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Power to X and Carbon Capture & Utilization Roadmap
for Belgium

Perspective for a viable Power to Chemicals pathway/roadmap in view of the renewable energy transition

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AUTHORS

Agneev Mukherjee, MATCH, VITO
Pieterjan Debergh, MATCH, VITO
Roy Hendrikx, MATCH, VITO

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TABLE OF CONTENTS

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LIST OF FIGURES

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1 THE NEED FOR A ROADMAP

The European Union (EU) has set for itself the ambition of becoming the 'first climate-neutral continent' by 2050 [1]. This long-term target, enshrined in the 2019 European Green Deal, has been broken down into sub-targets, both on a temporal and a geographic basis. On the temporal front, the EU has shorter-term targets, for 2030 and 2040. The 2030 target, outlined in the Fit for 55 package [2], is for a reduction of net GHG emissions in the EU by at least 55% compared to 1990 levels by 2030. In 2024, the European Commission outlined their 2040 targets, aiming for a 90% net GHG emissions reduction by 2040 compared to 1990 [3]. Unlike the 2030 and 2050 targets, the 2040 target is not yet a legally binding objective set out in the European Climate Law.

On the geographical front, the overall EU target is split on a Member State (MS) basis. This is done via the Effort Sharing Regulation (ESR) mechanism, wherein each member state is set national targets for reducing emissions in domestic transport (excluding aviation), buildings, agriculture, small industry and waste [4]. In total, the emissions covered by the ESR account for about 60% of total domestic EU emissions. The MS targets are set on the basis of Gross Domestic Product (GDP) per capita and the cost-effectiveness of possible decarbonisation options. Confusingly, these targets have 2005, not 1990, as the baseline year. MS must submit national energy and climate plans (NECP) to the EU outlining how they intend to meet their targets.

The 2030 target for Belgium, as set in 2023, is 47% [5]. Belgium was one of the six EU MS who missed the June 2023 deadline for submitting their updated NECP, with the draft plan being finally published in December 2023. This draft plan sets Flanders a reduction target of 40% (2030 compared to 2005), while Wallonia and the Brussels Capital Region both have 47% reduction targets [6]. The total targeted reduction is only 42.6%, which represents a deficit of 4 million tonnes of $CO_{2,eq}$ in 2030. The plan states that 'Belgium commits to reduce Belgium's emission allowance deficit by taking necessary measures and to compensate it with the use of flexibility, through additional agreements during the burden-sharing negotiations.'

The EU has elaborated on the complement of measures to be taken to achieve the decarbonisation targets, with increased electrification, greater uptake of renewable energy sources and energy efficiency all a part of the picture. However, the EU recognises the existence of hard-to-decarbonise sectors like certain transport modes and industrial processes. For decarbonising these sectors of the economy, renewable hydrogen and carbon capture, utilisation and storage (CCUS) are likely to be needed. This necessity also holds good at the MS level, underlining the need for MS like Belgium to come up with a strategy for an increased deployment and utilisation of renewable hydrogen and CCUS.

Power-to-X (PtX) is the conversion of electricity, generally from renewable sources like wind or solar, to liquid or gaseous fuels. It is one of the most prominent methods of generating renewable hydrogen and is therefore expected to play a prominent role in Belgium's decarbonisation scenarios.

[1] European Commission, '2050 long-term strategy'
[2] European Council, 'Fit for 55'
[3] European Commission, '2040 climate target'
[4] European Commission, 'Questions and Answers - The Effort Sharing Regulation and Land, Forestry and Agriculture Regulation'
[5] European Commission, 'Effort sharing 2021-2030: targets and flexibilities'
[6] Draft update of the Belgian National Energy and Climate Plan

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The Belgian NECP acknowledges the importance of hydrogen, stating that ‘hydrogen plays a crucial role in decarbonising heavy industry and is an essential part of the puzzle to achieve our climate goals.’ CCUS is also identified as an important contributor to decarbonisation, although the extent of its utility differs between the three regions.

This report lays out a roadmap for Power-to-X and CCUS technologies in Belgium.

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2 PTX AND CCU TECHNOLOGIES

The role of fossil fuels in climate change need not be detailed here, and the necessity of an urgent switch away from these fuels is therefore clear. Despite this, the composition of the global energy mix has remained strikingly similar for decades (Figure 1), with fossil fuel consumption continuing to grow in absolute terms even as renewable energy sources like solar and wind are deployed in greater quantities.

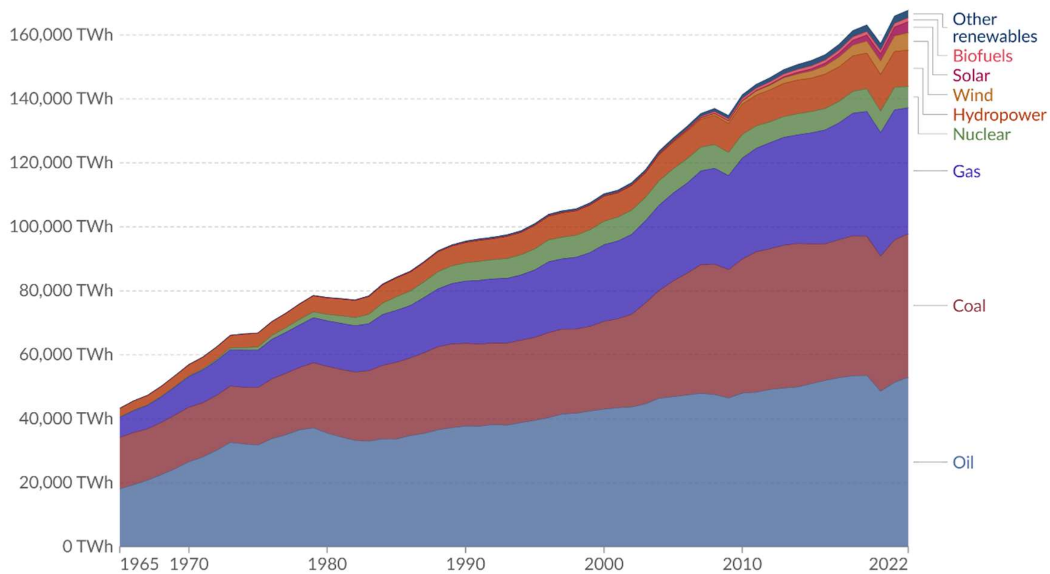
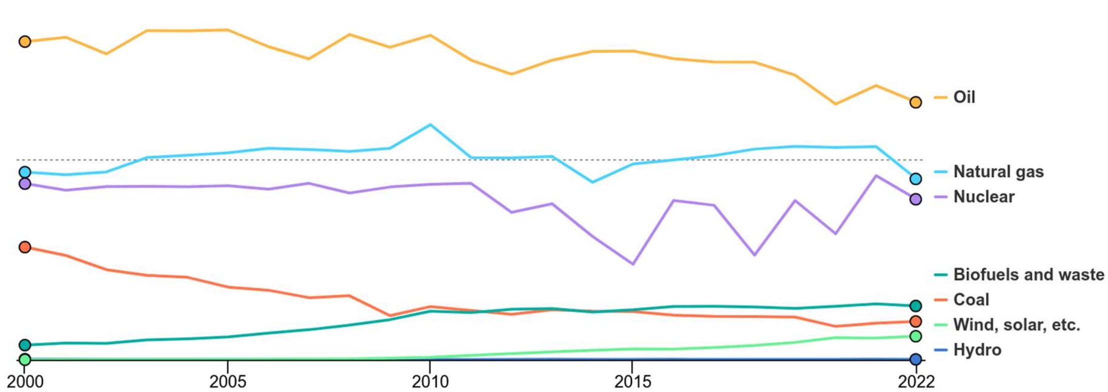


Figure 1: Evolution of world energy consumption by source [7]

The picture is slightly better in Belgium, with fossil energy sources like oil and coal showing a modest decline over the past two decades (Figure 2). Despite this, oil and gas remain the dominant sources, and the trend clearly indicates that this is expected to remain the case for decades to come.



[7] Our World in Data, 'Energy Mix'

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Figure 2: Evolution of total energy supply in Belgium [8]

2.1 Relevance of PtX and CCU

Before ways to change this fossil energy-dominant scenario can be worked out, it is necessary to first examine the reasons for the enduring appeal of fossil fuel sources in spite of their obvious culpability in climate change. One reason is 'carbon lock-in', as the ubiquitous fossil fuel-intensive infrastructure hinders the deployment of low-carbon alternatives that would require an overhaul of this existing infrastructure [9]. A second reason is the ease with which fossil fuels can be transported and stored, making them readily available at the time and place of use, a marked contrast to solar and wind energy, for instance. A third is the high energy density of these fuels, both in volumetric and gravimetric terms. This makes these fuels uniquely suited to applications like aviation, for example, where using large weights or volumes of less energy dense fuels would be uneconomical at best.

All these factors mean that alternative fuels that closely mimic the above advantages of fossil fuels have a much better chance of gaining widespread acceptance than those that diverge along any of these axes. In other words, the best bet for creating a renewable future energy sector is producing renewable analogues of today's fuels – the so-called 'drop-in' fuels that can substitute petroleum-derived fuels without significant disruptions to infrastructure [10].

These drop-in renewable fuels have to, by definition, resemble petroleum-derived fuels in chemical composition. They must, therefore, be hydrocarbon derivatives, which means that their production will require a source of green hydrogen and of green carbon.

While there are several methods of renewable hydrogen production, such as biomass gasification, photocatalytic decomposition of water, thermochemical water splitting, etc., the most developed method is electrolysis of water using renewable electricity, with the EU using this technology as the basis of its renewable hydrogen policy [11]. This can be considered to be a part of the wider group of technologies called 'power-to-X' (PtX). The term 'power-to-X', in its most elementary form, simply means converting power or electricity into something else (X). Most commonly, the 'X' is a fuel like hydrogen, methane, methanol, ammonia, etc.

Green carbon can come from diverse sources like biomass, used cooking oil and carbon capture and utilisation (CCU). CCU refers to applications in which CO_2 is captured, either from a point industrial source like a steel or cement plant or directly from the atmosphere, and converted into diverse carbon-containing products. These products include fuels and chemicals like methane, methanol and formic acid.

While the desirability of reusing the existing fuel infrastructure has been emphasised above, the adoption of alternative fuels that do not score highly on this front cannot be ruled out, if they have advantages that offset this drawback. Renewable hydrogen, in particular, has potential as an alternative fuel due to its high gravimetric energy density (120 MJ/kg) and it not producing any GHG emissions at the point of use. Its low volumetric energy density and challenges associated with its transport and storage mean that the use of hydrogen derivatives

[8] International Energy Agency, 'Belgium'
[9] World Resources Institute, 'What Is Carbon Lock-in and How Can We Avoid It?'
[10] Treehugger, 'Drop-in Fuels Are Road Ready'
[11] European Commission, 'Renewable hydrogen'

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like ammonia has also been proposed as a way of developing the ‘hydrogen economy’. As they contain no carbon, renewable hydrogen and ammonia production represent fuel pathways that require PtX but not CCU, although ammonia production does require a nitrogen source (see Figure 3).

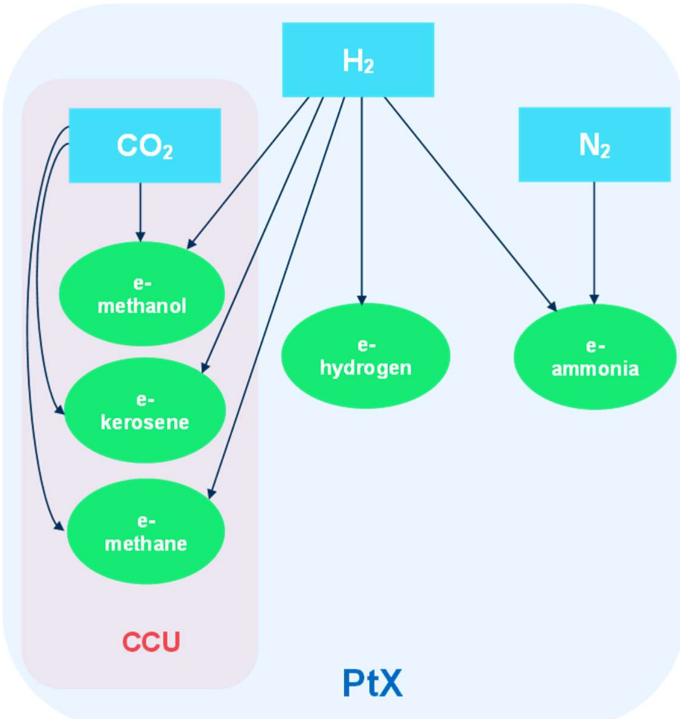

Figure 3: Schematic showing a selection of PtX and CCU fuels

The above makes clear that PtX and CCU are vital components of any decarbonisation pathway. The following subsections look at some of these technologies in more detail.

2.2 PtX technologies

As outlined in Section 2.1, the production of green hydrogen via water electrolysis (PtH) can be considered the cornerstone of PtX fuels. The electrochemical splitting of water into hydrogen and oxygen is a mature, but nevertheless still advancing, technology. The three most commercially important electrolyser technologies are:

2.2.1 Alkaline electrolysers

These electrolysers are the oldest and most mature technology. These electrolysers have a working temperature of 70-90 °C, with 25-40 wt% aqueous solutions of KOH or NaOH as electrolyte [12]. These relatively mild operating conditions allow for the use of cheaper non-precious metal catalysts based on nickel, cobalt or stainless steels. These electrolysers have high efficiency and product purity and are suitable for large-scale hydrogen production. On the

[12] Aalborg University, Power-to-X: Technology overview, possibilities and challenges

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flipside, the low current densities and corrosive alkalinity of the solutions leads to high operational costs. Research is therefore ongoing to reduce these drawbacks, such as by increasing current densities [13] and synthesising novel catalyst coated membranes [14].

2.2.2 Polymer Electrolyte Membrane (PEM) electrolysers

These electrolysers use a polymeric membrane as the electrolyte instead of a liquid. This membrane is used to transfer protons from the anode to the cathode side and to separate the evolved hydrogen and oxygen gases. PEM electrolysers have several advantages over their alkaline counterparts, such as faster cold starts, higher current densities, higher flexibility, compact design and elevated pressure operation. However, the iridium and platinum-based catalysts, polymer film electrolytes and titanium-based porous transport layers used in PEM electrolysers are all expensive, hindering the commercial penetration of this technology [12].

2.2.3 Solid oxide electrolysers

Solid oxide electrolysers use ceramic solid oxide electrolytes, such as nickel/yttria stabilized zirconia. They operate at high temperatures (800 – 1000 °C), which leads to a significant increase in ionic conductivity and the rates of electrochemical reactions on the surface of electrodes [15]. At these high temperatures, water is in the form of steam, which means that a part of the energy required for splitting water is provided thermally, reducing electricity requirement and increasing electrolyser efficiency compared to other electrolyser types [12]. These electrolysers can also be operated in reverse mode as fuel cells, which can be used for grid balancing. These electrolysers are still in an early stage of development, with the material requirements that high temperature operations entail limiting their durability and commercial deployment.

2.3 CCU technologies

As described in Section 2.1, the production of CCU fuels requires a carbon source in addition to a source of hydrogen. The carbon source used is CO_2 captured from any of a number of sources, with numerous capture technologies also commercially available. These aspects are briefly described below.

2.3.1 CO_2 sources

The typical CO_2 sources that are relevant for CCU at an industrial scale can be broadly split into four categories.

I. **Power plants**
II. **Industrial processes**
III. **Biogenic CO_2**
IV. **Direct air capture (DAC)**

[13] Zappia, et al., Front. Chem., 2022
[14] Hnát, et al., Int. J. Hyd. Ener., 2019
[15] Dahiru, J. Ener. Stor., 2022

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Category	Source	CO_2 concentration (vol%)	Reference
Power plants	Natural gas Coal Petroleum	3 - 4 12 – 15 3 - 8	*17* *17* *17*
Industrial processes	Iron & steel Cement Ethylene & ethylene oxide Ammonia (SMR) Ethanol	15 20 12 & 100 8 - 100 95	*17* *17* *17* *17*
Biogenic CO_2	Bioenergy Fermentation	3 - 8 100	*17* *17*
Direct air capture	Atmosphere	0.04	

** Profile of worldwide large CO2 stationary sources emitting more than 0.1 Mt CO2 per year (Source: IEA GHG, 2002a)*

2.3.1.1 Power plants

Electricity and heat production are the largest sectoral contributors to anthropogenic CO_2 emissions worldwide, emitting over 15 billion tonnes of GHG in 2020, almost all of it CO_2 [16]. These emissions arise due to the still large-scale use of coal and natural gas for electricity and heat production, despite the recent increase in the use of renewable energy. Power plant emissions are therefore an obvious target for CCU applications. The concentrations of CO_2 in power plant flue gas are moderately high (3 – 15 vol% [17]), giving a capture cost of 50 – 100 USD/t [18].

2.3.1.2 Industrial processes

Several industrial processes also produce a considerable quantity of CO_2, with iron and steel (2.6 GT/y), cement (2.4 GT/y), chemicals (1.3 GT/y), aluminium (0.2 GT/y) and pulp and paper (0.15 GT/y) being the biggest emitters [19]. The flue gas streams from these industries often have high CO_2 concentrations (14 – 95 vol%), allowing for capture costs in the 15 – 120 USD/t range [18].

2.3.1.3 Biogenic CO_2

Biogenic CO_2 emissions vary depending on the feedstock, with CO_2 concentrations typically ranging from 3 up to 8 vol%[20], facilitating more economically feasible capture processes. Capture costs are estimated to range between 15 and 85 USD/t CO_2[21]. However, the smaller scale of biogenic emission sources presents challenges for CCUS transport and logistics, complicating the overall viability of widespread implementation. Estimated potential of bioenergy with CCUS by 2050 is 11.3 Gt CO_2/year[20].

2.3.1.4 Direct Air Capture

Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere (0.04 vol% CO_2) at any location, unlike carbon capture which is generally carried out at the point of emissions, such as a steel plant with a given capture cost of 134 – 342 USD/t CO_2[22]. In the ideal scenario, DAC systems are coupled with renewable energy sources. This coupling is

[16] Our World in Data, Breakdown of carbon dioxide, methane and nitrous oxide emissions by sector
[17] IPCC, Carbon Dioxide Capture and Storage
[18] International Energy Agency, Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019
[19] Canary Media, The huge climate problem of cement, steel and chemicals, visualized
[20] IPCC, Carbon Dioxide Capture and Storage
[21] Your ultimate guide to carbon capture and storage technologies
[22] Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019 – Charts – Data & Statistics - IEA

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crucial for minimizing the life-cycle emissions of DAC operations, as the process is energy-intensive and requires substantial electricity and heat.

2.3.2 CO_2 capture technologies

Carbon capture technologies can be categorized depending on their ability to process feed gases across a range of CO_2 concentrations (Figure 4). These technologies can capture between 85-95% of all CO_2 produced (IPCC, 2005), but net emission reductions are in the order of 72 to 90% due to the energy requirements to separate the CO_2 and the upstream emissions (Viebahn et al., 2007). The landscape of CO_2 capture technologies is quite diverse, as illustrated by the more detailed breakdown of capture technologies provided in Figure 5.

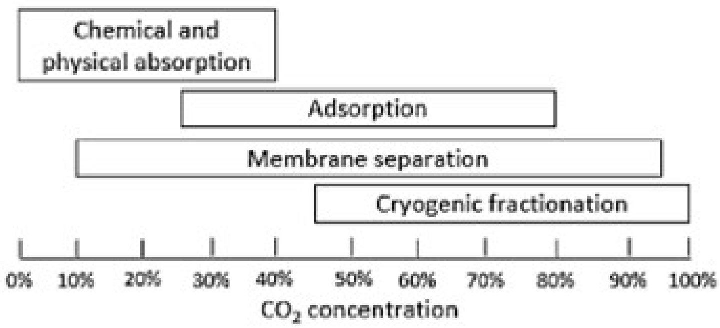

Figure 4 Schematic of main carbon capture technologies versus feed gas CO_2 concentration (excluding DAC).

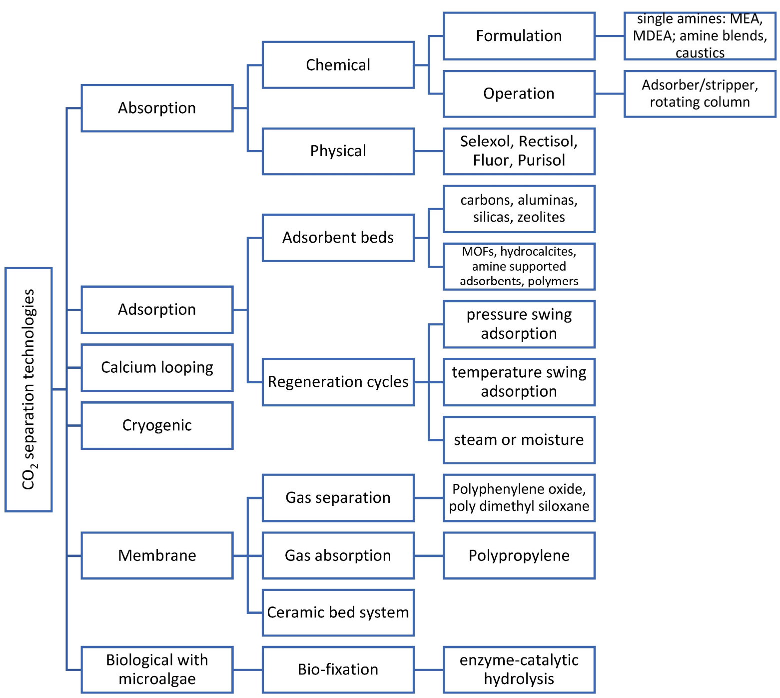

Figure 5 Overview of carbon capture technologies[23]

[23] Font-Palma et al. 2021 Journal of Carbon Research

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The cost of carbon capture is influenced by several factors, notably the CO_2 concentration, as for low concentration sources more volumes need to be processed and generally a stronger capture agent needs to be used, raising both energy use and CAPEX (Figure 6). As with all technologies, also process scale plays a big role. While capture technology is a vital consideration in CCUS, the total cost is also influenced by transport and storage methods, which often involve additional process steps such as dehydration, compression, or liquefaction.

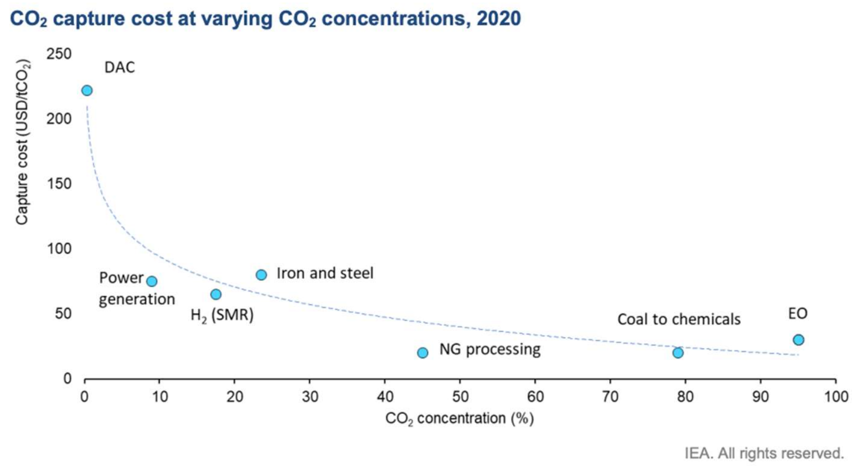

Figure 6 Overview of CO2 capture cost versus CO2 concentrations, 2020 status[24]

2.3.3 CO_2 conversion technologies

To convert CO_2 into value-added products, a wide range of technologies is available, and even more are currently the subject of research and development. While an exhaustive discussion of all options is left out of the scope here, the example of sustainable aviation fuels (SAFs) is taken to illustrate the typical working of such processes (Figure 7). Generally, CCU pathways start with the CO_2 capture step along with water electrolysis, which yield the two feedstocks (CO_2 + H_2) for subsequent conversion. In most cases, the next steps include thermocatalytical processes, which are among the most mature technologies to convert CO_2.

In the first case, syngas (CO + H_2) is generated by means of a reverse water gas shift reaction followed by the well-known Fischer-Tropsch (F-T) reaction to yield a broad set of hydrocarbons, for which a number of post-processing steps will be required to obtain SAFs along with other fuels (e.g. gasoline). In the second case, the CO_2 + H_2 mixture is sent to a methanol synthesis unit, whereafter the methanol is converted to olefins, and subsequently the olefins are oligomerised into longer chain hydrocarbons, usable as fuel. This second route is relatively younger but has the advantage that relatively more carbon is turned into SAFs, whereas as F-T has more by-products that may be less easy to valorise in a climate neutral economy[25].

Several new technologies are emerging especially in the field of producing syngas, that is the starting point for F-T. Solid Oxide electrolysis is a technology that unlike PEM or alkaline electrolysis works at very high temperatures (> 600°C). It is capable of doing co-electrolysis, i.e. converting H_2O to H_2 and CO_2 to CO at the same time, and has very high energy efficiency,

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24 Carbon Credits

25 Bube et al. Fuel 366 (2024) 131269

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yet is still in scale-up phase. Similarly, low temperatures electrochemical CO_2 reduction (eCO_2R) is able to produce both products simultaneously but is still largely pre-commercial[26]. Plasma technology is along emerging as an alternative for the production of CO, and is currently being commercialised by the Belgian company D-CRBN[27].

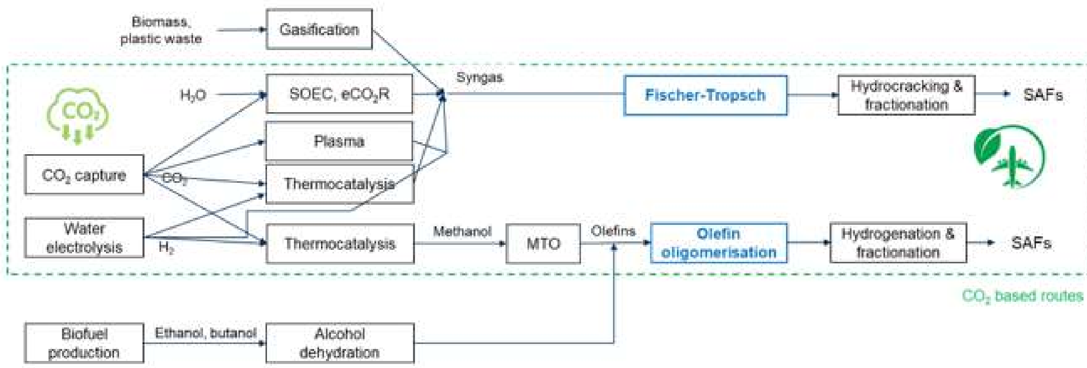

Figure 7 Overview of CO_2 based routes to SAFs alongside with selected biomass routes.

2.4 Hydrogen use priorities

Green hydrogen production involves the expenditure of renewable energy, which is currently only available in limited supply. Its transport and use will also require substantial investments, for which it will also have to compete with other avenues of public and private expenditure. It is therefore important to prioritise the areas where hydrogen and its derivatives need to play a central decarbonisation role, and leave other areas to alternatives like direct electrification, biomass use and CCU.

There are essentially two reasons why hydrogen would be preferred in a particular application. The first is that hydrogen is used as a feedstock in that application, which makes its use mandatory. The second is that the particular sector might be 'hard-to-decarbonise' using alternative means. The sectors where hydrogen and its derivatives can be expected to play a major role in decarbonisation are briefly explained below.

2.4.1 Industry

Hydrogen is already used on a large scale in industry. As Figure 8 shows, this use can be divided into four principal industrial segments.

26 Huang et al. *Energy Environ. Sci.*, 2021, 14, 3664
27 D-CRBN – CO2 recycling for industrials

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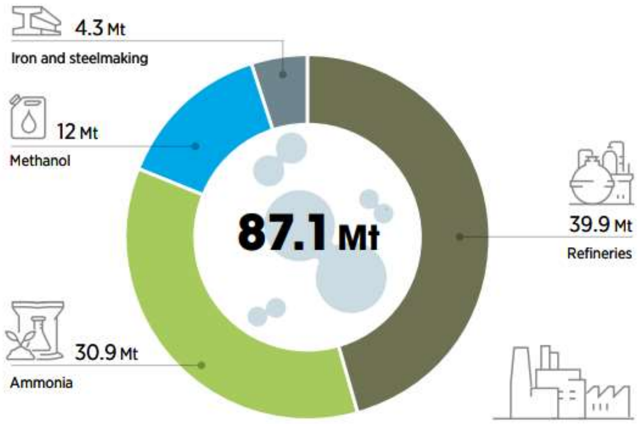

Figure 8: Global pure hydrogen demand in industry in 2020 (from '[Green Hydrogen for Industry](#)', IRENA 2022)

The largest industrial consumers of hydrogen are crude oil refineries, where they are used in two processes: hydrocracking and hydrotreating. Hydrocracking is the process of catalytically upgrading heavy and low-quality gas oil into diesel, gasoline and jet fuel in the presence of hydrogen, while hydrotreating is the process of mixing hydrogen with petroleum products to remove sulphur and other contaminants. With a projected decline in fossil fuel consumption in the coming decades, this source of hydrogen demand should likewise decline.

The second and third largest industrial consumers of hydrogen are ammonia and methanol, which can be clubbed together under the head of 'chemical industry'. Hydrogen is used as a feedstock for the production of both these chemicals, which are among the most widely produced industrial materials. They are also both hydrogen derivatives that could potentially be used as alternative fuels, as discussed in Section 4. Since hydrogen is a raw material in the production of these chemicals, it is clear that this is a definite green hydrogen application.

The fourth major industrial consumer of hydrogen is the iron and steel industry. There are two main processes for steel production – the blast furnace-basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF) route. The BF-BOF is the dominant method, accounting for 71% of global steel production. It is a carbon intensive process, with emissions per ton of steel often exceeding 2 tons. Emissions in this process can be reduced by over 20% replacing a portion of the coke used as reducing agent with green hydrogen, although hydrogen cannot fully substitute the use of coking coal. The EAF process, used for 24% of global steel production, produces secondary steel by melting steel scrap with the heat generated by an electric arc, Given supply limitations of steel scrap, it can also be used to make steel from sponge iron produced by the direct reduction of iron (DRI) process. Hydrogen can be used as the primary reducing agent in the DRI-EAF process, and indeed, this accounts for the 4.3 Mt of hydrogen demand in the steel industry shown in Figure 8. This hydrogen is almost entirely fossil-based at the moment, with green hydrogen consumption restricted to demonstration plants.

As the steel industry is currently responsible for 7-9% of global anthropogenic CO_2 emissions, its decarbonisation is naturally a pressing concern. The Belgian hydrogen strategy accordingly considers the DRI-EAF process to be an important future consumer of gaseous green hydrogen. Belgium's steel making capacity currently stands at around 7.8 million tons. Estimates for the amount of hydrogen required per ton of steel vary greatly, from 50 kg/t estimated by the European Parliament Research Service to 72 kg/t assumed by BHP to 104 kg/t estimated by Shahabuddin, et al. The amount of green hydrogen required to fully

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decarbonise Belgian steel making would therefore be 400,000 to 800,000 t/y (13-27 TWh/y), a considerable portion of the estimated domestic hydrogen demand. Other options, such as CCU, may therefore also be worth considering.

Another possible use of green hydrogen in industry is as an industrial heat source. Hydrogen combustion produces very high-grade heat that can serve virtually any industrial application (Figure 9). However, several options exist for low and medium temperature heat requirements, while electric heating could also potentially meet most of the high temperature heating requirements. For instance, in addition to the electric arc heating in steel mentioned above, electric chemical crackers are in the pilot phase, while resistively and plasma heated cement calciners are also being researched. Depending on how successfully these technologies can be developed and upscaled, industrial heating may not be a priority area for green hydrogen use.

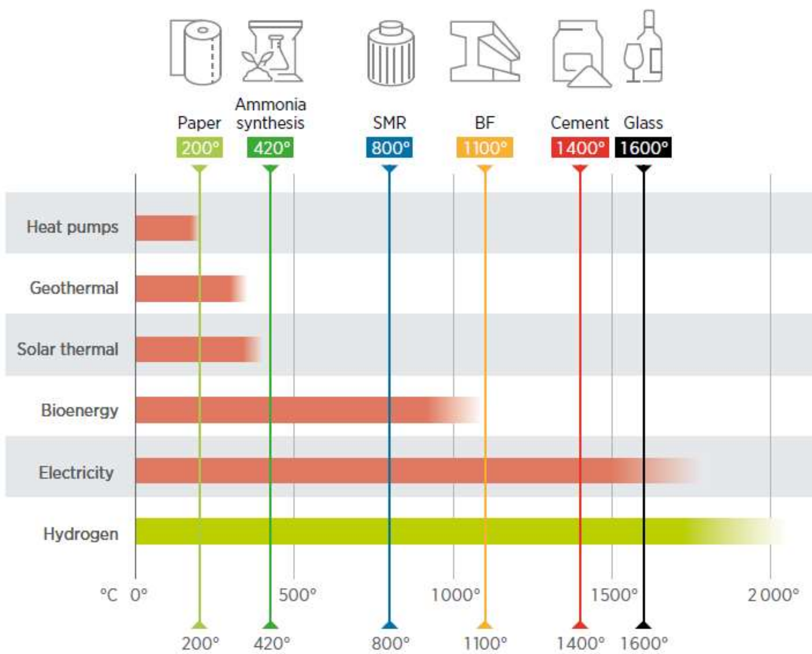

Figure 9: Working temperature by source and temperature requirements of selected industries (from 'Green Hydrogen for Industry', IRENA 2022)

2.4.2 Transport

Projections for the evolution of global transport differ widely, both in terms of the magnitude of energy required and the composition of the energy mix (Figure 10) due to differing assumptions on decarbonisation targets, societal changes, techno-economic developments, etc.

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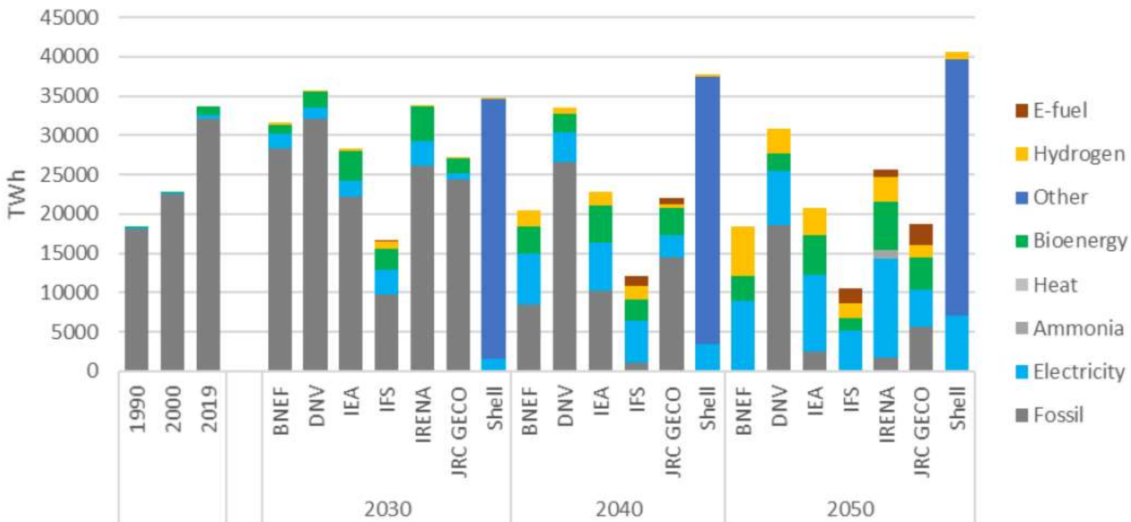

Figure 10: Projections for evolution of global transport energy demand and mix (from '[The role of hydrogen in energy decarbonisation scenarios](#)', JRC (EC), 2022)

Nevertheless, most projections agree that hydrogen will play a limited but definite role in transport decarbonisation. Short distance and light road transport, it is generally agreed, will be decarbonised via electrification. Railway transport is already mostly electrified, and this can be expected to increase further. The role of hydrogen and its derivatives could be more prominent in heavy-duty, long-haul road transport and in the maritime sector. Aviation is generally considered to be the most difficult transport sector to decarbonise, with liquid fuels, either fossil-derived, hydrogen-based or bio-based, expected to continue playing a role for decades. Green hydrogen and its derivatives are therefore very likely to be needed in decarbonising Belgium's transport sector, especially in the aviation, maritime and long-distance road transport sectors.

2.4.3 Other uses

Besides the main uses mentioned above, there might be other niche application areas for hydrogen use in Belgium. One such possibility is in building heating. Currently, buildings in Belgium are mainly heated with natural gas and oil. However, this is expected to change in the coming years, with increased uptake of electric heat pumps for heating and cooling. Flanders, for instance, has released the 'Warmteplan 2025', which aims to provide financial support for heat pump installation and bans gas connections in new buildings. While some buildings will nevertheless continue to use fuel-based heating for years to come, the federal government does not consider this to be a priority area for green hydrogen use.

Another area where green hydrogen may have a role to play is in energy storage. Renewable energy sources like solar and wind are intermittent and rather unpredictable, necessitating backup storage to ensure grid stability and balance variable supply and demand. Battery storage and green hydrogen storage are two of the most promising energy storage technologies, both with their own pros and cons. Depending on the specificities of the application, either one or a combination of the two storage technologies may be deployed, and hence this may also be a possible area of green hydrogen use.

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2.5 Hydrogen derivatives

Hydrogen is considered to be an indispensable part of the technological mix that will lead to decarbonisation globally. Green hydrogen production does not entail significant GHG emissions, while its use is entirely GHG emissions-free. It can be produced from a variety of sources (such as solar, wind and biomass) and used in a range of applications (such as power, transport and steel-making).

Nevertheless, the use of green hydrogen also comes with some challenges. One is the fact that only 1% of global hydrogen production is currently renewable, due to the production costs of renewable hydrogen being two or three times higher than fossil hydrogen. These costs are expected to reduce in the coming years thanks to technological improvements and increased deployment (see Figure 11).

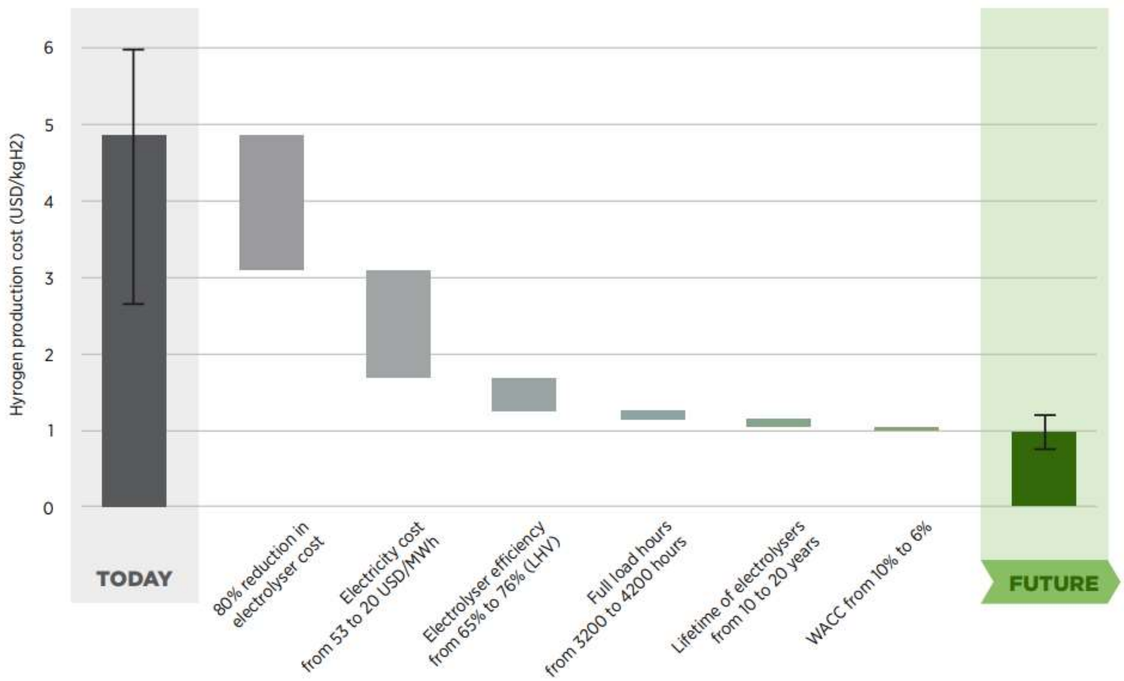

Figure 11: Sources of future cost reduction in green hydrogen production (from 'Green Hydrogen Cost Reduction', IRENA 2020)

A second serious concern in green hydrogen deployment is related to the intrinsic shortcomings of hydrogen as an energy carrier. Hydrogen has a high gravimetric energy density but a very low volumetric energy density (see Figure 12). This makes it use impractical in applications like aviation, since the storage space required for the fuel will be too large to be economically feasible. Additionally, hydrogen storage and transport poses additional challenges related to safety, due to its ability to embrittle materials, its ease in escaping from containment, its wide flammability range, and ease of ignition. Even at the point of end-use, problems may arise due to need to install compatible engines or fuel cells.

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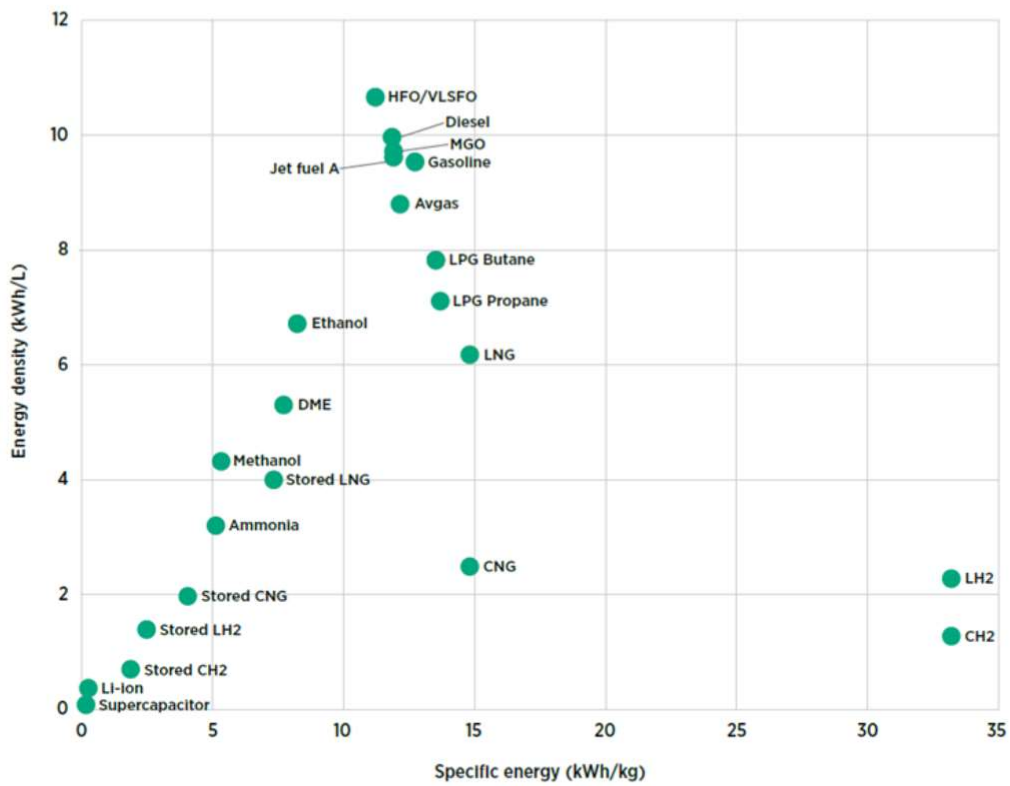

Figure 12: Comparison of gravimetric and volumetric energy density of energy carriers *(from 'Hydrogen', IRENA)*

The challenges related to storage, transport and use can be tackled to a large extent by the use of hydrogen derivatives in place of pure hydrogen. Hydrogen derivatives like methanol, methane, ammonia and kerosene are already in wide use as fuels and chemical feedstock, and hence have a well-developed infrastructure in place, and the 'green' versions of these fuels can therefore be easily deployed (drop-in fuels). Further, these fuels do not, by and large, have the limitations of storage and transport described above for pure hydrogen.

Some important hydrogen derivatives are briefly described below.

2.5.1 Methanol

Methanol is a major chemical commodity with an annual production of about 100 Mt[28]. The main applications of methanol include the production of formaldehyde, acetic acid, olefins and methyl tert-butyl ether (MTBE), which in turn are used in the production of other chemicals and materials, which ultimately can be found back in many daily life applications[29]. In addition, methanol is also sometimes used as fuel additive due to its attractive fuel properties[30]. Today, methanol is largely produced from natural gas, and to some extent also from coal (mostly in China).

[28] IRENA (2021). Innovation outlook renewable methanol
[29] About Methanol | Methanol Institute
[30] Blending-Handling-Bulletin-Final.pdf (methanol.org)

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The energy transition may entail a role for methanol much larger than the applications its serves today. Renewable methanol is also often considered as transport fuel for cases that are hard to electrify directly, e.g. shipping. Furthermore, renewable methanol could also be used to produce olefins, monomers of commonly used plastics, which are today still produced mostly from petrol. As a result, IRENA estimates that methanol market could significantly grow towards 2050, with e-methanol taking up largest share but also a strong growth in biomethanol is expected (Figure 13). As explained in D2.3, mature technologies are available to produce such methanol, however cost is significantly higher than that of fossil methanol, and access to large amounts of affordable renewable energy will be required in combination with process improvements to realise this shift.

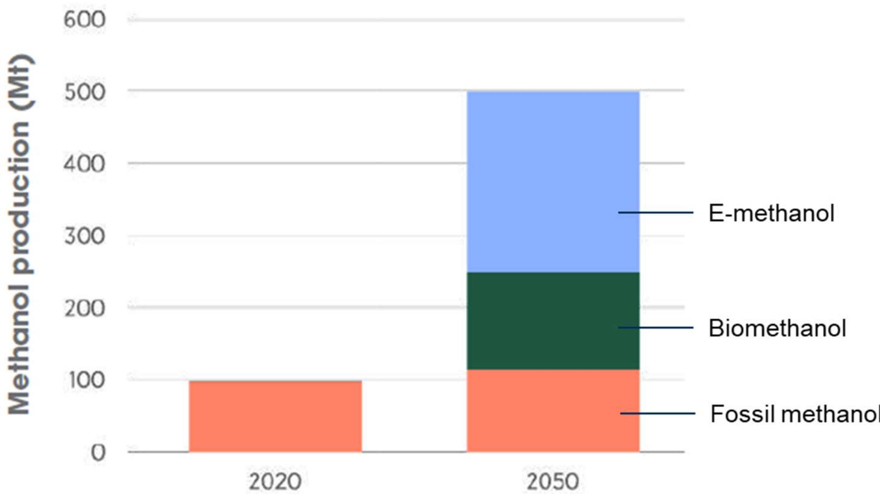

Figure 13 Future methanol market assessment (from: IRENA 2021 Innovation outlook renewable methanol)

2.5.2 Ammonia

Ammonia is a compound of nitrogen and hydrogen with the chemical formula NH_3. It is a gas at standard temperature and pressure, but can easily be liquefied and transported or stored in refrigerated or pressurised vessels. Ammonia is the chemical with the second-highest production tonnage [31], with about 70% being used to make fertilisers and the remainder used for industrial applications, such as plastics, explosives and synthetic fibres [32]. Besides these traditional uses, its use as a fuel is expected to grow in the coming decades, particularly in the power generation and shipping sectors.

Ammonia differs from the other hydrogen derivatives discussed here in being an inorganic compound. This means that its combustion produces no carbon dioxide, which is one of its major advantages as an alternative fuel. However, nearly all the ammonia produced industrially today is derived from fossil fuels, with coal or natural gas being used to power the Haber-Bosch (H-B) process for ammonia production. This process is very energy intensive, resulting in 2.3 to 3.9 tonnes of CO_2 being emitted per tonne of ammonia produced [33]. This, along with the fact that around 185 million tonnes of ammonia are produced annually [34], leads to ammonia production emitting over 450 million tons of CO_2 annually, equal to around 1.3%

[31] The Essential Chemical Industry, Ammonia
[32] IEA, Ammonia Technology Roadmap
[33] RMI, Clean Energy 101: Ammonia's Role in the Energy Transition
[34] AmmPower, Major Ammonia Producing Companies and Their Capacities

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of anthropogenic CO_2 emissions [35]. It is clear that only the use of green ammonia can be considered for decarbonisation.

The simplest option for producing green ammonia using PtX technologies is simply substituting fossil-derived hydrogen with hydrogen produced via water electrolysis. Planned examples of this route include the HØST PtX Esbjerg project in Denmark [36] and the MadoquaPower2X project in Portugal [37]. An interesting alteration to this route is Topsoe and First Ammonia's process that uses solid oxide electrolyser cells (SOEC), which can achieve higher efficiency by utilising the waste heat from the H-B process [38] and can potentially also eliminate the need for an air separation unit for the nitrogen [39]. Another option in the longer term is an electrochemical H-B process, with one potential configuration promising up to a fourfold reduction in energy consumption and a halving of CO_2 emissions [40]. However, the Faradaic efficiency and productivity of this process are far below commercial requirements, meaning that significant optimisation is required for this process to become a reality [41]. The use of the 'Gen 2' technology , viz. H-B plants fed by green hydrogen derived from electrolytic water splitting, has been projected to achieve commercialisation by 2030, with the electrochemical 'Gen 3' processes following in the 2040s [42] (Figure 14).

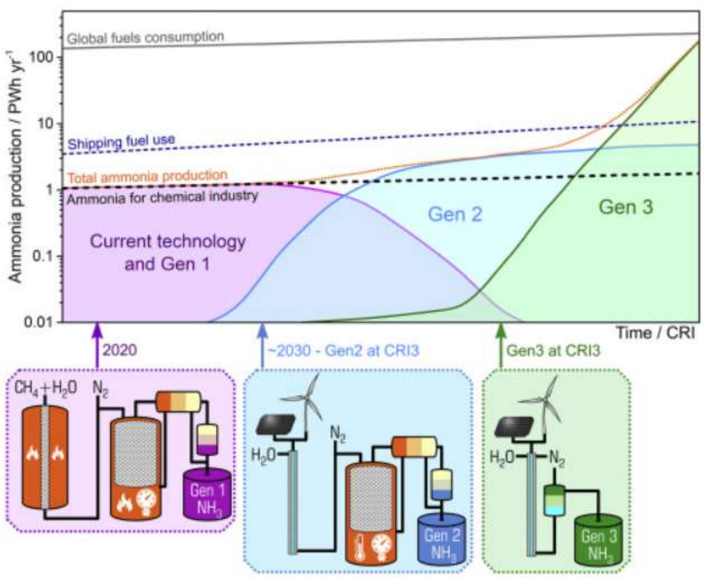

Figure 14 Ammonia Economy Roadmap Showing Current and Projected Contributions of the Current and Gen 1 (purple), Gen 2 (light blue), and Gen 3 (green) Ammonia Production Technologies [42]

Aside from clean production, another major challenge in using ammonia as a green fuel is its toxicity [43], which precludes its use in the automotive or residential sectors. Its use as a power generation fuel is more possible, due to decades of experience in safe handling of ammonia

[35] World Economic Forum, Ammonia Industry
[36] State of Green, HØST: Green ammonia on a gigawatt scale
[37] MadoquaPower2X
[38] Recharge, Topsoe wins world's largest ever hydrogen electrolyser order in 5GW green ammonia deal
[39] The Royal Society, Ammonia: zero-carbon fertiliser, fuel and energy store
[40] Kyriakou, et al., Joule, 2020
[41] McPherson and Zhang, Joule, 2020
[42] MacFarlane, et al., Joule, 2020
[43] UK Health Security Agency, Ammonia: toxicological overview

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in industrial settings, although strict safety protocols are still needed to mitigate the toxicity and environmental risks [44]. Ammonia use as a shipping fuel is also possible, though subject to more constraints than in a stationary application. The International Maritime Organization (IMO) is working on developing guidelines for ammonia use as fuel, with interim guidelines released in 2024 [45]. There is some additional controversy over the actual climate and air quality impact of ammonia use in shipping, with stringent emissions controls probably being required to reduce emissions of NO_x - responsible for air pollution – and N_2O, a potent greenhouse gas, in addition to ammonia itself [46].

2.5.3 Kerosene

Synthetic kerosene, also known as e-kerosene, is an emerging alternative to conventional petroleum-based fuel. This combustible hydrocarbon liquid is primarily used in aviation (sustainable aviation fuel - SAF) and related industries, such as space propulsion, industrial heating, and other sectors requiring high-energy-density liquid fuels.

As described in Section 2.3.3, there are two principal routes for producing e-kerosene, viz. the Fischer-Tropsch (F-T) route and the methanol-to-olefins (MTO) pathway. The F-T route is approved for blending with conventional aviation fuel up to a 50% blending limit under ASTM D7566, while the methanol to jet fuel route is currently under evaluation. Synthetic kerosene derived from the higher alcohols ethanol and isobutanol are also approved for blending up to a 50% limit [47], although the difficulty of higher alcohol synthesis makes this route harder to achieve from a PtX perspective. Also worth mentioning are non-drop-in SAFs, which are aromatic-free fuels that will require new fuel specifications, supply chains and engines but will help reduce non-CO_2 emissions and contrails [48].

Depending on the feedstock, technology and supply chain, synthetic kerosene can reduce life cycle emissions by up to 99% [49]. They are designed as drop-in fuels, meaning they can be used without requiring substantial modifications to current aircraft, engine design, or airport infrastructure, which makes them a practical choice for the aviation industry. However, SAFs currently cost 3 to 10 times more than conventional fossil-based fuels, which remains a key challenge for large-scale adoption [50].

Today, the SAF production volumes remain very limited, representing only 0.3% (~1.25 billion litres) of global jet fuel consumption in 2024 [51]. To meet the net-zero aviation emissions targets by 2050, significantly larger volumes will be required. To accelerate the adoption of SAFs, the European Union has established a regulatory framework through the ReFuelEU Aviation regulation. This initiative obliges aviation fuel suppliers to ensure that the fuel at EU airports contains a minimum of 2% sustainable aviation fuels in 2025, 6% in 2030 and 70% in 2050 [52]. From 2030, 1.2% of the aviation fuels must also be synthetic fuels (e-fuels), rising to 35% in 2050. This mandate is expected to greatly increase demand for e-kerosene in the coming decades (Figure 15).

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[44] International PtX Hub, How safe are hydrogen, ammonia and methanol?
[45] DNV, IMO CCC 10: Interim guidelines for ammonia and hydrogen as fuel
[46] Wong, et al., Env. Res. Lett., 2024
[47] International Civil Aviation Organization, Conversion processes
[48] European Union Aviation Safety Agency, European Aviation Environmental Report 2025
[49] McKinsey and World Economic Forum - Clean skies for tomorrow - 2020
[50] Current landscape and future of SAF industry | EASA Eco
[51] Net zero 2050 - sustainable aviation fuels
[52] European Parliament, 70% of jet fuels at EU airports will have to be green by 2050

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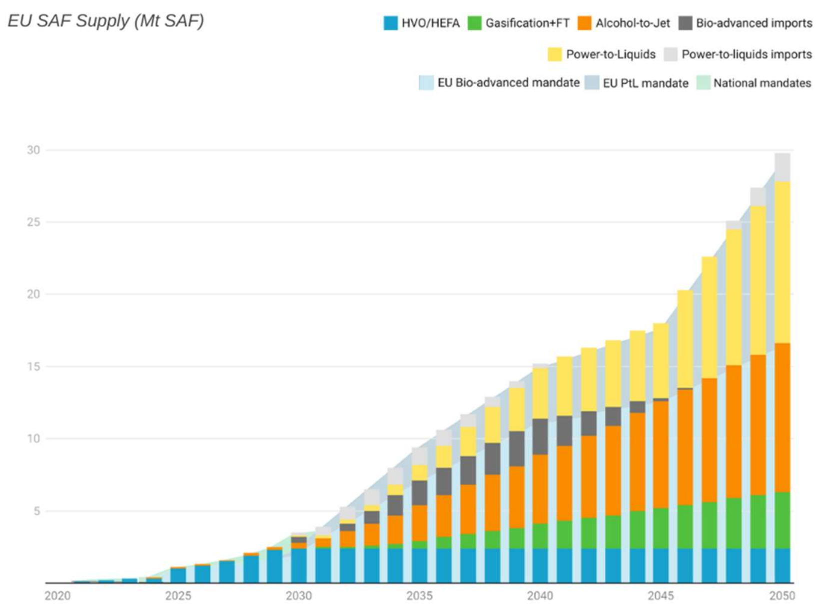

Figure 15 SAF mandates in the EU and contribution of potential routes towards fulfilling these [53]

3 NEED FOR PTX AND CCU IN BELGIUM

3.1 Belgian GHG emissions scenario

Belgium's domestic GHG emissions were 106.5 $MtCO_{2,eq}$ in 2022, a figure that was 27% lower than its emissions in 2005. While this is good news, as mentioned in Section 1, under the Fit for 55 package, Belgium has a GHG emissions reduction target of 47% by 2030 compared to its 2005 levels. This target is set to be missed, with the measures outlined in Belgium's NECP – such as improved energy performance of buildings, more ambitious offshore wind capacity after 2025, further measures to reduce the number of vehicle kilometres travelled, and increased use of renewable heat sources such as heat pumps [54] – only succeeding in achieving a 42.6% reduction. More worryingly, these measures are only expected to lead to a 57% decrease in emissions by 2050, which is far from the EU's climate neutrality target (Figure 16).

[53] Greenair News, EU SAF blending mandate proposals ambitious but feasible, says SkyNRG analysis report

[54] UNFCCC, 'Report on the technical review of the eighth national communication and the technical review of the fifth biennial report of Belgium'

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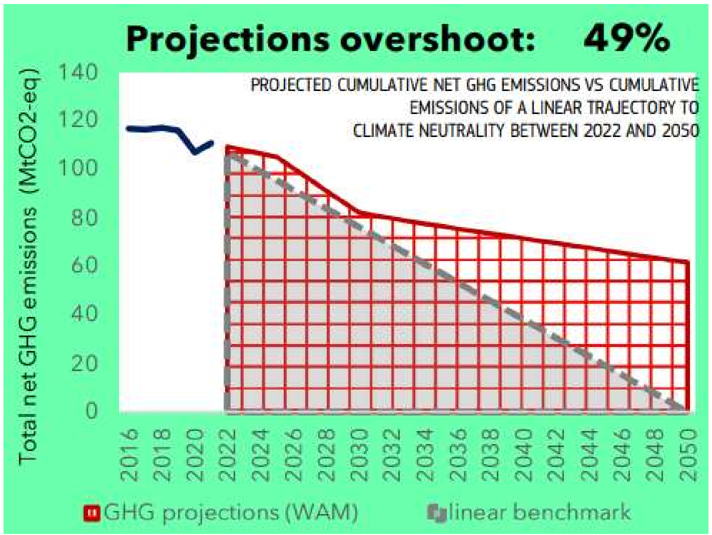
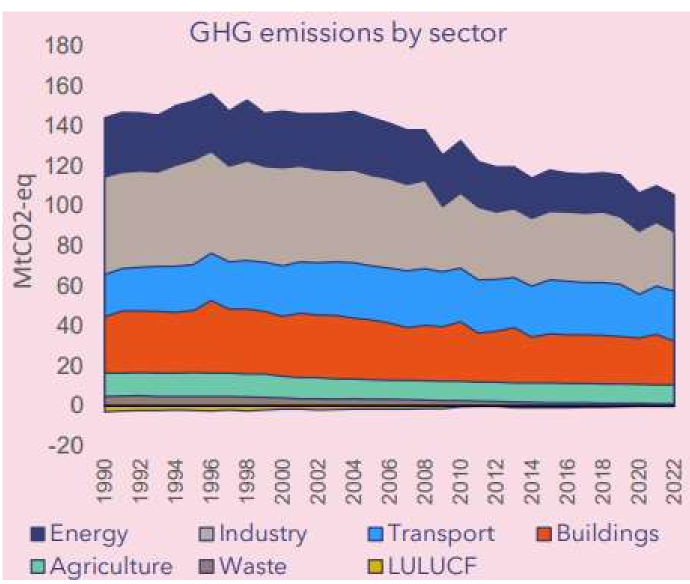


Figure 16: Projected GHG emissions in Belgium with existing and additional reduction measures, compared to linear decarbonisation trajectory [55]

It is evident that additional measures are needed to reduce the overshoot in Belgium's GHG emissions. To see what these could be, one first needs to understand Belgium's present emissions picture.

As seen in Figure 17, there are 5 major sources of GHG emissions in Belgium. The biggest emissions source is the industrial sector, accounting for over 28% of the national emissions. In the second place is the transport sector, with over 23% of emissions, while buildings (21%), energy (18%) and agriculture (9%) are the other major emitters. The respective proportions of these sectors have remained relatively constant over the past decades, as they have all seen modest declines in their absolute numbers, with one notable exception – emissions from the transport sector rose 18% between 1990 and 2022.



[55] European Commission, '[Climate Action Progress Report 2023: Belgium](#)'

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Figure 17: Evolution of GHG emissions in Belgium by sector [55]

3.2 Belgian industrial sector

Belgium is a modern industrialised economy, which, despite the recent growth of the services sector, still derives over 20% of its GDP from industry [56]. This status' sector as the largest GHG emitter is therefore not very surprising. As it operates at an international level, decarbonising the sector while maintaining its competitiveness is a challenge. Measures like the EU-ETS scheme and CBAM will help in this quest, but ultimately, the adoption of technological measures to lower carbon emissions organically will also be needed.

Within the Belgian industrial sector, the largest GHG emitter is the chemical industry [57]. This is also unsurprising, as the sector is one of the most important industries in Belgium, accounting for over a third of Belgian exports [58]. The largest source of CO_2 emissions here is steam cracking in the petrochemical industry to produce light hydrocarbons from heavier feedstock, while the production of ammonia using natural gas as the hydrogen source is another major contributor. Additional CO_2 emissions come in the form of byproduct formation in reactions like the production of ethylene oxide and production of acrylic acid from propene, production of cyclohexanone from cyclohexane, carbon black production, etc.

The second largest emitter is the 'mineral products' category, which includes the production of cement, lime, ceramics, etc. [59] In cement production, CO_2 is emitted as a byproduct during the clinker formation process, which accounts for about 65% cement's carbon footprint [60]. The rest comes from the high temperatures needed for this process being usually generated via fossil fuel combustion. In lime production, the conversion of limestone (mostly $CaCO_3$) to quick lime (CaO) results in CO_2 emissions as byproduct.

Close behind minerals as the third biggest industrial GHG emitter in Belgium is metal production, mainly iron and steel. The primary sources of CO_2 emissions in the iron and steel making processes are raw materials, including coke, and fuel combustion.

In each of the above cases, PtX and CCU represent both solutions and opportunities. In the chemical sector, CCU can be used to first capture the byproduct CO_2 process emissions mentioned above. The captured CO_2 can be combined with renewable hydrogen to produce synfuels and materials which can substitute fossil fuel feedstock, thereby closing the loop. Additionally, the current natural gas-based hydrogen used in the chemical sector, such as for ammonia production, can be substituted with green hydrogen.

In the material products sector, CCU is perhaps even more crucial. As stated above, CO_2 is a byproduct during clinker formation and limestone conversion, and this is unavoidable due to chemistry. Capturing this CO_2 and using this is a raw material can help mitigate the sectoral emissions. Renewable hydrogen may also have a part to play in providing the high process temperatures, although electrification is also a potential candidate here [60].

[56] Statista, 'Belgium: Distribution of gross domestic product (GDP) across economic sectors from 2012 to 2022'
[57] UNFCCC, 'Summary of GHG Emissions for Belgium'
[58] Cefic, 'Belgium: Chemical Industry Snapshot'
[59] Klimaat.be, 'Belgium's greenhouse gas inventory (1990-2021)'
[60] European Commission, 'Deep decarbonisation of industry: The cement sector'

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In the iron and steel sector, natural gas-derived hydrogen can be replaced by green hydrogen as a reducing agent. This can be complemented by ‘Power-to-syngas’ and ‘Power-to-methane’, which uses CO_2 captured from the process emissions to generate syngas or methane for use as fuel or as reducing agent (Figure 18).

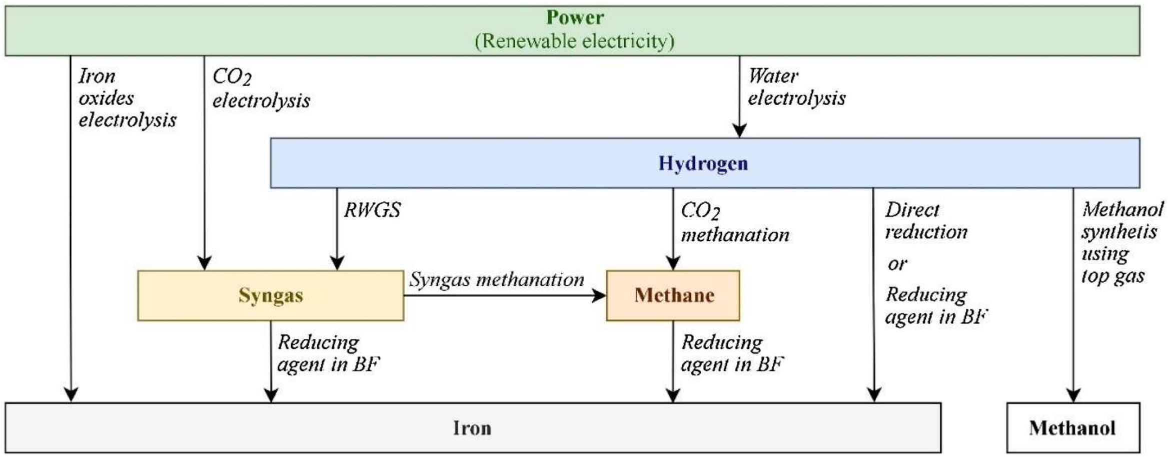

Figure 18: Applicability of CCU/PtX in the iron and steel industry [61]

3.3 Belgian transport sector

The share of transport in Belgium’s emissions has risen steadily for decades, and this trend seems set to continue in the near future. Road transport accounts for 96% of total GHG emissions from this sector, underlining how vital its decarbonisation is for the country as a whole [59]. Cars accounted for 56% of transport emissions in 2017, while heavy and light duty vehicles accounted for 29% and 12% respectively [62]. While limiting transport demand and modal shifts have a part to play in reducing transport emissions, technological choices will also have a role. Electrification may be the best option for cars, but for heavier vehicles, internal combustion engines (ICE) will likely continue to be used till 2050, and fuel cells may become an important choice as well [63]. For ICE vehicles, CCU-derived synfuels will be a good drop-in decarbonisation option, while fuel cell vehicles may be expected to run on green hydrogen.

The GHG emission figures for the transport sector exclude emissions from international air and maritime transport, in line with UNFCCC guidelines. Nevertheless, as home to Europe’s second-biggest port (Antwerp) and one of the busiest airports (Brussels), Belgium does see significant GHG emissions from these sectors – equal to 22% of national emissions, in fact [59]. Decarbonisation of these sectors, therefore, is something that cannot be ignored in the national climate ambitions. PtX fuels like ammonia and methanol are potential decarbonisation candidates for the shipping sector, and sustainable aviation fuels (SAF) for the aviation sector.

[61] Bailera, et al., Journal of CO_2 Utilization, 2021
[62] Climat.be, ‘Vision and strategic workstreams for a decarbonised Belgium by 2050’
[63] Climat.be, ‘Scenarios for a climate neutral Belgium by 2050’

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Clearly then, PtX and CCU fuels will have a role to play in decarbonising Belgium's transport sector as well.

3.4 Comparison with direct electrification

The key role that electrification will play in decarbonisation is widely acknowledged – indeed, advantages like the higher efficiency of electrical systems in end applications and lower emissions of local air pollutants mean that direct application is the default choice for many use cases [64]. The conversion of electricity into fuels in PtX processes actually erodes some of these advantages – the PtX process inevitably has some energy losses, while combustion of PtX fuels causes local emissions in the same way as conventional fuels.

Despite this, there are several reasons why PtX fuels should have a place in Belgium's decarbonisation plans. As has already been mentioned earlier, applications like cement, steel, maritime transport and aviation are very hard to electrify directly due to reasons such as high temperature requirements, high energy density needs, capital intensive existing infrastructure, etc. PtX also provides an avenue for the constructive usage of the unavoidable CO_2 emissions from industries like cement and lime.

An additional important reason is the need for flexibility in renewable electricity-heavy systems [65]. Energy demand is always variable, subject to daily and seasonal fluctuations, as well as occasionally abruptly experiencing spikes or drops. For the non-electrical part of the energy demand, these issues are addressed by fuel stockpiling and inventory management. For electricity, conventionally a combination of baseload, load following and peaking power plants are employed to harmonise demand and supply. For the increasingly renewable electricity-based Belgian grid (Figure 19), however, the picture will be more complicated. Not only can the output of solar or wind power plants not be augmented or reduced in tune with electricity demand, these outputs are intrinsically erratic (variable renewable energy sources (VRES)). This means that even for constant demand, the system may be adversely affected by events like prolonged cloudy weather.

[64] Enel, 'Electricity's strategic role in leading Europe's decarbonization'

[65] European Environment Agency, 'Flexibility solutions to support a decarbonised and secure EU electricity system'

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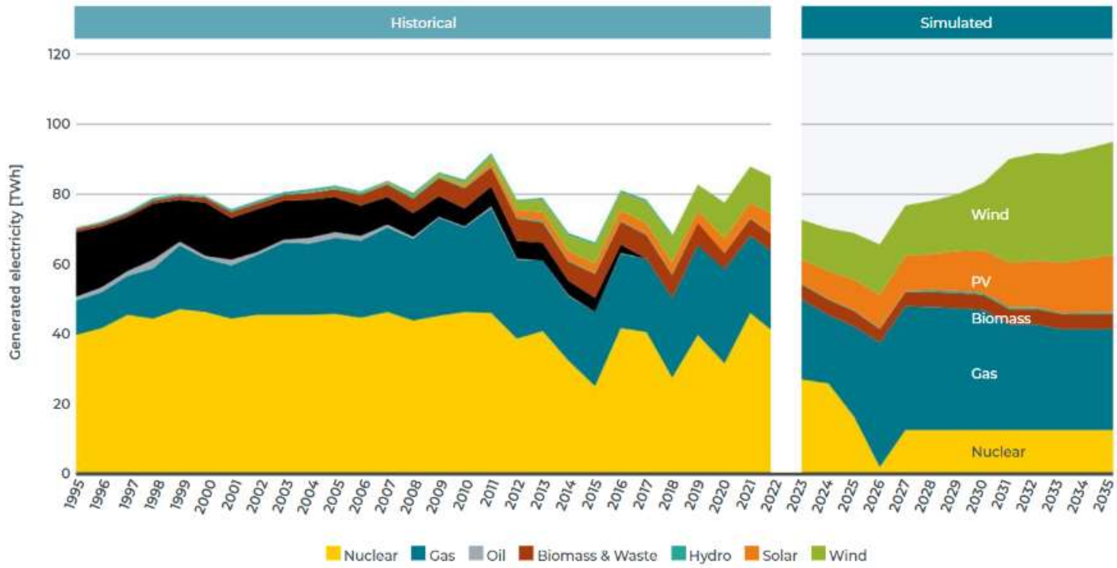

Figure 19: Historical and expected evolution of the Belgian electricity grid in terms of energy source [66]

Oversizing VRES power plants to deal with these contingencies may appear to be a possible solution, but this will not only raise the capital cost of the plants but also lead to wastage of produced electricity during periods of high production and low demand. A better option is to store the electricity generated during peak production periods and use this stored electricity during periods of lower production and higher demand. While several storage options do exist (e.g., batteries, flywheels, etc.), PtX fuels produced by the surplus electricity have the advantage of being storable almost indefinitely and easily transportable to different points of use. This allows PtX to offer additional flexibility to the system by enabling the coupling of different sectors like electricity, gas, transport, chemicals, etc. [67]

The above arguments make clear that PtX and CCU will be important components of Belgium's decarbonisation strategies. The following sections elaborate on the current status of PtX and CCU in Belgium.

[66] Elia, 'Adequacy and Flexibility Study for Belgium'

[67] Federal Planning Bureau, 'Fuel for the future'

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4 BELGIUM NATIONAL HYDROGEN STRATEGY

Belgium unveiled its national hydrogen strategy in 2021, with an update issued the following year. The strategy document emphasises that electrification should remain a priority wherever techno-economically possible, but as the Belgian energy demand is expected to surpass local renewable energy production, the import of electricity and hydrogen molecules will play a major role in the country's decarbonisation. Accordingly, the strategy is based on 4 pillars, which are:

1. Positioning Belgium as an import and transit hub for renewable molecules in Europe
2. Expanding Belgian leadership in hydrogen technologies
3. Establishing a robust hydrogen market
4. Investing in cooperation as a key success factor

4.1 Positioning Belgium as an import and transit hub for renewable molecules in Europe

Under RePowerEU, the EU foresees importing 6 million tons of renewable hydrogen and 4 million tons of renewable ammonia every year from 2027 [68]. Belgium is centrally located in Western Europe and has one of the most important ports in the region. The federal Belgian government therefore aims to position Belgium as an import and transit hub for renewable molecules in Western Europe. Belgium was already the top hydrogen exporter in the EU in 2022, but essentially all the hydrogen was exported to the Netherlands [69]. To broaden the hydrogen trade, Belgium is projected to import significant quantities of renewable H_2-molecules and H_2-derivatives (20 TWh in 2030 and between 200 and 350 TWh in 2050), covering its domestic demand as well as the transit activities to neighbouring countries. Three major routes have been identified for this [70]:

a) North Sea route: The North Sea region benefits from favourable wind patterns which allow for the production of renewable hydrogen at a low cost. The idea is to coordinate with other countries in the North Sea region and synchronise the development of offshore electricity and hydrogen networks.

b) Southern route: In the long term, hydrogen may be imported from southern Europe and northern Africa, which are blessed with abundant solar energy. This, however, will require the development of dedicated hydrogen piping networks for import and distribution.

c) Shipping route: This option involves importing hydrogen derivatives via ships from diverse locations. In the near-term, this might be the most techno-economically competitive option, with the hydrogen derivative molecules (like methanol and ammonia) either being used as-is or being converted to hydrogen near the points of use.

Progress has already been made in these areas. In September 2021, Belgium signed a Memorandum of Understanding (MoU) with Oman to develop green hydrogen technologies,

[68] European Commission, 'Implementing the Repower Eu Action Plan: Investment Needs, Hydrogen Accelerator And Achieving The Bio-Methane Targets'
[69] European Data, 'What does open data reveal about renewable hydrogen?'
[70] Economie.fgov.be, 'Vision and strategy: Hydrogen – Update October 2022'

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with Belgian participation expected in the construction of a 250-500 MW green hydrogen factory in Duqm [71]. The first phase of this factory is expected to start operation in 2026, and produce both green hydrogen and ammonia. Accordingly, the Belgian energy infrastructure company Fluxys has also strengthened its partnership with the Omani state-owned transmission system operator OQ Gas Networks (OQGN) by committing to a stake acquisition in OQGN and signing an additional MoU on strategic cooperation in the development of Oman's hydrogen and CO_2 infrastructure [72]. An agreement was also signed in May 2023 between Oman and Belgium to evaluate the adherence of green hydrogen projects in Oman to EU criteria [73]. Subsequently, the HYPORT Duqm green ammonia secured a certification from CertifHy, making its green ammonia eligible for export to the EU [74]. This is an important step for paving the way for exporting green hydrogen and its derivatives to European markets in the future.

Similar steps have been taken in regard to a partnership with Namibia. Namibia, which published its hydrogen strategy in 2022, aspires to reach green hydrogen production volumes of 10-15 Mtpa by 2050 [75]. A first MoU of cooperation between Belgium and Namibia was signed at COP26 in November 2021 [76]. This can be seen as complementary to the planned strategic partnership between Namibia and the EU as a whole [77].

COP26 also saw the signing of a MoU between the Belgian ports of Antwerp and Zeebrugge with Chile, with the goal of removing roadblocks to green hydrogen flows between Chile and Western Europe [78]. Chile has abundant solar and off-shore wind potential, and aims to be producing the cheapest green hydrogen by 2030 and become one of the top 3 exporters of green hydrogen by 2040. At the same time, only around a quarter of Chile's electricity production is currently renewable, making the upscaling of green hydrogen production a challenge [79]. This, along with setting up an effective logistics chain between the continents, is among the issues that the MoU hopes to address via knowledge transfer and other collaboration.

4.2 Expanding Belgian leadership in hydrogen technologies

Belgium already has organisations operating at all levels along the entire hydrogen industry value chain. The federal Belgian government targets expanding this leading position of Belgium-based companies and research institutions active in the technologies of H_2-molecules and H_2-derivatives, and there has consequently been a lot of activity on this front. One initiative is the Belgian Energy Transition Fund which will, until 2025, provide €20–30 million in support funding, with a further €60 million allocated by the government elsewhere to support projects to scale up promising technologies [80]. The 'Clean Hydrogen for Clean Industry' is another project call via which the Belgian government is supporting innovative hydrogen projects, to

[71] Energy News, 'Oman and Belgium sign MoU on green energy cooperation'
[72] Fluxys, 'Fluxys and OQ Gas Network (OQGN) are setting up a strategic partnership to support the global energy transition'
[73] Zawya, 'Oman, Belgium sign pact for green hydrogen certificate pilot'
[74] WaterstofNet, 'DEME project HYPORT Duqm Achieves Key Certification for Green Ammonia Exports to EU'
[75] Ministry of Mines and Energy Namibia, 'Namibia: Green Hydrogen and Derivatives Strategy'
[76] CBL-ACP, 'The signing of a MOU between Minister Alweeendo (Namibia) and Minister Van der Straeten (Belgium)'
[77] European Commission, 'Global Gateway: EU and Namibia agree on next steps of strategic partnership on sustainable raw materials and green hydrogen'
[78] Port of Antwerp Bruges, 'Port of Antwerp, Port of Zeebrugge and Chile join forces to foster hydrogen production'
[79] Euractiv, 'Hydrogen trade: Belgium signs deal with Chile, Germany woos UAE'
[80] PWC, 'Fueling our future'

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the tune of €30 million [81]. Finally, the 'Clean Hydrogen to Belgium' call aims to promote research into the development and demonstration of hydrogen import technologies and infrastructure [82]. The federal government has also supported the development of the VKHyLab, a test infrastructure which will help research institutes and companies scale up their H_2 technologies, and which is expected to be operational by 2025.

Although Belgium's focus is more on developing itself as a green hydrogen import hub than as a green hydrogen producer, it is nevertheless targeting the setting up of a minimum strategic electrolysis capacity of 150 MW by 2026. One initiative in this regard is the 100 MW project, producing about 12,500 t/yr of green hydrogen, that Plug Power intends to commission by 2025 in Antwerp-Bruges [83]. A consortium is also building a 25 MW electrolyser facility, called Hyoffwind, in Zeebrugge [84].

4.3 Establishing a robust hydrogen market

As the hydrogen economy has a notorious chicken-and-egg problem, establishing the demand-side of the equation is as vital for ensuring the success of Belgian hydrogen strategy as the supply-side. The Belgian federal government recognises the need to establish an uptake mechanism, but is simultaneously cognizant of its limited competences on this matter, and hence proposes investigating together with the Regional governments and the European Commission how best to put in place a system to unlock the demand for renewable H_2-molecules and H_2-derivatives.

One area where the government does foresee the need for additional development is in pipeline networks. A hydrogen market will require the stakeholders to be able to freely supply and obtain hydrogen, and pipeline transport is the most efficient option for this, with the high initial costs offset by the low operational costs. The initial capital expenditure can also be reduced if existing natural gas pipelines are repurposed to transport hydrogen.

The federal government assesses that the hydrogen transport network in Belgium should be usable under non-discriminatory third-party access conditions. Belgium currently has the second largest hydrogen transport network in the world – and the largest in Europe – but this is in private hands [85]. Hydrogen transport pipeline networks have a high capital cost and provide strong competitive advantages, and hence can have a strong tendency to lead to monopoly formation. While the European Commission is also aware of this issue and is working to address it via the Gas Package [86], Belgium has pushed things ahead by adopting its own Hydrogen Act [87]. The goal is to develop, by 2026, 100 to 160 km of additional hydrogen pipelines (new and/or repurposed) to be operated under these non-discriminatory third-party access conditions. This network is to be extended by 2030 to connect the ports of Zeebrugge, Ghent and Antwerp to industrial zones and neighbouring countries.

It should be noted that the Flemish government has introduced its own Regional Act regarding the distribution of hydrogen through pipelines on Flemish territory [88] and filed an action for

[81] Economie.fgov.be, 'Clean Hydrogen for Clean Industry'
[82] Economie.fgov.be, 'Clean Hydrogen to Belgium'
[83] Argus Media, 'Plug to build 100MW green hydrogen plant in Belgium'
[84] Parwind NV, 'Hyoffwind'
[85] Belga News Agency, 'Will Belgium become the first country in the world with a hydrogen law?'
[86] European Council, 'Gas package: Council and Parliament reach deal on future hydrogen and gas market'
[87] Loyens & Loeff, 'The Belgian Hydrogen Act enters into force'
[88] Vlaamse Regering, VR 2023 0707 DOC.0889/2BIS

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annulment of the federal Hydrogen Act before the Belgian Constitutional Court [89], on the grounds that hydrogen is primarily a regional matter [90] and hydrogen transport can therefore not be designated to a single national authority at the behest of the federal government. This standoff creates uncertainties in the applicable legal framework and is thus a barrier to the rapid deployment of the hydrogen infrastructure in Belgium.

Fluxys is developing the Belgian Hydrogen Backbone. It's strategy is to progressively reconfigure parts of the natural gas network and build new infrastructure in Belgium to develop complementary systems for transporting methane (in which biomethane and synthetic methane will increasingly replace natural gas), hydrogen, carbon dioxide, and potentially other molecules needed for the energy transition [91].

4.4 Investing in cooperation as a key success factor

Successfully developing a hydrogen economy in Belgium will require intra- and international cooperation. At the intra-national level, the required cooperation is between the federal and regional governments, as well as Companies, research institutions and universities active in hydrogen solutions and services. At the international level, besides the partners mentioned above (like Oman and Namibia), European collaboration is obviously a necessity. The Belgian Hydrogen Backbone, for instance, forms part of the European Hydrogen Backbone initiative, which envisions a shared hydrogen transport infrastructure across 28 European countries [92]. The European Hydrogen Backbone has 5 hydrogen supply corridors, two of which pass through Belgium. For the synchronised development of the Belgian backbone, therefore, Fluxys needs to coordinate with 30 other energy infrastructure companies, or at least with those involved in the corridors passing through Belgium.

[89] Eubelius, 'Looking ahead: the energy sector in 2024'

[90] Energy News, 'Regional vs. Federal: The Battle Over Belgium's Hydrogen Laws'

[91] Fluxys Belgium, 'Information Memorandum for H_2 infrastructure'

[92] European Hydrogen Backbone, 'Five hydrogen supply corridors for Europe in 2030'

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5 CURRENT BELGIAN STATUS

5.1 PtX status in Belgium

The discussion in Section 2 made clear that hydrogen derivatives will have a place alongside pure hydrogen in decarbonisation. The proportion, and type, of the derivatives, will however depend on technological advances and the geographic and temporal availability of the different molecules, besides their price. The Belgian federal government expects 30-60% of the demand in molecules in 2050 to be satisfied by hydrogen, with the rest being divided among the different hydrogen derivatives. Given a projected domestic demand of 125-200 TWh of hydrogen and hydrogen derivatives in 2050, this means a demand between 50 and 140 TWh for hydrogen derivatives [70]. As explained in Section 4, the majority of this demand will be imported, with a small amount possibly being produced locally in order to foster technological development of Belgian companies.

One major development in this regard in recent years was the announcement of the North-C-Methanol project in Ghent. With ten public and private sector partners, this project aimed to capture 65,000 tons of CO_2 from industrial point sources to produce 44,000 tons of methanol annually [93]. The hydrogen for the methanol production was to be produced by a 63 MW electrolyser running on offshore wind energy, with the byproduct oxygen from the electrolyser used in nearby steel plants. This project is now called ‘North-C-Hydrogen’, with its focus reoriented towards green hydrogen production instead of green methanol [94]. The CO_2 capture aspect appears to have been dropped, with a 67 MW electrolyser now planned to generate 10,000 tons of green hydrogen annually from 2026 onwards [95].

A second planned project along these lines was the ‘Power to Methanol’ project at the port of Antwerp. This pilot plant aimed to produce 8000 tons of sustainable methanol annually from 2022 onwards [96]. However, it was cancelled in early-2024 due to ‘the reluctance of potential buyers to commit to long-term contracts’ [97].

A blue hydrogen project (i.e. fossil hydrogen + CCS) is being developed at Rodenhuize in the Ghent area by ENGIE and Equinor [98]. The feasibility study of this project was completed in early 2023 and a joint development agreement (JDA) signed between the partners to move further with the project [99]. This 1 GW project aims to produce hydrogen at competitive prices from natural gas using auto thermal reforming (ATR) technology combined with CCS. The captured CO_2 is planned to be transported in liquid form and stored at a site in the sub-surface of the Norwegian North Sea. To ensure that the necessary CO_2 and hydrogen transport infrastructure are in place for this project, the project has also brought on board Fluxys. Fluxys is building, in collaboration with Equinor, a 1,000 km subsea pipeline to transport compressed CO_2 from its Zeebrugge terminal to the Norwegian North Sea bed [100]. The pipeline is expected

93 CO_2 Value Europe, ‘North-CCU-Hub’
94 Clean Hydrogen Partnership, ‘Study on hydrogen in ports and industrial coastal areas’
95 ENGIE, ‘Joining forces for a sustainable hydrogen region’
96 Port of Antwerp Bruges, ‘New milestone in sustainable methanol production in the port of Antwerp’
97 Hydrogen Insight, ‘Government-backed green hydrogen-to-methanol pilot in Belgium scrapped due to 'escalating costs'’
98 ENGIE, ‘ENGIE & Equinor launch the H2BE project to kick-start low-carbon hydrogen market in Belgium’
99 Equinor, ‘Update on H2BE hydrogen project in Belgium’
100 Fluxys, ‘Fluxys and Equinor launch solution for large-scale decarbonisation in North-Western Europe’

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to start operation in 2025, with up to 40 million tons of CO_2 (equal to the total emissions of Belgian industry [55])) transported every year by 2030. The Antwerp@C consortium is also working on developing similar infrastructure to transport CO_2 by ship or pipeline to the North Sea or the Netherlands for local blue hydrogen production [101,102].

On the ammonia front, there do not appear to be any projects planned for producing green ammonia in Belgium. However, given the importance of importing ammonia, Fluxys and Advario are developing a green ammonia import terminal at the Port of Antwerp-Bruges [103]. The planned terminal will deliver storage and transit solutions for ammonia, while optionally also providing facilities to convert ammonia back into hydrogen. The terminal will also connect to the Fluxys open-access hydrogen network to ensure supply throughout northwest Europe. This is in sync with the planned ammonia cracking plant to be set up by Air Liquide in Antwerp to convert imported ammonia into hydrogen and nitrogen [104].

All the above developments are in the Flanders region. In Wallonia, a major project was ‘Columbus’, a CCU project in which green hydrogen from a 100MW electrolyser (powered by renewable electricity) was to be combined with concentrated CO_2 captured from a concentrated lime kiln to produce synthetic methane [105]. Surplus heat from the project was to be fed to a local district heating network, and the byproduct oxygen valorised in industry. This project aimed to produce 330 GWh/y of e-methane and save up to 187,000 t CO_2/y. However, the project developers, ENGIE and Carmeuse, decided in November 2024 to terminate this project because market conditions did not assure its viability [106].

5.2 CCU status in Belgium

As mentioned in Section 2, carbon capture and utilisation (CCU) refers to a range of applications in which CO_2 is captured and used either directly or via transformation into products like synthetic fuels and chemicals. CCU, along with carbon capture and storage (CCS), is an important part of the EU Strategic Energy Technology (EU SET) plan [107], with the Zero Emissions Platform (ZEP) set up under this plan to advise the EU on CCS and CCU deployment [108]. The CCU-CCS SET plan, however only has 11 participating countries (8 of these being EU MS), and Belgium is not a member of this plan [109].

Nevertheless, Belgium has been quite active in CCU deployment. The Flemish government released a concept note in 2021 outlining how it intends to exploit its CCU potential [110]. It mentions that Flanders has several large CO_2-emitting industries clustered in the Antwerp and Ghent regions, which will be hard to decarbonise using measures other than carbon capture and can thus potentially provide millions of tons of CO_2 for downstream applications. It also highlights the financing provided in the Flemish Climate Plan and the Flemish Resilience Plan for CCU and CCS projects. It recommends the deployment of supportive EU policies, such as

101 Port of Antwerp-Bruges, ‘Hydrogen’
102 Port of Antwerp-Bruges, ‘Antwerp@C’
103 Fluxys, ‘Fluxys and Advario drive forward with their low-carbon ammonia terminal, paving the way for the energy transition’
104 Hydrogen Insight, ‘Hydrogen imports’
105 Columbus Project
106 ENGIE, ‘ENGIE and Carmeuse announce end of Columbus project due to economic and regulatory considerations’
107 European Commission, ‘SETIS: Implementing the actions’
108 Zero Emissions Platform
109 European Commission, ‘SETIS: CCS-CCU’
110 Vlaamse Regering, VR 2021 2611 MED.0413/1

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incentives in the EU Emissions Trading Scheme (EU-ETS), and the clear demarcation of the powers of the federal regional authorities for facilitating CCU and CCS rollout in Flanders.

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6 FUTURE ROLE FOR PTX AND CCU IN BELGIUM

Section 3 outlined the need for PtX and CCU in Belgium, making clear that PtX and CCU will be important components of Belgium's decarbonisation strategies. Sections 4 and 5 provided insight into Belgium's plans to position itself as a transit hub for hydrogen and renewable molecules, and on the present status of PtX and CCU in the country. From this background, it would be worthwhile to predict the future scenarios for the deployment of these technologies in Belgium till 2050. Such an exercise is obviously complicated and inherently involves assumptions, but done correctly, can still provide a glimpse of the expected trajectory of these technologies and help identify potential headwinds and tailwinds.

In WP3 of Procura, the TIMES energy system model has been used to evaluate the role of PtX and CCU in the Belgian context under several long-term scenarios. These scenarios will be discussed here briefly before the main takeaways for these technologies are elaborated upon. Subsequently, the results of this exercise specifically for PtX and CCU are analysed and put in perspective to the current situation, and the road ahead is discussed.

The 4 scenarios modelled in TIMES are labelled 'Evolution', 'Acceleration', 'Amplification' and 'Transformation'. A table showing the main scenario parameters is given in the Annexure, but some of the important assumptions in the Evolution scenario are:

- Natural gas prices will remain stable
- CO_2 prices will rise to around 473 €/t by 2050
- The aviation and shipping sectors will reduce emissions by 65% by 2014
- Hydrogen imports of up to 1.5 GW will be realized via pipeline by 2050, and terminals for low carbon molecules will be deployed from 2030
- DAC will be available at large scale by 2050
- Unlimited CCS will be available at relatively low costs
- Belgian offshore wind capacity will max out at 8 GW, with a similar quantity available from the North Sea
- High voltage direct current (HVDC) rollout will be slow and only reach 4 GW by 2050 due to non-technical barriers
- Nuclear power will be revived with the advent of Gen-3 and small modular reactors (SMR)
- Solar PV and onshore wind will be restricted due to public opposition
- Heat pumps will be widely deployed residentially and vehicle to grid (V2G) and smart charging in more limited amounts

The other 3 scenarios are based on the Evolution scenario, but differ in some key assumptions. The major differences between each of these scenarios and the Evolution scenario are listed below.

Acceleration:

- Hydrogen pipeline capacity will be 3 GW by 2050
- A 90% reduction in aviation and shipping emissions will be achieved by 2050
- HVDC will be available in high capacity
- SMRs will be deployed by 2045
- DAC will not be available at large scale and CCS will be limited and costly
- Imported low carbon molecules will become cheaper due to large scale global production

Amplification:

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- Hydrogen import infrastructure will be 5 GW by 2050
- A 90% reduction in aviation and shipping emissions will be achieved by 2050
- CCS capacity will be limited, reaching only 10 MT/a by 2050
- HVDC will be available in high capacity, and North Sea wind will provide 16 GW by 2050
- The maximum solar PV and onshore wind potential are reached
- Higher V2G, smart charging and heat pump deployment
- More import of biomass will be achieved, but imports of semi-finished products like NH_3 and sponge iron will fall due to regulations and policies

Transformation:

- A revolution will occur in the low carbon molecules market, resulting in lower import prices, cheaper electrolysers and 5 GW of hydrogen import infrastructure by 2050
- CCS capacity will be limited, reaching only 10 MT/a by 2050
- Natural gas prices will rise due to policy and geopolitical reasons
- SMRs will be deployed by 2040
- HVDC will be available in high capacity, and North Sea wind will provide 16 GW by 2050
- Very high V2G, smart charging and heat pump deployments will be achieved
- Imports of semi-finished products like NH_3 and sponge iron will be made impossible by regulations

While each of the above scenarios can permit Belgian CO_2 emissions to approach zero by 2050, the trajectories differ, as do the mix of technology solutions. However, in each scenario, refineries and the fertiliser sector are expected to remain the main end-users of hydrogen or clean molecules till 2040, as other sectors rely on electrification, energy efficiency, and other methods to reduce emissions. Clean hydrogen demand only really picks up post-2040, as the approaching net-zero targets and the depletion of alternatives increase the importance of CCUS technologies.

Sectors like power and transport (aviation and maritime) are likely to be among the users of renewable fuels in this time period. This is line with the hydrogen and derivatives use cases mentioned in Sections 2.4 and 2.5. The biggest consumer of these fuels, though, might be the steel industry. Steel making can essentially be decarbonised either via electrification (iron oxide electrolysis, electric arc furnace for recycled steel, etc.), the use of green hydrogen in direct reduced iron routes, or carbon capture followed by storage or conversion to products like methanol [111, 112] (see also Sections 2.4 and 3.2). The green hydrogen route is generally held to be the most promising and worthy of prioritisation, with more limited roles played by the other options [111, 112]. One exception is the Evolution scenario above, with the limited availability of renewable electricity and clean molecules blended with the large availability of low cost carbon storage making the CCS route more attractive and diminishing clean molecule demand. This trade-off between renewable electricity and CCS is actually visible across most segments, with greater availability of the one reducing demand for the other. An exception is lime and cement production, where carbon capture appears to be the only realistic decarbonisation solution.

In all the TIMES scenarios, large-scale green ammonia import is considered unlikely, as import prices are expected to be close to local production prices. This is a surprising conclusion, given the absence of green ammonia production facilities in the country at present, and an important one considering Belgium's focus on ammonia imports as a hydrogen carrier

[111] European Parliamentary Research Service, Carbon-free steel production
[112] Sandbag, Steel and CCS/U

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molecule (see Section 4.1). It may ultimately depend on type of import infrastructure that is developed and whether is more optimal to import H_2 or NH_3, but in any case the energy intensive step (H_2 production) will likely occur primarily in countries with abundant renewable energy availabilities. Imports of green methane and green hydrogen, on the other hand, are expected to play a large role, provided that they are actually available in sufficient quantities. In the Transformation scenario in particular, green methane imports are expected to be very large (over 450 PJ) due to the drop in import prices.

The local production costs of hydrogen and its derivatives like methane and ammonia will depend partly on the extent of blue and green hydrogen production in Europe. From a legislative standpoint, the EU Hydrogen and Decarbonised Gas Market Package makes clear that while green hydrogen, produced through electrolysis, is the preferred technology, its high cost means that blue hydrogen can be used in the 'short-to-medium term' in hard-to-decarbonise sectors [113]. By lowering the cost of available hydrogen, this strategy is positive for the deployment of hydrogen infrastructure as a decarbonisation method, but it does mean that green hydrogen must compete with cheaper blue hydrogen in downstream applications. This is likely to hamper larger-scale development of PtX technologies, which will in turn affect potential cost reductions due to learning effects and economies of scale. Section 5.1 already commented on the low number of green hydrogen developments in Belgium, and the relatively greater activity in blue hydrogen projects, and this imbalance is unlikely to be improved by this.

In any case, renewable electricity availability in Belgium is likely to act as a roadblock for local deployment of PtX technologies. Overall electricity demand in Belgium is expected to rise between 95 and 130% by 2050 (compared to 2020), with local low-carbon electricity generation unable to keep pace with this rise in demand [114]. This will mean a doubling in Belgian dependence on electricity imports (70-90 TWh by 2050), which makes large-scale domestic green hydrogen production an unlikely prospect. It is in principle possible to run PtX plants with imported renewable electricity, but directly importing green molecules would appear to be a more sensible option.

An interesting side-effect of the likely proliferation of carbon capture in the cement and steel sectors is the surge in methanol production that can be expected post-2040. If the captured carbon cannot be stored underground, due to either high costs or limited availability of storage facilities, then its conversion to a chemical feedstock is the most reasonable choice. Methanol, being relatively easy to produce and with a large market size (see Section 8.1), is an attractive candidate. Producing this methanol will require large quantities of hydrogen, incentivising PtX technologies or green hydrogen imports. The target market for this methanol is harder to predict. The EU's delegated acts on RFNBO production come with a 'sunset clause' under which captured emissions from combustion of non-sustainable fuels for electricity production will be considered avoided emissions only up to 2035, with emissions from other uses of non-sustainable fuels considered avoided emissions up to 2040 [115]. If this remains the case, then methanol from steel or cement CO_2 emissions will effectively be barred from serving the RFNBO market just when its production starts to peak, bringing the feasibility of this route into question. Such methanol will also not be considered a sustainable aviation or shipping fuel, as the ReFuelEU Aviation and FuelEU Maritime Directives hew to the RED definition of RFNBOs. There remains, of course, the possibility of these legislations evolving to accept the use of such CO_2 emissions for RFNBO synthesis post-2040, but this is speculative for now.

113 EU Hydrogen and Decarbonised Gas Market Package

114 Elia, Belgian Electricity System Blueprint 2035-2050

115 EU Delegated Act on RFNBO production

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Overall, it appears that the future PtX and CCU scenario in Belgium will be an extension of the present. Due to limitations in domestic renewable energy availability, green molecules are likely to be imported, and this expectation is perhaps reflected in the lack of interest in domestic green hydrogen projects. However, recent developments elsewhere in the EU have also not been positive, with several blue or green hydrogen projects being shelved [116, 117, 118], meaning that the large quantity of hydrogen that is projected to be imported by Belgium in the coming decades will perhaps prove hard to come by. The high costs of green hydrogen [119] and the insufficient renewable electricity availability in Europe [120] means that this picture is unlikely to improve soon. Blue hydrogen is comparatively more economical, but faces barriers related to CCS availability and public acceptance.

Nevertheless, it has already been seen that PtX and CCU must necessarily be important parts of Belgium's decarbonisation strategies if net-zero is to be reached, meaning that the above problems need solutions. On the supply side, it is possible that greater deployment of PtX projects across Europe, encouraged by EU policies, will lead to increased availability of green hydrogen at reduced costs due to learning effects and economies of scale. If European green hydrogen production does not suffice, Belgium must look further afield – in other words, the 'Southern route' and 'shipping route' described in Section 4.1 must gain precedence over the 'North Sea route'. Belgium's recent agreements with countries like Oman, Namibia and Chile are therefore a step in the right direction. This could be supplemented by agreements on blue hydrogen, towards which joining the EU CCU-CCS SET plan might be a reasonable first move if it is extended beyond 2030.

On the demand side, further measures to incentivise the adoption of green molecules are necessary. As an example, given the recent hesitation of steel majors to commit to green steel investments – in Belgium [121] as well as more broadly in the EU [122] – measures such as carbon contracts for difference and creating lead markets to guarantee demand might be in order [123, 124], alongside existing legislative measures like CBAM and EU-ETS [125]. Likewise, initiatives for ensuring that CCU products from such industries, like methanol, can find a market are essential. Given the limited size of the Belgian markets, such steps will have to be taken in coordination with other EU countries.

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[117] Reuters, Shell shelves Norway hydrogen project due to lack of demand
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[120] Ajanovic, et al., Appl. Ener., 2024
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[123] IN4climate.NRW, Carbon contracts for an accelerated industrial transformation
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ANNEX 1 TIMES SCENARIOS ASSUMPTIONS

PARAMETERS	UNIT	EVOLUTION	ACCELERATION	AMPLIFICATION	TRANSFORMATION
CO2 price 2050	[€19/t]	390	390	390	390
NG price today-2035-2050	[€19/t]	25-25-26	25-25-26	25-25-26	25-30-35
international trasnport climate target	%	65%	90%	90%	65%
H2 pipeline net import capacity limit 2030-2035-2050	GW	1 - 1.3 - 3	1 - 3 - 5	1 - 3 - 5	1 - 3 - 5
Import terminals for molecules start year	year	2030	2030	2030	2030
Passthrough H2 (2030-2040-2050)	TWh/yr	0-7-15	0-7-15	0-7-15	0-7-15
Passthrough CO2 (2030-2040-2050)	Mta	0-2-5	0-2-5	0-2-5	0-2-5
import sponge iron (starting year)	year	2035	2035	no	no
import ammonia for derivitaves (starting year)	year	2030	2030	no	no
North Sea offshore wind max by 2050	GW	8	8	16	16
Belgian offshore wind max by 2040	GW	8	8	8	8
HVDC limit (year:capacity)	GW	4	optimized	optimized	optimized
SMR (start year: CAPEX [€19/kW])		2050: 7500	2045: 7500	2050: 7500	2040: 7500
Nuclear GEN3+ (start year: CAPEX [€19/kW])		2040: 7500	2040: 7500	2045: 7500	2040: 7500
Max solar PV	GW	60	60	104	60
Max onshore wind	GW	10	10	20	10
V2G participation	%	14%	14%	48%	70%
smart charging participation	%	13%	13%	38%	72%
Molecule prices range		average	optimistic	average	optimistic (or lower)
DAC (year: capex [€19/ta])		2045	no	2045	2045
CCS limit and cost (Mta: €24/t by 2050)		unlimited: 35€/t	unlimited: 100€/t	10Mta: 35€/t	10Mta: 35€/t
Biomass increase by 2050	fator	x1.6	x1.6	x2.2	x1.6
Electrolyzer capex by 2050 (e:g: alk large)	€19/kW	720	720	720	576

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