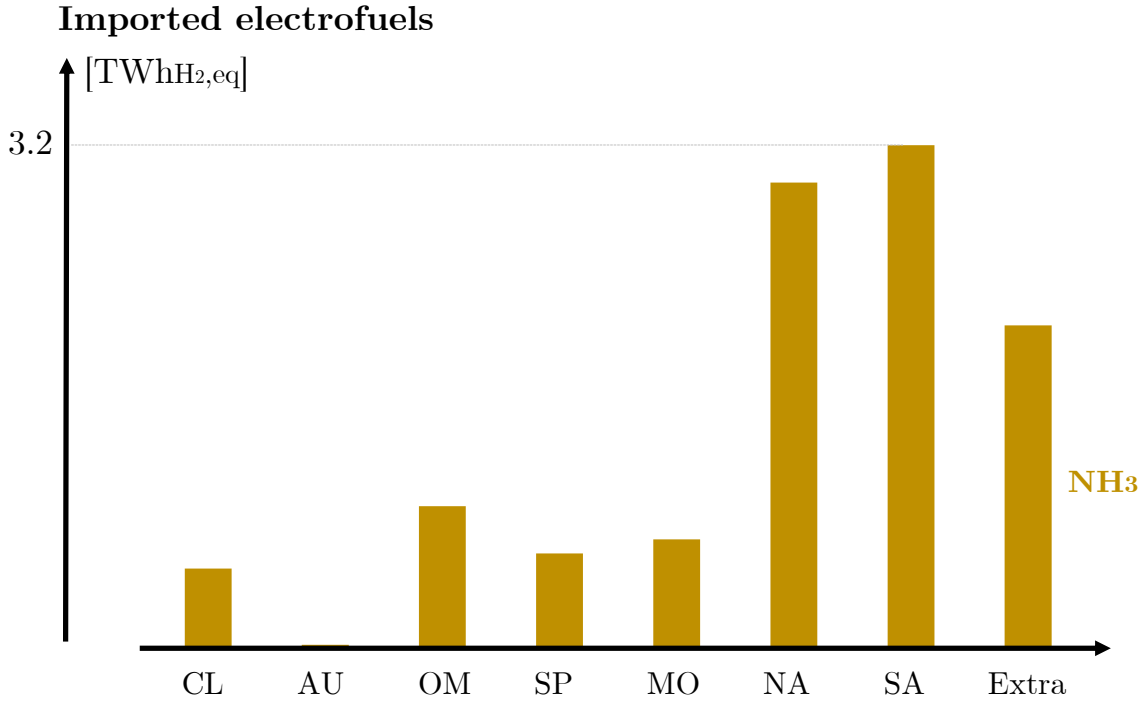


Figure 3.2: Electrofuels imported in 2030 constrained by the LB. Ammonia is imported from all EC: Chile ($0.5 \text{ TWh}_{H_2,eq}$), Australia ($0.01 \text{ TWh}_{H_2,eq}$), Oman ($0.9 \text{ TWh}_{H_2,eq}$), Spain ($0.6 \text{ TWh}_{H_2,eq}$), Morocco ($0.7 \text{ TWh}_{H_2,eq}$), Namibia ($3.0 \text{ TWh}_{H_2,eq}$) and Saudi Arabia ($3.2 \text{ TWh}_{H_2,eq}$). Moreover, extra expensive electrofuels are required ($2.1 \text{ TWh}_{H_2,eq}$).

3.2.2 Upper bound (UB)

From the $565 \text{ TWh}_{H_2,eq}$ available, only $68 \text{ TWh}_{H_2,eq}$ are imported. Figure 3.3 shows that, in this case, electrofuels are imported from only a few countries. This is explained by the fact that EnergyScope TD will prefer to import from the exporting country where the concerned electrofuel is the cheapest. Indeed, when referring to Table 2.1 that compares the LCOH by electrofuel and country, it appears that hydrogen is the cheapest in Morocco, ammonia in Saudi Arabia and methanol in Chile and Oman. EnergyScope TD has chosen to import most of the methanol from Oman. The model could also have chosen to import methanol from Chile. However, this does not change anything for the optimisation as it aims to minimise the cost. Furthermore, hydrogen is the cheapest in Morocco since it can be transported by pipelines. No local electrofuel conversion technologies are considered by EnergyScope TD. This means that it is cheaper for the model to import an electrofuel in its requested state, rather than importing another one and then convert it where it is consumed.

The total cost of the system is about 48 b€. The $68 \text{ TWh}_{H_2,eq}$ of imported electrofuels cost 5 b€ to the system.

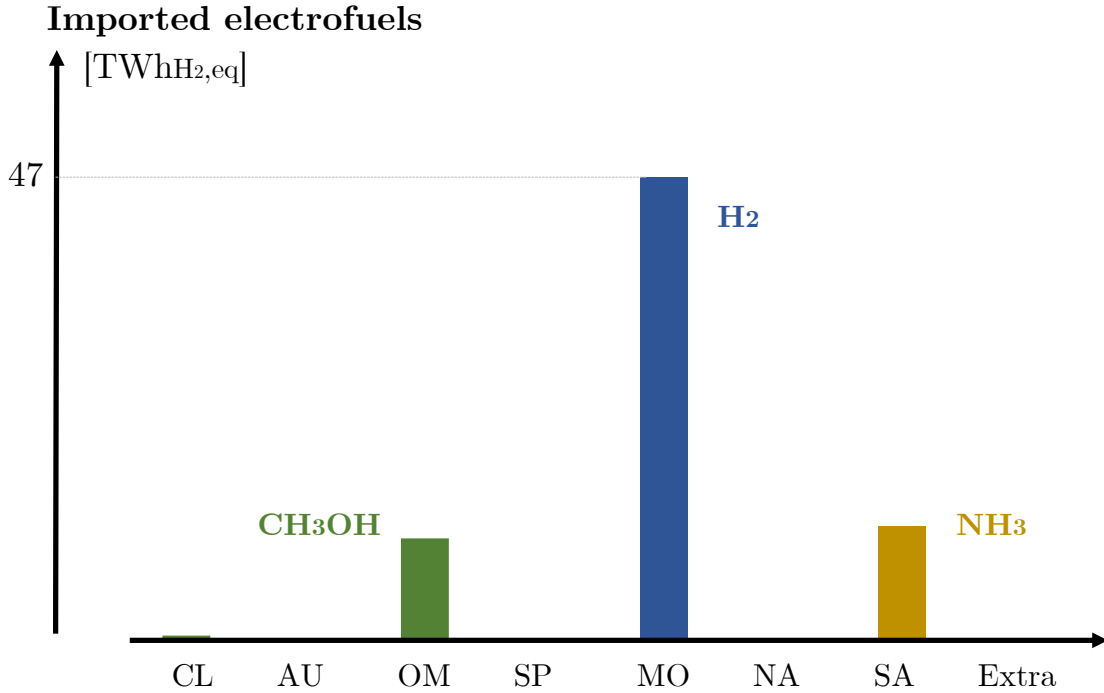


Figure 3.3: Electrofuels imported in 2030 constrained by the UB. Methanol is imported from Chile ($0.3 \text{ TWh}_{H_2,eq}$) and Oman ($10.1 \text{ TWh}_{H_2,eq}$), hydrogen from Morocco ($46.5 \text{ TWh}_{H_2,eq}$) and ammonia from Saudi Arabia ($11.3 \text{ TWh}_{H_2,eq}$).

3.2.3 Overview

Previous scenarios have quite different outcomes. The LB scenario reaches its total electrofuel availability and must even use virtual electrofuels to converge. On the other hand, the UB scenario is far from its availability. A difference of 57 TWh_{H₂,eq} of electrofuels is observed between the two scenarios, as illustrated in Figure 3.4. The LB case must compensate for this huge gap with alternative resources in order to meet the same demand as the UB case. This is covered more in detail in Subsection 3.5.1.

Furthermore, the resources and technologies used to compensate the lack of electrofuels in the LB case study are more expensive than the one used in the UB (otherwise EnergyScope TD should have preferred those even for the UB). This results in a considerably higher total cost of the system. Indeed, the LB has an annual total cost of about 51 b€, while the one in the UB case is about 48 b€. This means an increase of 6% which is not negligible.

The main conclusion for 2030 is that, in the LB scenario, the model needs 2 TWh_{H₂,eq} of virtual electrofuels to converge. However, it needs 68 TWh_{H₂,eq} in total to be cost-optimal. Because they are not available in the LB scenario, alternative resources and technologies are required to compensate for this lack. This has a substantial consequence on the cost of the system.

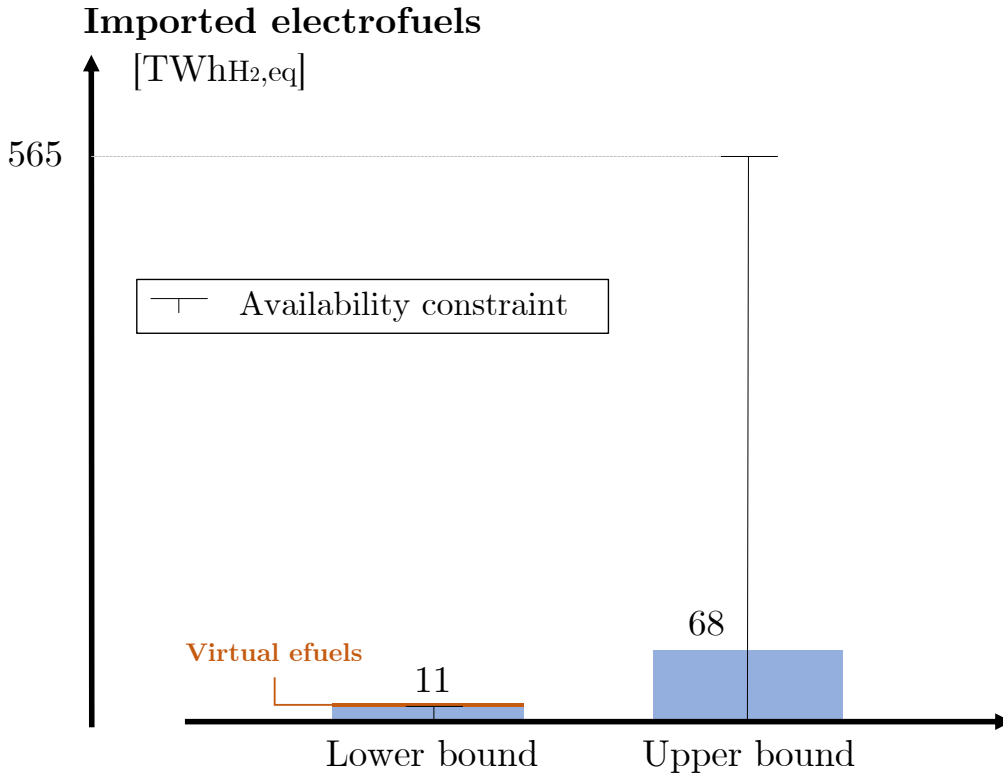


Figure 3.4: Comparison of electrofuels imported in 2030 constrained by the LB and the UB. For the LB 11 TWh_{H₂,eq} are necessary from which 2 TWh_{H₂,eq} are virtual. The UB requires 68 TWh_{H₂,eq}.

3.3 2050, a decarbonised Belgium

As a reminder, the EU has to be fully decarbonised in 2050. Due to limitations of EnergyScope TD, the authorised limit in GHG emissions is assumed to be at 5% of the ones in 1990 (5.27 MtCO₂-eq./year). Like for the 2030-scenario, two case studies concerning the LB and UB are covered.

3.3.1 Lower bound (LB)

When constrained by the LB, the model rapidly depletes its electrofuel supply and is required to get the expensive virtual ones, as shown in Figure 3.5. It means that to converge, it is forced to pay a lot for these virtual resources, for which no alternatives exist. At least 125 TWh_{H₂,eq} in addition to the 28.5 TWh_{H₂,eq} available must be found to reach the target of 2050. Imported electrofuels are used without being converted where they are consumed. This means that they are imported in their required state.

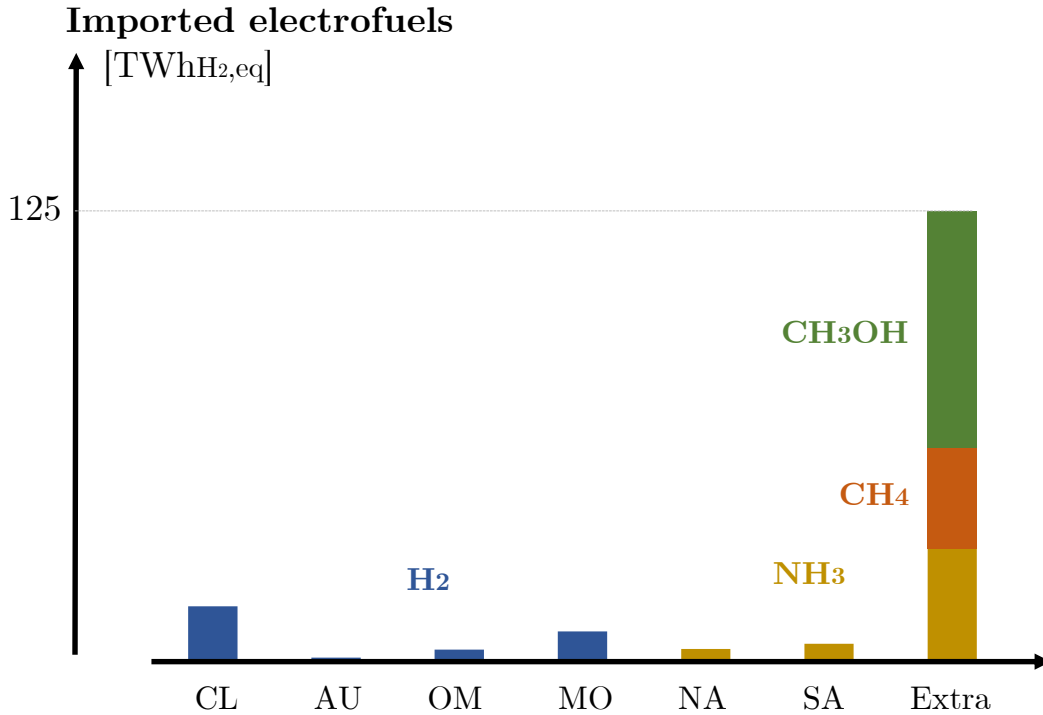


Figure 3.5: Electrofuels imported in 2050 constrained by the LB. Hydrogen is imported from Chile (10.6 TWh_{H₂,eq}), Australia (0.2 TWh_{H₂,eq}), Oman (2.7 TWh_{H₂,eq}) and Morocco (7.6 TWh_{H₂,eq}). Ammonia is imported from Namibia (3.0 TWh_{H₂,eq}) and Saudi Arabia (4.4 TWh_{H₂,eq}). Extra expensive electrofuels are necessary: methane (28.0 TWh_{H₂,eq}), methanol (65.7 TWh_{H₂,eq}) and ammonia (30.7 TWh_{H₂,eq}).

It is interesting to notice that hydrogen is imported by pipeline (from Morocco) and by ship (from Chile, Australia and Oman). As mentioned in Section 1.3, hydrogen transportation by ship is expensive. The model estimates that it is more cost-optimal to transport in hydrogen by ship, than to transport in the form of another electrofuel

and then convert it back in hydrogen on site. However, it is important to distinguish between what is the cost-optimal solution and the reality (cfr. Subsection 1.4.1).

The total cost of the system is about 80 b€, which is expensive and mainly due to the cost of the virtual electrofuels. Indeed, 30 b€ are spent in the expensive virtual electrofuels. If their cost would have been of the same order of magnitude as the normal ones, the total cost of the system would have been at 60 b€. Therefore, this value should not be used as a benchmark for comparison as virtual electrofuels have too great impact on the total cost.

3.3.2 Upper Bound (UB)

In the case of the UB scenario, the model chooses to import electrofuels only from the EC where they are the cheapest: hydrogen from Morocco (by pipeline), methanol from Oman and ammonia from Saudi Arabia. This is shown in Figure 3.6. A total of 225 TWh_{H₂,eq} are imported, which is way less than the 585 TWh_{H₂,eq} renewable green hydrogen potential in the EC, meaning that the targeted amount could be reached without exploiting all the renewable potential. Again, the electrofuels are imported in the state in which they will be used.

The total system cost is of about 55 b€. The 225 TWh_{H₂,eq} imported electrofuels are responsible for 14 b€, which is about 25% of the total cost.

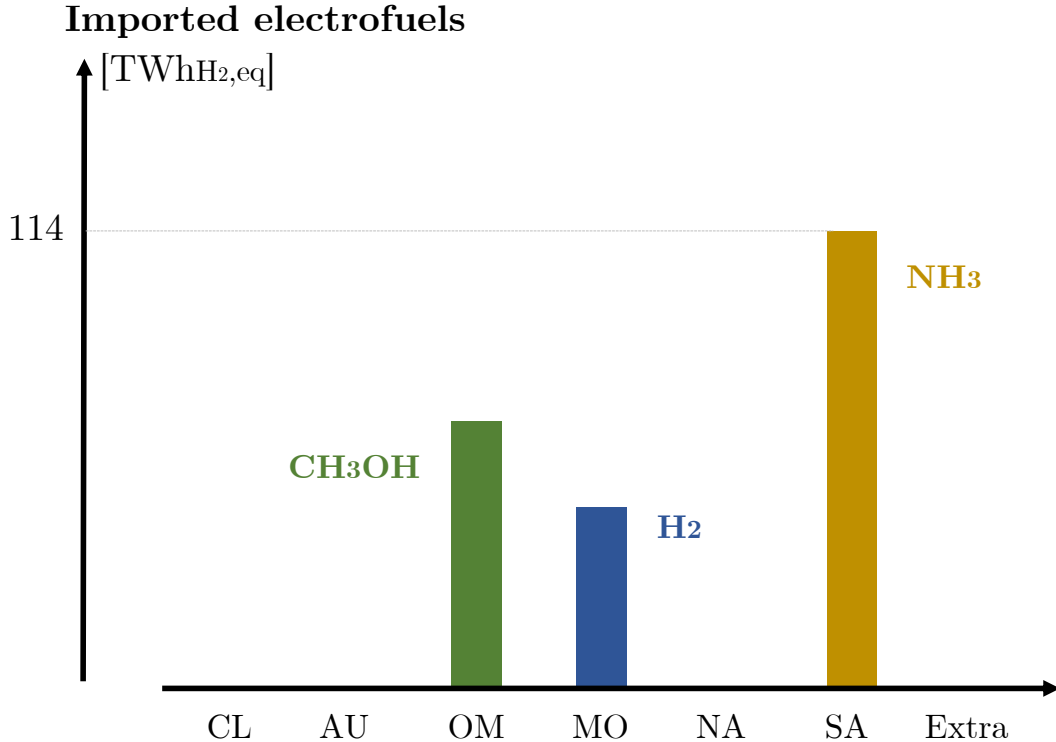


Figure 3.6: Electrofuels imported in 2050 constrained by the UB. Methanol is imported from Oman (66.3 TWh_{H₂,eq}), hydrogen from Morocco (45.0 TWh_{H₂,eq}) and ammonia from Saudi Arabia (113.8 TWh_{H₂,eq}).

3.3.3 Overview

The results for 2050 are a real warning. The objective cannot be achieved without considering a significant amount of electrofuels, at least $153 \text{ TWh}_{H_2,eq}$ according to EnergyScope TD. However, this is far from being the case if one considers the current agreements and forecasts (LB), with only $28.5 \text{ TWh}_{H_2,eq}$ available. Despite the need to use virtual electrofuels in the LB case, the absolute amount of electrofuels is about $70 \text{ TWh}_{H_2,eq}$ lower than the UB scenario (153 vs. $225 \text{ TWh}_{H_2,eq}$). As for the 2030-scenario, other resources have to be used to compensate for this gap and meet the same demand in both scenarios. This is covered in Section 3.5.

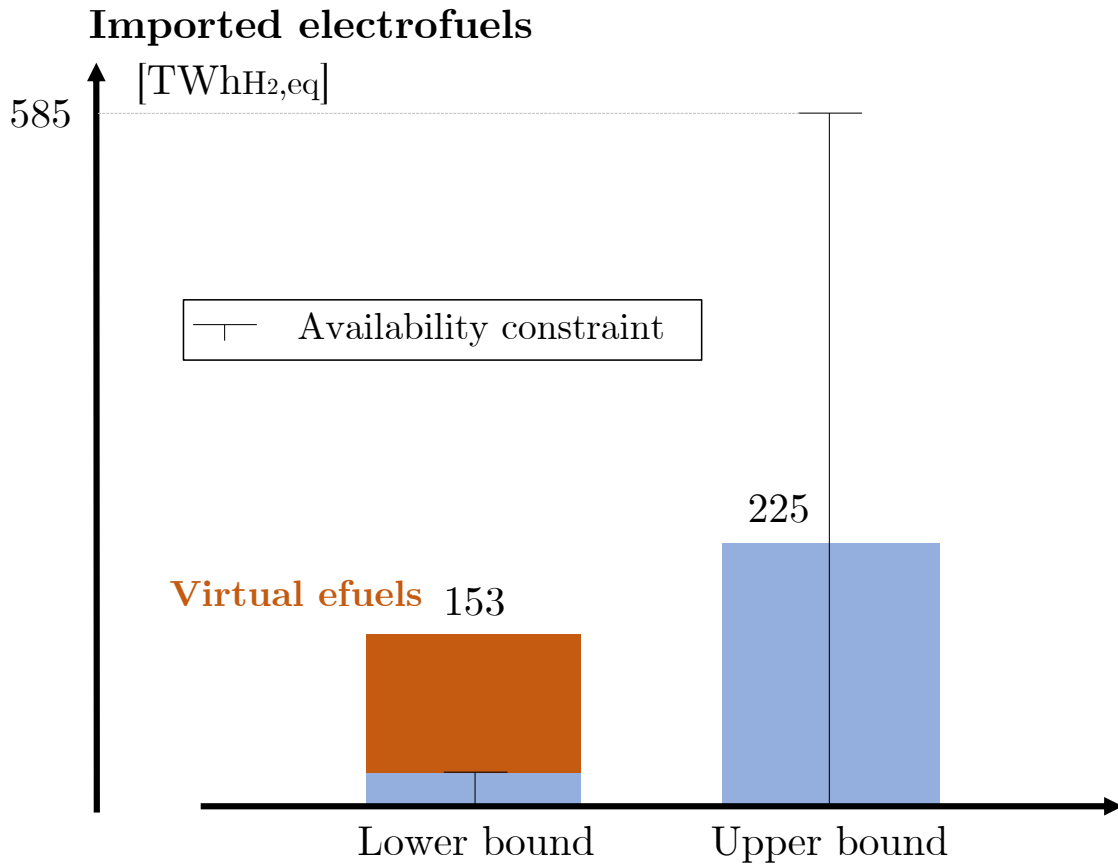


Figure 3.7: Comparison of electrofuels imported in 2050 constrained by the LB and the UB. $153 \text{ TWh}_{H_2,eq}$ are necessary for the LB, from which $124.5 \text{ TWh}_{H_2,eq}$ are virtual ones. The UB requires $225 \text{ TWh}_{H_2,eq}$.

3.4 Demand supplied by electrofuels

According to EnergyScope TD, the electrofuels will meet the following sectors in the future: the mobility, the NED, the power sector and the heating sector. Energy flow diagrams are available in Appendix B.1 to help understand how the electrofuels are integrated in the energy system for each scenario.

3.4.1 Mobility sector

The mobility demand is divided into two categories: the passenger mobility and the freight transport. The passenger mobility is then again subcategorised into public and private mobility, and the freight transport into road, train and boat. The shares of EUD between the different subcategories are given in a range of values. This means that the demand of a specific subcategory is not deterministic, but can vary between a minimum and a maximum value. For example, the share of public mobility in the total passenger mobility lies in $[0.2;0.5]$ and the one of the private mobility in $[0.5;0.8]$. The ranges of values are given in Table 3.1, which also includes the computed amount supplied by electrofuels. The values are given in [Gpkm] (billions of passenger-km) and [Gtkm] (billions of tons-km) for the passenger mobility and the freight transport respectively. The fractions (expressed in %) represent the relative amounts of electrofuels used to meet the end-use. For instance, the end-use of private mobility for the UB in 2030 is of 93 Gpkm and fully provided (100%) by electrofuels.

In 2030 up to 50% of the passenger mobility and 45% of the freight transport could be provided by electrofuels. More specifically, the entire private mobility sector is powered with hydrogen in FC-cars. In addition, the whole road freight transport could be ensured with FC-trucks using green hydrogen.

However, the LB private mobility is provided by battery electric vehicles (BEV) (41 Gpkm) and FC-cars (57 Gpkm) supplied by grey hydrogen. The road freight transport is ensured by trucks powered by biodiesel.

In 2050 up to 50% of the passenger mobility and 48% of the freight transport could be provided by electrofuels. Like for 2030, FC-cars and FC-trucks could fully ensure private passenger mobility and road freight transport respectively. Moreover, 11% of the boat freight transport is supplied by methanol instead of natural gas. For the LB, some private passenger mobility uses biofuels in gasoline-powered cars, and road freight transport biodiesel in diesel-powered trucks.

Table 3.1: Amount of electrofuels supplying the mobility end-uses in 2030 and 2050 for the LB and UB. A distinction is made between passenger mobility and freight transport, expressed in [Gpkm] or [Gtkm] respectively.

	End use demand	Electrofuel supply (LB)	Electrofuel supply (UB)
2030			
Private	93-149	0	93 (100%)
Public	37-93	0	0
Total passenger	186	0	93 (50%)
Road freight	41-68	0	41 (100%)
Train freight	10-23	0	0
Boat freight	14-28	0	0
Total freight	92	0	41 (45%)
2050			
Private	110-176	90 (82%)	110 (100%)
Public	44-110	0	0
Total passenger	220	90 (41%)	110 (50%)
Road freight	51-84	0	52 (100%)
Train freight	13-29	0	0
Boat freight	18-35	0	4 (11%)
Total freight	115	0	56 (48%)

3.4.2 Non-energy demand (NED)

The NED in the model considers ammonia, methanol and HVC as end-use types. They are then responsible for the production of products such as fertilisers and plastics (see Section 1.2).

Table 3.2 shows that the demand of ammonia will be almost entirely met by electrofuels in 2030. A small part of ammonia needed is provided by the Haber-Bosch process, but not from green hydrogen.

For the UB, the methanol is imported for its own end-use (100%) and responsible for 13% of the production of HVC. More methanol (4.9 TWh) is created by the conversion of biomass with pyrolysis, which is then converted into HVC. The remaining HVC demand is provided by light fuel oils.

In 2050 all the NED is supplied by electrofuels. The HVC is obtained entirely through the conversion of methanol. The model clearly shows the necessity of electrofuels for the NED.

Table 3.2: Amount of electrofuels supplying the non-energy demand in 2030 and 2050 for the LB and UB, expressed in [TWh]. A distinction is made between the different end-use types: ammonia, methanol and HVC.

	End use demand	Electrofuel supply (LB)	Electrofuel supply (UB)
2030			
Ammonia	10.0	9.6 (96%)	10.0 (100%)
Methanol	1.5	0	1.5 (100%)
HVC	40.7	0	5.4 (13%)
Total	52.2	9.6 (18%)	16.9 (32%)
2050			
Ammonia	10.6	10.6 (100%)	10.6 (100%)
Methanol	1.6	1.6 (100%)	1.6 (100%)
HVC	42.8	42.8 (100%)	42.8 (100%)
Total	55.0	55.0 (100%)	55.0 (100%)

3.4.3 Power sector

Electricity can be used as end-use, but also to power other sectors. 150 TWh local renewable electricity and 32 TWh imported electricity are available according to EnergyScope TD. It seems to be enough to supply the power EUD of 108 TWh in 2050, but needs much more electricity to supply the other sectors (e.g. trains in the mobility sector and electric resistances or electric heat pumps in the heating sector). In 2030 electrofuels are not expected to be converted into electricity, as shown in Table 3.3. However, in 2050, they are responsible for the production of 20% to 44% of the electricity end-use. The lower value (LB) is ensured by CCGTs fueled by ammonia and industrial cogeneration plants fueled by methane. The upper value (UB) is ensured by CCGTs fueled by ammonia. This electricity production is here considered to provide the power sector, but could also be used in other end-use sectors.

Table 3.3: Amount of electrofuels supplying the electricity end-use in 2030 and 2050 for the LB and UB, expressed in [TWh].

	End use demand	Electrofuel supply (LB)	Electrofuel supply (UB)
2030			
Electricity	89	0	0
2050			
Electricity	108	22 (20%)	47 (44%)

3.4.4 Heating sector

The heating sector will hardly be powered by electrofuels, as shown in Table 3.4. It is the case only for the LB for 2050 where 23 TWh methane is imported and used to supply industrial cogeneration plants to produce 25% of the high temperature heat demand. The remainder of the heating sector in 2050, for both high and low temperatures, is mainly provided by electricity, but also fossil waste and woody biomass.

Table 3.4: Amount of electrofuels supplying the heating sector in 2030 and 2050 for the LB and UB, expressed in [TWh]. A distinction is made between the high temperature heat, the low temperature heat for hot water and the low temperature heat for space heating.

	End use demand	Electrofuel supply (LB)	Electrofuel supply (UB)
2030			
High temp.	58	0	0
Low temp. (space heating)	119	0	0
Low temp. (hot water)	29	0	0
2050			
High temp.	44	11 (25%)	0
Low temp. (space heating)	124	0	0
Low temp. (hot water)	30	0	0

3.4.5 Overview

Electrofuels will have an important role in the future, especially for the mobility sector and the NED. A significant part of electricity is supplied by the electrofuels which can be used for the power sector itself, or to supply others. Although the heating sector is hardly powered by electrofuels, it mainly requires electricity that could be derived from them. It is therefore incorrect to say that they will have no influence on the heating sector. As a reminder, the electrofuel flows of the LB and UB of 2030 and 2050 are illustrated in Appendix B.1. They give a clear overview for each case of the different electrofuels supplying technologies and in the end the EUDs.

3.5 How to compensate for an electrofuel shortage

For 2030 as well as for 2050 there is a shortage of electrofuels if we consider the LB scenarios. To compensate for this shortage, other resources and technologies can be used to meet part of the demand. However, some electrofuels are still necessary and cannot be replaced, which is explained by the presence of virtual electrofuels. The 2050-scenario is considered for this analysis since the shortage is more extreme. Finally, other alternative solutions will be discussed.

3.5.1 Alternative resources and technologies

Resources Electrofuels can be substituted by biofuels (56 TWh), of which biodiesel accounts for a large part (47 TWh), in the mobility sector. In this study, bioethanol (9 TWh) takes into account the other possible biofuels. However, to supply other sectors like electricity, heat and NED, electrofuels are a must. The different resources used between the LB and the UB are shown in Figure 3.8. The resources labelled under "Other" include woody biomass, wet biomass, fossil waste, coal and gas. As many biofuels (56 TWh according to EnergyScope TD) will be required as alternative to electrofuels, their availability is important. However, the model does not constrain the amount of biofuels that should be available in the future. According to the Imperial London College [61], the annual European availability of biofuels for the transport sector varies between 820 and 2050 TWh. The Belgian share is estimated to vary between 32.8 and 82 TWh, which is discussed in Appendix B.2. In case of biofuel shortage, electrofuels would be required.

Technologies Since 47 TWh of biodiesel are used to replace electrofuels in the transport sector, the technologies provided by diesel are favoured according to the LB scenario:

- Public mobility: diesel-powered buses replace buses powered by compressed natural gas (CNG), trains and FC-powered cars.
- Maritime freight transport: diesel-powered boats replace natural gas- and methanol-powered boats.
- Road freight transport: diesel-powered trucks replace FC-powered trucks.

Bioethanol is also used to compensate for the lack of electrofuels, about 9 TWh according to the EnergyScope TD simulation. It can be used in engines powered by gasoline. Accordingly, gasoline cars are preferred for the private mobility to replace some FC-powered cars.

Numerical tables comparing the resources and technologies to compensate for a lack of electrofuels are represented in Appendix B.3.

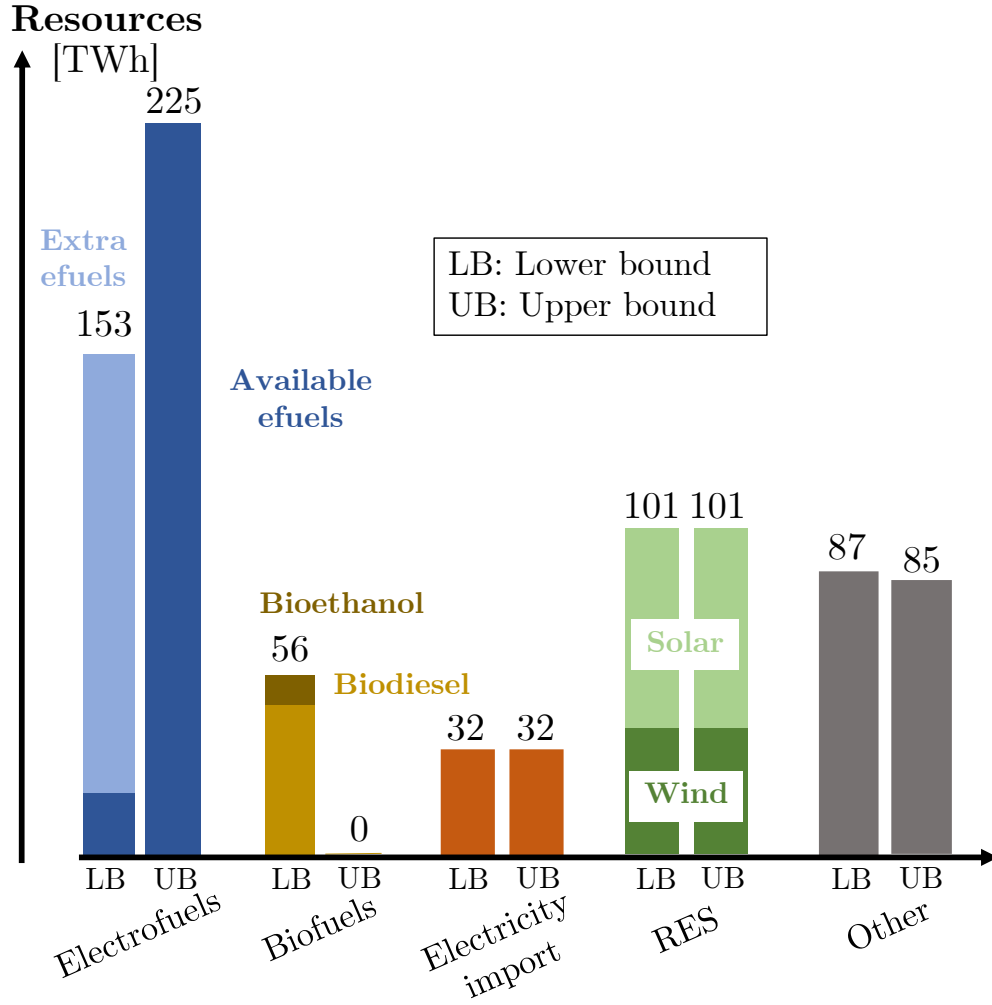


Figure 3.8: Comparison of resources used in 2050 when constrained by the LB and the UB. The gap due to the electrofuel shortage is filled by biofuels to supply the mobility sector. The other resources remain more or less the same. The resources called "Other" include wet biomass, fossil waste, woody biomass, coal and gas.

3.5.2 Alternative solutions

Other alternative options to a likely shortage of electrofuels are possible. They are discussed in this section using variation analyses. This gives an idea of the impact of varying certain parameters on the use of electrofuels.

Reduction of the consumption By reducing considerably the consumption, the EUD will automatically decrease as well as the primary energy supply. An analysis is done on the impact of the potential variation of the total EUD. A variation of $\pm 20\%$ is chosen compared to the reference value. The analysis is done for the case of 2050 since the shortage is the most extreme, as shown previously.

Figure 3.9 shows that the decrease in the EUD is linked to a decrease in the supply of electrofuels. Taking 80% of the final EUD, 70 to 130 TWh_{H₂,eq} are needed

in the LB and UB respectively. This is much less than the 153 to 225 $\text{TWh}_{H_2,eq}$ needed when 100% of the EUD is considered. By reducing the EUD by 20%, the supply of electrofuels reduces more or less by half ($-100 \text{ TWh}_{H_2,eq}$). Moreover, when increasing the EUD by 20%, 240 to 335 $\text{TWh}_{H_2,eq}$ are necessary, which is about 100 $\text{TWh}_{H_2,eq}$ more than in the reference case. This means that the required amount of electrofuels is sensitive to changes in the EUD.

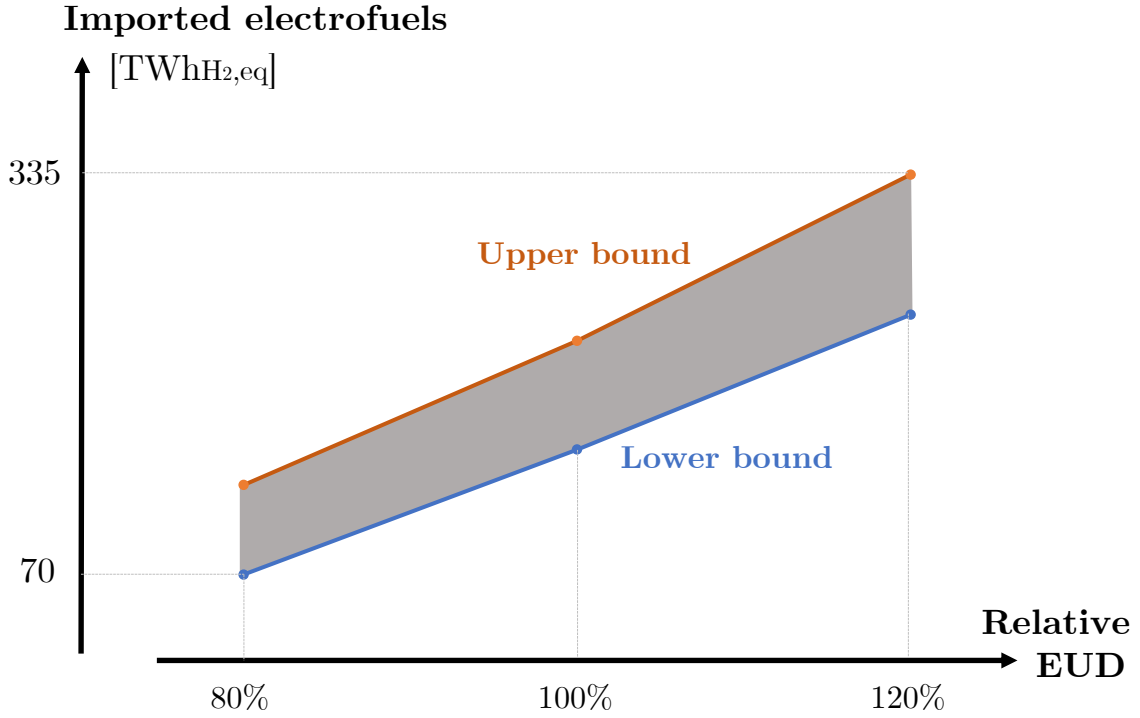


Figure 3.9: End-use demand variation of $[-20\%;+20\%]$ to analyse its impact on the electrofuel supply. The electrofuel supply is sensitive to the EUD variation by about $[-100;+100] \text{ TWh}_{H_2,eq}$ with respect to the reference case.

Addition of nuclear power Nuclear energy is considered to be green, emitting very little GHGs. It has a worldwide median value of $12 \text{ mgCO}_{2,eq}/\text{kWh}$ on the basis of its entire life cycle. This is comparable to wind energy and even lower than PV [62]. To produce the current 400 GW of global installed capacity, 67.5 tonnes of uranium are needed annually. The availability of uranium is estimated at 6.1 Mt, which ensures 90 years of supply for the current installed capacity. Moreover, other resources are promising such as thorium [63]. This means that, in theory, it is possible to install more nuclear power plants. On the other hand, other issues need to be tackled such as nuclear waste, extraction, security and time needed to install power plants. The impact of the variation of the installed capacity is analysed for 2050. The maximum nuclear power capacity is assumed to be at 0, 2, 5 and 10 GW. As a reminder, the Belgian government has taken the decision to extend 2.1 GW of nuclear power until 2030. After that, no nuclear power should be available anymore, which is therefore the reference value in this case [59]. Currently 5.5 GW of nuclear power are installed in Belgium.

Figure 3.10 shows an important decrease of electrofuel supply with increasing nuclear power capacity. Indeed, if 2 GW of nuclear power are maintained until 2050, the required amount of electrofuels would be between 133 and 195 TWh_{H₂,eq} at the LB and UB respectively. This is a significant decrease compared to the 153 to 225 TWh_{H₂,eq} needed if no nuclear power is available. For 5 GW nuclear capacity the demand would be reduced to 100 to 150 TWh_{H₂,eq} and for 10 GW it would be further decreased to 60 to 98 TWh_{H₂,eq}. The addition of nuclear power would have a substantial impact in the event of a lack of electrofuels. Of course, as already mentioned, nuclear power has several drawbacks that make the decision not as simple.

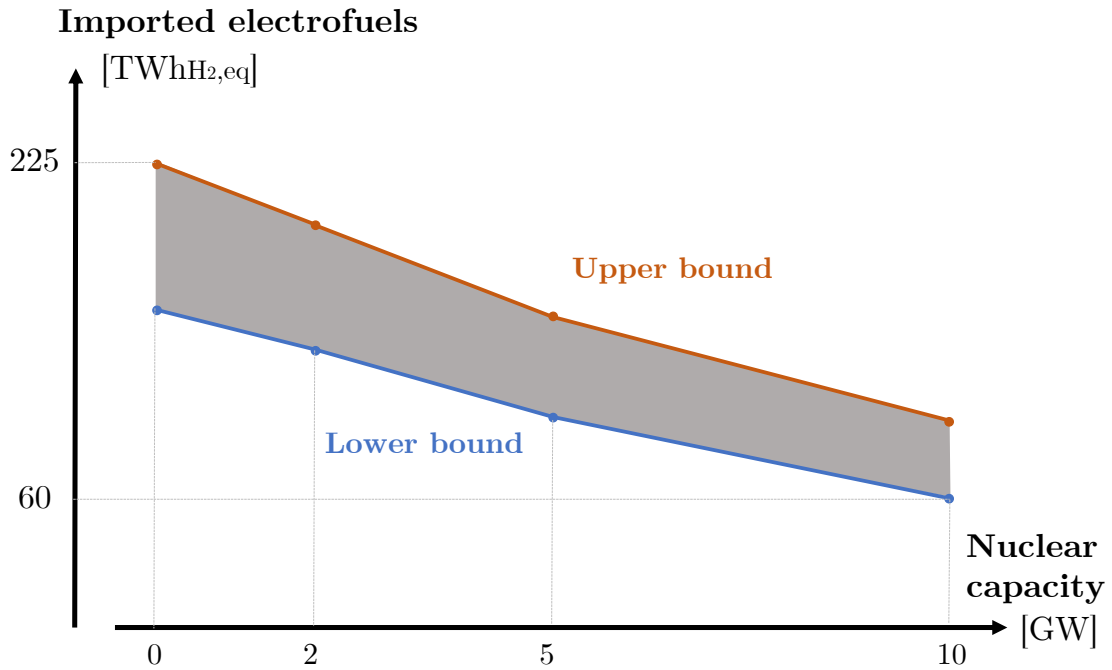


Figure 3.10: Variation in nuclear power generation capacity and its impact on electrofuel supply. The considered nuclear powers are 0, 2, 5 and 10 GW. Adding nuclear power helps to reduce the electrofuel demand.

Improvement of technologies Improving technologies by increasing their efficiency could be a solution to reduce the primary energy demand. Previous work has been done concerning the improvement of the technologies [64]. It focuses primarily on the best available technology (BAT) which represents the most efficient technologies currently available. Secondly the technical efficiency limits (TEL) are considered which are the upper limits of the technology efficiencies that can theoretically be reached. It takes into account material properties, unavoidable energy losses and non-ideal thermodynamic cycles, excluding all economical and manufacturing constraints. These two different assumptions result in a decrease of the energy consumption. Table 3.5, extracted from the reference article [64], shows the decrease in final energy consumption in the UK for each sector compared to final energy consumption in 2013, as a result of technical improvements.

Table 3.5: Final energy consumption decrease by sector for the UK compared to its energy consumption in 2013, if improvements are made up to the best available technology (BAT) and the technical efficiency limits (TEL).

Sector	Relative final energy consumption decrease with BAT	Relative final energy consumption decrease with TEL
Overall transport	28%	46%
Road	34%	51%
Aviation	15%	37%
Navigation	21%	32%
Rail	11%	27%
Overall buildings	10%	14%
Residential	10%	13%
Services	9%	16%
Overall industry	4%	8%
Industry	4%	7%
Primary	6%	14%
Total	15%	25%

The total final energy consumption decrease represents savings of 15% to 25% depending on the assumed limit (BAT and TEL), which is non-negligible. Its impact is similar to a decrease of the EUD as studied in the beginning of this subsection.

Chapter 4

Discussion

4.1 Limitations and improvements

This section covers the limitations of the methodology, as well as the uncertainties it creates in the results. Possible improvements and future research to address these limitations will also be discussed.

4.1.1 Exporting countries

As indicated in Section 2.1, the countries selected and analysed as potential import sources for Belgium will not necessarily export to the country. In some cases Belgium has signed MoUs with EC, for example Namibia or Chile [12], and it is therefore expected that there will be a future supply of electrofuels from these countries. Moreover, the field of hydrogen is in constant development. As of March 2022 [12], only 22 countries have published their hydrogen strategy and 26 others are preparing it. This means that new countries may emerge as potential exporters in the near future.

For other countries, nothing is set in stone, which means that no bilateral agreement could ever be reached. Additionally, MoUs can be broken in case of important political disagreements as recently demonstrated by the Ukraine-Russia conflict¹. Since the EU is supporting Ukraine, the imports of gas from Russia by some European countries becomes more difficult [65]. It results in the fact that the number of EC can vary in time.

Furthermore, the approach adopted assumes that all imports coming to Europe will be distributed among all its countries according to their needs. Only EC for which information was available were included in the analysis. Figure 4.1 shows an updated status of current partnerships (May 2022). It identifies more relationships that should be considered in the analysis to obtain a more accurate amount of importable electrofuels. Additional EC to consider are for example Canada, Tunisia, UAE or Uruguay, since they have partnerships with Germany and/or The Netherlands.

¹The Russian invasion started in February 2022

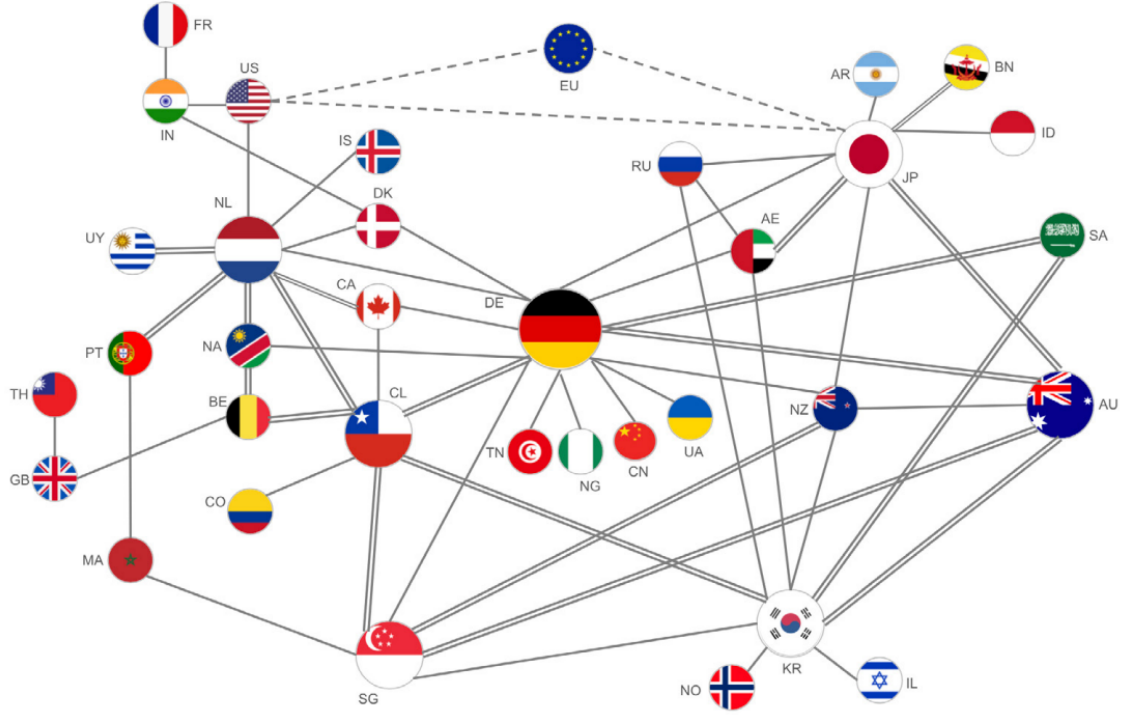


Figure 4.1: Current state of bilateral hydrogen partnerships [12]. Countries like, Canada, Tunisia, UAE or Uruguay should be included in the analysis to obtain more accurate results. A simple line corresponds to a bilateral partnership, a double line to a bilateral partnership with planned trade and a dashed line to a trilateral partnership.

4.1.2 Availabilities

The predicted availability lies between the LB and the UB. However, this range is quite wide and gives rather different results. As is explained in Subsection 2.3.3 the UB is a maximum that will probably never be reached. Thus, it would be more accurate to redefine this boundary and replace it with a more reasonable one. This would reduce the range and should give more realistic results. The main way to achieve this is to collect more information for each EC. Unfortunately, as the green hydrogen field is still in its starting phase in most of these countries, it is not easy to identify reliable sources of exportable supplies. This should improve over time, as green hydrogen may become a more common form of energy in the world and R&D should devote more time to this issue.

Moreover, the European fraction of the amounts exported from the EC were roughly estimated. The addition of competitors of the EU could reduce that share.

Due to lack of information, some availabilities were assumed to be the same in 2050 as in 2030. It is reasonable to assume that the quantity of exports to the EU is going to increase over a 20 year period, especially if the demand increases during those years. The assumption made in the LB is therefore rather conservative.

In the cases of Oman and Saudi Arabia, blue hydrogen is included as a possible import. As Belgium aims to be carbon neutral by 2050, blue hydrogen is not an option anymore. Moreover, in this analysis it is assumed that the production-to-consumption chains are entirely GHG-free. Further research on the emissions by performing a life-cycle analysis of these chains would certainly be useful.

Finally, the Belgian fraction γ_{BE} could also be slightly improved. Indeed, this fraction, based on 2030 values, could increase over the years if the import dependency (ID) of European countries decreases due to the installation of more electrolyzers. On the other hand, if Belgium does not reach the announced electrolyser capacity, its ID will increase and more imports will have to fill the gap.

4.1.3 Results

The results were computed with EnergyScope TD, which is one model among many others. Comparing this study with others, using different models, could make the analyses more robust and reliable. As mentioned in Subsection 1.4.1, EnergyScope TD has some drawbacks and limitations which would make these comparisons more interesting.

4.1.4 Overview

As mentioned above, many assumptions have been made during the methodology. Cross-checking several sources (which was not always possible at the time of writing) and doing an uncertainty analysis on certain parameters (costs, reported EC production, subdivision of EU and BE shares, etc.) would be an optimal way to take these multiple assumptions into account. As written previously, more data should become available in the coming years as hydrogen becomes a growing focus of interest in the energy sector.

4.2 Contribution and perspectives

This master thesis answered the question: *How will the electrofuel supply in Belgium influence its transition towards carbon neutrality?*. The study can be used by policymakers to take decisions and for further research. We first estimated the future electrofuel imports to the country. It showed that much more electrofuels would be necessary to meet the demand in 2030 and 2050, when looking at current agreements and articles. Therefore, the government should approach potential exporters to increase the amount. Moreover, the technologies using the electrofuels and meeting EUDs were highlighted. It is clear that the transition towards those technologies does not happen overnight. The infrastructures need to be adapted, the industry must develop, and the people must accept and integrate them in their day-to-day life. To have a continuous and smooth progress, it will require some time. For example, by 2030 the fuel cell technologies could take a significant place in the mobility sector. Industries and consumers will need time to plan for these changes. It will not be easy to impose such a change in a short period of time. This goes hand in hand with the supply, which will also increase gradually. Moreover, the integration of electrofuels and their technologies must be clearly defined to target the R&D efficiently.

This work opens questions for future research. The ones that concern us the most are listed hereunder:

- Firstly, as is described in Subsection 3.5.2, the electrofuel supply is strongly dependent on the total demand. This begs the following question : *How can the global energy demand be reduced?* What part of the reduction depends on the system or policymakers and what is the influence of individual behaviour?
- Secondly, as seen in Subsection 3.5.1, an alternative to electrofuels in the transport sector are biofuels. This raises the following question: *Could biofuels, and more broadly the biomass, constitute a viable substitute of low-carbon fuels in case of electrofuel shortage?* This could reorient the policymakers if the reality does not allow for the desired number of electrofuels.
- Furthermore, since in this analysis the international exchange is key, a geopolitical point of view can be raised. *Which countries can Belgium count on in a sustainable and secure way? Concerning the EC, are these agreements really beneficial for both parties? Are there adverse effects on the local population?* The geopolitical factor is a non-negligible aspect in this kind of studies.
- Finally, the hydrogen world is evolving rapidly, with more predictions, agreements and decisions year after year. We are convinced that one would obtain improved and more precise results if this research is repeated in following years. A reiteration of the research is therefore encouraged.

Conclusion

In order to reach the GHG reduction targets set for 2030 and 2050, the EU and thus Belgium must rethink and adapt their entire energy system. One way of doing this would be to replace the current fossil fuels with electrofuels. Belgium will not have enough renewable energy to be self-sufficient and produce its own [7]. Therefore, it is crucial to import these resources from countries with a higher potential.

This master thesis first investigated the possible supplies in electrofuels in 2030 and 2050. Analyses were made to integrate those new fuels into the Belgian energy system. EnergyScope TD was used as an optimisation model to perform case studies and to better understand their impacts. The different electrofuels supplying the EUDs, as well as the conversion technologies, were highlighted. Finally, other resources and alternative solutions were discussed in case of electrofuel shortage.

Two different approaches were used to quantify the supply of electrofuels in Belgium: a lower and an upper bound. They should be seen as the minimum and maximum possible availabilities respectively. The lower bound is based on bilateral agreements and articles confirming electrofuel exports to the EU or Belgium. The availabilities are low compared to the expected demand in 2030 and 2050. However, the assumptions for the lower bound were pessimistic and it is hoped that their quantities will increase significantly over the years. The upper bound is based on the renewable energy potential of the identified exporting countries. Upper bound availabilities seem to be more than sufficient but should be considered as the maximum, which cannot be exceeded and will probably never be reached.

Case studies were carried out with the data obtained in the import analysis. For **2030**, where a decrease of 55% of the GHG emissions compared to 1990 is required, 11 to 68 TWh_{H₂,eq} are necessary to meet the EUD. The electrofuel imported in priority is ammonia, used in the non-energy sector. The imported methanol would be sufficient to meet its own demand and could also replace part of the oils needed to produce HVC. Then, up to 50% of the mobility sector (both for passenger as freight transport) can, already in 2030, be supplied by green hydrogen in cars and trucks powered by fuel cells.

In **2050**, where net carbon neutrality must be reached, 153 to 225 TWh_{H₂,eq} of electrofuels are required by the energy system. This is much more than the 29 TWh_{H₂,eq} available in the lower bound, which is a real warning. This means that additional electrofuels are necessary for the system to converge. It is expected that the whole NED will be provided by electrofuels, more precisely ammonia and methanol. Then, the private mobility sector could be fully supplied by green hydrogen using FC-cars. Also freight transport could use electrofuels in FC-trucks and boats powered by methanol. Finally, electrofuels could produce almost half of the electricity EUD. However, much more electricity is needed for other end-use categories such as the heating and mobility sectors.

Sufficient supply of electrofuels in 2030 and 2050 is quite uncertain. Alternative solutions to fill the gap were analysed. In a first instance biofuels could replace part of the electrofuels in the mobility sector. Then, more indirect solutions could help to reduce the electrofuel demand. Those include the addition of nuclear power, a decrease of the EUD, and the improvement of the technologies.

Imported electrofuels could account for up to 15% and 48% of the total primary energy consumption in 2030 and 2050 respectively. they will constitute an important part of the Belgian energy mix and should therefore not be taken lightly. This report gives a version, according to EnergyScope TD, of the influence that the electrofuel supply will have on the Belgian energy transition. Policymakers can use it as a basis for decisions or for further studies and analyses.

Appendices

A Import analysis

A.1 HIC costs in figures

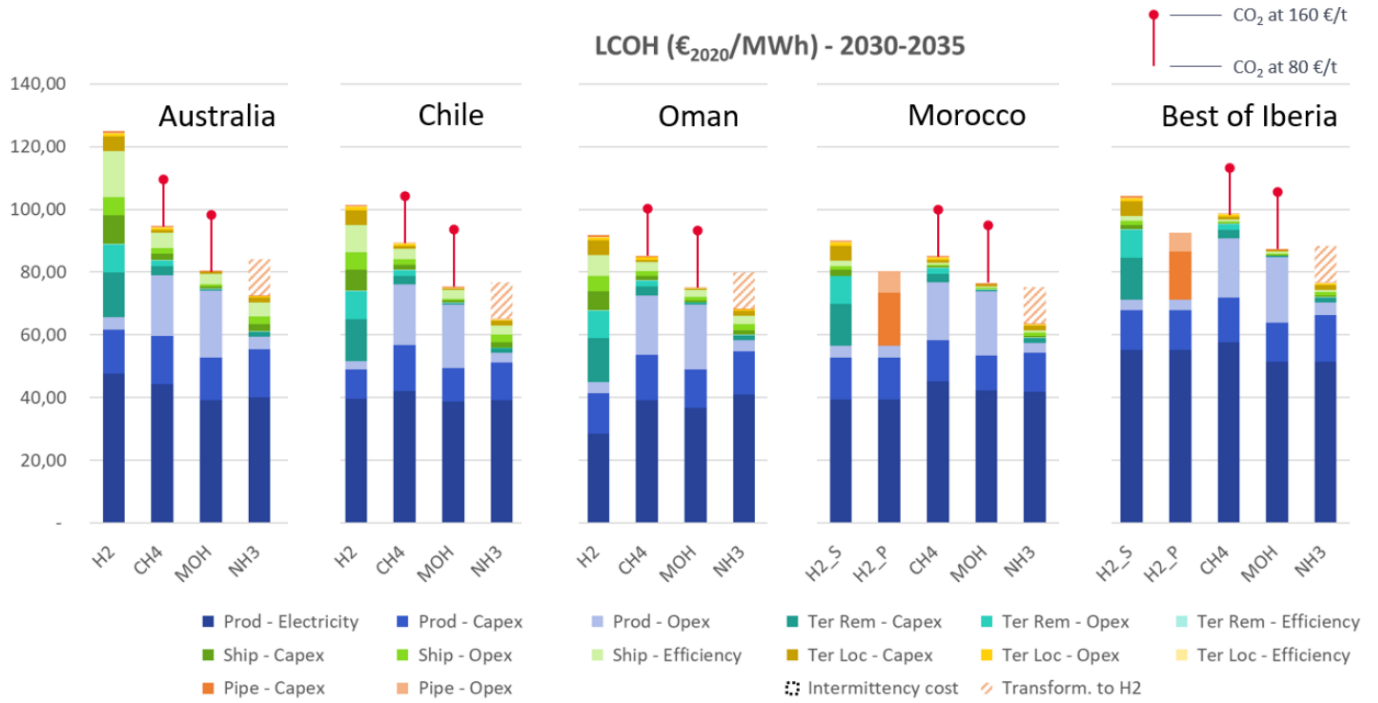


Figure 4.2: LCOH of the HIC countries in 2030.

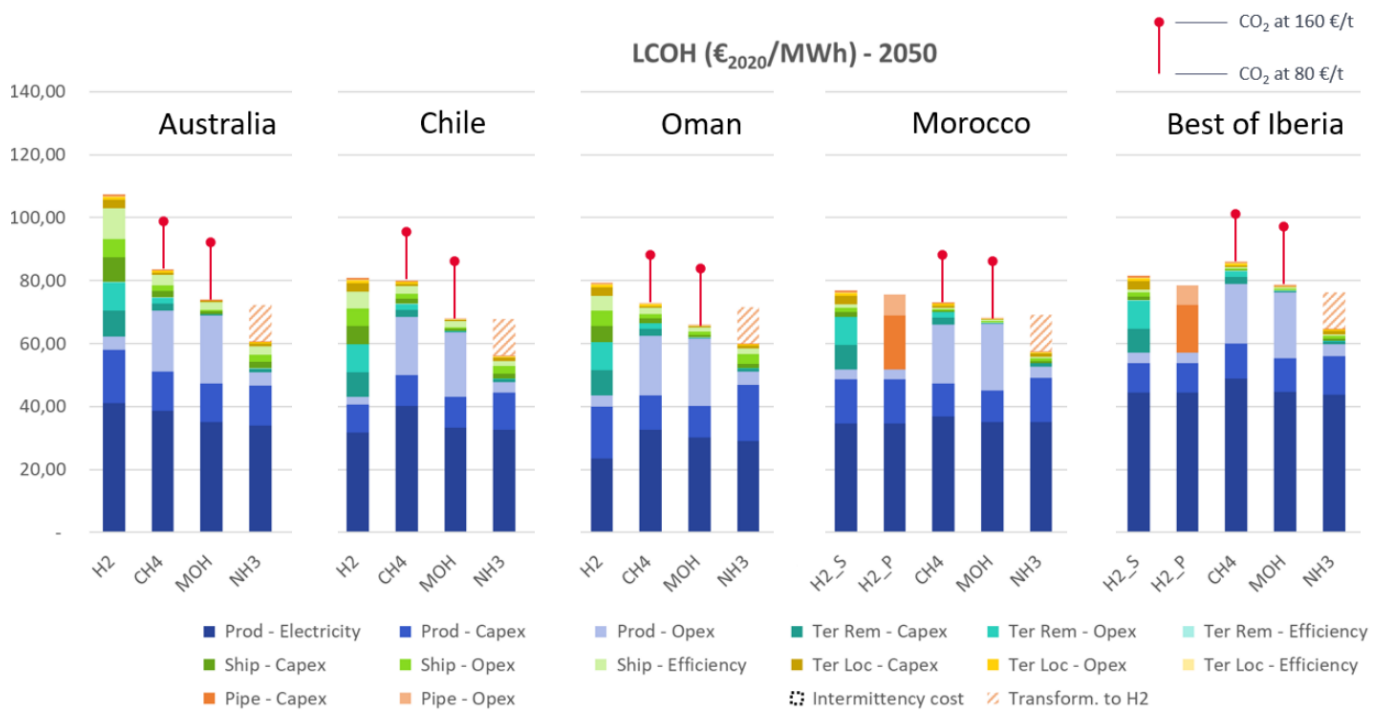


Figure 4.3: LCOH of the HIC countries in 2050.

A.2 Hydrogen equivalence

The availabilities are most of the time expressed in TWh of green hydrogen. The green hydrogen can afterwards be converted in other electrofuels. Each electrofuel is given an *hydrogen equivalence* $H_{2.eq}$, which corresponds to the amount of hydrogen, in TWh, needed to create 1 TWh of the given electrofuel. This makes it possible to estimate the availability of each electrofuel in function of the availability of hydrogen. These equivalents are given in Table 4.1 and are based on the values of the database of EnergyScope TD [66].

Table 4.1: H_2 equivalents of the electrofuels, expressed in $[TWh_{H_2}/TWh_{fuel}]$.

	H_2	NH_3	CH_4	CH_3OH
2030	1	1.13	1.20	1.26
2050	1	1.13	1.20	1.20

A.3 LCOH estimation for Namibia and Saudi Arabia in 2050

Since the LCOH of NH_3 of Namibia (NA) and Saudi Arabia (SA) in 2050 was not found, one chose to estimate them. This is done based on the relationships between the LCOH in 2030 and 2050 given in the HIC.

The mean of the fractions of $NH_{3,2050}/NH_{3,2030}$ is used to compute the LCOH of NH_3 of NA and SA in 2050.

Table 4.2: Fractions based on the values given by the HIC.

$NH_{3,2050}/NH_{3,2030}$	
Australia	0.836
Chile	0.848
Oman	0.870
Morocco	0.905
Spain	0.844
Mean	0.860

The LCOH's can thus be estimated by multiplying the ones in 2030 by the mean values given in Table 4.2. It is interesting to note that the fractions are of a similar order of magnitude, thus using their mean value to estimate others constitutes an acceptable approximation. The final values of LCOH in 2050 are all displayed in Table 2.1.

A.4 Fraction of EU imports

Table 4.3: Hydrogen production, demand, import dependency and fraction of EU imports of all the EU countries + UK for 2030 [18, 19, 20, 44].

EU Country	Production [GW]	Production [TWh _{H₂,eq}]	H ₂ demand [TWh _{H₂,eq}]	Imp. dep. [TWh _{H₂,eq}]	Frac. EU imp. [%]
Austria	0.40	0.77	8.35	7.59	2.82
Belgium	1.40	2.69	20.49	17.81	6.63
Bulgaria	0.22	0.42	3.6	3.18	1.18
Croatia	0	0	2.13	2.13	0.79
Cyprus	0	0	0	0	0
Czech Republic	0.45	0.86	4.21	3.35	1.25
Denmark	5.60	10.74	3.08	0	0
Estonia	0.03	0.06	0.14	0.08	0.03
Finland	1.80	3.45	6.01	2.56	0.95
France	3.10	5.95	36.60	30.35	11.41
Germany	5.40	10.36	71.64	61.28	22.82
Greece	5.40	10.36	9.95	0	0
Hungary	0.02	0.04	3.56	3.52	1.31
Ireland	0.05	0.10	1.67	1.57	0.59
Italy	1.60	3.07	36.95	33.88	12.62
Latvia	0	0	0.15	0.15	0.06
Lithuania	0	0	2.92	2.92	1.09
Luxembourg	0	0	0.39	0.39	0.14
Malta	0	0	0.11	0.11	0.04
Netherlands	11	21.10	28.59	7.49	2.79
Poland	0.26	0.50	16.52	16.03	5.97
Portugal	2.70	5.18	6.86	1.68	0.62
Roumania	1.60	3.07	8.84	5.78	2.15
Slovakia	0.30	0.58	2.88	2.30	0.86
Slovenia	0	0	0.47	0.47	0.18
Spain	2.40	4.6	32.67	28.07	10.45
Sweden	2.10	4.03	9.16	5.13	1.91
UK	0.40	0.77	31.25	30.48	11.35

A.5 Renewable potential

Table 4.4 gives a more detailed overview of the values obtained during the methodology described in Subsection 2.3.3.

Table 4.4: For each exporting country the following elements are quantified for the years 2030 and 2050: The *total renewable potential*, including solar as well as off- and onshore wind; The *total local demand*, assumed to be fully fulfilled by the renewable potential; The *excess of renewable energy*, being equal to the difference between the total potential and the total local demand; The *potential H_2 production*, assuming that all the excess of renewables would be transformed into H_2 and considering an efficiency of the electrolyser of 73%[44]; The *European fraction* of the produced H_2 ; The *European share* of the produced H_2 , same shares as given in section 2.3.2; The *Belgian share* of the EU imported H_2 . All of these values are given in [TWh].

	AU	CL	OM	SP	MO	NA	SA	TOT
Potential renew.	53,820	2,520	2,860	1,680	1,700	4,970	12,540	80,090
2030								
Local demand	2,180	560	360	1,710	290	30	3,600	/
Excess renew.	51,640	1,960	2,500	0	1,410	4,940	8,940	/
Pot. H_2 prod.	37,670	1,430	1,830	0	1030	3,600	6,520	/
Frac. to EU [%]	2	50	100	100	100	25	50	/
Share to EU	750	715	1830	0	1030	900	3260	8,485
Share to BE	50	50	120	0.6	70	60	215	565
2050								
Local demand	2,890	750	475	1,740	380	40	4,780	/
Excess renew.	50,930	1,770	2,385	0	1,320	4,930	7,760	/
Pot. H_2 prod.	37,180	1,290	1,745	0	970	3,600	5,660	/
Frac. to EU [%]	5	42	100	100	100	25	50	/
Share to EU	1,860	540	1,745	0	970	900	2,830	8,845
Share to BE	125	35	115	0	65	60	185	585

B Case studies

B.1 Energy flows from the electrofuels to the EUDs

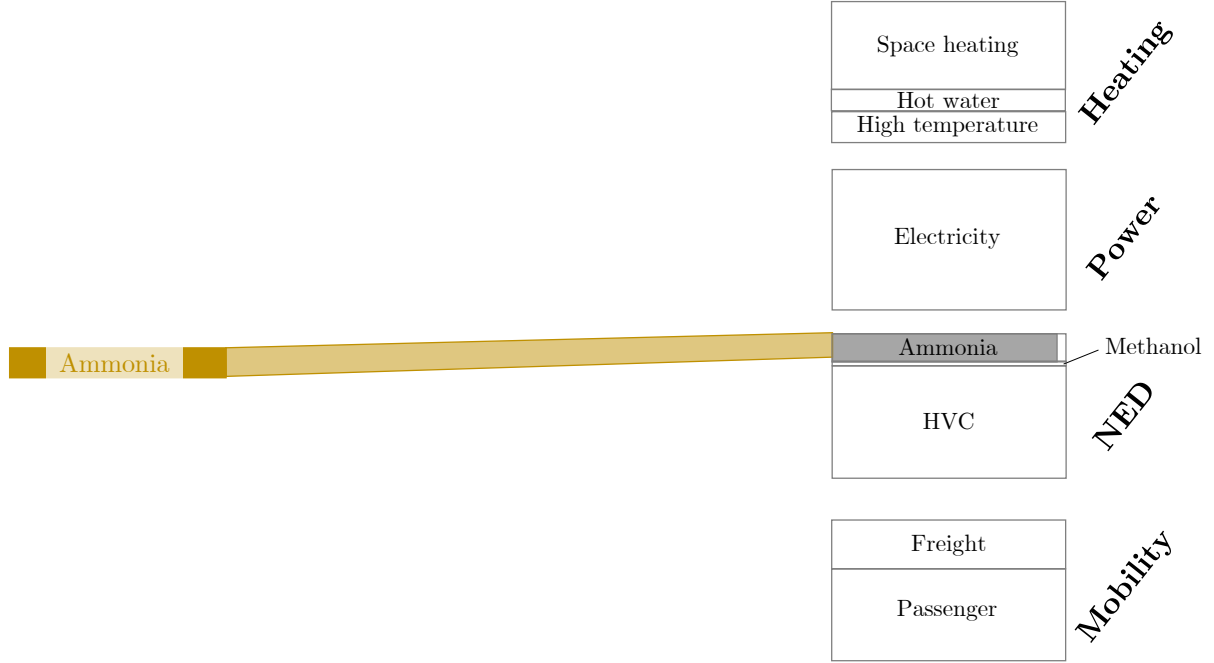


Figure 4.4: Energy flow from the electrofuels to the end-use demands in 2030 (LB). Only the NED is provided by electrofuels, more precisely ammonia.

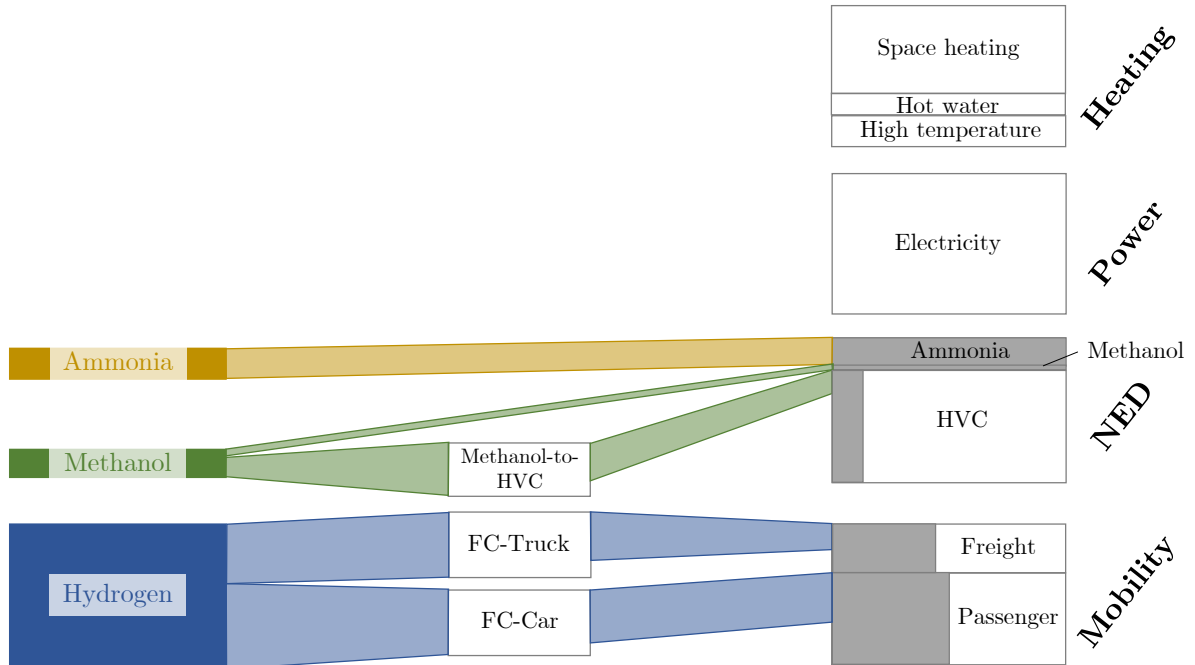


Figure 4.5: Energy flow from the electrofuels to the end-use demands in 2030 (UB). The NED and the mobility sectors are partially provided by electrofuels.

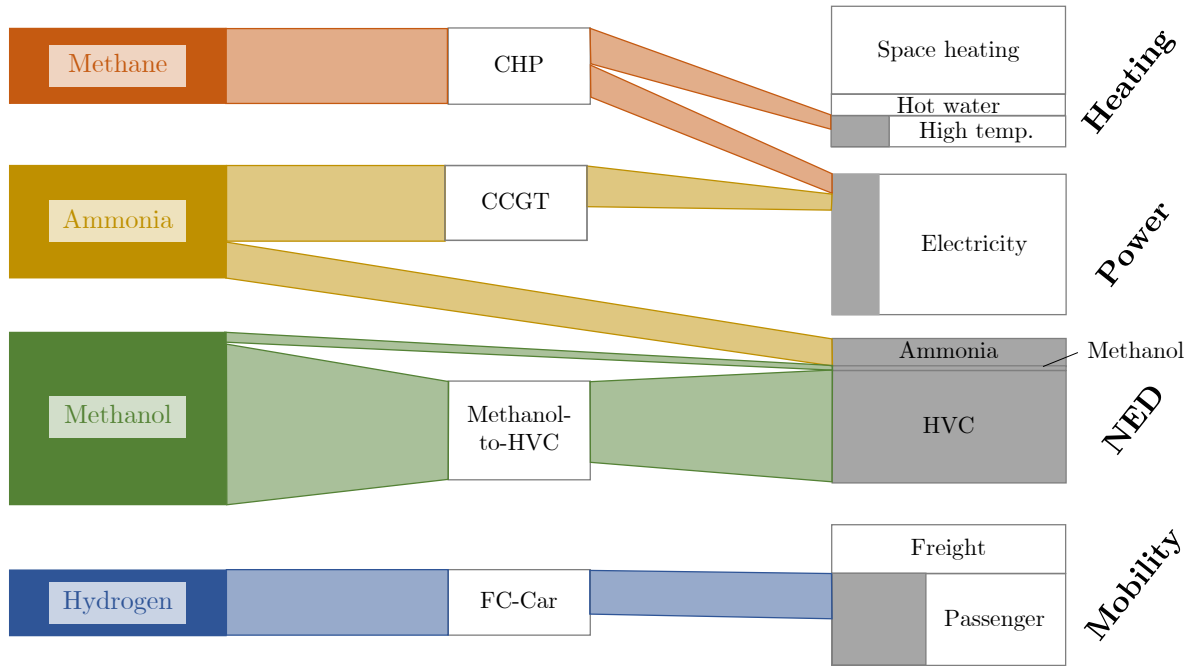


Figure 4.6: Energy flow from the electrofuels to the end-use demands in 2050 (LB). All the EUDs are provided at least partially by electrofuels. The NED is even fully supplied by them.

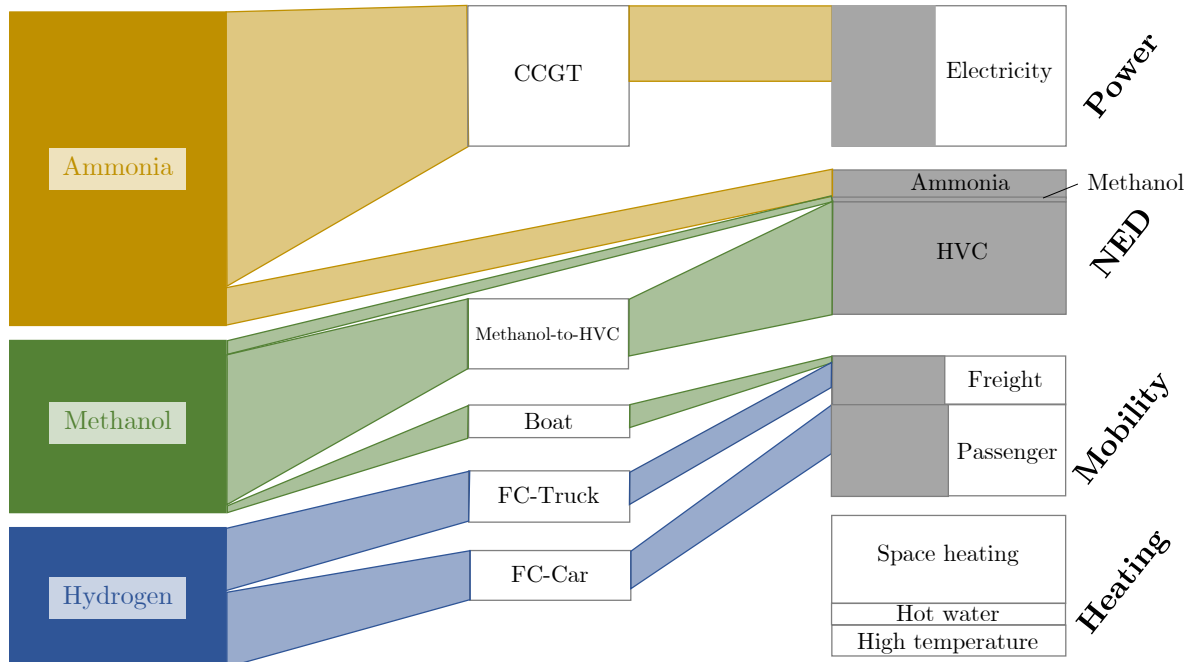


Figure 4.7: Energy flow from the electrofuels to the end-use demands in 2050 (UB). Except the heating sector, all the EUDs are provided at partially by electrofuels. The NED is even fully supplied by them.

B.2 Availability of biofuels

In the LB scenario in 2050, EnergyScope TD uses 56 TWh of biofuels to compensate for the lack of electrofuels while keeping the global price as low as possible. These biofuels are all used in the transport sector. Since the model does not constrain their availability, it is interesting to analyse it.

The European potential of biofuels meant for transportation in 2050, out-of-Europe imports included, is projected to be between 820 and 2050 TWh according to the Imperial London College [61]. To know what part is available to Belgium, the projected demand of all EU countries (+ UK) of biofuels in 2050 can be used. Indeed, similarly as in Table 4.3 the fraction between the demand of Belgium and the total EU demand (see Table 4.5) can be used to estimate what part of the potential should go to Belgium. As the fraction between the Belgian demand and the total European demand is equal to 4%, the potential of biofuels for Belgium is projected to vary between 32.8 and 82 TWh. This means that in some cases Belgium won't have enough biofuels to compensate for the lack of electrofuels in the LB scenario in 2050.

Table 4.5: Demand in biofuels and the fraction of the total European demand per EU country + UK [67].

Country	Biofuels demand [TWh]	Fraction of EU demand [%]	Country	Biofuels demand [TWh]	Fraction of EU demand [%]
Austria	6.2	2	Italy	23.6	9
Belgium	10.9	4	Latvia	0.9	0
Bulgaria	2.6	1	Lithuania	1.2	0
Croatia	2.5	1	Luxembourg	2.4	1
Cyprus	0.5	0	Malta	0.1	0
Czech Republic	7.3	3	Netherlands	7.5	3
Denmark	4.6	2	Poland	17.8	6
Estonia	0.6	0	Portugal	5.4	2
Finland	4.5	2	Roumania	7.1	2
France	39.9	15	Slovakia	2.5	1
Germany	38.5	14	Slovenia	2.1	1
Greece	4.1	1	Spain	26.3	10
Hungary	4.8	2	Sweden	13.2	5
Ireland	3.1	1	UK	31.5	12

B.3 Resource and technology compensation for shortage of electrofuels

When electrofuels are missing (i.e. LB), they can be partially substituted by other resources. These will of course supply other technologies. Tables 4.6 and 4.7 give the results of EnergyScope TD comparing respectively the resources and technologies used in the LB and UB scenarios. The tables only take into account the ones that differ in the two cases.

Table 4.6: Comparison of resources between the LB and UB scenarios, expressed in [TWh].

	Available efuels	Expensive virtual efuels	Biodiesel	Bioethanol
UB	225	0	0	0
LB	28.5	124.5	47	9
$\Delta_{Upper-Lower}$	196.5	-124.5	-47	-9

Table 4.7: Comparison of technologies between the LB and UB scenarios in 2050, expressed in [GW].

Public mobility			
	Diesel bus	CNG bus	Train
UB	0	8	23
LB	30	0	0
$\Delta_{Upper-Lower}$	-30	8	23
Private mobility			
	Gasoline car	FC car	
UB	0	245	
LB	45	200	
$\Delta_{Upper-Lower}$	-45	45	
Maritime freight transport			
	Diesel boat	Natural gas boat	Methanol boat
UB	0	31	4
LB	35	0	0
$\Delta_{Upper-Lower}$	-35	31	4
Road freight transport			
	Diesel truck	FC truck	
UB	0	64	
LB	64	0	
$\Delta_{Upper-Lower}$	-64	64	

C EnergyScope TD modifications

Only the data of 2030 and 2050 have been modified since those years were studied.

Resources

- Remove lines of $H2_RE$, GAS_RE , $METHANOL_RE$ and $AMMONIA_RE$.
- Add lines for $ELECTROFUEL_i_COUNTRY_j$ where:

$$\text{label} = -ELECTROFUEL = \{H2, GAS, METHANOL, AMMONIA\}, \\ COUNTRY = \{AUSTRALIA, CHILE, OMAN, MOROCCO, SPAIN, \\ SAUDI_ARABIA, NAMIBIA\}^2$$

- Set the cost (c_op) of each $ELECTROFUEL_i_COUNTRY_j$ to its corresponding value.
- Set the availability ($avail$) of each hydrogen resource (resp. ammonia resource for Saudi Arabia and Namibia) to its corresponding value: $H2_COUNTRY_j$ (resp. $AMMONIA_COUNTRY_j$ for Saudi Arabia and Namibia).
- Set the availability ($avail$) of all other electrofuels ($ELECTROFUEL_i_COUNTRY_j$ except $H2_COUNTRY_j$) to *Infinity*.
- Add lines for $ELECTROFUEL_i_EXTRA$ that represent the expensive virtual electrofuels.
- Set the cost (c_op) of each $ELECTROFUEL_i_EXTRA$ to its corresponding value ³.
- Set the availability ($avail$) of each $ELECTROFUEL_i_EXTRA$ to *Infinity*.

Technologies

- Set f_max of $NUCLEAR$ to 2.076 for 2030 and keep it at 0 for 2050

²For Saudi Arabia and Namibia only ammonia is taken as electrofuel

³As a reminder, one assumed the cost of an expensive electrofuel as three times the cost of the most expensive electrofuel, each exporting country combined.

Layers_in_out

- Remove lines of *H2_RE*, *GAS_RE*, *METHANOL_RE* and *AMMONIA_RE*.
- Add lines for *ELECTROFUEL_i_COUNTRY_j* as well as for *ELECTROFUEL_i_EXTRA*.
- For a given *ELECTROFUEL_i_COUNTRY_j* or *ELECTROFUEL_i_EXTRA* set the value 1 in the column corresponding to *ELECTROFUEL_i*. For example, for *METHANOL_OMAN* set the value 1 in the column *METHANOL*.

usefull_functions

- Remove *H2_RE*, *GAS_RE*, *METHANOL_RE* and *AMMONIA_RE* from the set *RES_IMPORT_CONSTANT*.
- Add *ELECTROFUEL_i_COUNTRY_j* and *ELECTROFUEL_i_EXTRA* to the set *RES_IMPORT_CONSTANT*.

estd_model

- Add a new constraint to limit the use of electrofuels from a same country to its availability. The lines are written as follows:
"subject to electrofuels_availability_limit_country_i:
sum {t in PERIODS, h in HOUR_OF_PERIOD [t], td in TYPICAL_DAY_OF_PERIOD [t]} (F_t ["H2_COUNTRY_i", h, td] + c_gas * F_t ["GAS_COUNTRY_i", h, td] + c_methanol * F_t ["METHANOL_COUNTRY_i", h, td] + c_ammonia * F_t ["AMMONIA_COUNTRY_i", h, td]) <= avail ["H2_COUNTRY_i";"
where:

c_gas, c_methanol and c_ammonia correspond to the hydrogen equivalence of gas, methanol and ammonia, respectively. Those are given in Appendix A.2.

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