FOD Economie, K.M.O., Middenstand en Energie

FPS Economy, S.M.E.s, Self-employed and Energy

ETF- PROCURA project WP3, final report

Results of Work Package 3, by VITO/Energyville

AUTHORS: Juan Correa Laguna, Joris Valee

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Executive Summary

Context

In Belgium, wind and solar PV today are already cost-competitive and are projected to become the most economical energy sources. However, recent increases in investment costs, due to commodity price volatility e.g., steel, interest rate increases and global supply chain challenges for mainly offshore wind and solar PV technologies require a renewed focus on overall cost-effective energy systems to reduce fossil fuel reliance and CO_2 emissions. This shift coincides with renewed discussions on the phase-out of Belgium's existing nuclear capacity, now that the law has been revised, increasing the urgency to ensure a stable, secure electricity supply through renewable alternatives.

To support Belgium's decarbonisation goals, Power-to-X (PtX) and Carbon Capture, Utilization, and Storage (CCUS) are seen as essential components. PtX enables surplus renewable energy to be converted into various energy carriers (e.g., hydrogen, synthetic methane, and chemical feedstock), which can contribute stabilizing the electricity grid and support clean molecule production. When combined with CCU, PtX offers additional decarbonisation potential.

The Energy Transition Fund (ETF) supported PROCURA project, granted by the Federal Public Service Economy of Belgium, aims to develop a quantitative roadmap for PtX and CCUS in Belgium. By engaging stakeholders from industry, technology, and energy sectors, the project seeks to provide actionable insights and accelerate the transition to a low-carbon energy system. Challenges persist, particularly in hydrogen and clean molecule production, where initial cost projections have proven overly optimistic. Economic and geopolitical disruptions from COVID-19, the invasion of Russia in Ukraine, rising material costs, and competing decarbonisation strategies (e.g., nuclear energy and CCUS) add further complexity to shaping the future energy roadmap.

The TIMES-BE model is used to draft a PtX and CCUS (molecules) roadmap. The model can represent the full value chain from the import or mining of energy and material resources up to meeting final demand of products and services, such as e.g.: tons of ammonia, glass, space heating, lighting, kilometres driven etc. Full documentation of TIMES-BE can be found on the EnergyVille website PATHS2050.[1]

PROCURA scenarios

The exploration of several future energy system scenarios provides insights as standalone cases or by contrasting results among them. However, scenario development can be a tedious task due to data availability, stakeholder inputs, long time horizons and computational demand, to name a few. This can quickly lead to a multitude of scenarios, which can clutter a focussed discussion of the model results. Therefore, the number of scenarios is limited to four. The definition of a central scenario can often be ambiguous and not consensual. Instead of developing a dedicated reference scenario, each scenario serves as a reference case based on what one considers to be most aligned with one's future vision.

The four scenarios are:

EVOLUTION (EVL): In this scenario, the price of CO_2 continues to rise to 480 €/tCO_2 in 2050. Natural gas prices are expected to remain relatively stable at 32 €/MWh by 2050. International aviation and maritime will reduce CO_2 emissions by 70% and 100% respectively. In 2035, hydrogen imports via pipeline will take off with a maximum net import capacity of 0.5 GW and up to 1.5 GW by 2050. Additionally, import terminals for low-carbon molecules are expected to be deployed starting in 2030. Furthermore, semi-finished products based on molecules, such as ammonia and sponge iron will be traded internationally, making them potential import by ship options from 2035.

It is expected that Belgium will have access to an additional 8 GW of far offshore wind in the North Sea (e.g. in the Dutch or Danish Exclusive Economic Zone), besides 8 GW near its coast. However, the High Voltage Direct Current (HVDC) electricity transmission grid rollout will slowly reach a maximum of 6 GW by 2050 due to social and regulatory factors. New nuclear Generation III (GENIII) is available from 2040 at 9220€/kW overnight cost, and new nuclear Small Modular Reactors (SMRs) as of 2050 at a similar cost as GENIII but with higher flexibility. However, the total Belgian nuclear capacity is limited to 4 GW.

Due to potential public opposition, solar PV is limited to 40 GW and wind onshore to 10 GW. Moreover, participation and technology adoption from households are not absolute, with a lower uptake of maximum 70% of domestically installed heat pumps by 2050, electric vehicles (EV) participating in vehicle-to-grid (V2G), and smart charging of vehicles will reach 14% and 13% respectively. DAC is available from 2045 on, while CO_2 storage cost reaches 37 €/tCO_2 by 2050.

ACCELERATION (ACC): Conversely to EVOLUTION, hydrogen infrastructure across Europe is deployed faster, with a net H_2 pipeline import capacity increasing to 1.5 GW and 3 GW by 2035 and 2050 respectively. Simultaneously, molecule import prices decrease as global production picks up faster. On the other hand, nuclear SMRs are available at large scale and five years sooner, starting in 2045. While focusing on nuclear and molecules, Direct Air Capture (DAC) is not made available to the model at large scale and CCS facilities are limited which keeps CO_2 storage costs relatively high at 123 €/tCO_2.

AMPLIFICATION (AMP): In this scenario, based on EVL, hydrogen import infrastructure will reach a larger capacity (5 GW) by 2050. Although global demand for molecules increases rapidly, it is not expected that prices will differ than in the EVL scenario. Moreover, nuclear GENIII is now

[1] https://perspective2050.energyville.be/results/main-edition-2025

available in 2045 at the same cost as nuclear SMRs. Carbon storage remains highly competitive in Europe, hence, 10 Mta is assumed as a maximum for Belgium by 2050. Solar PV and wind onshore are allowed to reach their maximum potential capacity of 104 GW and 20 GW, smart charging of vehicles are heavily incentivized up to 48%, V2G participation increases to 38% and financial and technical hurdles are sorted out to unblock domestic heat pump adoption. To support this transition, Belgium increases its access to far offshore wind, from 8 to 16 GW, without limits to HVDC infrastructure. Furthermore, the import of biomass will increase by 14 TWh/yr by 2050. Finally, the import of semi-finished products is more difficult due to regulations and policies, targeted to keep all industrial activities in Belgium.

TRANSFORMATION (TRF): Based on EVL, this scenario sees a revolution in the molecule market which is characterized by lower molecules import prices, cheaper electrolysers and 5 GW of net-import pipeline hydrogen capacity by 2050. CCS is expected to reach a maximum of 10Mta by 2050. As natural gas prices go up due to market effects, geopolitical tensions and EU/Belgian policy revisions, there is an effort to make the installation of nuclear SMRs available sooner, already starting in 2040. Moreover, 16 GW of far offshore wind dedicated to Belgium are made available. In this context, electricity demand flexibility is promoted by allowing vehicle smart charging up to 70%, V2G up to 72% and faster domestic heat pump deployment. In this scenario, domestic localisation of industry is supported by regulations and policies, making the import of semi-finished products impossible.

Results

General results

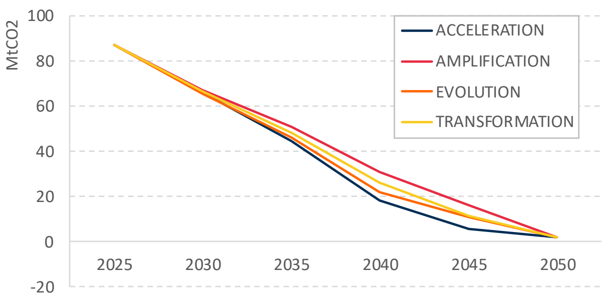

Figure 1: Decarbonisation pathways across four PROCURA scenarios and various time horizons

Belgium follows a decarbonisation trajectory, reaching net-zero by 2050 in all the cases as this is imposed as a target in the model. Nevertheless, the transition period between 2035 and 2045 is different in each scenario a shown in Figure 1. The ACC scenario shows a faster decarbonisation trajectory as it considers the availability of more low-carbon electricity sources. Final energy consumption is projected to decrease by 20% between 2040 and 2050. Increased electrification of demand occurs across all scenarios, although the pace of implementation varies as seen in Figure 2. The use of natural gas declines steadily as it is increasingly replaced by electricity and bioenergy, with alternative molecules playing a more limited role, except for fossil fuel replace in maritime navigation and aviation, shown in Figure 3. CCUS becomes very important in the decarbonisation strategies of some industrial sectors such as cement, lime and steel, leading to captured volumes around 13-30 MtaCO2.

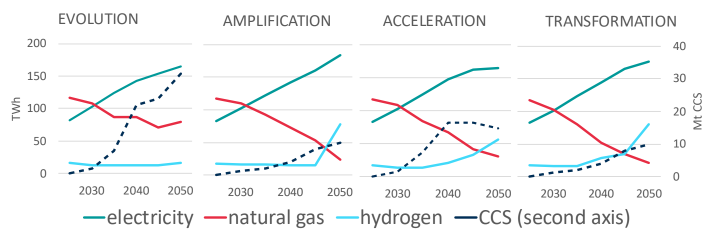

Figure 2: Trajectory of final electricity, natural gas and hydrogen energy and non-energy consumption, as well as carbon capture and storage.

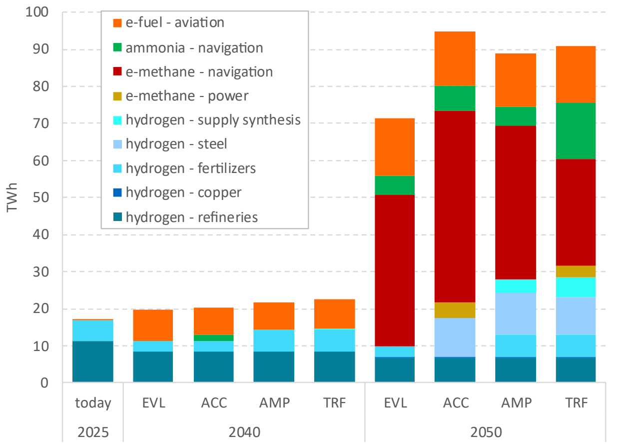

Figure 3 Projected final molecules demand: eFuels, Ammonia, e-methane and hydrogen across four PROCURA scenarios and time.

Power to heat

Power-to-heat solutions are emerging as a vital strategy for the decarbonisation of industry and buildings, facilitating the integration of renewable energy while phasing out reliance on fossil fuels. Electrification through heat pumps and electric boilers, paired with thermal energy storage, enhances grid flexibility by optimising energy consumption according to renewable availability.

By 2040, the electrification of the residential sector could see the deployment of two million heat pumps, while commercial heat pump installations may range between 10,000 and 30,000. In industry, electrification will initially be adopted in low- and medium-temperature processes (e.g., food and paper sectors), expanding to high-temperature applications (e.g., steel finishing, naphtha cracking) as we approach 2050 and climate policies tighten.

The energy transition progresses throughout all modelled sectors, beginning with residential and commercial sectors, see Figure 4, agricultural, and subsequently extending to commercial and industrial sectors. While heat pumps drive gains in energy efficiency and cost savings, industrial electrification contends with higher production costs - ranging from a 60% to 300% increase - though some industries may benefit from by-product valorisation. Ultimately, widespread heat electrification, bolstered by building renovations, district heating, and policy incentives, will be crucial to achieving net-zero emissions in Belgium by 2050.

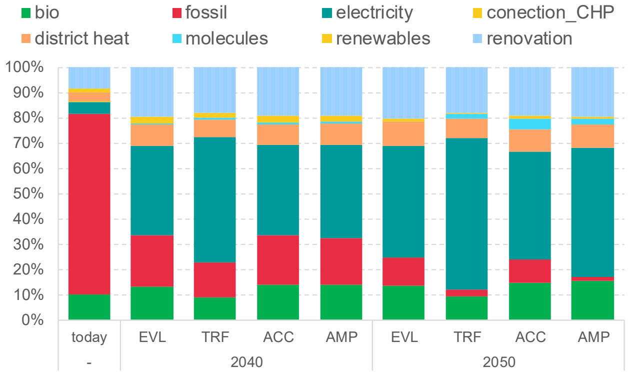

Figure 4: Heat source shares across all sectors per scenario for 2040 and 2050.

Defining options for Power to mobility P2M

Direct electrification through EVs, supported by smart charging and V2G, can enhance grid flexibility by aligning charging with renewable generation and potentially feeding electricity back into the grid during peak demand. Indirect electrification, through hydrogen production via electrolysis, offers additional storage and flexibility by converting surplus renewable electricity into clean fuels such as e-methanol and e-kerosene. By 2050, these strategies are expected to improve renewable energy penetration, enhance grid stability, and reduce curtailment of excess wind and solar power.

In all four scenarios, road transport is almost fully electrified by 2040, leading to a 75% reduction in final energy consumption in this subsector, see Figure 5. Smart charging and V2G technologies significantly contribute to accommodating large volumes of renewable energy. However, local hydrogen production from renewables proves to become costly as Belgium faces limited availability of low-carbon affordable electricity. Consequently, direct electricity use is prioritised by the optimisation objective in the model, while hard-to-electrify sectors, such as aviation and maritime shipping, will rely on imported synthetic fuels (e.g., ammonia, e-methane, e-kerosene).

Full electrification of road transport will require substantial infrastructure investments in charging networks and grid expansion. Meanwhile, as clean fuels and synthetic molecules will remain essential for decarbonising certain sectors, strategic import agreements and infrastructure development at airports and seaports, to secure future energy supply, are essential.

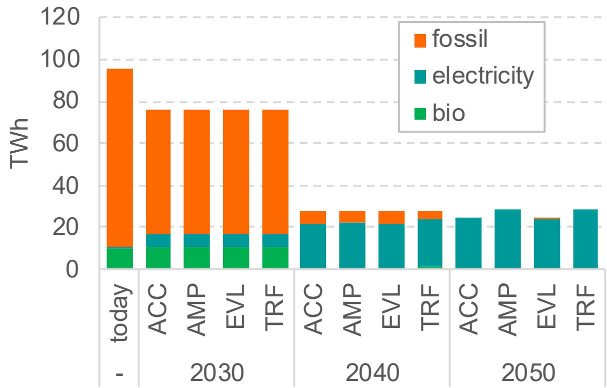

Figure 5: Final energy consumption per vector of road transport, per scenario between 2030 and 2050

Power to Industrial Processes

As CO_2 prices rise and free allowances decline, industries are expected to transition toward low-carbon production methods. While hydrogen will play a limited role as an energy carrier, direct electrification is emerging as a key alternative, particularly for low- and medium-temperature heat through heat pumps, electric boilers, and thermal storage. For high-temperature heat, electric furnaces and hybrid electric-gas systems could replace fossil fuels, while electrochemical technologies may enable cleaner chemical and fuel production.

By 2050, electricity and biomass will account for nearly 40% of industrial energy use, yet full electrification remains challenging, with fossil fuels still supplying 60% of final energy demand as shown in Figure 6. Low-temperature heat is expected to be fully decarbonised by 2035, where certain high-temperature processes may rely on CCUS instead of adopting full electrification. Strategic policy support, infrastructure investment, and innovation will be critical in driving industrial electrification, ensuring a smooth transition to a net-zero future.

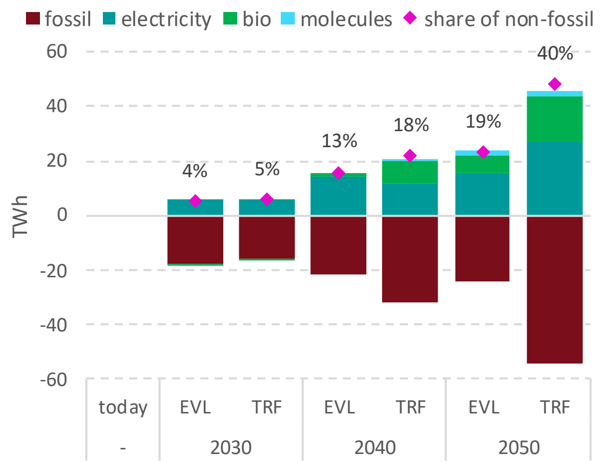

Figure 6: Energy variation compared with today per energy vector, across all industrial sectors, per scenario

Power to energy for dealing with intermittency of renewable energy supply.

The integration of wind and solar PV in Belgium's energy system requires solutions to address their seasonal variability and hourly intermittency. Dispatchable capacity and long-term storage will be essential to balance supply and demand. Power-to-energy technologies, such as hydrogen and clean molecules production, can store excess renewable electricity and serve as backup when generation is low.

By 2050, short-term storage, particularly stationary batteries (4 to 7 GW) and vehicle-to-grid (V2G) technology (0.6 GW), will play a more dominant role than molecule-based alternatives. Clean molecule power plants will be used mainly during demand peaks, with an installed capacity reaching between 2 and 5 GW depending on the scenario. However, their low utilisation will require strong financial incentives.

Belgium's transition will rely more on European grid integration than on large-scale seasonal storage. Imports of clean molecules will complement short-term storage to manage seasonal demand variations, supporting a flexible, low-carbon power system while reducing dependence on fossil-based backup electricity generation, as illustrated in a typical spring day in April in 2050 in Figure 7.

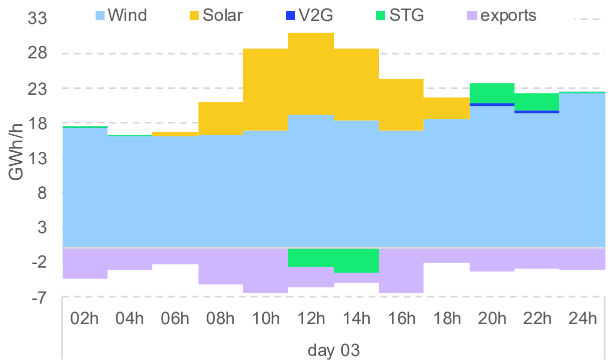

Figure 7 Dispatch of wind, solar, V2G, imported and exported electricity, and storage (STG) for one representative day, 21 April in 2050

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Table of Abbreviations

CAGR	Compound annual growth rate
CF	Capacity factor
CHP	Combined heat and power plant
COP	Co-efficient of performance
CCU	Carbon capture and utilization
CCUS	Carbon capture, storage and utilization
DSM	Demand side management
DAC	Direct air capture
EH	Electric heater.
EV	Electric vehicle
HP	Heat pump
HVDC	high voltage direct current
LCOE	Levelized cost of electricity
O&M	Operation and maintenance
ORC	Organic Rankine cycle systems
PtG	Power to gas
PtX	Power to X
PV	Photovoltaic
RE	Renewable energy
TS	Time-slice
VRES	Variable renewable energy source
WP	Work package
€	Euros are expressed in 2024 values.

1 Introduction

Renewable energy is essential to fulfil the requirements of the Paris Agreement on CO_2-neutral future economies. Within the renewable revolution, investing costs of wind and solar energy generation have decreased remarkably over the past 10 years all over the world. In many countries, these technologies are already the cheapest option and completely harnessed when their electricity generation can be consumed directly. In the Belgian situation, they are already competitive with conventional electricity generation techniques and are expected to become the cheapest technology from approximately 2025 onwards. However, wind and, to a lesser extent, solar PV sectors have experienced a rapid increase in investment costs, due to an increased price of steel and interest rates, and supply chain bottlenecks. Therefore, it is key to investigate their potential given a cost-effective electricity system which leads to a reduction of the use of fossil fuels and CO_2 emissions. All this is happening at the same time the phasing out existing old nuclear capacity is discussed. Thus, it is very important to study how these renewable technologies can substitute conventional electricity generation technologies while ensuring the security of supply and balancing the electricity system at all time horizons. Due to the variable nature of renewable energy production a buffer system is required to stabilize the electricity grid. This can be battery-based storage or Power-to-X (PtX) approaches where surplus electric power is flexibly utilized to produce several products or energy carriers (e.g.: synthetic methane, chemicals, hydrogen, heat, etc.). The PtX approach has the additional advantage that it can be combined with carbon capture & utilization (CCU). In summary, PtX is especially useful in energy systems with a high share of renewables and a decarbonizing target, as well as a potential increase in clean molecules demand. This is expected to be the case for Belgium within the next decades as clean molecules are gaining protagonism in several sectors as decarbonisation options. In particular, for regions with high energy and feedstock consumption and low local renewable potential, clean molecules trading is expected to be part of the future solutions. Within this context, Belgium is an important hub due to its strong petrochemical sector as well as the energy consumption of its ports, among others.

The objective of the PROCURA project is to detailly describe quantitative scenarios and to develop a roadmap on the role of PtX and Carbon Capture Utilization and Storage (CCUS) in Belgium. The results will contribute to the current discussion in Belgium with regard to these topics.

New tools and methodologies facilitate the development of a quantitative roadmap and allow the involved stakeholders (e.g.: chemical industry, technology vendors and energy consumers) to accelerate the energy transition. This will allow Belgium to reach its long-term decarbonisation goal as set by EU policy, and lead to the realization of a phased rollout of PtX and CCUS in Belgium. Potentially, PtX will grow as an important aspect of the Belgian industry. In Figure 8 the hydrogen strategy for Flanders is depicted.

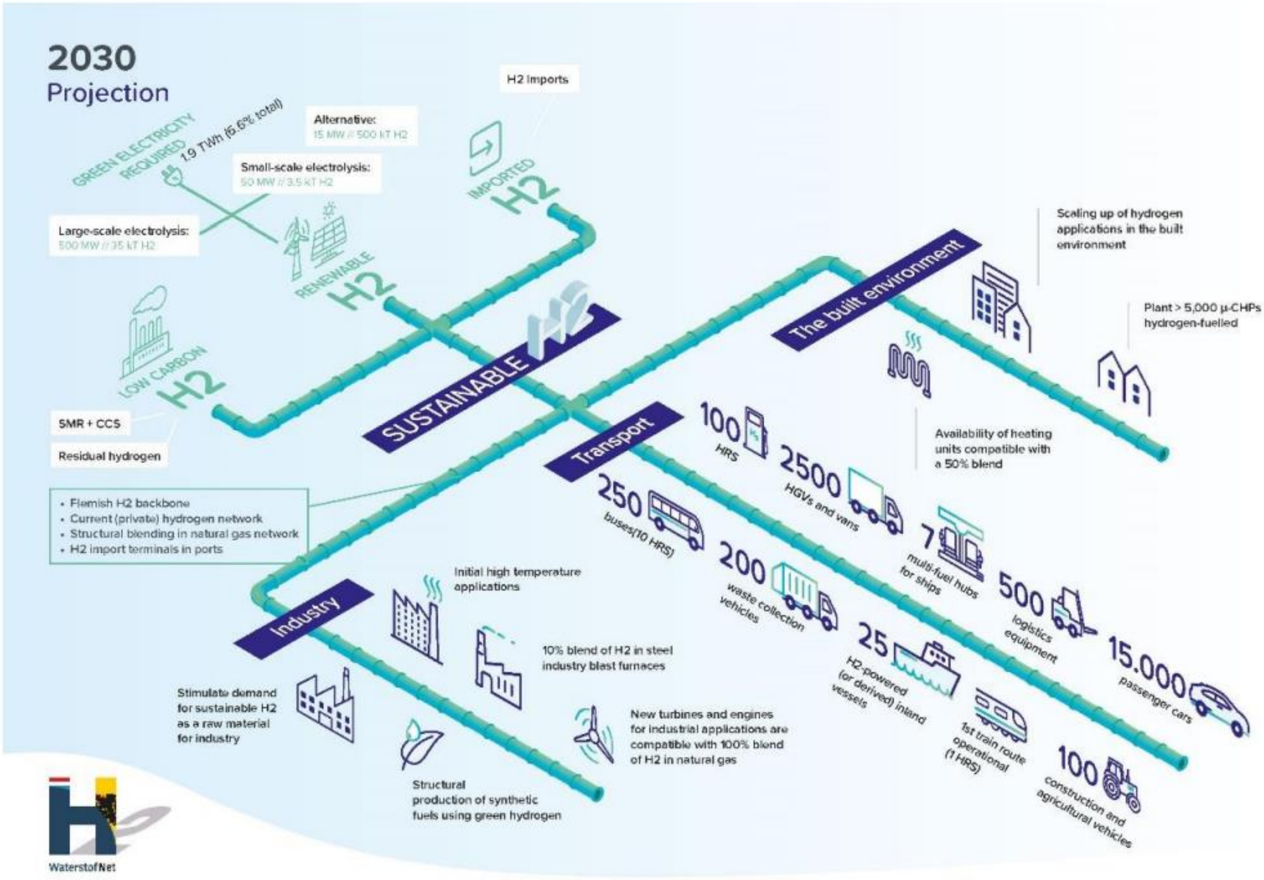


Figure 8. The Hydrogen Industry Cluster member targets for 2030[2].

Much has happened in the last five years in the context of hydrogen and clean molecules. The initial optimism has encountered challenges and barriers not easy to overcome. For instance, in 2020 the expected electrolyser CAPEX for 2050 was around 510 €/kW [3], while more recent outlooks lay in the range of 900 – 1480 €/kW [4,5]. Moreover, the economic turmoil after the COVID pandemic has increased material, capital and labour costs; made markets unstable and projections more uncertain. Almost right after the COVID pandemic, Russia has started a full-scale war in Ukraine, which has directly led to an energy crisis in the EU with rocket high prices for natural gas. Though the extreme price peaks have eased, still natural gas prices during the past year are in average double those of pre-war situation. This all together poses a problem for the rollout of a global clean molecules' economy. On top of the difficulties experienced by the hydrogen and hydrogen-derived molecules sectors, GHG emissions reduction alternatives arise in competition for financing and long-term strategies. This is, for instance, the case with nuclear power generation, CCUS, and behavioural changes, among others.

[2] A Flemish Hydrogen Strategy 2025 – 2030, H2 Waterstof Industrie Cluster, 7 December 2020, https://www.waterstofnet.eu/_asset/_public/WIC/2020-12-7-Flemish-Hydrogen-Strategy_Hydrogen-Industry-Cluster.pdf
[3] IEA G20 Hydrogen report: Assumptions, IEA, December 2020, https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf
[4] Belgian electricity system blueprint for 2035-2050, ELIA, September 2024, https://www.elia.be/en/press/2024/09/20240924_elia-publishes-blueprint-for-the-belgian-electricity-system-2035-2050
[5] CLEAN HYDROGEN PRODUCTION PATHWAYS, Hydrogen Europe, 2024, https://hydrogeneurope.eu/wp-content/uploads/2024/06/2024_H2E_CleanH2ProductionPathwaysReport.pdf

In the PROCURA project, WP3's initial objective was to answer questions related to harnessing variable renewables, providing flexibility to the power system, and storage options (short- and medium-term). However, the scope has changed and has been expanded to incorporate all energy sector changes and insights of the last four years. Therefore, the explorative scenarios and results' analysis are devoted to exploring the role of molecules and CCUS in decarbonising the Belgian economy, the dependency on imported molecules and the possible role of the country as a molecule hub to transit molecules to and from neighbouring countries. Several contributions and developments to the TIMES-Be during the PROCURA project have been used in other Energy Transition Fund Projects such as CIREC[6], TRILATE[7], HEFAISTOS [8]to name a few, and VITO/EnergyVille projects, providing valuable insights to reshape the research goal of the study. For instance, the molecules and CCUS modules developed within PROCURA were used for the scenarios published on the PATHS2050 website[9], and will be also part of ETFs projects ending in 2025 and 2026.

The report is structure in a way that the original research questions are answered in a dedicated section. All under the new perspective, which change has been explained before, leading to a Belgian roadmap and discussion of PtX, CCUS and clean molecules in general.

WP3: Long-term modelling - power to energy

- T 3.1 Power to heat + chapter/section references (see section 4.1)
    - Defining the application fields of heating by electrical solutions
- T3.2 Defining options for Power to mobility P2M (see section 4.3)
    - production of synthetic fuels will be evaluated for different transport modes.
- T 3.3 Power to industrial processes (see section 4.4)
    - Screening of novel technologies are under development allowing to eliminate the use of fossil fuels: steel based on electrolysis or hydrogen, syngas production using CO2 and electricity.
- T 3.4 Power to energy for dealing with intermittency of renewable energy supply (see section 4.5)
    - Benchmark Power to X with other (seasonal) storage and flexibility options.
- T 3.5 Developing low carbon scenarios with the updated model (see section 3).
    - The potential of the new technologies model will be evaluated by developing low carbon scenarios for the complete Belgian energy system with a horizon to 2050.
    - Uncertainty for critical parameters will be assessed by sensitivity analysis.
    - The scenario results will be documented.

[6] ETF CIREC Project 2025. https://energyville.be/en/project/cirec-secure-and-circular-material-flows-for-electricity-security-of-supply/
[7] ETF TRILATE Project 2025. https://energyville.be/en/blogs/applied-research-institutes-launch-cross-border-collaboration-platform-to-facilitate-transition-to-industrial-carbon-neutrality-in-the-trilateral-region/
[8] ETF HEFAISTOS Project 2025. https://hefaistos.icedd.be/
[9] PATHS2050 The Power of Perspective, EnergyVille-VITO, 2025, https://perspective2050.energyville.be/results/main-edition-2025

2 TIMES-BE Model development.

TIMES Belgium (TIMES-Be) is an energy system model created using the TIMES framework (see next section). The model has been developed over the last 20 years by more than 15 researchers with various backgrounds at VITO and used in several diverse projects. TIMES is able to represent the full value chain from the import or mining of energy and material resources up to meeting final demands, either energy or products (e.g.: ammonia, glass, space heating, lighting). The modelling framework uses what is called commodities to represent the flow of energy carriers and materials between processes. These processes can represent transformation processes such as electricity production, coke ovens, transmission and distribution equipment, biofuels production; or final energy-consuming processes such as vehicles, industrial processes, light bulbs, refrigerators, boilers, air-cooling, etc. The processes, commodities and commodities flows are used to build the mathematical representation of the energy system, the Linear Program (LP), which is solved (minimizing system cost) finding the optimal solution. The LP includes the constraints defined by physics such as the balance between electricity demand and electricity generation in each period, as well as user-defined constraints such as maximum capacity, annual growth and emissions targets. Finally, the results of the model provide detailed information such as installed capacity, energy and material flows, marginal production cost, CO_2 emissions, investments and O&M cost needed to meet the different demands in a cost-optimal manner. Full documentation of TIMES-Be, prepared for the EnergyVille website PATHS2050, can be found online[10]. The are some updates in assumptions that are described in the scenarios' description and annexes.

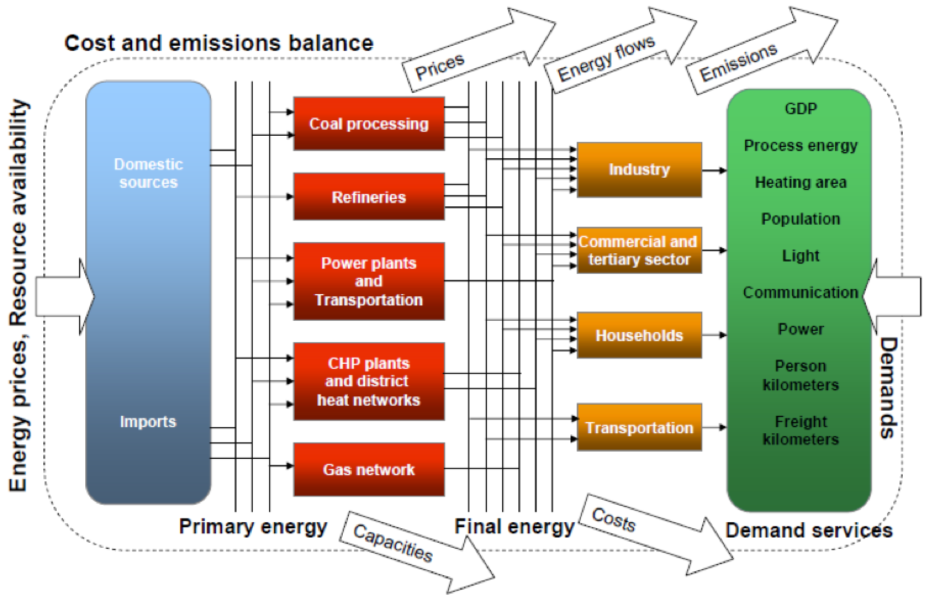


Figure 9. Schematic of TIMES inputs and outputs; source: (Remme et al., 2001). (ETSAP, 2005)

[10] Correa-Laguna, J., Moglianesi, A., Viengerhoets, P., & Lodewijks, P. (2023). PATHS2050 - Scenarios towards a carbon-neutral Belgium by 2050 (Version 20230706). Zenodo. https://doi.org/10.5281/zenodo.8388939

3 Developing low carbon scenarios.

Although the future is uncertain, the exploration of several and varied scenarios' storylines provides insights as standalone cases or by contrasting results among them. Therefore, and to cover different conditions that might promote or hinder the deployment of PtX solutions and CCUS in Belgium, as well as the reliance on imported molecules or electricity, four scenarios were drafted. As the definition of a central scenario can be ambiguous and not consensual, there is no dedicated reference scenario. Conversely, each scenario serves as a reference case based on what one considers to be most aligned with one's future vision. The four scenarios include several changes to the main parameters and assumptions within a narrative of a future situation. The scenarios are EVOLUTION (EVL), ACCELERATION (ACC), AMPLIFICATION (AMP) and TRANSFORMATION (TRF), which are explained more in detail hereafter:

EVOLUTION: a "plausible" future

In this scenario, the price of CO_2 continues to rise to 480€/tCO_2[11]in 2050, which is a key factor in achieving net zero by 2050. Natural gas prices are expected to remain relatively stable, reaching 32€/MWh by 2050, as long-term demand decreases, and new production sites are developed in the short and medium term. Furthermore, CO_2 emission cost and decarbonisation targets are extended to include international aviation and maritime sectors, with the expectation that the maritime sector will reach net zero by 2050, while international aviation reduces emissions by 70%[12].

In 2035, hydrogen imports via pipeline from European countries will begin with a maximum net import capacity of 0.5 GW and up to 1.5 GW by 2050. Additionally, terminals for low-carbon molecules are expected to be deployed starting in 2030 as infrastructure development in this case takes less time and ammonia as feedstock and energy carrier is gaining traction. Furthermore, as molecule production increases globally, semi-finished products based on molecules, such as ammonia and sponge iron, will be traded, making them potential import options from 2035. In this context, DAC will be available on a large scale in Belgium starting in 2050 at a 1750€/ta investment cost.

As molecules compete, but are also intertwined with electricity production, Belgium is expected to have access to 8 GW of far offshore wind in the North Sea, in line with European ambitions[13]. This capacity comes in addition to the 8 GW near its coast (Princess Elizabeth zone and repowering existing sites)[14] . However, due to various reasons, HVDC rollout will slowly reach a maximum of 6 GW by 2050 and 8 GW afterwards. The revival of the nuclear power industry can bring the technology into the market but not as soon as announced. Then, nuclear GENIII is available from 2040 at 9220€/kW (overnight cost), and nuclear SMR from 2050 at a similar overnight cost and higher flexibility, both are affected by the financial cost over the construction time. Nevertheless, it is expected that the nuclear capacity in Belgium won't go beyond 4 GW due to non-technical reasons (e.g. policy, permits).

[11] Climate Impact Assessment Part 2 annex 6 Table 1, p43. European Commission, 2024, https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en constraint

[12] ReFuelEU Aviation, ANNEX I Shares of SAF referred to in Article 4, October 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202302405

[13] Belgian electricity system blueprint for 2035-2050 by Elia Group - Issuu [Internet]. [cited 2025 Mar 19]. Available from: https://issuu.com/eliagroup/docs/20240924_belgianelectricitysystemblueprint2035-205?fr=sYTY2Zjc4MTAxOTI

[14] Belgian electricity system blueprint for 2035-2050 by Elia Group - Issuu [Internet]. [cited 2025 Mar 19]. Available from: https://issuu.com/eliagroup/docs/20240924_belgianelectricitysystemblueprint2035-205?fr=sYTY2Zjc4MTAxOTI

Public opposition and engagement play an important role in the energy transition, limiting the deployment of solar PV to 40 GW and wind onshore to 10 GW, instead of their technical maximum of 104 GW and 20 GW. Moreover, participation and technology adoption from households are not complete, thus, up to 70% of houses install heat pumps by 2050, and EVs participating in V2G and smart charging go up to 14% and 13% respectively.

ACCELERATION: carbon storage bottleneck

Based on EVOLUTION, the hydrogen infrastructure across Europe is deployed in such a way that hydrogen net import capacity through pipeline goes up to 1.5 and 3 GW by 2035 and 2050 respectively. Simultaneously, molecule import prices go down as global production increases faster, as well as electrolyser costs. On the other hand, additional effort, and investment in nuclear SMR make it possible to have the technology 5 years sooner (2045), and the maximum nuclear capacity in Belgium is set at 8 GW. As a result of the focus on nuclear and molecules, DAC is not available at large scale and CCS facilities are limited keeping storage cost at 123 €/t towards 2050.

AMPLIFICATION: full societal engagement

Based on EVOLUTION, hydrogen import infrastructure will be larger (5GW) by 2050. However, although global demand for molecules increases rapidly it is not expected that prices will be any different. Moreover, nuclear Gen III is now available in 2045 at the same cost as SMR. Carbon storage remains highly competitive in Europe, hence, 10 Mta is expected to be the maximum for Belgium by 2050. In this context, it is necessary to increase public engagement, reaching solar PV and wind onshore maximum potential (104 GW and 20 GW), smart charging is heavily incentivized up to 48%, V2G participation increases to 38% and financial and technical hurdles are sorted out to unblock heat-pump adoption. To support this transition, Belgium increases its access to far offshore wind, from 8 to 16 GW, and can install all needed HVDC direct connections capacity. Furthermore, biomass availability will increase by 14 TWh/yr by 2050. Finally, the import of semi-finished products is more difficult due to regulations and policies.

TRANSFORMATION: low carbon molecules revolution

Based on EVOLUTION, the final scenario sees a revolution in the molecule market that is noted in lower import prices, cheaper electrolysers and 5 GW of net-import pipeline hydrogen capacity by 2050. CCS is expected to reach a maximum of 10 Mta by 2050. As the natural gas price goes up due to market, geopolitical situations and policy, there is an effort to bring the installation of nuclear SMR sooner, starting in 2040 with few SMRs (0.5 GW) and without capacity limitation by 2050. This will complement the 8 GW of far offshore wind dedicated to Belgium given the expected higher flexibility to react to the intermittency of renewables. In this context, flexibility is promoted by full smart charging, V2G engagement and heat-pump deployment. The industry is supported by regulatory bodies; thus, the import of semi-finished products is not possible.

The detailed description of attributes that vary between scenarios is shown in Table 1.

Table 1. Scenario main assumption variations

Table 1. Overview of parameters used in the four PROCURA scenarios, expressed in Euro2024

PARAMETERS	UNIT	EVOLUTION	ACCELERATION	AMPLIFICATION	TRANSFORMATION
NG price 2025-2035-2050	[€/MWh]	31-31-32	31-31-32	31-31-32	31-37-43
International navigation decarbonisation target	%	100%	100%	100%	100%
International aviation decarbonisation target	%	70%	70%	70%	70%
H2 pipeline capacity limit 2030-2035-2050	GW	1 - 1.3 - 3	1 - 3 - 5	1 - 3 - 5	1 - 3 - 5
Import terminals for molecules from	year	2030	2030	2030	2030
Import sponge iron (starting year)	year	2035	2035	no	no
import ammonia for derivatives (starting year)	year	2030	2030	no	no
Far offshore wind potential by 2050	GW	8	8	16	16
Belgian offshore wind by 2040	GW	8	8	8	8
HVDC limit to far offshore	GW	4	optimized	optimized	optimized
SMR	Year	2050	2045	2050	2040
Nuclear GEN3+	Year	2040	2040	2045	2040
Solar PV potential	GW	40	40	104	40
Onshore wind potential	GW	10	10	20	10
Maximum adoption of HP share of total	%	70%	70%	100%	100%
V2G participation	%	14%	14%	48%	70%
Smart charging participation	%	13%	13%	38%	72%
Molecule prices range		average	low	average	very low
DAC	Year	2045	No	2045	2045
CCS limit and price	(Mta €/t)	unlimited: 37€/t	unlimited: 123€/t	10Mta: 37€/t	10Mta: 37€/t
Biomass increase by 2050	factor	x1.6	x1.6	x2.2	x1.6
Electrolyser capex by 2050 (e.g.: alkaline large)	€/kW	890	890	890	710

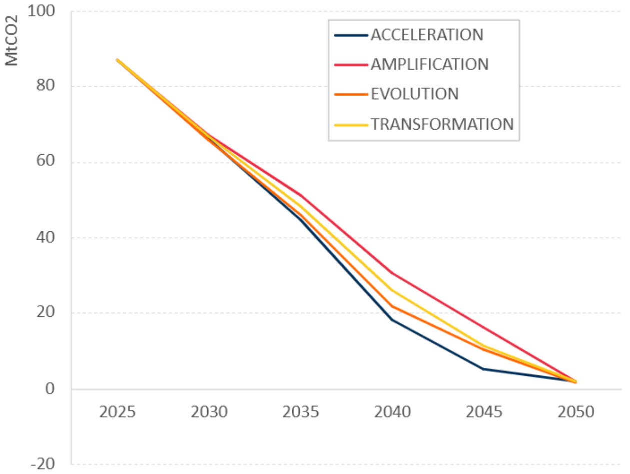
4 Results and discussion

This section examines the results through the lens of the research question, offering insights into key topics such as power-to-heat, power-to-mobility, and power-to-molecules. By structuring the analysis around these specific areas, its findings contribute to a deeper understanding of the role of electrification and sectoral integration in the energy transition in the future energy system.

To establish context, the initial subsection presents general results on emissions trends, the evolution of the energy mix, and decarbonisation pathways across the four scenarios. This comparative overview provides a concise snapshot of key trends, enabling a clearer distinction between different pathways. These high-level findings serve as a foundation for the more detailed, sector-specific analyses that follow in subsequent sections, ensuring a coherent and structured interpretation of the results.

4.1 General results

The four scenarios reach decarbonisation as this is a constraint of the model. Nevertheless, the trajectory to 2050 is different, see Figure 10 and implies different cumulative CO2 emissions, energy mix and costs. The reduction of emissions depends on four main strategies which are electrification, clean molecules, carbon capture and bioenergy. Figure 11 shows the trajectory of the most important parameters, electricity, natural gas, hydrogen and CO_2 emissions, which provide a glimpse of the behaviour of each one in each scenario.



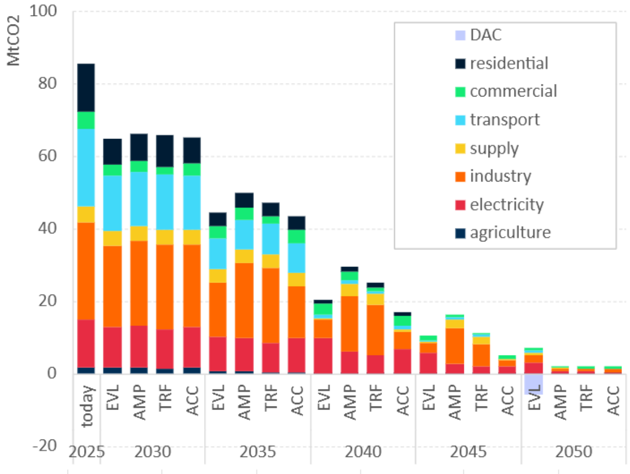


Figure 10. CO2 emissions trajectory by scenario.

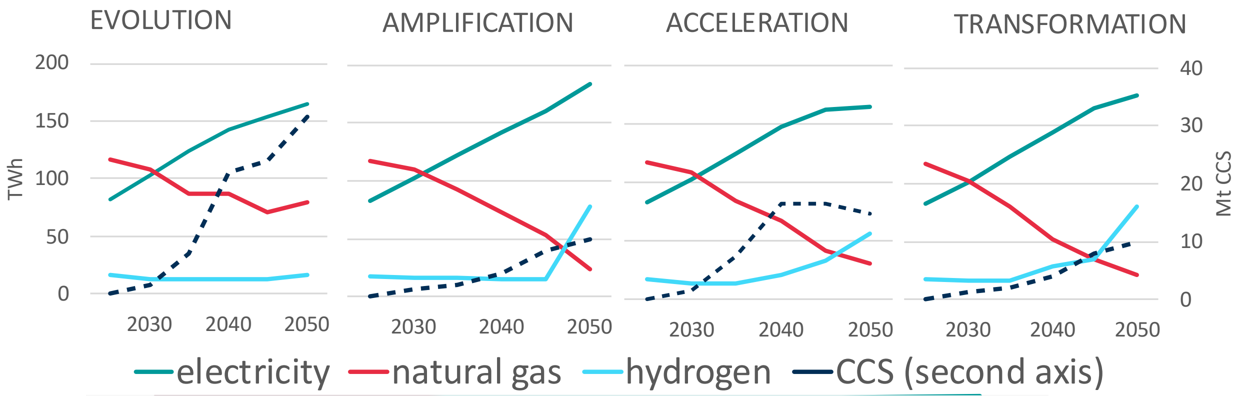


Figure 11. Trajectory of final electricity, natural gas and hydrogen energy and non-energy consumption, as well as carbon capture and storage.

Final energy consumption is projected to decrease by 20% between 2030 and 2040 (Figure 12), followed by a slight increase toward 2050 due to the adoption of energy-intensive carbon capture technologies. While electrification of demand occurs across all scenarios, the pace of implementation varies. The use of natural gas declines steadily as it is increasingly replaced by electricity and bioenergy, with alternative molecules playing a more limited role. In this context, hydrogen demand remains moderate, with a notable surge only in the APLIFICATION and TRANSFORMATION scenarios, where industrial hydrogen consumption rises sharply by 2050.

There is an increase in final energy consumption due to CCS, ranging from 1% to 3% of total final energy consumption, this is around 4-14 TWh. CCUS becomes very important in the decarbonisation strategies of some sectors such as cement, lime and steel, leading to captured volumes around 13-30 MtCO_2. Considering the energy consumption and the captured CO_2, the energy intensity of this technology will be around 0.5 MWh/tCO_2, which could be 50-100% electrified.

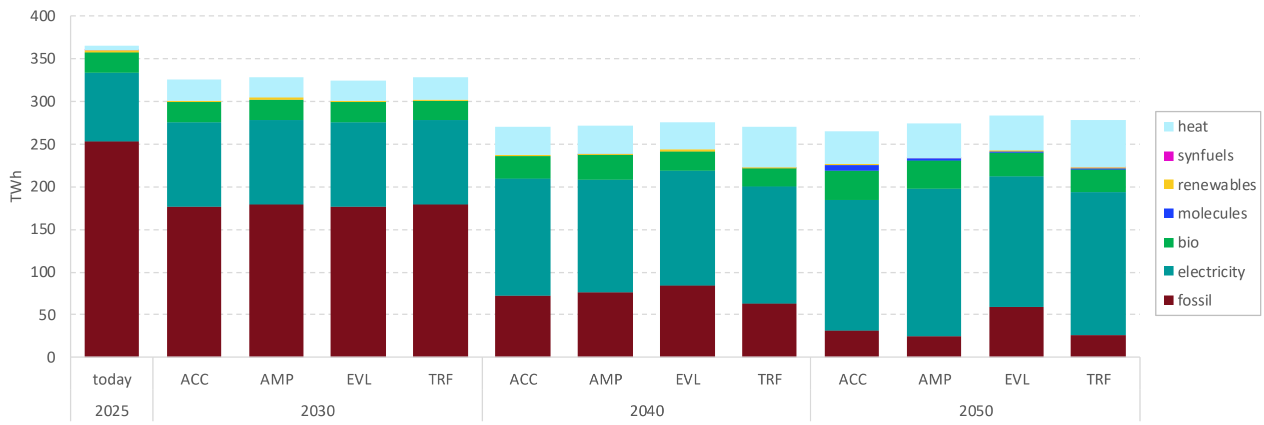


Figure 12. Final energy and non-energy consumption for all scenarios between 2025-2050

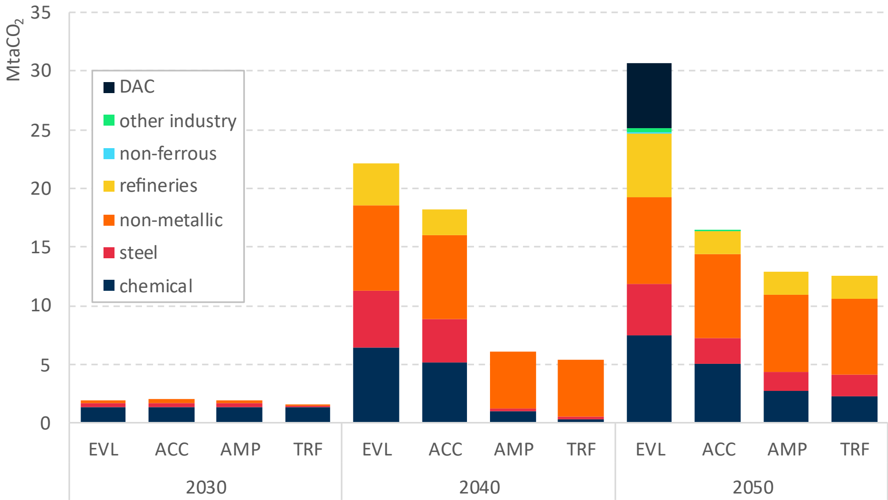


Figure 13. Carbon capture by sector for all scenarios between 2030-2050.

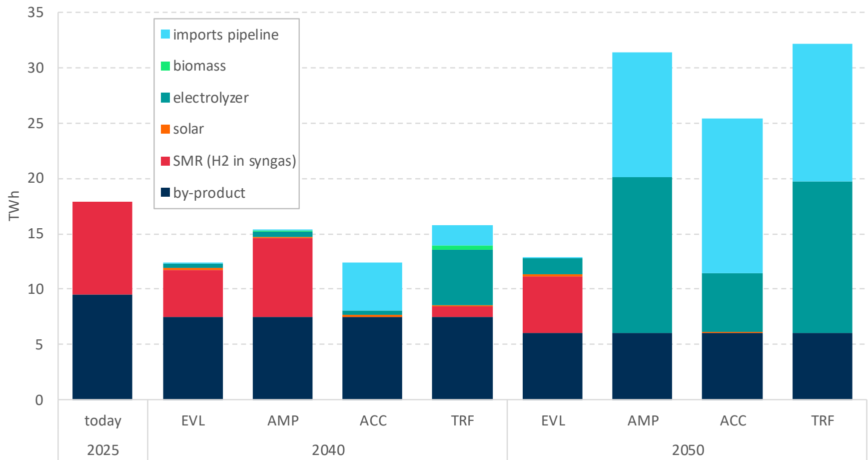


Figure 14. Hydrogen production by source for all scenarios focussed on 2040-2050

4.2 Power to heat

Hypothesis

Power to heat is gaining importance in the decarbonisation efforts both in industry and buildings. In this case, not only by electrifying the heat production via heat-pumps or electric boilers, but also by implementing heat buffers such as tanks could help in rolling out such electric technologies powered by renewables.

Power-to-heat solutions could contribute to the transition to a low-carbon energy system, both in industry and buildings. Electrifying heat production through heat pumps and electric boilers is a key strategy, but its effectiveness can be enhanced by the integration of thermal energy storage, such as heat buffer tanks. These buffers allow for greater flexibility in electricity demand, enabling industries and buildings to optimize energy consumption based on renewable energy availability and grid conditions. Besides the energy gains obtained from replacing traditional boilers with heat pumps. This approach reduces reliance on fossil fuels while supporting the efficient integration of intermittent renewables like wind and solar power.

The electrification of heat could lead to an increase in renewable energy integration, reducing curtailment and helping with supply and demand balance. Lower CO_2 emissions by replacing fossil-based heat generation with electrified and storage-backed solutions are fundamental in a net-zero energy system. Besides the technical benefits, electrification of heat could lead to cost savings, as industries and buildings reduce final energy consumption and can store heat when electricity prices are lower.

Results

In buildings, electrification goes hand in hand with renovation efforts as can be seen in Figure 15. By 2040, ten years from now, there could be around 2 million heat pumps in the residential sector[15], while the commercial heat pumps could range from 10.000 to 30.000. In the case of industry, the sectors where the electrification of heat starts to happen first are food and paper, as electrifying low and medium-temperature heat is easier with heat pumps than in cases where the heat goes beyond 300°C. Towards 2050, and pushed by stringent climate targets, there is additional potential to decarbonize high-temperature heat processes in industry. This is the case, for example, of electric furnaces in naphtha cracking and steel finishing as can be seen in TRANSFORMATION and AIMPLIFICATION in 2050.

[15] Average size for heat pumps in the residential sector is assumed to be 8 kWth, while for the commercial sector it is 600-1200 kWth.

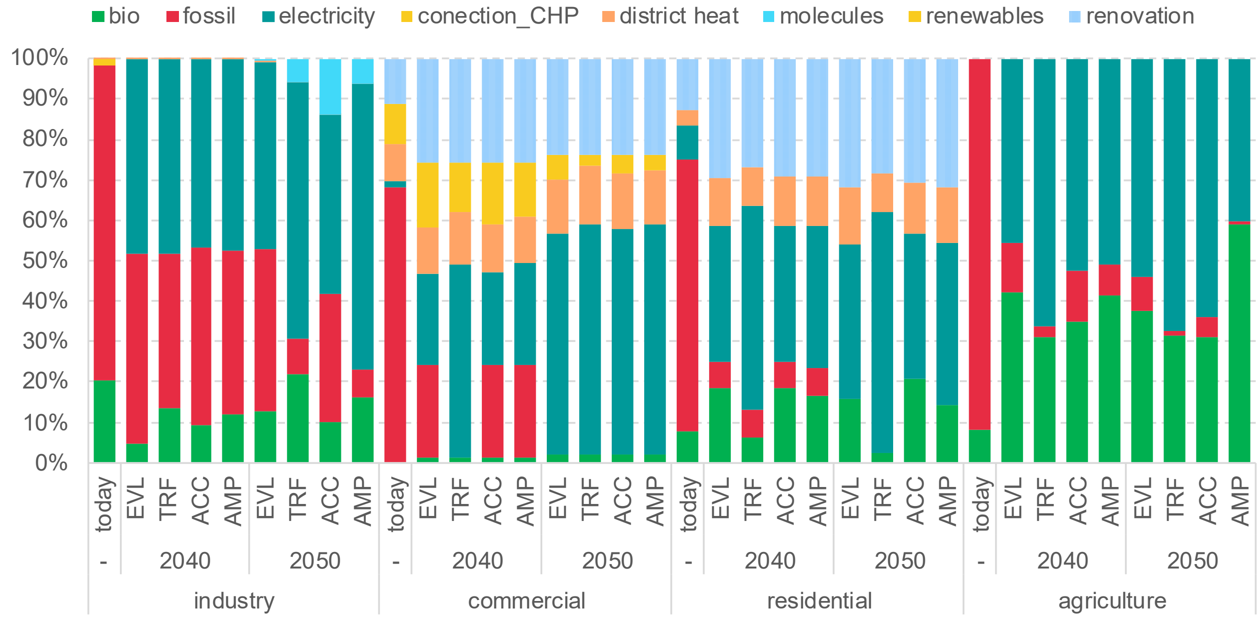


Figure 15. Heat production by technology main energy source and by sector.

Conclusion

The electrification of heat follows a sectoral progression, occurring first in residential and agricultural sectors before expanding to commercial buildings and industry. In all cases, the adoption of heat pumps results in energy efficiency gains and cost savings. However, in residential buildings, widespread deployment must be accompanied by building renovations and stringent energy performance standards for new constructions.

In the agriculture sector, biomass-based CHPs provide both heat and electricity, offering grid flexibility as dispatchable energy sources. Similarly, in the commercial sector, CHPs play a significant role in heating, though by 2050, high electrification and district heating are expected to dominate the heat supply.

In industry, low-temperature heat electrification via heat pumps becomes viable around 2030, with further electrification accelerating after 2040 due to rising CO_2 prices, expanded low-carbon electricity capacity, and climate targets. While this transition may lead to higher production costs—averaging 60% and up to 300% in some cases—certain industries may benefit from reduced production costs and enhanced by-product valorisation, highlighting the complex economic dynamics of industrial decarbonisation.

4.3 Defining options for Power to mobility P2M

Hypothesis

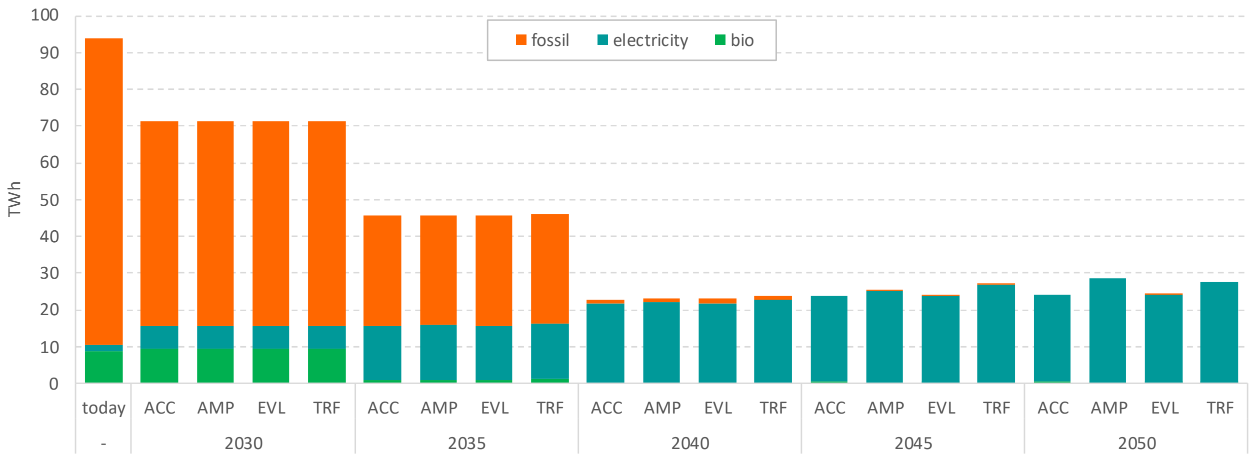
This section explores how power-to-mobility solutions, both direct and indirect electrification, can enhance the integration of renewable energy into Belgium's power system. Direct electrification involves the widespread adoption of EVs, which can support grid flexibility through smart charging and V2G technologies—charging during periods of high renewable generation and potentially feeding electricity back to the grid when demand is high. Indirect electrification, on the other hand, leverages surplus renewable energy to produce hydrogen via electrolysis. This hydrogen can be used directly or converted into synthetic fuels (e.g., methanol, diesel, or gasoline) using biogenic or atmospheric carbon captured via DAC, providing additional storage and energy system flexibility.

By 2050, integrating these technologies is expected to lead to higher renewable energy penetration, improved grid stability, and reduced curtailment of excess electricity from wind and solar sources. Smart charging and V2G could help balance supply and demand, while flexible hydrogen production could absorb surplus renewable electricity, reducing reliance on fossil-based energy carriers. Therefore, it is estimated that sector coupling between power and mobility will play a critical role in the energy transition, contributing to lower carbon emissions, enhanced energy security, and a more resilient power system.

Results

In all scenarios, road transport will be fully electrified by 2040, leading to a 75% reduction in final energy consumption. Moreover, the way that smart charging and V2G are scheduled shows the potential they can have to accommodate large volumes of PV and wind in the energy system as well as to support power generation during peak periods as can be seen in Figure 16.

In the case of hydrogen production from renewables, it has proven to be a costly case in Belgium under the explored scenarios, and electricity is preferred to be used as such given the likely scarcity of low-carbon and affordable electricity in Belgium. However, specific transport sectors will require clean fuels to be imported from outside Belgium, as is the case of ammonia, e-methanol, e-methane and e-kerosene, which are mainly used in bunkers and international aviation (see Table 2).



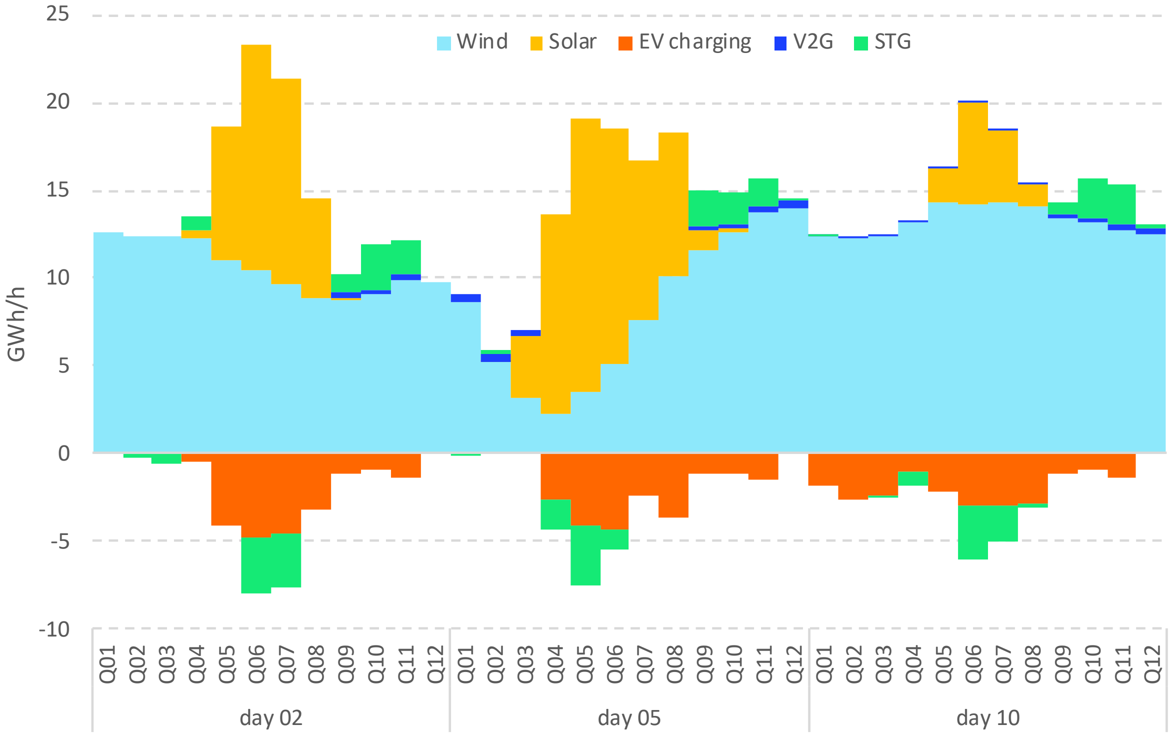


Figure 16. Renewables generation, EVs and batteries profile for selected representative days by 2050 in the EVOLUTION scenario.

Table 2. Molecules and derivatives demand by scenario [TWh]

		today	2040				2050			
	sector		ACC	AMP	EVL	TRF	ACC	AMP	EVL	TRF
hydrogen	refineries	11.21	8.48	8.48	8.48	8.48	6.71	6.71	6.71	6.71
	Copper	-	-	-	-	-	0.31	0.31	0.31	0.31
	fertilizers	5.80	2.89	2.89	5.80	5.80	2.89	-	5.80	5.80
	Steel	-	-	-	-	-	-	10.33	11.50	10.33
	supply synthesis	-	-	-	-	0.39	-	-	3.49	5.42
e-methane	power	-	-	-	-	-	-	4.47	-	2.89
	navigation	-	-	-	-	-	40.88	51.60	41.61	28.78
ammonia	navigation	-	-	1.66	-	-	4.96	6.67	4.96	15.50
e-fuel	aviation	0.03	8.44	7.31	7.46	7.89	15.70	14.70	14.62	15.03

Conclusion

After 2030, road transport in Belgium will be fully electrified, drastically increasing the need for infrastructure (e.g. public and private chargers, distribution grid). The integration of smart charging and V2G technologies will not only enhance grid flexibility but also facilitate the large-scale integration of renewable energy, minimizing curtailment and supporting power generation during peak demand periods.

While local hydrogen production from renewables remains costly under the explored scenarios, direct electricity use is prioritized due to the limited availability of low-carbon and affordable electricity in Belgium to produce large volumes of hydrogen and synthetic fuels. However, synthetic fuels and clean molecules will still play a critical role in decarbonizing sectors where electrification is not feasible or more difficult, such as maritime shipping and aviation. These fuels will primarily be imported, therefore importing infrastructure and agreement with synfuel providers will be fundamental for important assets such as airports and seaports.

4.4 Power to Industrial Processes

Hypothesis

Increasing CO_2 emissions price and the reduction of free CO_2 allowances is expected to drive the industry to choose low-carbon production routes. In this way, the CO_2 footprint of products will diminish. Besides the use of hydrogen and derivatives, direct electrification is thought to be the best alternative in some cases. For example, the electrification of low and medium-temperature heat via heat pumps, which can be coupled to heat buffers to benefit from moments of low-price electricity. Alternatively, the electrification of high-temperature heat and the adoption of electrochemical reactions could be an alternative to the existing fossil-fuel-based processes.

In Belgium, the electrification possibilities include the following (not prioritized)

- Low and medium temperature heat: heat pumps, electric boilers, electric heaters and storage devices.
- High temperature: electric furnaces, electric boost, hybrid electric-gas furnaces,
- Electrochemistry: base chemical production (e.g. ethylene), fuel production, electrodeposition, electro-crystallization, flow batteries, among others.

As CO_2 price increases and free CO_2 allowances decline, industries are expected to transition towards low-carbon production pathways. This shift will significantly reduce the carbon footprint of industrial products. While hydrogen and its derivatives will play a role in decarbonisation, direct electrification is emerging as a key alternative. In particular, electrification of low- and medium-temperature heat through heat pumps, electric boilers, and heaters offers a viable solution, especially when paired with thermal storage to take advantage of periods with lower electricity prices. Similarly, high-temperature heat applications could see the adoption of electric furnaces, hybrid electric-gas systems, and electric boosting technologies to replace fossil fuels in industrial processes. Moreover, the adoption of electrochemical technologies could be an alternative to the existing fossil-fuel-based processes such as naphtha cracking and ammonia from natural gas.

By 2050, renewable energy integration will be closely linked to industrial electrification. Electrochemical processes, such as base chemical production (e.g., ethylene), fuel synthesis, electrodeposition, electro-crystallization, and flow batteries, could reshape the industrial landscape. These technologies not only enable CO_2-neutral production but also provide opportunities for flexible electricity demand, helping to stabilize the grid as renewables like wind and solar become dominant.

Results

As shown in the Figure 17, fossil fuels are progressively replaced by electricity and biomass, which together account for nearly 40% of total final energy consumption by 2050. This shift highlights a clear trend toward industrial electrification. However, full electrification remains infeasible across all sectors, with approximately 60% of final energy consumption still dependent on fossil fuels. This persistence is largely due to hard-to-decarbonize processes, such as the use of raw materials in non-metallic minerals and the continued deployment of CCUS in existing assets, including naphtha crackers.

Low-temperature heat is expected to be fully decarbonized by 2035, as heat pumps offer substantial energy savings, particularly with increasing CO_2 prices. In contrast, high-temperature heat remains a greater challenge, as current conditions make full electrification less viable. As a result, some industrial sectors prioritize CCUS over transitioning to entirely new production routes. Additionally, no new electrochemical technologies have been adopted within the analysed scenarios, indicating limited innovation in this area under existing regulations and market conditions.

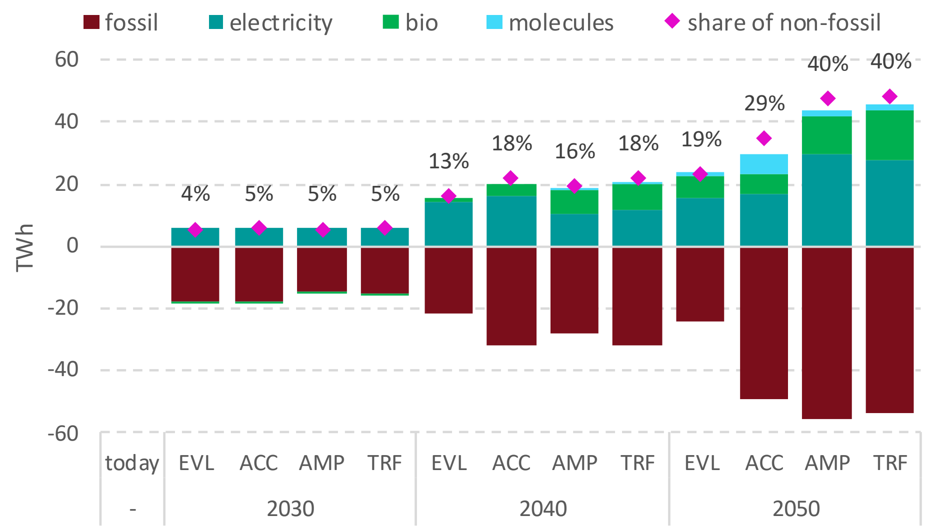


Figure 17. Energy variation compared with today's levels by energy type.

Conclusion

The electrification of low-temperature heat should be actively promoted in the near future, facilitating the widespread adoption of heat pumps in industry. Conversely, the electrification of high-temperature heat will depend on guaranteeing a reliable energy supply and affordable electricity prices to make it a feasible option for industrial applications. Furthermore, the uptake of disruptive full-electric and electrochemical production technologies will necessitate targeted incentives and policy mechanisms to enhance their cost competitiveness. The successful deployment of these solutions will rely on strategic investments in infrastructure, regulatory support, and ongoing technological innovation, thereby ensuring a smooth transition towards a net-zero industrial sector.

4.5 Power to energy for dealing with intermittency of renewable energy supply.

Hypothesis

The seasonal behaviour and annual intermittency of wind and solar PV will require that, at certain moments, the system is designed to provide dispatchable capacity and long-term support storage. In this context, power-to-energy can function as seasonal storage, such as hydrogen or clean molecules, as well as other energy storage.

The successful integration of renewable energy sources in Belgium will depend on managing the seasonal variability and intermittency of wind and solar PV. Since these energy sources are weather-dependent, periods of high generation will not always align with demand, requiring a mid-term flexible energy system. The system must incorporate dispatchable capacity and long-term energy storage that can compensate for the seasonal availability of renewable generation.

One solution is power-to-energy technologies, such as hydrogen and clean molecules, which can store excess renewable electricity for extended periods and be used when renewables are not available. Additional storage solutions will contribute to harnessing the potential of renewables and reduce the reliance on fossil-based backup capacity. The mid-term storage will complement other strategies such as power-to-mobility, power-to-heat and power-to-flexible industrial processes as explained in previous sections.

This section provides a detailed analysis of the technical and economic potential of mid-term storage to facilitate the integration of renewables and reduce the participation of fossil-based electricity generation.

Results

The use of power-to-molecule storage to manage annual intermittency remains unused as clean molecules play a minor role in the power sector and imports from outside Belgium are considered a reliable supply source. Countries such as Chile, Morocco, and Oman offer significant potential for clean molecule production, particularly for winter energy needs.

By 2050, short-term storage solutions will play a more dominant role than molecule-based alternatives, with stationary battery capacity reaching 4–7 GW. Additionally, EVs batteries will contribute to grid flexibility through V2G technology, supplying 0.6 GW to power generation at peak times, with the potential for an even greater impact as adoption increases. Clean-molecule power plants are used during moments of low renewable electricity availability and demand peaks. These technologies reach 2 GW of installed capacity in ACCELERATION, APLIFICATION and TRANSFORMATION, while they go up to 5 GW in EVOLUTION. Nevertheless, the electricity generated is 5.4 TWh only in EVOLUTION, while in the other three scenarios, it is merely 0.1-0.5 TWh.

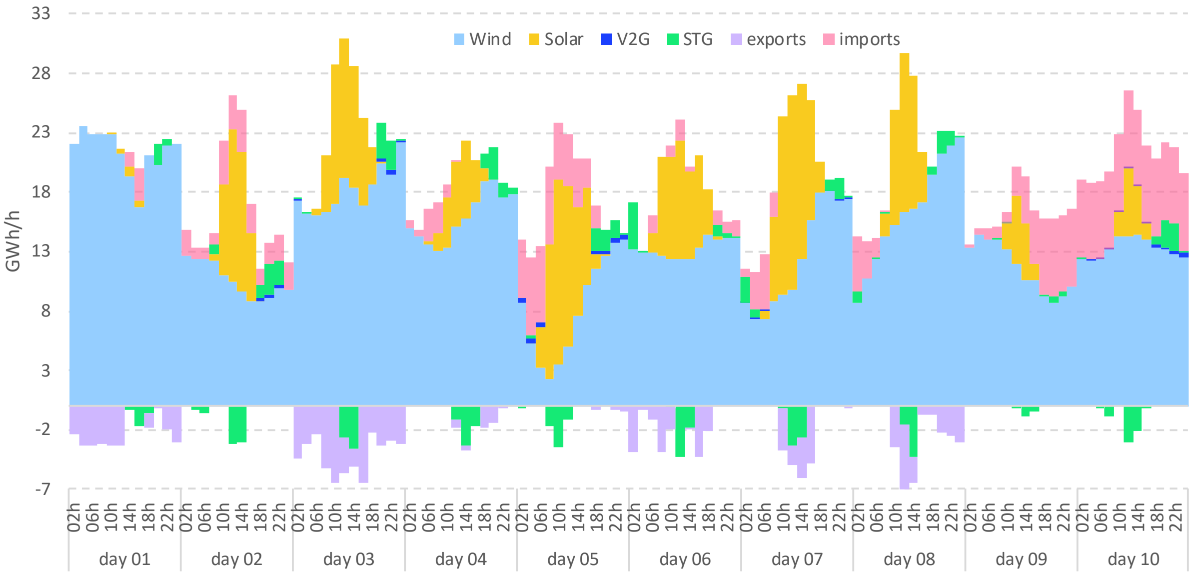


Figure 18. Dispatch of wind, solar, imports electricity, exports electricity and storage along the year using a time-slice structure in TIMES-Be.

Conclusion

Seasonal storage is expected to play a limited role in Belgium's energy transition, as the country moves toward a more integrated European power system, where cross-border electricity trade provides a key source of seasonal flexibility. Similarly, clean molecules will have a limited but essential role in the power sector, primarily as backup technologies. However, their low utilization factor necessitates strong economic incentives to ensure viability. To address seasonal demand variations, molecule imports will likely become an important complement to short-term storage solutions, helping to smooth residual demand fluctuations and enhance grid stability.

5 Conclusions and discussion

The decarbonisation of Belgium's energy system requires a multidimensional strategy, combining electrification, carbon capture, clean molecules and a reduced dependency on fossil fuels and feedstock. The results from the four scenarios demonstrate that while net-zero by 2050 is technically achievable, the path significantly influences cumulative emissions, energy system costs, and infrastructure needs. Power-to-X and CCUS emerge as crucial enablers of deep decarbonisation, yet their optimal roles differ depending on the pace of technological adoption, geopolitical factors (global prices), and policy ambitions.

From today until 2035, immediate focus should be placed on non-regret actions. These include the accelerated electrification of low-temperature (< 200 °C) heat (Power-to-heat) through electrical heat pump deployment in residential, commercial, and industrial sectors such as paper & pulp and food production; the rapid expansion of electric vehicle charging infrastructure; and the rollout of smart charging and vehicle-to-grid technologies (Power-to-mobility). These measures offer clear energy efficiency gains, cost savings, and flexibility benefits for the grid. Furthermore, building renovation policies must be reinforced to ensure that the efficiency of heat pumps is maximised, especially in the residential sector. In parallel, strategic investments in offshore wind capacity and the grid infrastructure, including HVDC interconnections between neighbouring countries, should be prioritised to unlock access to abundant low-carbon electricity.

For CCUS, early-stage deployment should be targeted at hard-to-abate sectors such as cement, lime, and steel, where alternatives to fossil fuels are less mature or technically impossible. Public-private partnerships, regulatory clarity, and long-term CO_2 pricing signals will be essential to scale up capture and storage volumes in a cost-effective and socially acceptable manner. Likewise, policy support for early clean molecules ecosystem development e.g., harbour terminals, pipelines, markets, regulation, and international agreements for imports, will be essential to prepare for its future role in industry and international transport.

Beyond 2035 and toward 2050, Belgium must increasingly focus on addressing decarbonisation of high-temperature industrial heat, process emissions, and hard-to-electrify segments. This will require targeted support for emerging technologies such as electric furnaces, electrochemical processes, and synthetic fuel production. While Power \-to-molecules solutions are unlikely to become widespread in the near term due to cost and efficiency concerns, their importance will grow for specific applications, especially in aviation, maritime, and certain industrial processes. Given Belgium's limited renewable potential, the country must prepare to rely heavily on international imports of clean molecules and semi-finished products, making the development of long-term trade agreements and import infrastructure a strategic necessity.

All four scenarios show clear divergence in hydrogen uptake and CCS deployment, reflecting a degree of uncertainty surrounding the availability, cost, and adoption of these technologies , as clearly shown in Figure 13 and Figure 14. These uncertainties must be addressed through robust monitoring mechanisms, adaptive policy frameworks, and investment in demonstration projects to accelerate learning and reduce technology risks. Additionally, insights should be integrated into national and regional strategies to jointly coordinate and reduce risk and uncertainty for these technologies, as well as to adjust as conditions evolve. Additionally, insights should be integrated into jointly coordinated national and regional strategies and actions to reduce risk and uncertainty for uptake of these technologies, as well as to adjust as conditions evolve over time.

Seasonal energy storage remains underutilised, with clean molecule-based power generation playing only a marginal role due to its low-capacity factor and high cost. However, its importance may increase if electrification stalls, or renewable integration is slower than anticipated. Similarly, while DAC does not appear prominently in the modelled pathways, it could become relevant if residual emissions persist, and other abatement options fail to scale. Therefore, pursuing the installation of DAC outside Belgium to compensate these remaining emissions or developing the technology in the country to export it could be of intertest.

Belgium should aim to secure strategic autonomy over critical technologies and inputs, invest in workforce development for new industrial processes, and address social acceptance challenges for large-scale infrastructure projects such as CCS, nuclear, on-offshore wind and electricity grid development.

In conclusion, while the path to net-zero offers multiple viable trajectories, the most prudent approach is to focus on actions that are beneficial under all modelled scenarios: efficient electrification, building renovations, strategic infrastructure investments, and enabling frameworks for clean molecules and carbon capture. Implementing these non-regret actions are the best guarantee for laying a strong foundation for deeper decarbonisation by 2050. Risk management through additional and periodically updated research on scenario flexibility, technology diversity and assessment, as well as international cooperation will be key to navigating the uncertainties ahead.

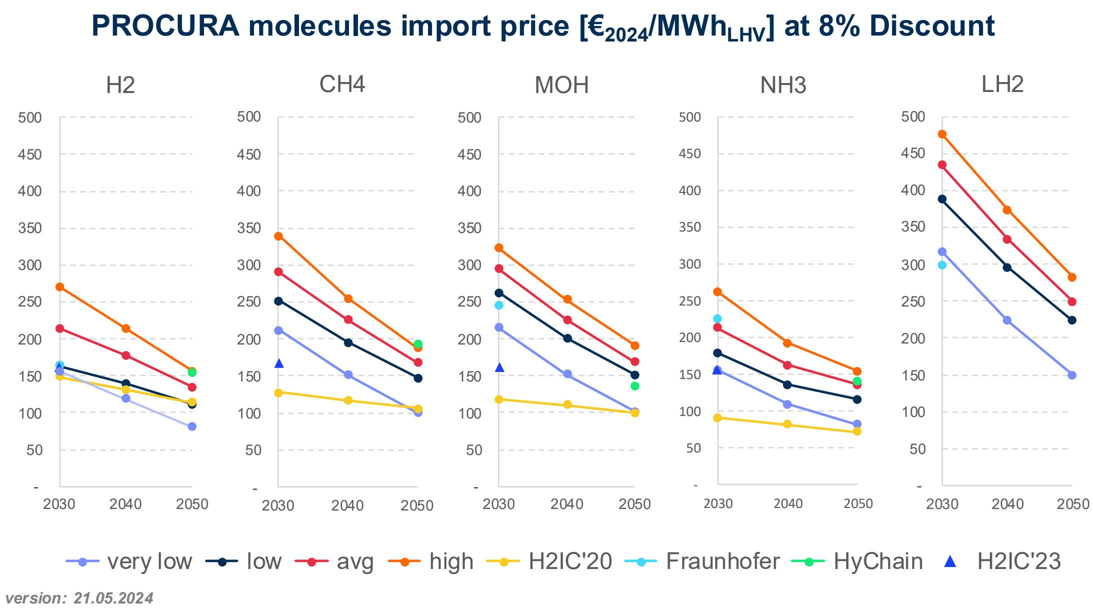
Annex 1: Assumptions

The version of TIMES-Be used for PROCURA evolved from the version used in PATHS2050 version 2022, which is documented in the full report[16]. The most relevant assumptions, differences and updates are included in the table below, where the values for the PROCURA project are shown.

Table 3: Energy commodity price projections in TIMES-BE

Commodity	Unit	today	2030	2040	2050	Source
Natural Gas	€/MWh	31.57	35.00	35.00	35.00	VITO/Energyville/UGent as part of ETF CIREC project, pending publication.
Coal	€/MWh	28.59	13.89	13.89	14.29	World Energy Outlook 2022
Crude Oil	€/MWh	38.85	39.30	37.51	35.72	World Energy Outlook 2022
LPG	€/MWh	54.34	54.98	52.47	49.96	Historical + driver: Crude Oil
Gasoline	€/MWh	47.61	48.14	45.94	43.76	Historical + driver: Crude Oil
Kerosene	€/MWh	64.48	65.20	62.24	59.30	Historical + driver: Crude Oil
Naphtha	€/MWh	41.98	42.47	40.50	38.58	Historical + driver: Crude Oil
Diesel	€/MWh	50.37	50.96	48.67	46.35	Historical + driver: Crude Oil
Fuel oil	€/MWh	28.36	28.72	27.38	26.07	Historical + driver: Crude Oil
Oven coke	€/MWh	37.21	37.21	37.21	37.21	Historical + constant
Biomass	€/MWh	20.99	20.99	22.33	22.33	IEA Bioenergy
Biodiesel	€/MWh	105.81	128.40	126.17	123.93	Fixed spread with fossil equivalent[17]
Renewable diesel	€/MWh	118.09	145.58	143.35	141.12	Fixed spread with fossil equivalent
Bioethanol	€/MWh	141.90	180.15	177.96	175.77	Fixed spread with fossil equivalent
Ren. gasoline	€/MWh	-	180.11	178.00	175.77	Fixed spread with fossil equivalent

Import prices of molecules (H2, NH3, eCH4 and MeOH) were calculated based in Hydrogen Import Coalition handling costs, selected countries' annual average availability factor of wind and solar PV and the technology assumptions in TIMES-Be for the technologies involved in the production of these molecules (i.e.: wind offshore, wind onshore, solar PV, electrolysers, methanation, methanol synthesis, ammonia synthesis, ASU and DAC).



[16] Correa-Laguna J, Moglianesi A, Viengerhoets P, Lodewijks P. PATHS2050 - Scenarios towards a carbon neutral Belgium by 2050 [Internet]. Zenodo; 2023 Feb [cited 2025 Jun 3]. Available from: https://zenodo.org/records/8388939

[17] Assumpton is to keep the historical spread between the two until 2030, when, due to the REDIII, the spread would increase by a 40%