The Power
Of Perspective

Empowered by: KU Leuven, VITO, imec & UHasselt

Work document:

Description of the EnergyVille TIMES Be model

Author: Juan Correa Laguna, Andrea Moglianesi, Pieter Vingerhoets, Pieter Lodewijks

Date: 07/11/2022

Versions and changes

Version	Changes
12/10/2022	• Original version published on 12th October 2022
07/11/2022	• Table 4: Fixed OPEX €/kW changed to €/kW/y • Table 4: VAROM was in €/GJ, changed to €/MWh. From 2.09 [€/GJ] to 7.52 [€/MWh] • Page 4: "Belgium has an average per capita ~~final~~ **primary** energy consumption of 64.9 MWh/person"

Table of Contents

1. Introduction and scope

The results of the study towards net zero emissions in Belgium 2050 can be found on the website of 'Paths 2050' https://perspective2050.energyville.be , of which this document is a part. This document aims to provide more details on the modelling approach, the method and the values of the model parameters.

The EU aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement. All parts of society and all economic sectors will play a role – from the power sector to industry, mobility, buildings, agriculture and forestry.

Belgium, as a member of the EU, is moving towards achieving climate goals by promoting and supporting progress in all the social and economic sectors. This transition will impose stress on the energy system, not only on the power sector, as society moves to new and emerging technologies to meet service and product demands (i.e.: space heat, mobility, steel, cement).
Belgium is one of the most densely populated countries in Europe and houses large industrial clusters. Belgium has an average per capita primary energy consumption of 64.9 MWh/person[1]. Compared with Germany (44.2 TWh/person), France (41.9 MWh/person) and Denmark (33.9 MWh/person), Belgium requires more energy, not only for buildings but mostly for the industry and transport sectors, which together account for roughly 70% of total energy and non-energy final consumption. When compared based on land energy intensity[2], Belgium has an intensity of 18.4 TWh/km^2, which is almost twice as in Germany and four times higher than in France and Denmark. Then, Belgium is positioned as one of the most energy-intensity regions in Europe, which will require a giant transformation of the energy system to support a carbon-neutral economy.

On the other hand, the geographical location of Belgium reduces its access to energy resources such as onshore wind, and solar capacity factors are lower than in the Mediterranean regions. Nevertheless, the same geographical location provides Belgium with a strategic position to serve as an energy-carriers import hub for Europe. This is the case today for petroleum products[3] and natural gas (i.e.: gas pipelines and LNG) –around 80 bcm of natural gas transit through Belgium each year[4].

Innovations in energy and industry open up more alternatives to reduce carbon intensity in several applications, which also increases the uncertainty of the future energy landscape. In general, gaining insight into possible future solutions results in great value for decision-makers today. This is the reason why FEBELIEC VZW wanted to obtain deeper insights into the effectiveness, efficiency and costs of potential innovation pathways for achieving carbon neutrality in Belgium. This transition towards a carbon-neutral economy is a complex interplay between sectors, technologies and energy carriers. Therefore, we explore how the future energy system could look like when decisions are based on system cost minimization with a holistic view using a highly detailed energy system model. Thus, this study is unique in its kind by pioneering on:

- **An integrated system approach**: Not only sector-specific technical solutions and pathways towards a net zero carbon emissions 2050 future but exploring these in an integrated energy system approach in which full system cost efficiency is the driving factor.
- **A high level of industrial process detail,** allowing to gain insights on investment pathways towards carbon neutrality for specific industries,
- **Working in tandem**: A close collaboration between industry and researchers has been set up, so we could build upon the insights and industrial needs.

This approach allows us to explore the impact –or sensitivity– and effect of certain choices on the cost-optimal scenario.

For this complete system analysis of the Belgian energy and industry system (including feedstock), we used the Belgian TIMES model (TIMES-BE). The TIMES model is a well-known energy system model which is further developed in a community of research teams around the world. Cost efficiency is the driving force in the scenario setup of this techno-economic modelling framework. Given the parameter and boundary assumptions, the model will always give the cost-

[1] https://ourworldindata.org/grapher/per-capita-energy-use?tab=table&time=earliest..2019&region=Europe
[2] Primary energy consumption divided by country area.
[3] https://www.iea.org/articles/belgium-oil-security-policy
[4] An Overview of LNG Import Terminals in Europe (pg.8), King & Spalding, 2018.
https://www.kslaw.com/attachments/000/006/010/original/LNG_in_Europe_2018_-_An_Overview_of_LNG_Import_Terminals_in_Europe.pdf?1530031152

optimal pathway solution to reach a net zero energy system in 2050. The 2022 version of the EnergyVille TIMES-BE model is the result of years of development in recent research projects, most of which were funded within the Energy Transition Fund of the Belgian FOD Economie. Within the EPOC, Bregilab and PROCURA project the following model functionalities were implemented:

EPOC:
- Detailing the industrial processes in Belgium with their technical potential to evolve to net-zero by 2050.
- Improving the representation of import/export of electricity in Europe and towards Belgium.

BREGILAB:
- Detailing the technical potential of wind onshore and PV per province in Belgium.
- Improving flexibility options to accommodate large volumes of intermittent renewable electricity production: smart charging of electric vehicles, battery storage, heat pumps, water buffers, and so on.

PROCURA:
- Detailing the production of clean molecules like hydrogen and derivates in Belgium: blue hydrogen (from natural gas and carbon capture and storage), green hydrogen
- Including import of molecules in Belgium through pipelines or by ships

In working with our clients such as Febeliec, we provide detailed insights in the granularity and assumptions of the model. For this study, together with Febeliec, we have identified possible scenarios/storylines towards 2050 which will be elaborated more in the following sections.

With this report, we want to give insights into the level of detail and assumptions included in the latest version of the EnergyVille TIMES-BE model. In Section 2, we describe the TIMES modelling framework as well as the main macro-economic assumption, energy carriers' prices projections and availability of resources. In section 3, we provide more background on the scenarios and elaborate more on the storyline of each one. Then, in Section 4, we describe in more detail for each sector (i.e.: industry, transport, residential) the demands or production rate, the structure of the base year and the processes implemented in TIMES-BE. In Section 5, we briefly explain the structure of the power generation sector and the power grid, as well as refineries and the future production of molecules. The complete results of this study can be found in the PATHS 2050 platform (https://perspective2050.energyville.be). Finally, in the conclusions section, we discuss the results and provide conclusions and policy implications. A summary of assumptions and model parameters is given in *Annex A. Main techno-economic assumptions*.

2. Model framework

2.1. The TIMES model

TIMES, as defined on its website[5], is a modelling framework used to model energy systems varying the spatial and temporal resolution (e.g.: regions, countries, hours, seasons, years) which allows the development of both top-down and bottom-up models. The TIMES model is developed as part of the IEA-ETSAP's methodology for energy scenarios to conduct in-depth energy and environmental analyses (Loulou et al., 2004). The TIMES model generator combines two different, and complementary approaches to modelling energy: a technical engineering approach and an economic approach. In a nutshell, TIMES is used for, the exploration of possible energy futures based on contrasted scenarios" (Loulou et al., 2005).".

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 energy 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 then needed to optimize. 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, and the defined scenarios, 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 (see Figure 1). The TIMES-BE model has been developed by VITO - EnergyVille for several years, incorporating insights and good practices from projects in which the model has been used.

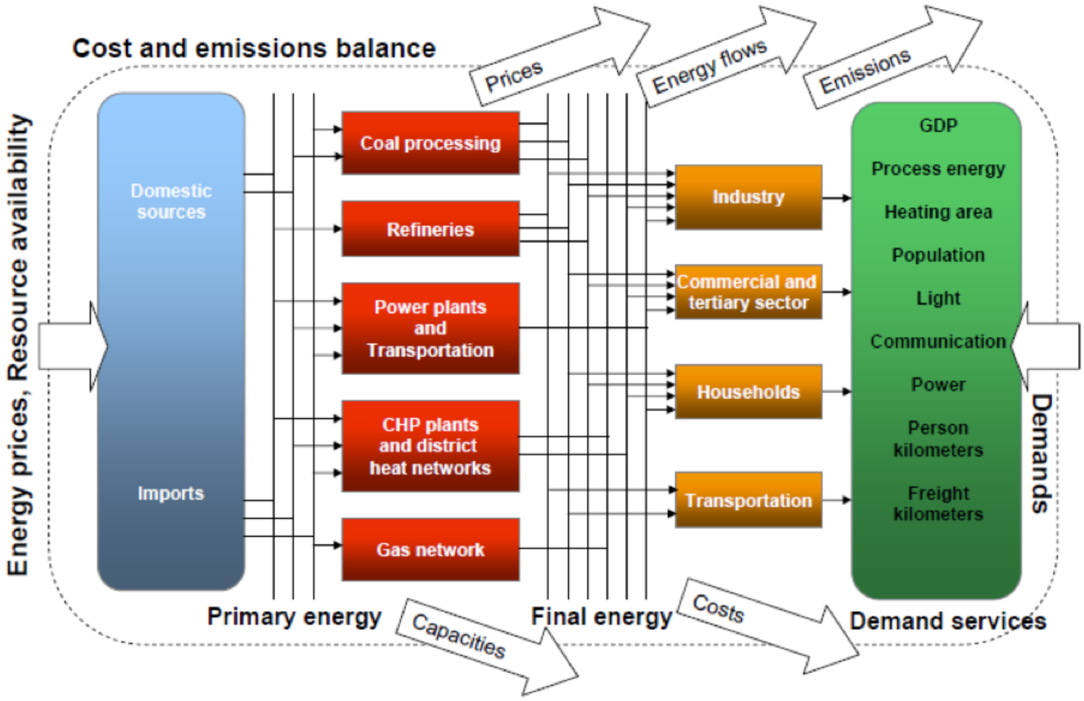

Figure 1. Schematic of TIMES inputs and outputs; source: (Remme et al., 2001). (ETSAP, 2005)

[5] https://iea-etsap.org/index.php/etsap-tools/model-generators/times

2.2. Macro-economic assumptions.

The future energy landscape will be driven by changes in final energy demand and consumption patterns across all sectors (i.e.: industry, residential, transport). Therefore, demand projections are a crucial input for any energy system model. TIMES-BE differentiates between service demands (i.e.: space heating, passenger transportation), product output (i.e.: steel, ammonia, bricks) and energy demands (i.e.: annual energy consumption in PJ or TWh). TIMES has the option to use macroeconomic parameters as drivers of activity level or final demand. This is, for example, to link the demand in the residential sector to population growth or associate the increase of energy demand to the sector-specific GDP annual increase. Although this approach offers the chance to easily and quickly update future scenarios based on these macroeconomic and demographic parameters, TIMES-BE uses the output of more elaborated models designed for each sector (e.g.: KU Leuven transport and mobility-TML), as well as fair assumptions, which is explained in more detail in the following sections.

Main assumptions used for future sector demands:

- **Industry:** In 2050, the throughput of products will have the same level as in 2020. Already planned new investments, such as Project One of INEOS and the investments in the blast furnaces in Arcelor Mittal, are taken into account.
- **Transport:** Annual demand of passenger-km, tonne-km, and energy demand are taken from the results of the TREMOVE model developed by Transport and Mobility Leuven (TML)[6].
- **Residential:** Final energy services demand is driven by population growth according to the federal bureau. The population will increase from 11.5 million in 2020 to 12.4 million by 2050 [7].
- **Commercial:** Final energy services demand is driven by economic growth projections according to the Federal Panning Bureau[8].
- **Agriculture:** Energy demand will remain at the same level as today. Agriculture energy consumption, although with yearly variations, has been rather stable during the las 20 years. Greenhouse gas emissions from non-CO_2 sources (methane, N_2O) are not taken into account.
- **Transformation:** The transformation sector, which includes refineries and the power sector, reflects the changes in demand sectors. Nonetheless, as Belgium exports a large volume of petroleum products, refineries are set to follow the downward trend in crude intake expected by CONCAWE as a low boundary of their activity[9].

TIMES discounts all costs of the energy system to a user-selected year. Additionally, the model uses the discount rate to calculate the annualized payment of the investment cost of each process. TIMES offers the possibility to define different discount rates for each process, or sector (e.g.: industry, residential). TIMES-BE works with a discount rate of 3%. Additionally, there is the alternative to use sector-specific rates. Nonetheless, this feature is disabled for the moment.

BE-TIMES considers only the underlying techno-economic costs of the system and does not take into account taxes, subsidies etc. For instance, the costs of electricity and distribution grids are taken into account, but non-technical costs such as green certificates, and social tariffs are not. This is an explicit choice made in the model, as this allows a view of the energy system which is unbiased by politically inspired taxes and subsidies.

[6] Projections done within the Energy Transition Found project EPOC. https://www.tmleuven.be/en/navigation/TREMOVE
[7] Demografische vooruitzichten 2020-2070, Federal Planning Bureau, 2021. (pg.3) https://www.plan.be/uploaded/documents/202103310840330.FOR_POP2070_12389_N.pdf
[8] Economische vooruitzichten 2021-2026 (Table 7), , Federal Planning Bureau, 2021. https://www.plan.be/uploaded/documents/202102260904210.Rapport_feb2021_12364_N.pdf
[9] A demand reduction of all refinery products of 43% compared with 2014 levels from *Refinery 2050: Conceptual Assessment* (Table3.3-2), CONCAWE, 2019. https://www.concawe.eu/wp-content/uploads/Rpt_19-9-1.pdf

2.3. Fuel and material prices

Belgium relies heavily on the import of energy carriers. In 2019, Belgium's primary energy production was 0.6 EJ and the country imported 3.7 EJ to cover a final demand of 1.7 EJ. The final demand of the country is similar to the total exports of 1.6 EJ. In this case, Belgium is an important passing point for the European energy system, particularly for oil and petroleum products[10]. Table 1 shows an overview of the fuel and material price assumptions currently in place in the model.

In particular, an important trend to capture is the current high natural gas price, following the rapid economic recovery after the COVID-19 pandemic and the strongly reduced Russian pipeline delivery after the start of the war in Ukraine. , In this study, we consider a current price peak in 2022-2023 at €125/MWh. In the mid-term, around 2025, natural gas prices are assumed to drop to €50/MWh, reaching a final long-term projected price of €35/MWh.

Finally, CO_2 prices will increase the cost of services and products based on fossil fuels, this is why we assume that by 2050 CO_2 emission will reach a price of €350/tCO_2, which is in line with results from IEA and the European Commission (see Table 2). The CO_2 cost is applied equally for ETS and non-ETS sectors, also in residential and commercial sectors where currently no CO_2 tax is in place.

Table 1. Energy commodity price projections in TIMES-BE.

Commodity	Unit	2018	2020	2025	2030	2035	2040	2045	2050	Source
Natural Gas[11]	€/MWh	27.16	33.86	72.15	38.52	35.00	35.00	35.00	35.00	EnergyVille/VITO
Coal	€/MWh	13.61	15.50	23.05	11.20	11.11	11.20	11.47	11.52	IEA[12]
Crude Oil	€/MWh	35.76	30.60	31.32	31.68	30.96	30.24	29.52	28.80	
LPG	€/MWh	73.56	68.40	43.81	44.32	43.31	42.30	41.29	40.28	Adapted from IEA[12]
Gasoline	€/MWh	43.24	29.20	38.38	38.81	37.91	37.04	36.14	35.28	
Kerosene	€/MWh	78.96	28.01	51.98	52.56	51.37	50.18	49.00	47.81	
Naphtha	€/MWh	25.88	24.12	33.84	34.24	33.44	32.65	31.90	31.10	
Diesel	€/MWh	43.78	26.28	40.61	41.08	40.14	39.24	38.30	37.37	
Fuel oil	€/MWh	25.88	13.86	22.86	23.15	22.61	22.07	21.56	21.02	
Oven coke	€/MWh	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	steelonthenet[13]
Nuclear fuel	€/MWh	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	ENTSO-E[14]
Biomass	€/MWh	16.20	16.20	16.92	16.92	16.92	18.00	18.00	18.00	HRM-EU[15]

Table 2. CO_2 cost projection in TIMES-BE

	Unit	2020	2025	2030	2035	2040	2045	2050	Source
CO_2 emissions cost	€/t	50	100	150	200	250	300	350	IEA[16], EU[17]

2.4. Maximum resource availability

As is the case in reality, resources are limited, especially those that are essential and appealing for the energy transition. Such is the case with sustainable biomass. Limitations are translated into mathematical constraints in TIMES-BE, which reduces the solution space of the optimization and increases, in some cases, the computational time. Once the constraint is binding –the solution reaches the predefined limit– TIMES-BE tries to find the next optimal solution to meet the system

[10] Values from Eurostat energy balance 2019.
[11] takes into account the current energy prices after the Russia-Ukraine conflict, inflation and post COVID-19 economic impact.
[12] IEA-WEO 2021 - https://prod.iea.org/reports/world-energy-outlook-2021
[13] https://www.steelonthenet.com/files/blast-furnace-coke.html
[14] https://2020.entsos-tyndp-scenarios.eu/fuel-commodities-and-carbon-prices/
[15] https://heatroadmap.eu/wp-content/uploads/2020/01/HRE4_D6.1-Future-fuel-price-review.pdf
[16] Net Zero by 2050 (Table 2.2), IEA, 2021. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf
[17] SWD(2021) 612 final (pg. 149), European Commission, 2021. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SWD:2021:0611:FIN:EN:PDF

demand. This is why the definition of these constraints is paramount for the modelling exercise, as they have a large impact on the final solution. The limitations imposed on TIMES-BE, and common to all scenarios, are listed in Table 3.

Table 3. Maximum availability of selected resources in TIMES-BE.

Commodity	Unit	2020	2025	2030	2035	2040	2045	2050	Source
Biomass	TWh	13.89	13.89	13.89	13.89	13.89	13.89	13.89	Eurostat average
Municipal Solid Waste	TWh	3.67	3.67	3.67	3.67	3.67	3.67	3.67	Eurostat average
District Heating	TWh	1.21	5.20	9.20	13.54	17.87	20.89	23.91	EnergyVille
Rooftop PV	GW	104.1	104.1	104.1	104.1	104.1	104.1	104.1	BREGILAB study by EnergyVille
Onshore wind	GW	20.0	20.0	20.0	20.0	20.0	20.0	20.0	BREGILAB study by EnergyVille
Offshore wind	GW	2.26	2.26	4.60	4.60	8.00	8.00	8.00	Belgian offshore platform[18]

Where the previous table reflects the maximum technical potential, other external factors influence the growth rate of certain technologies. To reflect the current hurdles in the growth of onshore wind, mainly due to local acceptation, we have included an annual growth constraint of 250 MW from 2020 to 2030. After 2030, this annual growth constraint is released. For offshore wind we have included a maximum deployable capacity of 4.6 GW by 2030, reflecting the exploitation of the new Princess Elisabeth zone. By 2040, the model can invest up to the full potential of 8 GW.

[18] https://www.belgianoffshoreplatform.be/en/

3. Scenario description

3.1. Overview of scenarios

To assess the future landscape of the Belgian energy system, and in particular the role of the industry in the transition toward a carbon-neutral economy, we define a central scenario from which two additional scenarios and sensitivity cases are derived. The differences across these scenarios are described in Table 6. All scenarios are designed to reach a deep net zero CO_2 emissions of the Belgian energy system. The advantage of using an integrated energy system model is the possibility to capture synergies and cross-sector interactions, as well as the influence that decisions made in one sector have on others. This is possible due to the technology richness of TIMES-BE, which fairly compares the alternatives to meet all the demands specified in the model, deriving in a bottom-up approach to determine future energy needs. Assumptions for future demand and industrial production are explained in *section 4 Demand sectors*.

- In all scenarios, industrial production levels in Belgium are assumed to stay as today, where planned new investments are included. An exception is the production of refineries, which is assumed to decrease due to the decreasing international demand for fossil fuels.
- Population growth is reflected in the transport sector and buildings (residential and commercial sectors).
- In all scenarios, the lifetime of 2 GW of existing nuclear capacity (Doel 4 and Tihange 3) is extended by 10 years until 2035[19-20].
- Renewables take an important role in the power sector as demand for electrification is expected to increase. In this context, Belgium can invest in renewables up to its technical potential (see Table 3).
- Power interconnection capacity increases from 6.5 GW in 2020 to 13 GW by 2040. The transmission capacity increase is included as an exogenous assumption for all scenarios without a cost allocation.
- International shipping and aviation are not included in the results. Also, non-CO_2 emissions such as methane and N_2O emissions in the agriculture sector are not included.

3.1.1.Central scenario

In the central scenario, it is assumed that Belgium's energy system will reach net zero emissions by 2050, driven by the cost of CO_2 emissions and climate targets, both at national and EU strategies[21]. To reach carbon neutrality the sectors can invest in energy efficiency measures like building renovation, more efficient vehicles, efficiency gains in space heating systems, and so on. Furthermore, new process technologies are modelled: fuel substitution, electrification, the use of synthetic molecules like hydrogen or for the industry and supply sector in 'carbon capture utilisation or storage'. When it comes to molecules, import of hydrogen or derivates from outside of Belgium (EU and non-EU) is possible, where the import costs are derived from international studies. The option of carbon capture and storage (CCS) is not limited in the central scenario. Even though Belgium does not have its own storage locations for CO_2, it is assumed that Belgium will have unlimited access to the commercial phase of cross-border carbon storage in the North Sea and Norway.

Nonetheless, the results and insight of the three scenarios should be considered together as there is high uncertainty surrounding them, and the added value lies in exploring the differences between the scenarios.

3.1.2.Electrification scenario

As alternatives to the Central Scenario, and in line with other long-term decarbonization studies (i.e.: ELIA[22], McKinsey[23], ETIP[24], Material Economics[25]), we explore the effect of having direct access to more offshore wind and the option to invest in new nuclear technology in the Electrification Scenario.

---

[19] https://www.premier.be/fr/declaration-du-premier-ministre-et-de-la-ministre-de-l-energie
[20] https://www.belgium.be/sites/default/files/Accord_de_gouvernement_2020.pdf
[21] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en
[22] Roadmap to net zero, ELIA group, 2021. https://www.elia.be/-/media/project/elia/shared/documents/elia-group/publications/studies-and-reports/20211203_roadmap-to-net-zero_en.pdf
[23] How the European Union could achieve net-zero emissions at net-zero cost, McKinsey, 2020. https://www.mckinsey.com/capabilities/sustainability/our-insights/how-the-european-union-could-achieve-net-zero-emissions-at-net-zero-cost
[24] Getting fit for 55 and set for 2050, ETIP and Wind Europe, 2021. https://etipwind.eu/publications/getting-fit-for-55/
[25] Industrial Transformation 2050 (Exhibit 1.11), Material economics, 2019. https://www.climate-kic.org/wp-content/uploads/2019/04/Material-Economics-Industrial-Transformation-2050.pdf

Offshore wind

In this scenario, investment in direct access with a 'High Voltage Direct Current' (HVDC) connection to 16 GW of the vast offshore wind potential in other parts of the North Sea is possible.

For the availability factor of offshore wind far from the North Sea (i.e.: Doggerbank), we have used a capacity factor of 60%. More important to estimate is the total capacity of additional offshore wind to which Belgium could have direct access. In the 'Esbjerg Offshore Wind Declaration' of 19 May 2022, Belgium, Germany, Denmark and the Netherlands signed an agreement to jointly build at least 150 GW of offshore wind by 2050. We assumed that Belgium will have access to 16 GW of additional offshore potential outside of the Belgian territorial waters. Putting this in perspective, the Netherlands recently increased their target to 70 GW by 2050, Germany to 50 GW and Denmark to 35 GW. For the investment cost assumption, we have increased the cost of offshore wind with the cost of a 300 km HVDC cable connection and offshore convertors, amounting to an additional 950 million €/GW.

Nuclear energy

Furthermore, research in new nuclear technologies focused on 'Small Modular Reactors' is ongoing, which leads to the developing of different types of reactors -with an average size of 300 MWe- that comply with the EU Taxonomy requirements of 'passive safety, minimization of long-lived waste and non-proliferation'. What if we allow investments in this new nuclear technology that could be operational from 2045 onwards?

In the Electrification Scenario, we allow investments in SMR technology that complies with the most stringent EU Taxonomy guidelines: Advanced technologies with closed fuel cycle ("Generation IV") to incentivise research and innovation into future technologies in terms of safety standards and minimising waste (with no sunset clause[26]). At this moment, different reactor concepts are under investigation. We did not differentiate between these different technologies, but we work with a synthesised plant being able to operate flexibly, with a high investment cost of 7500€/kW, which is similar to current large Gen III design like Hinkley Point in the UK. This number is assumed to include waste management steps and risk insurance.

Table 4: Main parameters related to new nuclear power plants

Start year operation	Lead time [y]	Capex [€/kW]	Fixed OPEX [€/kW/yr]	Var OPEX [€/MWh]	Technical lifetime [y]	Efficiency [%]	Annual availability [%]
2045	9	7500	83.3	7.52	60	33	80

3.1.3. Clean Molecules scenario

In the Clean Molecules Scenario, we examine the impact of having synthetic molecules imports at lower costs and limited access to cross-border CO_2 storage.

Green hydrogen import

The production cost of synthetic molecules like green hydrogen and derivates is highly dependent on the electricity cost. Plans are being made to build up large electrolyser capacities at locations outside the EU where abundant renewable capacity is available to produce electricity and green molecules at low cost. In the federal hydrogen strategy, Belgium expressed the ambition to become a large import hub for hydrogen.

There are more locations worldwide to produce green hydrogen than there are countries with oil or natural gas resources today. What if Belgium could have access to these synthetic molecules at a hydrogen price that is almost 30% lower by 2050 (H_2 at 1.7 €/kg) compared to the central scenario? Import of ammonia is also possible in the model, however, it is the explicit assumption in this model that current ammonia production is not displaced and remains in Belgium.

Limit on carbon capture and storage

Belgium has no natural locations to store future captured CO_2 emissions from industry or the power sector. To ship and store Belgian CO_2 emissions we will have to rely on contracts with neighbouring countries like the Netherlands and Norway which are developing storage sites by reconverting old natural gas fields. These storage locations are expected to enter

[26] Source Q&A: EU Taxonomy Complementary Climate Delegated Act (Europa.eu)

their commercial phase within the next following years. What if Belgium has limited access of 5 Mton/y to these cross-border storage locations?

Table 5: Levelized cost of hydrogen import in Belgium in the three scenarios. The last-mile delivery cost within Belgium is distance dependent and not included in this number.

LCOH [€/kg]	2020	2030	2050
Central and Electrification scenario	4.50	2.91	2.37
Molecule scenario	4.50	2.16	1.71

3.1.4. Overview table

What will be the impact on the CO_2 reduction path towards 2050 and how will the costs be impacted in comparison with the Central Scenario?

Table 6. Parameters which vary in the main three scenarios.

Parameter	Central scenario	Electrification scenario	Clean Molecules scenario
New nuclear (SMR)	No investments in new nuclear possible	Investment in new SMR possible, in operation >2045 SMR in line with EU taxonomy	Same as Central Scenario
Offshore	The offshore potential is limited to the Belgian North Sea	Investment in direct access to 16 GW far offshore projects possible, capacity factor 60%	Same as Central Scenario
Carbon capture & storage (CCS)	No limitation to carbon capture & storage	Same as Central Scenario	The carbon capture process is not limited, but limited access to storage potential to 5 Mton/y
Molecule import	Molecule import at H_2 cost (LCOH) of • 2020: 4.5 €/kg (150 €/MWh) • 2030: 2.9 €/kg (97 €/MWh) • 2050: 2.4 €/kg (79 €/MWh)	Same as Central Scenario	Molecule import at lower H_2 cost (LCOH) of • 2020: 4.5 €/kg (150 €/MWh) • 2030: 2.2 €/kg (72 €/MWh) • 2050: 1.7 €/kg (55 €/MWh)

4. Demand sectors

4.1. Industry

As mentioned before, we assume that industrial activity in Belgium will stay mostly constant during the coming decades, with only some changes due to planned investments. This, in other words, means that the current production of goods such as steel, ethylene, ammonia or cement is considered to have similar levels by 2050. As such, this study explores the changes that the industry will undergo to reduce its carbon footprint and comply with national and European targets. In TIMES-BE, each industry has a set of decarbonization alternatives available grouped by decarbonization strategy as it is explained in this chapter, in the section for each industrial sub-sector. The current activity levels and energy demand of the industry used in TIMES-BE are presented in Table 7. According to the Belgian energy balance, the final energy consumption of the industry prior to the COVID-19 pandemic was 148.3 TWh [27] while the final non-energy consumption was 81.1 TWh[28]. During the same period, the industry was responsible for 23.1% (34.18MtCO_2) of the total Belgian GHG emissions[29]. Compared with 1990 values, the sector has reached a reduction of 31.1%, which reflects the effort of several sectors to reduce their carbon intensity.

Table 7: Industrial production levels in the BE-TIMES model

Sector	Sub-sector	Product	Unit	Demand/ production	Sources
Iron and Steel	Virgin steel	High-quality steel	Mt	5.14	Worldsteel[30]
	Scrap based steel	Low quality steel	Mt	2.46	
Chemical & petrochemical	Fertilizers	Ammonia	Mt	0.98	BE GHG inventory[31]
	Based chemicals	Chlorine	Mt	0.91	Euro Chlor[32], Ineos[33]
		Ethylene Oxide	Mt	0.83	Ineos[34], O.Tech[35]
	High-Value-Chemicals	Ethylene	Mt	1.35	Petrochemicals Europe[36], JRC[37]
		Propylene	Mt	1.52	
		BTX	Mt	0.70	
		C4	Mt	0.66	
	Other industries	Energy demand	TWh	25.5	Eurostat[38]
Non-ferrous metals	Detail production	Copper	Mt	0.39	BGS[39]
		Zinc	Mt	0.25	USGS[40]
	Other NFM	Energy demand	TWh	1.16	Eurostat[38]
Non-metallic minerals	Cement	Cement	Mt	6.64	FEBELCEM[41]
	Lime	Lime	Mt	1.90	CLIMAT[42]
	Glass	Container glass	Mt	0.26	CLIMAT [43]
		Flat glass	Mt	0.97	
		Fibreglass	Mt	0.32	
	Bricks	Façade	Mt	1.59	BRIQUE[44]
		Regular	Mt	0.94	BRIQUE[45]
	Other NMM	Energy demand	TWh	3.54	Eurostat[38]

[27] Industrial final energy consumption plus coal and coke input in coke oven and blast furnace.
[28] Eurostat Energy balance 2019.
[29] Sectoral shares in Belgium in 2019. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer
[30] https://www.worldsteel.org/en/dam/jcr:7f5a36e2-e71e-4c58-b93f-f78d0c5933e4/WSIF_2015_vfinal.pdf
[31] https://cdr.eionet.europa.eu/be/eu/mmr/art07_inventory/ghg_inventory/envxm3wfw/BEL_2020_2018_13032020_080456_started.xlsx/manage_document
[32] https://www.eurochlor.org/wp-content/uploads/2019/05/euro_chlor_industry_review_FINAL.pdf
[33] https://www.ineos.com/businesses/ineos-oxide/news/ineos-oxide-eo-and-derivatives-expansion-at-antwerp/
[34] https://www.ineos.com/businesses/ineos-oxide/news/ineos-oxide-eo-and-derivatives-expansion-at-antwerp/
[35] https://www.offshore-technology.com/marketdata/basf-antwerp-complex-belgium/
[36] https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/cracker-capacity/
[37] https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/energy-efficiency-and-ghg-emissions-prospective-scenarios-chemical-and-petrochemical
[38] Eurostat remaining energy and non-energy demand after discounting the detailed model process within the sector.
[39] British Geological Survey (pg.21), 2020. https://www2.bgs.ac.uk/mineralsuk/download/world_statistics/2010s/WMP_2014_2018.pdf
[40] Minerals Yearbook (Table 10), U.S. Geological Survey, 2016. https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/zinc/myb1-2014-zinc.pdf
[41] https://www.febelcem.be/fileadmin/user_upload/rapports_annuels/nl/RA_Febelcem_NL_2019.pdf
[42] https://climat.be/doc/nir-15-april-2020-final.pdf
[43] https://climat.be/doc/nir-2021-150421.pdf (Tables 4.3 and 4.4)
[44] https://www.brique.be/secteur-briquetier/le-secteur-en-quelques-chiffres/
[45] https://www.brique.be/media/2348/2021-rapport-annuel-fbb-version-publique.pdf

Sector	Sub-sector	Product	Unit	Demand/ production	Sources
Food, beverages & tobacco	Flanders	Energy demand	TWh	10.08	Flemish energy balance
	Brussels & Wallonia	Energy demand	TWh	3.08	Walloon energy balance
Paper, pulp & printing	Pulp and paper production	Non-wood containing	Mt	0.52	CEPI[46]
		Wood containing paper	Mt	0.16	
		Recycled paper	Mt	1.37	
Other industries	Transport equipment	Energy demand	TWh	1.39	Eurostat
	Machinery	Energy demand	TWh	3.33	Eurostat
	Mining & quarrying	Energy demand	TWh	0.60	Eurostat
	Wood & wood products	Energy demand	TWh	1.09	Eurostat
	Construction	Energy demand	TWh	2.35	Eurostat
	Textile & leather	Energy demand	TWh	2.15	Eurostat
	Not-elsewhere-specified	Energy demand	TWh	3.74	Eurostat
Non-energy demand	Non-energy demand	Feedstock	TWh	18.98	Eurostat[38]

4.1.1.Steel sector

The existing steel production technologies in Belgium are the Blast Furnace – Basic Oxygen Furnace (BF-BOF), which is assumed to be used for high-quality steel, and the electric arc furnace (EAF), used mostly for low-quality steel. The steel sector is generally divided into iron ore pre-treatment, iron reduction, steel production, rolling & casting, auxiliary processes and finishing and forming (this last process represents small and distributed companies at the end of the supply chain). The energy and mass balance for each process was defined from literature reviews, sector reports and the Belgian energy balance available in EUROSTAT. The age of the assets is another important parameter to consider, thus, the technical lifespan of the steel assets is constantly extended by annual investments. On the other hand, after a couple of decades, furnaces could go through an overhauling process as happened in the ArcelorMittal plant in Ghent[47]. In the steel sector, it is important to differentiate between process and combustion emissions. Process emissions are estimated to be around 80% of the total emissions. Moreover, the use of blast furnace gas for the production of electricity is accounted for in the power sector, which reduces the emissions allocated to the steel sector. There are two main paths for the steel sector: hydrogen for the direct reduction of iron (DRI) and CCUS. These strategies are in line with sector associations' roadmaps. For instance, EUROFER estimates that by 2050 the steel sector will consume 400 TWh (seven times the current EU steel industry current demand) for electric processes and hydrogen production[48]. Additionally, steelmaking in Europe will need to reduce around 21 MtCO_2/yr. through CCUS, this value could be higher depending on the availability of electricity and hydrogen[48].

Table 8. Emission reduction options for the steel sector in the TIMES model, grouped by strategy.

Demand/Product	Current process	Fuel replacement	Hydrogen/ Molecules	Electrification	Carbon Capture & Storage/Reuse CCUS
High-quality steel	- Blast Furnace-Blast Oxygen Furnace (BF-BOF)	- Blast Furnace-H_2_injections - Blast Furnace-Plastic use	- Hydrogen - Direct Reduction (DRI) - H_2-based heat (finishing)	- Molten Oxide Electrolysis - Electrowinning	- BF-BOF/ with carbon capture & storage - Natural Gas - DRI/CCUS
Low quality steel	- Electric Arc Furnace (EAF)	- Electric Arc Furnace (Electricity + Biomass)		- Electric Arc Furnace (100% Electricity)	- CCUS

[46] https://www.cepi.org/wp-content/uploads/2021/01/Key-Statistics-2014-FINAL.pdf
[47] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/020121-arcelormittal-confirms-ghent-blast-furnace-b-to-restart-production-by-mid-feb
[48] LOW CARBON ROADMAP (pg. 13), EUROFER, 2019. https://www.eurofer.eu/assets/Uploads/EUROFER-Low-Carbon-Roadmap-Pathways-to-a-CO2-neutral-European-Steel-Industry.pdf

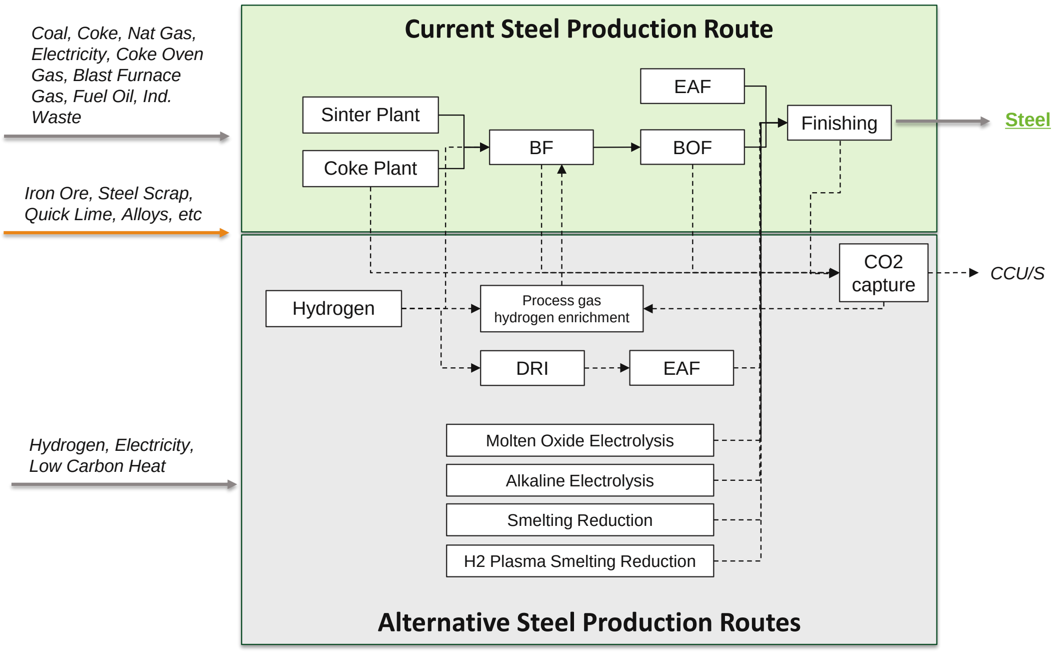

Figure 2. Steel current and alternative production routes in TIMES-BE (simplified).

4.1.2.Chemical sector

The chemical sector is responsible for 39% of the industrial final energy demand and a large part of the non-energy demand (feedstock). In TIMES-BE, the production of seven final products is modelled in detail: ammonia, chlorine, ethylene oxide, ethylene, propylene, C4s and BTX. Together, these products account for 64% of the energy and non-energy demand of the chemical sector. The remaining 36% is modelled as energy consumption.

The model takes into account carbon reduction commitments and the increase in the cost of energy-intensive products, which are two main factors that determine the risk of carbon leakage i.e. industries moving away to other parts of the world with more abundant access to renewables[49]. However, carbon leakage is not part of this study as we explicitly assume industrial production to be present in Belgium by 2050.

Table 9. Emission reduction options for the chemical sector grouped by strategy.

Demand/ Product	Base Technologies	Hydrogen/ Molecules	Electrification	Carbon Capture and Storage/Utilization (CCU/S)
Ammonia	Haber–Bosch (SMR)	- Haber–Bosch (H_2)	n.a.	- Pyrolysis - SMR+CCUS
Chlorine	Membrane cell electrolysis	n.a.	n.a.	n.a.
Ethylene Oxide	Catalyst synthesis	n.a.	n.a.	n.a.
High-Value Chemicals	Naphtha cracker PDH	- Methanol to Olefins (MTO) - Methanol to Aromatics (MTA) - Methanol to Propylene (MTP)	- Electric furnace	- Crackers & CCS
Other chemicals	Energy demand process (machine drive and heat)	- Hydrogen boiler - Hydrogen burner	- Heat pumps - Electric boiler - Electric heaters	

We will now discuss the most important processes in greater detail.

[49] https://climatepolicyinfohub.eu/carbon-leakage-and-industrial-innovation.html

Ammonia

Ammonia production in Belgium is done in two plants. One in Antwerp owned by BASF and another one in Tertre owned by Yara. Both plants are represented in TIMES-BE as one unique Haber-Bosch process coupled with a Steam Methane Reformer (NG/SMR). The options to decarbonize the production of ammonia include the integration of CCUS into the exiting processes –which already includes a CC unit to capture process-related emissions to prevent damaging the catalyst for the ammonia synthesis. This highly pure CO_2 stream is already captured and used in downstream utilizations such as urea production or the food industry. The remaining combustion emissions, which represent 1/3 of the total emissions, can be captured by installing an additional CC unit. This configuration (Natural Gas/Steam methane Reforming + carbon capture) produces the so-called blue hydrogen needed in the Haber-Bosch. A different alternative to grey hydrogen or blue hydrogen is the production of yellow hydrogen –hydrogen produced with grid electricity– both onsite or centralized, or the use of imported green hydrogen. In such cases, there is a need to provide nitrogen for ammonia synthesis using an Air Separation Unit (ASU). Nitrogen is currently obtained from steam methane reforming.

The chemical sector has been working towards making the low-carbon European economy a reality. In 2013, CEFIC already identified the fundamental role that energy efficiency, decarbonizing heat production and CCS will have by 2050, as well as the need to further explore and develop CCU cases [50]. DECHEMA identified the potential of so-called blue hydrogen in the effort to reach 2030 targets, however, they also highlighted the limited availability of CO_2 storage sites by 2030[51].

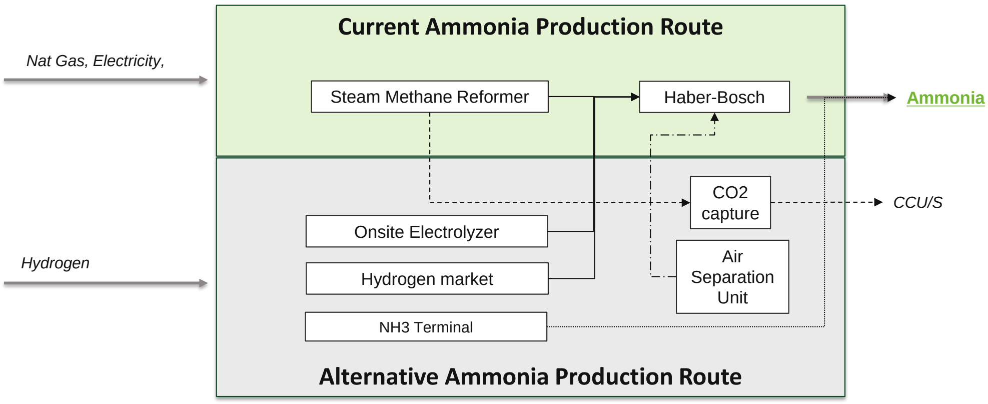

Figure 3. Ammonia current and alternative production routes in TIMES-BE (simplified).

Chlorine

Chlorine production in Belgium is done by INOVYN and Vynova in three different sites. The production is mostly done through membrane cell electrolysis (93%), while the rest is done with mercury cell electrolysis. Being the former the most recent and commonly used route worldwide. This process has already been fully electrified and produces hydrogen as a by-product. Consequently, chlorine production doesn't have direct CO_2 emissions. For this reason, in TIMES-BE chlorine is always produced through the membrane cell electrolysis, and refurbishment of existing assets is considered. The hydrogen that is obtained as a by-product (0.03MtH_2) is assumed to currently be consumed within the industry and, thus, it is not available for new processes such as DRI steelmaking.

High-Value Chemicals

High-Value Chemicals (HVC) cover the production of ethylene, propylene, BTX and C4s. The production of HVC is concentrated in a few production sites (Naphtha crackers and propane dehydrogenation) in the port of Antwerp. Each of these plants has a different design and, then, different yields and energy intensities. In TIMES-BE, the three Naphtha crackers are included as a single process with the weighted average yield and energy intensity of the existing crackers. The combined production capacity of the Naphtha crackers is 2.24Mta (this number is referring to the yearly ethylene production capacity)[52], while the propane dehydrogenation (PDH) has a capacity of 0.55Mta (referring to the yearly propylene production capacity). The cracker was split into the furnace and the cracking part, which allows the model to consider alternatives such as the electrification of the furnace without affecting the cracking step. This has an impact on

[50] https://cefic.org/app/uploads/2019/01/Energy-Roadmap-The-Report-European-chemistry-for-growth_BROCHURE-Energy.pdf
[51] https://dechema.de/dechema_media/Downloads/Positionspapiere/Studie+Ammoniak.pdf
[52] https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/cracker-capacity/

investments, as it is assumed that the cracking step will be operational beyond 2050. Additionally, TIMES-BE considers the export of HVC, similarly to oil products from refineries, as the boundaries of the model don't reach detailed downstream processes and Belgium is part of a complex trading network within Europe. The main emission reduction options for the Naphtha crackers are the electrification of the furnace or the installation of carbon capture units. More disruptive options include the use of methanol as a base molecule for the production of olefins (MTO) and aromatics (MTA), or a two-steps production from natural gas (currently at the lab stage and not included in TIMES-BE) [53]. The production of propylene is partially covered by the steam cracker routes, nonetheless, there are other production routes such as the methanol-to-propylene[54] (MTP) or the installation of a carbon capture unit.

The future envisioned by HVC producers comes with changes in the Naphtha crackers instead of exploring disruptive, but not yet ready, technologies. For example, Project ONE by INEOS, includes the use of hydrogen, partial electrification of the furnace, energy efficiency and CCUS to reach an initial reduction of 67% of CO_2 emissions compared with the average Naphtha cracker[55]. Other important companies in the sector such as BASF, SABIC and Linde announced the construction of a full electrified Naphtha cracker[56]. Therefore, in TIMES-BE, the need for fossil-based feedstock (i.e.: Naphtha, LPG, natural gas) is considered whether furnaces are electrified or CCUS is deployed, this amounts to 80 TWh. A fossil-based feedstock does not necessarily lead to increased emissions, as long as the carbon in the feedstock is contained within the final product and not released as CO_2 in the atmosphere. Nonetheless, the fossil-based feedstock can be replaced by clean molecules routes such as MTO and MTA, or synthetic production of naphtha through Fischer–Tropsch.

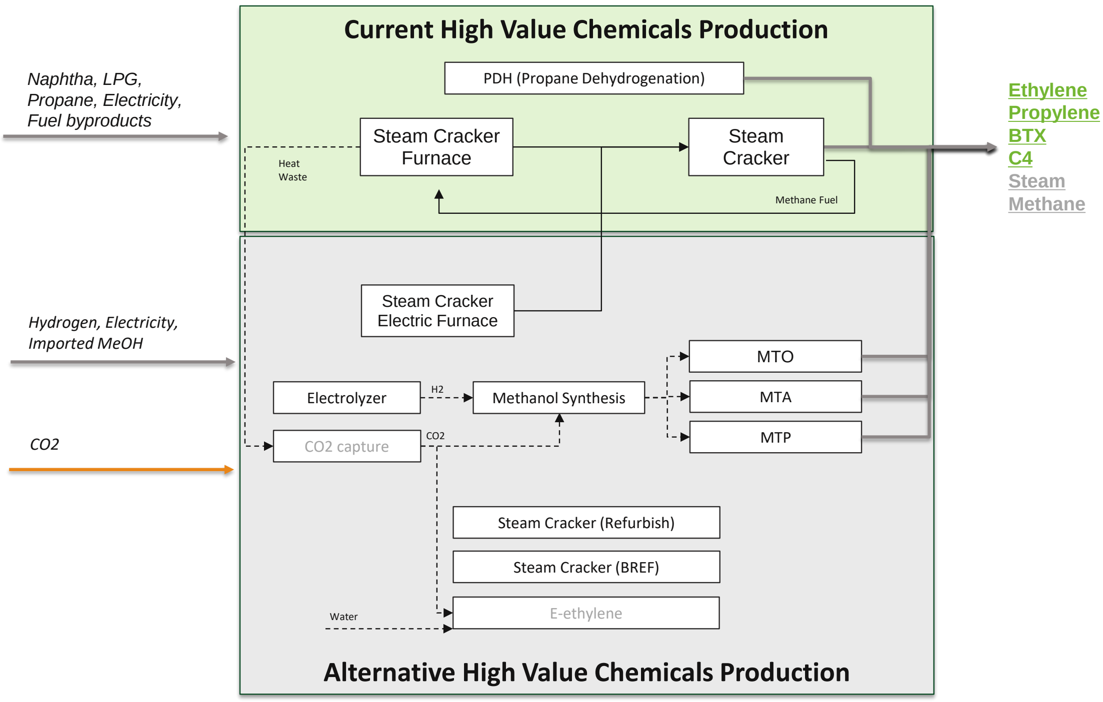

Figure 4. High-Value Chemicals current and alternative production routes in TIMES-BE (simplified).

Ethylene Oxide

Ethylene oxide is produced from ethylene. Thus, there is a strong link between its production and the Naphtha crackers. In fact, in TIMES-BE, part of the ethylene produced in the Naphtha cracker, or any other alternative, goes to the ethylene oxide plant. This process was selected to be modelled in detail due to the high CO_2 concentration in the flue gases, which makes it an attractive case for carbon capture. Additionally, BASF announced to increase in the ethylene oxide production

[53]https://sc.edu/study/colleges_schools/engineering_and_computing/news_events/news/2021/producing_ethylene_environmentally_safe_process.php#:~:text=The%20principal%20method%20of%20producing,degrees%20Celsius%2C%E2%80%9D%20Chen%20says.
[54]https://www.engineering-airliquide.com/lurgi-mtp-methanol-propylene#:~:text=Lurgi%20MTP%E2%84%A2%20%2D%20Methanol%2Dto%2DPropylene%20(MTP),a%20variety%20of%20petrochemical%20processes.
[55]A bridge to a more sustainable future for Antwerp chemicals (Table 1), INEOS, 2021. https://project-one.ineos.com/wp-content/uploads/2021/06/INEO21-033-Position_WP_Project_ONE_21_06_EN_V18.pdf
[56] https://www.basf.com/global/en/who-we-are/sustainability/whats-new/sustainability-news/2022/basf-sabic-and-linde-start-construction-of-the-worlds-first-demonstration-plant-for-large-scale-electrically-heated-steam-cracker-furnaces.html

capacity in Belgium with a new plant of 0.4 Mta[57]. To reduce the emissions of this process, not taking into account upstream emissions, carbon capture technologies are the main alternative. Another way to reduce CO_2 emissions is the use of a supersonic separator that increases the plant yield by recovering feedstock from the waste and by-products within the same production process.

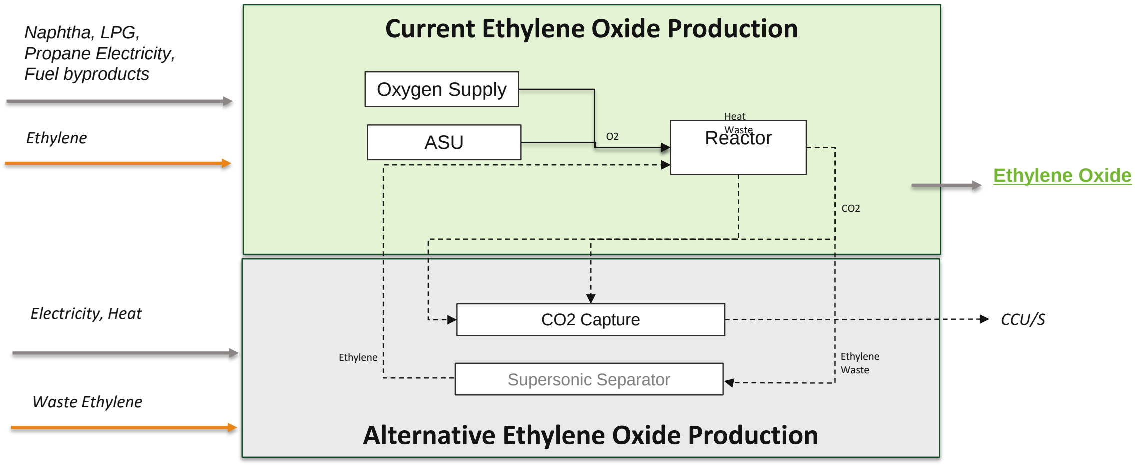

Figure 5. Ethylene oxide current and alternative production routes in TIMES-BE (simplified).

Other Chemical Industries

Finally, the remaining energy consumption of the chemical sector is allocated to Other Chemical Industries. For these chemical processes, there are no detailed data, therefore, it is modelled following a top-down approach. In other words, there is a fixed energy demand which is met by providing high-temperature heat, low-temperature heat, electricity and machine drive. Most of the energy used in Other Chemical Industries is for heating purposes. It is assumed that the heat demand above 400°C in the chemical sector is mostly attributed to the sectors which are explicitly modelled in TIMES-BE (i.e.: ammonia, HVC and ethylene oxide). Nearly 20% of heat demand in the chemical sector is below 100ºC and 30% between 100ºC and 400ºC. To decarbonize the heat demand of Other Chemical Industries, there are several alternatives for low and mid-temperature heat. These alternatives include heat pumps, which for low-temperature are already available[58] and for mid-temperature they are expected to be mature enough in the mid-term by developing hybrid or multistage heat pumps [59-60]. On the other hand, heat demand can be also supplied by hydrogen-based solutions.

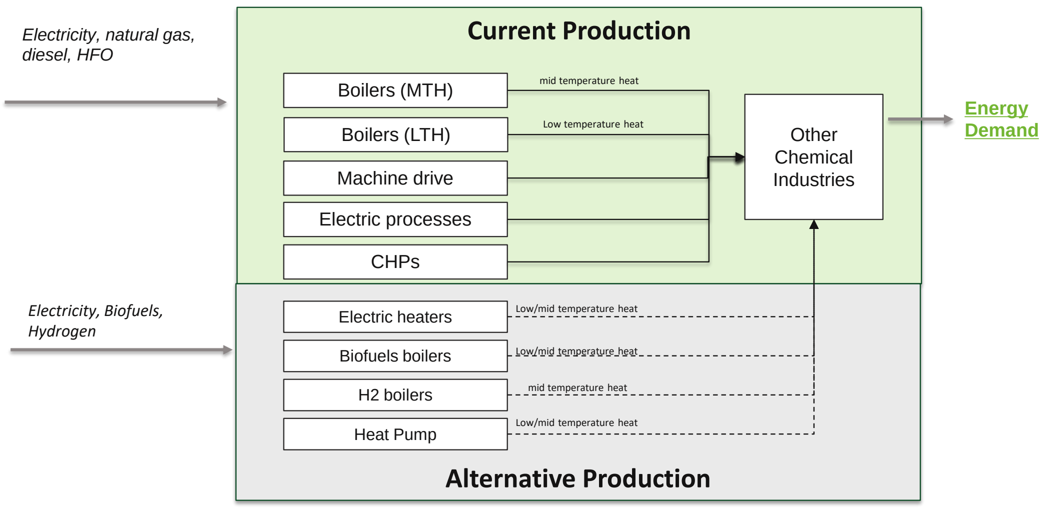

Figure 6. Other Chemical Industries' current and alternative production routes in TIMES-BE (simplified).

[57] https://www.basf.com/global/en/media/news-releases/2019/09/p-19-336.html
[58] https://www.ehpa.org/fileadmin/red/03._Media/03.02_Studies_and_reports/Large_heat_pumps_in_Europe_MDN_II_final4_small.pdf
[59] https://www.enertime.com/en/solutions/heat-pumps
[60] https://www-sciencedirect-com.proxy.library.uu.nl/science/article/pii/S1364032122000351

4.1.3.Non-metallic minerals

Non-metallic minerals include cement, lime, glass, bricks and other non-metallic minerals industries (NMM). The NMM industry accounts today for 13% (15.5 TWh) of the industrial final energy demand and 9.5% (7.9 $MtCO_2$) of total CO_2 emissions in Belgium. Nearly half of the emissions in the sector are non-energy-related process emissions (4.4 $MtCO_2$). In TIMES-BE, the production of four final products is modelled in detail: cement, lime, glass and bricks. The final energy demand that is not included in the production of these products (around 22% or 3.5 TWh) is allocated to other non-metallic mineral industries and modelled as energy consumption.

In TIMES-BE, the production route for these products for the base year, and future alternatives, are modelled separately. In the case of glass and bricks, there is a further differentiation of final products, this is fibreglass, flat and hollow glass, or façade and regular bricks. The technologies considered for reducing emissions in this sector are shown in Table 8. In this section, we further describe the characteristics of the sub-sector and the emission reduction options.

Table 10. Emission reduction options for the non-metallic minerals sector.

	Current Technologies	Fuel replacement	Hydrogen/Molecules	Electrification	CCU/S
Cement	- Kiln, milling, grinding	- Waste and biomass	- H_2 Kiln	- Partial electrification (plasma)	- Calcium looping - Oxy combustion
Bricks	- Drying and furnace	- Synthetic CH_4	- H_2 heaters	- Microwave heaters	- Amine absorption
Glass	- Container, Flat, Fiberglass	- Synthetic CH_4	- H_2-based heat	- 100% electric (flat, hollow) - Electric boosting (Fiberglass)	- Amine absorption
Lime	- Calcination and milling	- Waste and biomass	- H_2 substitution of fuel in Kiln	- Partial electrification (plasma)	- Amine absorption
Other Non-metallics	- Machine drive - Low-temperature heat (LTH) - High-temperature heat (HTH)		- H_2-based high-temperature heat	- Electric tunnel kiln for high-temperature heat - Heat pumps (LTH)	

Cement

The cement sector in Belgium is spread across different regions, while clinker production is concentrated in Wallonia[61]. There are several types of cement based on their production characteristics as well as on their final use. CEMBUREAU defines five types of cement based on the clinker-to-cement ratio[62]. To simplify the cement production, TIMES-BE considers only one type of cement demand, which is produced using blast furnace slag and clinker, with a clinker-to-cement ratio of 0.7, in line with European values[63]. The production of cement in TIMES-BE is modelled in such a way that represents the main steps, namely raw mill, kiln and precalcinator, and cement mill. Today, 70% (3.38 TWh) of the thermal consumption in the sector –almost entirely dedicated to the kiln & precalcinator– is provided by fossil fuels, while the remaining part comes from biofuels and waste. These values are aligned with the European estimated average consumption[64]. However, the increasing share of biomass and waste in the kiln has a limitation to reducing the emission of the cement sector, as roughly 2/3 of the emissions are attributed to the calcination of limestone, these are the so-called process emissions. TIMES-BE was designed to model process and combustion emissions separately, which allows the model to find alternatives to produce the heat needed in the kiln, while for the process emission CCUS options are explored.

For instance, hydrogen has the capacity to reach the high temperature required in the kiln (1400°C), nonetheless, the quality and type of flame are not ideal to dissipate the heat uniformly across the kiln on top of additional technical challenges that might require further research and development[65]. This is considered as an alternative in the model to

[61] https://www.cemnet.com/global-cement-report/country/belgium
[62] https://cembureau.eu/about-our-industry/cement/
[63] https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/
[64] Deep decarbonization of industry: The cement sector (Figure 1, 54% fossil fuels, 30% waste and 16% biomass), European Commission JRC, 2020. https://ee-ip.org/fileadmin/user_upload/IMAGES/Articles/JRC120570_decarbonisation_of_cement__fact_sheet.pdf
[65] https://cembureau.eu/media/uightfs0/16272-narrative-towards-zero-carbon-fuels-for-cement-manufacture_view-cement-sector.pdf

partially replace other fuels in the kiln. The same situation is seen for the use of a plasma torch[66]. In Europe, the cement sector explores several alternatives. For 2030, the CEMBUREAU roadmap considers seeking further energy efficiency gains, increase fuel replacement and clinker substitution. In the same roadmap, towards 2050, the cement sector expects to reduce CO_2 emissions by using decarbonated raw materials, increasing the use of biofuels and using H_2 and electricity in the kiln[67].

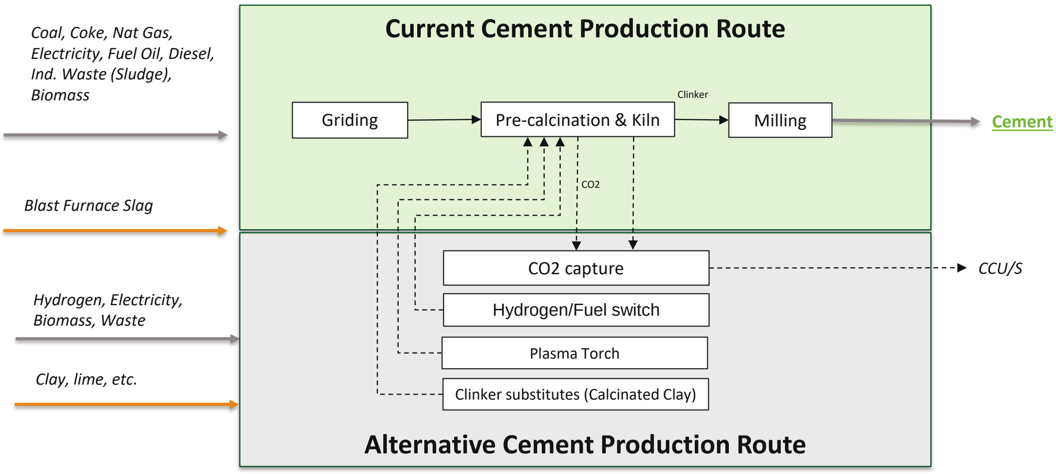

Figure 7. Cement current and alternative production routes in TIMES-BE (simplified).

Lime

Lime production has a similar structure as the production of cement. The raw material is crushed and then calcinated (1400°C) to produce quicklime. In the final hydration steps, hydrated quicklime and limewater are produced. Limestone is used in several applications, from steel to construction and agriculture. The calcination of limestone ($CaCO_3$) to produce lime (CaO) results in unavoidable process emissions, which account for 1/3 of the lime production emissions. The remaining emissions ae due to the combustion of fuels needed to produce the high-temperature heat required by the process, which currently relies 90% on fossil fuels[68]. In TIMES-BE, the production of lime is represented in a two-step process. First, the raw material is calcinated -this process consumes all the heat- and then the finishing part, which consumes only electricity. In the model, the production of lime in the current case requires nearly 5 GJ/t_{lime} and emits around 1.2 tCO_2/t_{lime}. In TIMES-BE, the sector has the option to be decarbonised by including the use of hydrogen and electricity in the kiln, for the combustion emissions, and using carbon capture for the process emissions. For instance, recently the lime sector has joined efforts with the chemical sector to test the use of CCUS technologies [69].

[66] https://www.e-asct.org/journal/view.html?uid=1837&vmd=Full
[67] Activity report (pg. 6-7) , Cembureau, 2020. https://cembureau.eu/media/m2ugw54y/cembureau-2020-activity-report.pdf
[68] A Competitive and Efficient Lime Industry (pg.11), EULA .https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Summary_0.pdf
[69] https://www.airliquide.com/group/press-releases-news/2022-05-09/air-liquide-and-lhoist-join-forces-launch-first-its-kind-decarbonization-project-lime-production

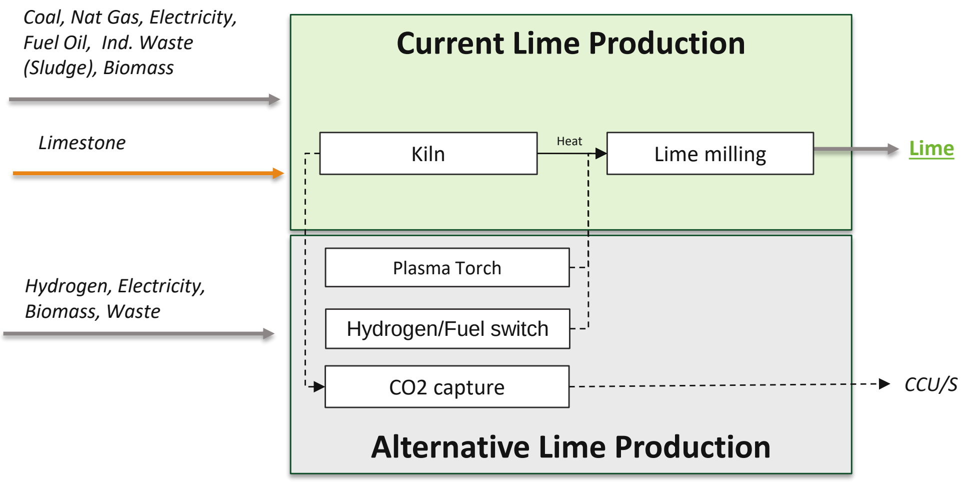

Figure 8. Lime current and alternative production routes in TIMES-BE (simplified).

Glass

There are three main glass products which different energy intensities and process-related emissions: fibreglass, container glass and flat glass. Container glass is used in several applications, from beverages and food packing to perfumes and pharmaceutics and the recycling rate is high. The European container glass federation estimates a recycling rate higher than 90% in Belgium[70]. Therefore, there is a high use of cullet to produce glass, which leads to less energy consumption and process emissions as less raw material (carbonates) are used in the production. In TIMES-BE, container glass has a specific energy consumption of 6.4 GJ/t.

Flat glass supposes a similar process as container glass although the last steps are different, especially in forming and cooling. These particular differences increase the specific energy consumption with respect to container glass by 15-50%[71], depending on the technology. In TIMES-BE the energy intensity of flat glass is set at 8.5 GJ/t. Finally, fibreglass is a more complicated process as it requires more energy for the special fibre forming required to produce fibre yarns or mats, with a total energy consumption of 11.5 GJ/t. Additionally, since it is a more sensitive product, the process cannot be fully electrified due to technical limitations[72] .

In TIMES these three processes are characterized as a single process with reflects the energy intensity of each one as well as the energy mix, which is currently dominated by natural gas. Similar to other sectors where process emissions are relevant, TIMES-BE differentiates process emissions from combustion emissions. This allows the model to explore decarbonization options for heat demand such as electric boosting or the use of clean molecules, while for the process emissions the sector relies more on novel material mixes or CCUS.

Besides the benefits of the use of better glass (i.e.: building glazing, Building Integrated Photo Voltaic), Glass for Europe identified three routes to reduce CO_2 emissions, starting from flat glass recycling (-7%) and switching to carbon-neutral powered furnaces (up to -75%) and CCUS (up to -85%)[73]. Another case is found in Germany, where the glass industry is exploring the use of hydrogen to replace the use of natural gas in furnaces through the HyGlass project[74]. Thus, considering the options identified by the glass industry, TIMES-BE covers these decarbonization strategies for each glass product.

[70] https://feve.org/glass_recycling_stats_2018/
[71] Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry (Table 7), Ernst Worrell et al, 2008. https://www.osti.gov/biblio/927883
[72] Decarbonisation Options For The Dutch Glass Fibre Industry (pg. 17), TNO, 2019. https://www.pbl.nl/sites/default/files/downloads/pbl-2019-decarbonisation-options-for-the-dutch-glass-fibre-industry_3721.pdf
[73] Flat glass in climate-neutral Europe (pf.20-21), Glass for Europe, 2020. https://glassforeurope.com/wp-content/uploads/2020/01/flat-glass-climate-neutral-europe.pdf
[74] https://www.bvglas.de/en/dekarbonisierung/hyglass-wasserstoffeinsatz-in-der-glasindustrie/

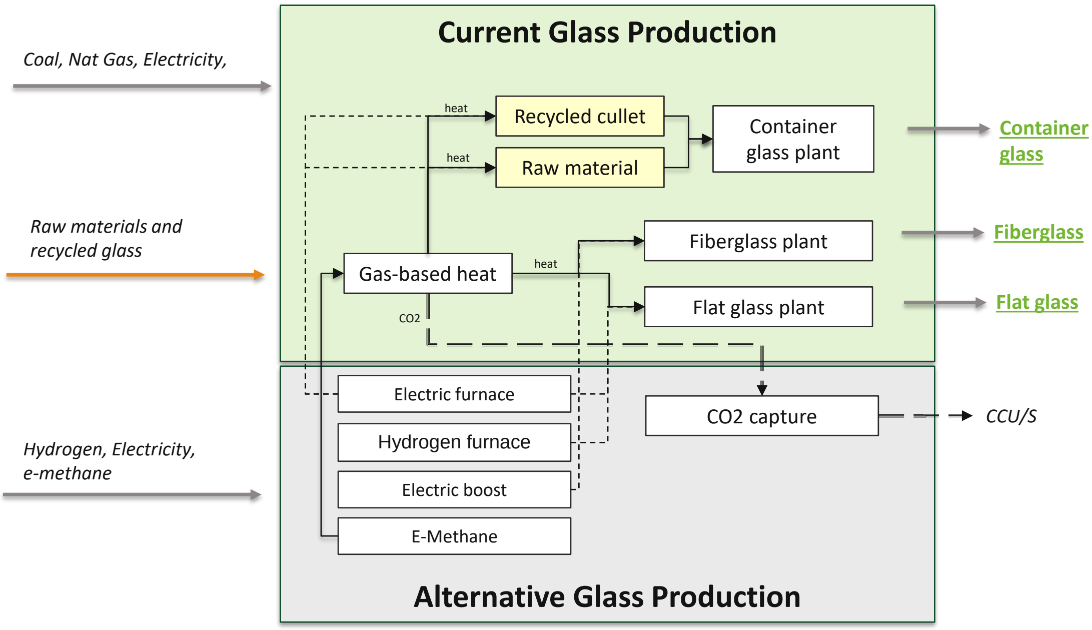

Figure 9. Glass current and alternative production routes in TIMES-BE (simplified).

Bricks

Bricks are an important material in construction, and with an increasing population, the need for this material is not expected to fall. Nonetheless, it is possible that in the future, when a circular economy takes place, the reuse of bricks might have an impact on local production. This is not covered in TIMES-BE, and the assumption of constant industrial activity still holds. We differentiate between regular and façade bricks, each of them has a different energy intensity as façade bricks require more energy due to quality and finishing. In TIMES-BE, façade bricks have a specific energy intensity (SEC) of 2.95 GJ/t, while the SEC of regular bricks is 2.4 GJ/t. These values are in line with other reports [75-76]. The production of bricks is divided in TIMES-BE to reflect the two levels of temperature that are used. Firstly, the clay must be prepared and dried, which usually requires temperatures of 75-90°C (low-temperature heat). Secondly, once ready and shaped, bricks go to the furnace where continuous firing takes place at 1000-1300°C (high-temperature heat). Then, the bricks are finished and packed. Process emissions in the production of bricks come from the chemical reactions of carbonates which depend on the mix of raw materials. These bricks process-related emissions are approximately 0.05-0.07tCO_2/t[77], which accounts for nearly 27% of the total emissions from brick production.

The division of temperature levels allows us to provide alternatives for low-temperature heat such as industrial heat pumps. In the case of high-temperature production alternatives for the firing, TIMES-BE includes hydrogen, electricity (i.e.: heaters and microwaves) and green methane solutions. If one of these solutions were implemented, the sector would reach maximum decarbonization of 73%, as the remaining emissions are process related. Hence, the deployment of CCUS technologies is necessary to reach higher emission reduction targets. Certainly, this is true as the European Ceramic Industry Association aims to reach climate neutrality by 2050 by fuel switching (i.e.: hydrogen, biofuels and electricity), increasing efficiency in the manufacturing process, CCUS, reducing carbon-containing additives, reducing the carbon content of clay mixes and using carbon removal and offsetting measures[78].

[75] BRICK Sustainability Report (pg. 8), BRICK, 2016. https://www.brick.org.uk/admin/resources/brick-sustainability-report-2016-1.pdf
[76] Brick by brick (Table 1), SDC et al, .https://www.shareweb.ch/site/EI/Documents/PSD/Topics/Social%20Aspects%20of%20Work/Brick%20by%20Brick%20-%20The%20Herculean%20Task%20of%20Cleaning%20up%20the%20Asian%20Brick%20Industry.pdf
[77] Decarbonization Options For The Dutch Ceramic Industry (Figure 8), TNO, 2019. https://www.pbl.nl/sites/default/files/downloads/pbl-2020-decarbonisation-options-for-the-dutch-ceramic-industry_4544.pdf
[78] Ceramic roadmap to 2050 (pg. 31-33), Cerame-Un,2012. ihttps://cerameunie.eu/media/ambd23os/ceramic-roadmap-to-2050.pdf

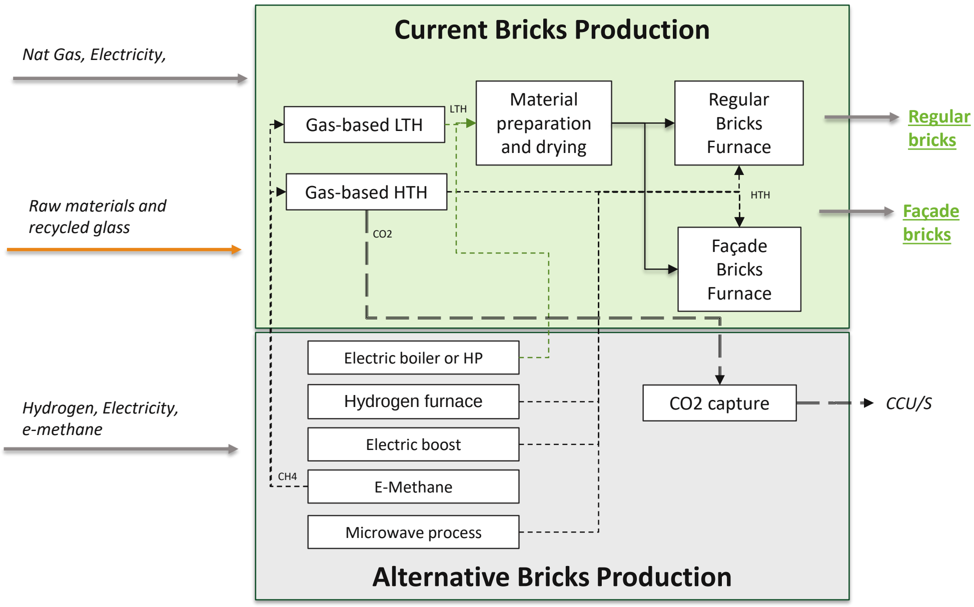

Figure 10. Bricks current and alternative production routes in TIMES-BE (simplified).

Other Non-metallic minerals industries

The remaining energy consumption of non-metallic minerals is represented in Other Non-Metallic Mineral Industries. These industries are not modelled in detail, as data are scarcely available. Therefore, this part of the industry is modelled by fixing a given energy demand (see Table 7) which is met by providing machine drive and high-temperature heat. Most of the energy used in Other Non-Metallic Minerals Industries is used to produce high-temperature heat. To decarbonize the heat demand of this sector, there are several alternatives which include clean molecules and electric furnaces.

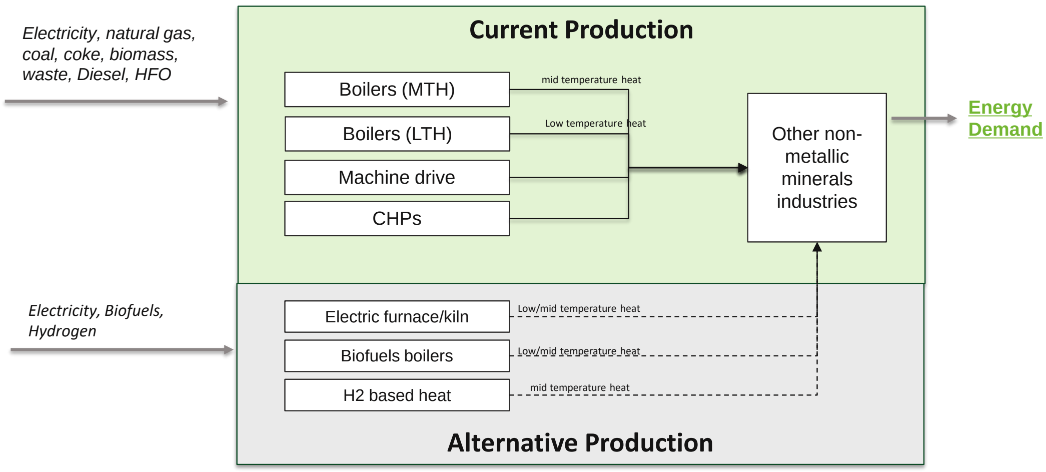

Figure 11. Other Non-Metallic Minerals Industries' current and alternative production routes in TIMES-BE (simplified).

4.1.4. Non-ferrous metals

Non-ferrous metals include copper, zinc and Other Non-Ferrous Metals industries (NFM). This sector is responsible for 2.8% (3.4 TWh) of the industrial final energy demand and 0.6 $MtCO_2$. A large part of emissions is related to the combustion of fuels. In TIMES-BE, the production of copper and zinc require 0.8 TWh and 1.1 TWh respectively. The final energy demand which is not included in the production of these products (1.5 TWh) is allocated to Other Non-Ferrous Metals industries and modelled as energy consumption. In TIMES-BE, the production route for these products can be replaced by future alternatives, which are modelled separately as can be seen in. In this section, we describe the structure of the sector as well as the decarbonization strategies and their possible implications.

Table 11. Emission reduction options for the non-ferrous metals sector by decarbonization strategy.

	Current Technologies	Fuel replacement	Hydrogen/Molecules	Electrification	CCU/S
Copper	- Copper electrolytic refining (anode furnace)		- H_2 anode furnace		
Zink	- Purification/Melting/Casting	- Biogas burners		- Electric burners	- Amine absorption
Other Non-Ferrous	- Energy demand (High/Low-Temperature Heat, machine drive)	- Biogas burners	- H_2-based heaters for high and low-temperature heat	- Electric heaters for high and low-temperature heat	

Copper

The production of refined copper is done through the hydrometallurgy process which takes copper oxide ore through leaching and solvent extraction prior to the main process. The main step in the copper hydrometallurgy process is electrowinning, where an electric current is applied to dissolve the copper from the anode onto the cathode as pure copper metal. Additionally, copper scrap and concentrated copper are used in the smelting process, before the fire and electrolytic refining. As the production of copper has a clear differentiation between thermal and electric-driven processes, in TIMES-BE this is modelled in two processes –one consuming mostly electricity and one consuming heat. The entire process has a specific energy consumption of 7.9 GJ/t of copper[79], of which is 54% covered with electricity. In TIMES-BE, hydrogen can produce the process heat required but also as a reducing agent. Hydrogen used as a reducing agent to replace natural gas will increase the energy demand for the reduction by 20.5%[80]. The use of hydrogen for the production of copper anodes is being already investigated in a pilot project by Aurubis in Hamburg, Germany[81].

Zinc

Zinc production in Belgium is done using the electrolysis smelting route. This process consists of roasting, leaching, electrolysis, melting and casting. This process replaced the imperial smelting process based on fossil fuels (i.e.: coke, natural gas). In TIMES-BE, the production of zinc has a specific energy consumption of 15.5 GJ/t of zinc. This process is divided into three steps. Roasting and leaching consume 9% (1.4 GJ/t_{zinc}), where several chemical reactions take place at 400-900ºC. Then, the purification and electrolysis of leach liquor consume 76% (11.8 GJ/t_{zinc}) to produce pure zinc which is finally melted and cast as a final product. As the production of zing has been highly electrified, the emission reduction options in TIMES-BE are focused on the heat used in the roasting and melting steps by replacing natural gas with clean molecules or biogas. Nevertheless, as nearly 66% of the direct CO_2 emissions are related to the carbon embodied in the zinc concentrates, CCUS technologies are needed to reach high emission reduction levels, which poses a big challenge as the CO_2 concentration is the flue gasses is very low. On the other hand, zinc plants have an excess of heat, which might be used in carbon capture units.

Other Non-ferrous metals industries

The energy that is not consumed by the production of copper and zinc is allocated to Other Non-Ferrous metal industries. This represents 44% (1.5 TWh) of the total consumption reported for the sector in the Belgian energy balance. 62% (0.9 TWh) of the energy consumed in the sub-sector comes from natural gas, 33% (0.5 TWh) from electricity (i.e.: machine drive) and the remaining 5% from other fossil fuels. As most of the final energy consumption can be assumed to be used for the production of heat and considering that around 55% and 35% are for high-temperature and low-temperature heat

[79] In line with Energy efficient copper electrowinning and direct deposition on carbon nanotube film from industrial wastewaters, Pyry-MikkoHannula et al.,2019. https://doi.org/10.1016/j.jclepro.2018.10.097
[80] Decarbonizing copper production by power-to-hydrogen: A techno-economic analysis, Röben et al., 2021. https://doi.org/10.1016/j.jclepro.2021.127191
[81] https://www.aurubis.com/en/media/press-releases/press-releases-2021/aurubis-first-copper-anodes-produced-with-hydrogen

respectively, the emission reduction options cover electrification, biofuels and clean molecules. As the industry works with metallic products, it is expected that the heat gets in contact with the product, therefore, heat pumps are not considered for this sub-sector. Instead, electric furnaces and heaters might be used in the sector.

4.1.5. Food and beverages

The food and beverage industry in Belgium is distributed across the country with some differences between Flanders and Wallonia due to the main products in both regions. Thus, in TIMES-BE, to represent the national food industry, which is responsible for 16% (19.1 TWh) of the final energy consumption in the industry, we divided it into Flanders and Wallonia food industries by making use of the regional energy balances. As such, Flanders accounts for 66% (12.6 TWh) of the energy consumption in the sector while Wallonia for the remaining 34% (6.5 TWh). Around 20% of the energy consumed in the sector is currently by CHPs, which produce part of the heat that is consumed by the sector.

The food sector, then, is characterized by electricity (38%) and heat (62%) demand, which remain constant throughout the modelling period. Moreover, the available biomass as a by-product of the sector is also represented, which is mostly consumed onsite to generate heat and is not traded with other sectors. Almost 60% of the heat demand in the sector is below 100°C[82], which makes it a good candidate to deploy heat pumps. Nonetheless, to decarbonize heat above 200°C other alternatives such as electric heaters or hydrogen boilers might be used.

4.1.6. Pulp and paper

The paper industry is the fifth most energy-intensive industry in Belgium, accounting for 6.5% (8.1 TWh) of the final energy demand in the industry. Paper is used in many different ways in society, from printing, and graphics to packaging and case material. The type, or quality, of paper, can be classified based on its final use, however, in TIMES-BE, the paper is classified according to the type of pulp used to produce it. There are mainly three types of pulp, namely the mechanical pulp, chemical pulp and recovered pulp[83]. Thus, in TIMES-BE, each production route is composed of two steps, pulp production and paper machine, with a total average specific energy consumption of 16 GJ/t of paper. The average specific energy consumption of the sector is reduced since the production of recycled paper requires almost half of the energy of mechanical and chemical pulp, and recycled paper represents almost 1/3 of the paper production in Belgium[84].

In the first step, the raw material (i.e.: wood, recycled paper) goes into pulp production, where electricity and heat are used to produce the different types of pulp. In this step, nearly 48% of the specific energy consumption is used. At this point, approximately 6 TWh of black liquor are produced as a by-product, which are consumed internally in the production of heat and electricity. Then, in the second step paper is produced by removing the water content and drying the final product using steam-heated drying cylinders.

As paper production requires temperatures between 60°C and 170°C[85], heat pumps will most likely be able to cover the heating demand.

4.1.7. Other industries, not elsewhere specified energy consumption and non-energy demand

Other industries include transport equipment, machinery, mining & quarrying, wood & wood products, construction, textile & leather and not elsewhere specified. These industries account for 13.7% (17.1 TWh) of the final energy consumption in the industry, therefore, they are modelled using a top-down approach. This is, in TIMES-BE, the total energy demand of the sector is given by the historical energy demand. However, from the final energy consumption, we estimate the heat demand, which is linked to the consumption of fossil fuels, biomass and the CHPs linked to these sectors. Thus, by differentiating the heat demand, TIMES-BE can select the most convenient technology to meet heat demand. Additionally, only in construction and not-elsewhere specified, the consumption of diesel is assigned to the off-road application. The final energy mix for each sub-sector of other industries can be seen in Figure 12.

---

[82] Residential Heat Supply by Waste-Heat Re-Use: Sources, Supply Potential and Demand Coverage—A Case Study (Figure 1), Wolfgang et al., 2017. https://www.mdpi.com/2071-1050/9/2/250

[83] Product Classification And Its Implication On Competitiveness And Carbon Leakage (Figure 1), Climate Strategies, 2011.https://climatestrategies.org/wp-content/uploads/2014/11/pulp-paper-and-paperboard-report-cs-final-with-executive-summary.pdf

[84] Annual statistics (pg. 4), COBELPA, 2014. http://www.cobelpa.be/pdf/stats2014.pdf

[85] Potential of Solar Energy Utilization for Process Heating in Paper Industry in India: A Preliminary Assessment (Table 2), Ashish K.Sharma et al., 2015.https://doi.org/10.1016/j.egypro.2015.11.486

The emission reduction strategies for these industries seek to replace the use of fossil fuels to produce heat by introducing electrification options (i.e.: heat pumps, electric boilers) and the use of clean molecules (i.e.: hydrogen, e-methane) as the heat required is mostly below 100ºC (on average 60%), and approximately 10% at 100-400ºC. For off-road applications, the use of biofuels and synthetic fuels is available in the model.

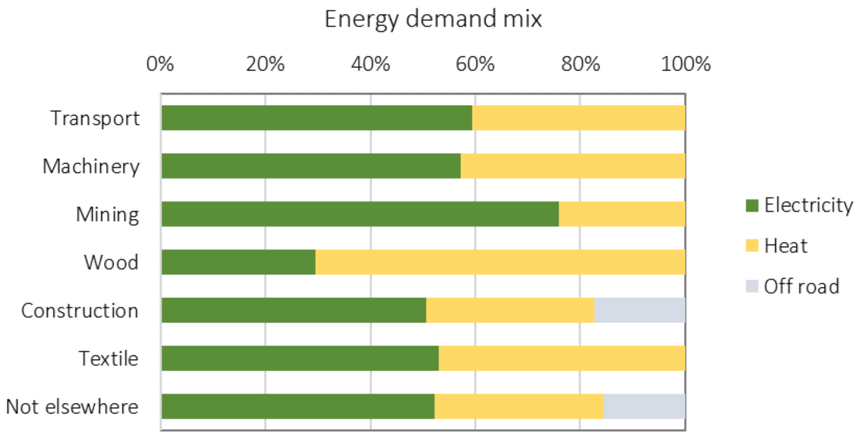

Figure 12. Energy demand mix for other industries in TIMES-BE.

Finally, the remaining non-energy demand that is not represented by the feedstock consumption of the industry is allocated to one single process that consumes 18.9 TWh, split into coal tar (2.9 TWh) and other oil products (16 TWh) such as lubricants, bitumen and other oil products reported in Eurostat energy balance. This non-energy consumption is not included in the feedstock of the chemical sector, and is, as in other cases, assumed to remain stable towards 2050.

4.2. Transport

During the COVID-19 pandemic in 2020, the consumption of the sector fell as passenger mobility was restricted and economic activity was reduced. In 2019, the domestic transport sector in Belgium consumed 27% (103TWh) of the total final energy demand. During the same period, the sector was responsible for 25.9 $MtCO_2$, being one of the sectors with the highest GHG emissions, only surpassed by industry. In 2019, the emissions were 24% higher than in 1990[29]. As roughly one-third of emissions in Belgium are in the transport sector, especially linked to diesel consumption, and considering that Belgium is one of the most road-dense regions in Europe[86], which is associated with economic activity (i.e. Antwerp and Ghent ports), the sector faces an enormous challenge to reduce GHG emissions. Since the main decarbonization options for the sector are electricity or hydrogen, it is expected that the power sector will be heavily impacted by such transformation.

The transport sector embeds all the national and international transport, both passenger and freight. However, international transport emissions are not accounted for in the Belgian GHG inventory and, therefore, are not part of the national emissions in TIMES-BE. The structure resembles the Eurostat energy balance, with different subsectors (i.e.: rail, domestic aviation, inland navigation and road). In the BE TIMES model, road transport is split into passenger cars, buses, freight and motorcycles. Within passenger cars, four categories are defined based on driving habits (Commuting/Non-Commuting, Long and Short distance). To represent the distribution of charging facilities for EVs between charging at home and charging in public spaces such as parking places, in TIMES-BE, passenger cars have the option to use chargers in the residential sector and chargers in the commercial sector as part of the optimization (see Figure 13).
In TIMES-BE, road and rail transport are defined with a non-energy demand (Billion passenger-km). The emission reduction alternatives, by drivetrain, that are included in TIMES-BE to reduce CO_2 emissions in each category of the transport sector can be seen in Figure 14.

[86] https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200528-1

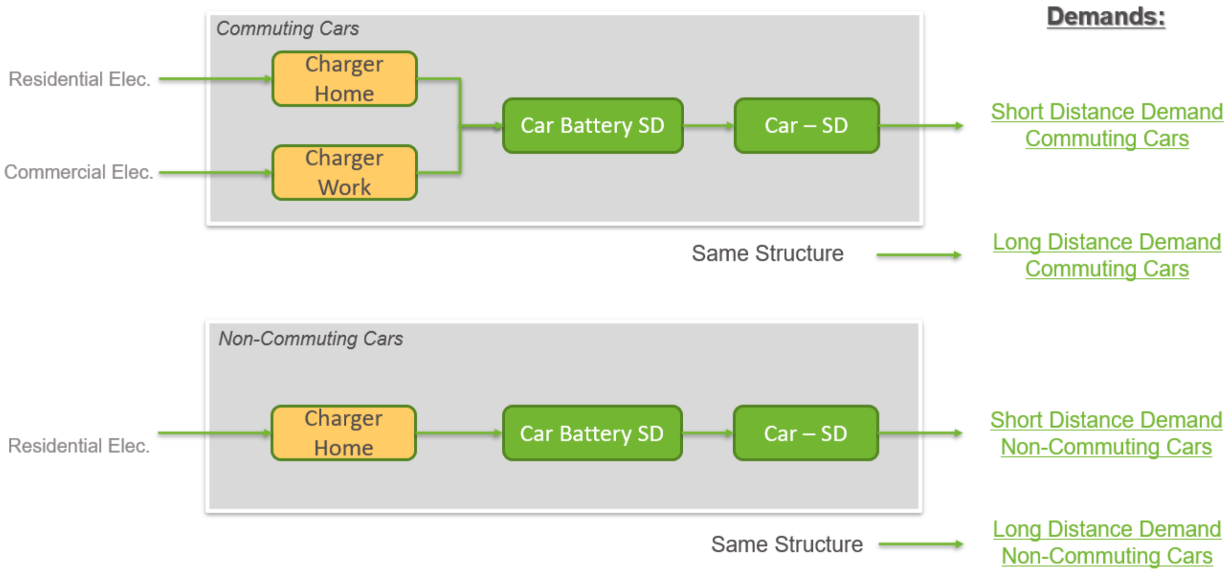

Figure 13. Scheme of charging options for passenger EVs in TIMES-BE.

The demand for road transport has been built in two ways. For passenger cars, an hourly demand profile was created for the four different categories. Instead, when it comes to buses (both urban and intercity), trucks and motorcycles demand is defined at the annual level. Demand projections for 2050 have been taken from TML's TREMOVE model, which foresees a demand increase for all passenger cars, buses and motorcycles of around 11-14%, and nearly 29% for trucks.

Table 12. Demand projection for the transport sector by category in TIMES-BE.

Subsector	Category	Unit	2020	2030	2040	2050
Aviation	International aviation	TWh	17.23	18.61	19.81	21.00
	Domestic aviation	TWh	0.05	0.05	0.06	0.06
Navigation	Inland navigation	TWh	2.13	2.33	2.45	2.58
	International bunkers	TWh	74.17	81.11	85.40	89.69
Road	Bus - Coach/Intercity	$Pkm*10^9$	3.71	3.87	3.97	4.06
	Bus urban	$Pkm*10^9$	14.80	15.34	15.64	15.94
	Commuting Car - Long Distance	$Pkm*10^9$	52.01	53.85	55.06	55.67
	Commuting Car - Short Distance	$Pkm*10^9$	13.00	13.46	13.76	13.92
	Freight	$Tkm*10^9$	33.47	36.07	38.51	40.94
	Motorcycles	$Pkm*10^9$	1.41	1.67	1.97	2.27
	Non-Commuting Car - Long Distance	$Pkm*10^9$	40.87	42.31	43.26	43.74
	Non-Commuting Car - Short Distance	$Pkm*10^9$	10.22	10.58	10.82	10.94
Rail	Rail Freight	$Tkm*10^9$	8.89	10.77	12.38	13.99
	Passengers Light	$Pkm*10^9$	1.13	1.22	1.28	1.34
	Passengers Heavy	$Pkm*10^9$	10.75	11.13	11.47	11.81

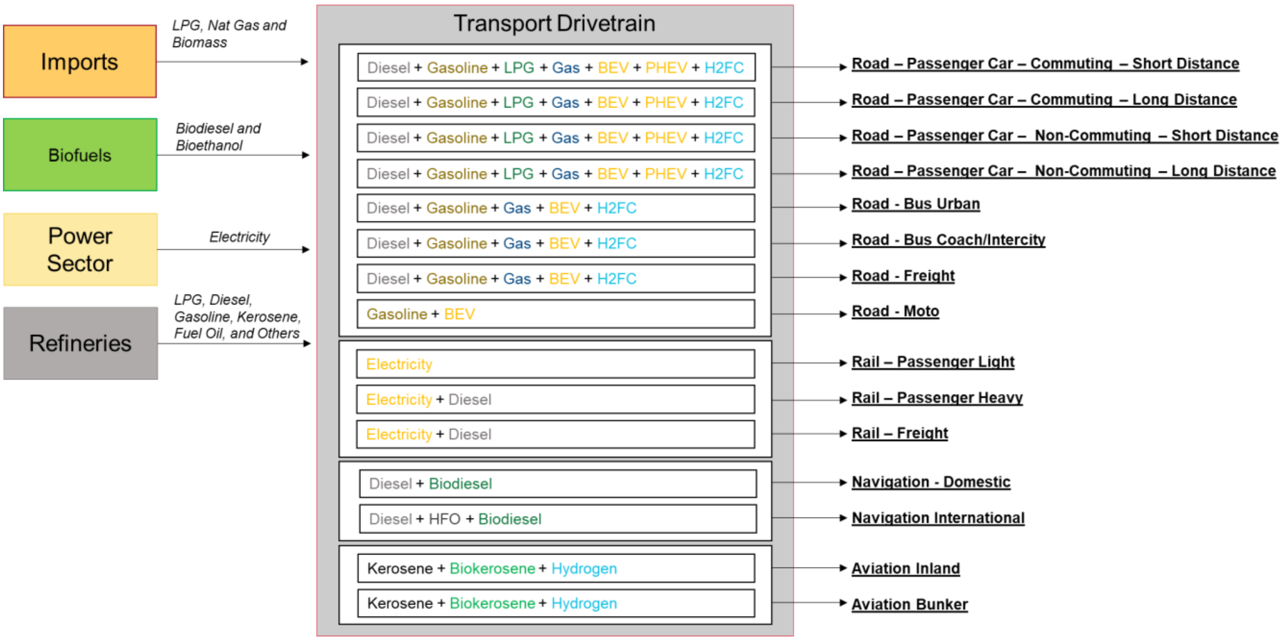

Figure 14. Decarbonization options for the transport sector by drivetrain in TIMES-BE.

4.3. Residential

The residential sector in Belgium accounts for 24.1% (91.4 TWh) of the final energy consumption. Most of the demand of the sector is met with natural gas 41.3% (37.8 TWh), Diesel 26.9% (24.6 TWh) and electricity 20.1% (18.4 TWh)[87]. This strong dependency on fossil fuels (nearly 78%) results in 16 MtCO_2 emissions, which is 19.4% of total CO_2 emissions[88]. Therefore, decarbonizing the residential sector is fundamental for reaching deep decarbonization of the economy. This is why the European Commission is promoting and emphasising the need for renovation and higher energy standards for new buildings, as well as moving away from fossil-based technologies such as gas or liquid fossil fuels boilers since 80% of the energy consumed in buildings in Europe is used for heating, cooling and domestic hot water[89].

In TIMES-BE, the residential sector has nine service demands: space heating, space cooling, water heating, lighting, cooking, refrigeration, cloth washing/drying, dishwashing and other electric. Additionally, some service demands are further divided into more categories depending on the age of the building[90] (Existing: built before 2006, Intermediate: built between 2006 and 2014, and New: built from 2015 onwards), and the type of household[91] (i.e.: Urban, Rural and Multifamily house). These subdivisions generate a total of nine categories for space heating, space cooling and water heating. Therefore, TIMES-BE has a total of 34 final service demands for the residential sector. Demands of the residential sector are shown in Table 13, which are driven by population growth[7]. In TIMES-BE, renovation and insulation are incorporated to simulate the decrease in energy consumption due to the renovation of the building stock, and due to an increase in insulation level. Thus, for existing and intermediate buildings the model can invest in technologies representing roof, wall and glass insulation. There are three technologies for each insulation option to represent the difference in cost and insulation level that can be implemented. Table 14 shows the energy savings that can be obtained from better insulation in existing houses in Belgium, which are differentiated by the investment needed. Thus, the average house might be able to annually save on average 6-14% (0.6-1.3 MWh) of the energy used in space heating in existing houses with insulation. Here, it is important to mention that the stock of existing houses declines over time and new, and more efficient, houses are built. These new houses are not subject to renovation measures in TIMES-BE.

[87] Eurostat energy balance 2019.
[88] https://climat.be/doc/nir-2021-150421.pdf
[89] https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6683
[90] Based on the EPC databank. https://documentserver.uhasselt.be/handle/1942/18940
[91] Based on Statbel data on buildings. http://statbel.fgov.be/nl/statistieken/cijfers/economie/bouw_industrie/gebouwenpark/

Table 13. Demand projection for the residential sector by service end demand in TIMES-BE.

End demand	Current energy mix	Current demand [TWh]	2030 demand [TWh]	2040 demand [TWh]	2050 demand [TWh]	Driver
Space heating[92]	Biomass (8%), Coal (2%), Electricity (4%), Natural Gas (45%), Diesel (38%)	36.53	41.64	42.06	44.39	Population growth, according to Federal Planning Bureau projections[93]. Adjusted by future temperature, and warm and cold days.
Space cooling	Electricity (100%)	0.31	0.48	0.53	0.64	
Water heating	Biomass (5%), Electricity (15%), Natural Gas (46%), Diesel (38%)	8.86	8.86	8.69	8.86	
Lighting	Electricity (100%)	2.08	2.19	2.28	2.33	Population growth, according to Federal Planning Bureau projections
Cooking	Biomass (1%), Electricity (38%), Natural Gas (50%), LPG (11%)	3.64	3.89	4.03	4.11	
Refrigeration	Electricity (100%)	3.97	4.22	4.36	4.47	
Cloth washing	Electricity (100%)	0.78	0.83	0.86	0.89	
Cloth drying	Electricity (100%)	1.19	1.19	1.19	1.19	
Dishwashing	Electricity (100%)	0.47	0.50	0.53	0.56	
Other electric	Electricity (100%)	5.47	5.83	6.03	6.19	

The residential sector has a clearly defined hourly electricity demand profile that reflects behaviour patterns and weather conditions. This is also the case for the consumption of natural gas, which accounts for nearly 40% of the total final energy consumption of the sector. Therefore, we defined hourly profiles for all service demands of the residential sector which were developed as part of the BREGILAB[94] project using the proportional input-output (or RAS) methodology[95].

Table 14. Space heating energy savings from insulation in residential sector existing houses in TIMES-BE.

	Unit	2014	2016	2020	2025	2030	2035	2040	2045	2050
Maximum	TWh	9.48	9.48	9.24	9.00	8.76	8.52	8.28	8.04	7.79
Average	TWh	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
Minimum	TWh	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19

In addition to many fossil fuels-based processes, such as gas-fired boilers, gas stoves and gas-fuelled heat pumps, the other possible processes available in the model are:

- Wood-pellet boiler
- Electric radiator
- Electric boiler
- Air heat pump (both with and without heating/cooling option)
- The advanced air heat pump (both with and without heating/cooling option)
- The ground heat pump (both with and without heating/cooling option)
- District heating (DH) heat exchanger
- Solar collector (with electric, gas and diesel backup)
- Biomass boiler
- Solar collector with electric/gas/oil backup
- Electric cooking stoves.

Finally, other service end-demands that are fully electrified such as lighting, space cooling and refrigeration have the option to invest in more efficient technologies to reduce the total final energy consumption of the sector. The introduction of highly efficient heat pumps lowers the overall energy consumption but can increase the peak electricity consumption. TIMES-BE has several options to cope with such peaks as can be seen in section *5.1*.

92 Space heating, space cooling and water heating demands refer to the end use. The final energy consumption to meet these demands reflects the efficiency of the technology used to this end.
93 https://www.plan.be/databases/data-36-en-energy_outlook_for_belgium_towards_2050_october_2017_edition_statistical_annex
94 https://www.energyville.be/en/research/bregilab-support-research-development-renewable-energy-belgian-electricity-grid
95 BACHARACH, Michael: (1970) Biproportional Matrices and Input-Output Change. Cambridge University Press, Cambridge

4.4. Commercial

Similar to the residential sector, the current energy consumption of the commercial & public services sector is dominated by electricity and natural gas, 40% (21.6 TWh) and 41% (22.1 TWh) respectively. Diesel accounts for 15% (7.9 TWh), which is used for diesel engine generators and boilers. As such, the effort to reduce direct CO_2 emissions in this sector must be directed to replace fossil fuels used for space and water heating, and reduce the reliance on diesel engine generators as back up of electricity supply and movable uses (i.e.: cultural and music festivals far from the distribution grid). Additionally, energy efficiency measures can reduce the electricity intensity of the sector and then the impact on the power sector.

The commercial sector in TIMES-BE is subdivided, similarly to the residential sector, into eight energy service demand categories: space heating, space cooling, water heating, cooking, lighting, refrigeration, public lighting and other electric applications. To differentiate the heat needs based on the characteristic of buildings, space heating and cooling and water heating are then characterized per type of building, depending on the size of the building (small and large). In total, therefore, there are eleven final energy service demands for this sector. The hourly profiles, as is the case for the residential sector, were obtained from the results of the BREGILAB project. The projected demand is shown in Table 15, and the energy savings due to insulation, as is the case for the residential sector, are shown in Table 16.

Table 15. Demand projection for the commercial sector by service end demand in TIMES-BE.

End demand	Currently satisfied with	Current demand [TWh]	2030 demand [TWh]	2040 demand [TWh]	2050 demand [TWh]	Source
Space heating	Biomass (<1%), Electricity (20%), Natural Gas (51%), Diesel (27%)	22.51	23.37	24.51	25.77	Study "Towards 100% renewable energy in Belgium by 2050"[96]
Space cooling	Electricity (100%)	2.36	2.68	2.95	3.26	
Water heating	Electricity (30%), Natural Gas (43%), LPG (4%), Diesel (22%)	3.18	3.44	3.70	3.98	
Lighting	Electricity (100%)	6.85	7.43	7.98	8.59	
Cooking	Electricity (41%), Natural Gas (50%), LPG (9%)	2.71	2.98	3.21	3.45	
Refrigeration	Electricity (100%)	3.17	3.44	3.69	3.98	
Public Lighting	Electricity (100%)	0.85	0.89	0.93	0.98	
Other electric	Electricity (100%)	5.00	5.41	5.63	5.86	

Table 16. Space heating energy savings from insulation in the commercial and public sector in TIMES-BE

	Unit	2014	2016	2020	2025	2030	2035	2040	2045	2050
Maximum	TWh	1.88	1.93	1.92	1.91	1.94	1.98	2.03	2.08	2.14
Average	TWh	1.33	1.35	1.35	1.34	1.36	1.39	1.42	1.46	1.50
Minimum	TWh	0.77	0.77	0.77	0.77	0.78	0.80	0.81	0.84	0.86

Similar to the residential sector, an effort to reduce direct CO_2 emissions often boils down to decarbonizing the supply of useful heat within the sector. For that purpose, the same alternatives used in the residential sector are available for the commercial sector. However, due to the larger scale of installations, this sector can in certain cases have access to lower cost per energy technology unit. The emission reduction options are the following:

- Electric boiler/radiator
- Electric heat pump (air/air advanced/ground), both with and without a cooling option.
- Gas boiler (simple/condensing), both with and without hot water option.
- Gas HP (Air), both with and without cooling option.
- District heating, with hot water option.
- Solar collector with electric/diesel/gas backup.

[96] https://energie.wallonie.be/servlet/Repository/130419-backcasting-finalreport.pdf?ID=28161

- Wood/pellets boiler.
- Electric air conditioner (both room and centralized).
- Electric air chiller.
- Electric air fan.
- Gas air conditioner (centralized)
- Biomass boiler
- Geothermal heat exchanger

4.5. Agriculture

Agriculture, forestry and fishing sector is the smallest demand sector, responsible for 2.8% (10.5 TWh) of the Belgian final energy demand and 2.7% (2.2 $MtCO_2$) of CO_2 total emissions. The highest energy consumption in the sector is attributed to diesel, which accounts for 41.2% (4.3 TWh), followed by natural gas at 33.3% (3.5 TWh) and electricity at 17.1% (1.8 TWh). The energy consumption profile of this sector shows the need to tackle heat production –currently from natural gas and biofuels– and off-road vehicles, which are almost entirely responsible for diesel consumption. Part of the heat demand is covered with CHPs, which also generate a large proportion of the electricity consumed within the sector. TIMES-BE focuses on energy-related emissions in the agriculture sector. As a consequence, non-CO_2 greenhouse gas emissions related to land use and livestock are out of the scope of this study.

Table 17. Demand projection for the agricultural sector by service end demand in TIMES-BE.

Demand	Current mix	Current demand [TWh]	2050 demand [TWh]	source
Electric appliances	100% electricity	1.46	1.46	Eurostat
Off-road transport	96% Diesel, 4% others	1.43	1.43	
Low-temperature heat	61% liquid fossil fuels 39% natural gas	1.08	1.08	
Greenhouse heat	90% natural gas 10% biofuels	6.03	6.03	

In TIMES-BE the agriculture sector has four types of end demands (I.e.: electric appliances, greenhouse heating, low-temperature heating and off-road). By using such a division of the sector demand, we can focus on the end demands that require non-fossil-based technologies to reduce CO_2 emissions. On the other hand, CO_2 is needed by greenhouses to enrich crops, which promotes the combustion of natural gas for heating purposes[97]. The IEA estimates that in the Netherlands alone, this technique to boost crops yield consumes around 5-6.3 $MtCO_2$ every year[98].

Table 18. Decarbonization alternatives for the agriculture sector in TIMES-BE

Greenhouse and low-temperature heat.	Off-road transport
- Biomass boiler - Biomass CHP - Ground heat pump (small and large size)	- Biofuel-based technology - Electric machine with battery - Cable-powered electric machine

[97] https://www.dutchgreenhouses.com/en/technology/co2-enrichment/
[98] Putting CO2 to Use (pg.64), IEA, 2019. https://iea.blob.core.windows.net/assets/50652405-26db-4c41-82dc-c23657893059/Putting_CO2_to_Use.pdf

5. Supply and transformation sectors

5.1. Power sector

The power sector is considered to be the cornerstone of the future energy system. Not only for the electrification of the demand, which is required to attain climate goals but for its role in the production of clean molecules, which strongly depends on the availability of clean electricity at low prices. Therefore, the reliability, adequacy and flexibility of the power sector have to be carefully considered in a long-term energy transition strategy. TIMES-BE represents the power sector in such a way that is possible to determine the future needs of the sector, as the model optimizes the sector to meet the electricity demand due to changes in the demand (i.e.: EVs, heat pumps, electric furnaces, molecules production).

TIMES-BE includes the existing power generation capacity grouped by technology and assigns a decommissioning profile as shown in Figure 15. This is done to mirror the future needs to replace the existing capacity, thus, the model decides which technology to install that minimizes the system cost considering the electricity demand and hourly profiles. The portfolio of technologies available for the model includes gas turbines, biomass plants, CHPs, solar PV, wind onshore and offshore, hydrogen turbines (from 2030 onwards), existing nuclear reactors and nuclear small modular reactors (available from 2045). Within the Energy Transition Fund Bregilab project, the Belgian technical potential for rooftop PV and onshore wind has been calculated by making use of the Dynamic Energy Atlas for Belgium. This geographically explicit exercise resulted in a technical potential of rooftop PV and onshore wind capacity and generation at a provincial level in Belgium, taking into account solar irradiation and wind speeds per province. The technical potential for rooftop solar PV amounts to 103,3 GW, onshore wind 20,5 GW. This technical potential is included as the upper limit in the TIMES Be model. (see How much renewable electricity can be generated within the Belgian borders? (Dynamic Energy Atlas) | EnergyVille).

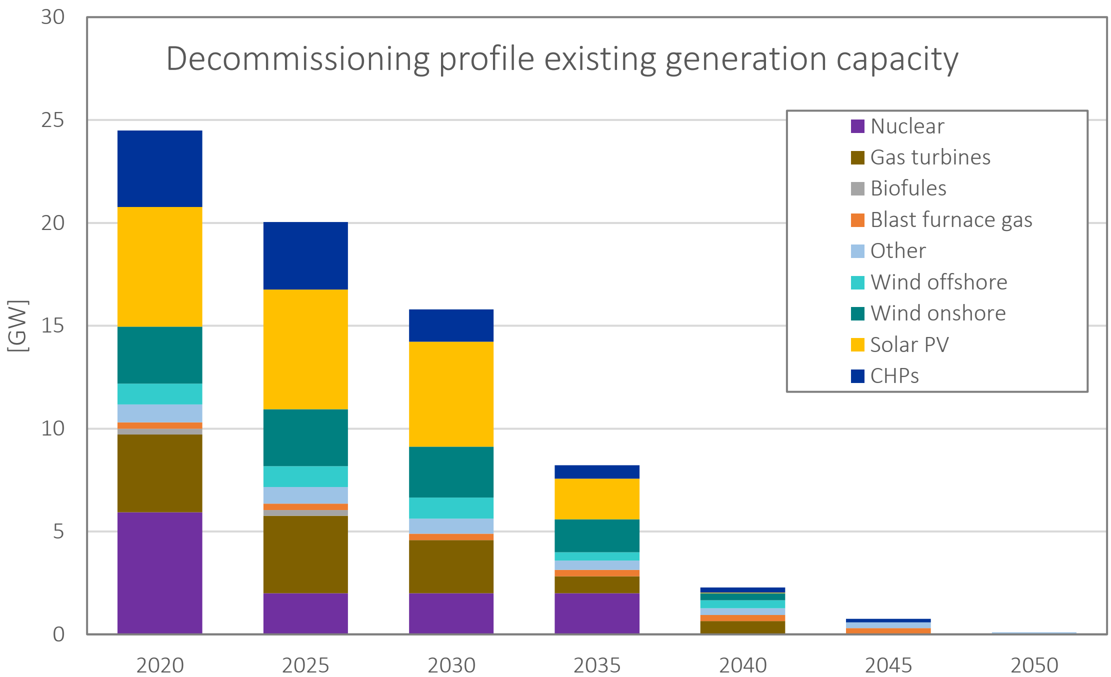

Figure 15. Decommissioning profile of existing power generation capacity in TIMES-BE.

To cope with the variability of solar and wind, the use of a robust interconnected grid is paramount. The European Commission identifies the relevance of the interconnection between member states to increase the share of variable renewable energy sources (VRES) and thus reduce curtailments. The European Commission has set a target of 15% of interconnection capacity[99] for each member state by 2030[100]. In TIMES-BE, the import and export capacities were defined according to the Ten Years Network Development Plan (TYNDP) published by ENTSO-E in 2022[101]. Since TIMES-BE's geographical representation is limited to Belgium, it was necessary to use a dispatch model developed by the *Katholieke*

[99] The 15% cross-border capacity ratio corresponds to the import capacity over EU countries' installed generation capacity.
[100] European Commission, 2018. Electricity interconnection targets [WWW Document]. URL https://energy.ec.europa.eu/topics/infrastructure/electricity-interconnection-targets_en
[101] ENTSO-E, 2022. TYNDP Scenarios 2022. https://tyndp.entsoe.eu/scenarios/

Universiteit Leuven (KUL) to cover the integrated European electricity market. The results of this model were integrated into TIMES-BE to represent the availability and price for imported electricity in each period (time-slice), as well as the price and willingness to consume exported electricity in other member states. The interconnection capacity is shown in Table 19. Export capacity is different to import capacity due to several technical reasons such as the uncertainties impacting the system as well as to cope with the occurrence of any single contingency (n-1 criteria)[102].

Table 19. Interconnection capacity (import and export) for Belgium in TIMES-BE

	Unit	2020	2030	2040	2050	Source
Import	GW	3.5	8.9	13.0	13.0	ENTSO-E[101]
Export	GW	2.3	7.9	11.5	11.5	

Another important aspect of the power sector, besides the generation capacity, is the capacity of the transmission and distribution (T&D) grid to handle the peaks of demand. As TIMES-BE is not designed to have a full representation of the topology of these two networks, the model uses three different levels of voltage to link supply and demand: High voltage, medium voltage and low voltage. For the latter, we assume an investment cost to capture the future investment needed to reinforce the distribution grid. TIMES works with the concept of 'copper plate', which simplifies the actual electricity flow in the grid. However, although this approach guarantees the energy balance in all periods (time-slice) and provides insight into the quantity of electricity flowing in each voltage level, it doesn't assess the flow balance and possible congestion of the grid.

5.2. Supply sector

The supply or transformation sector, according to the Eurostat energy balance classification, cover several processes:

- Electricity and heat production: cover in the power sector and CHPs
- Coke ovens and blast furnaces: reported in the steel sector.
- Refineries and petrochemical industry
- Other transformation activities

In this section, we explain the modelling of the refineries and include the future molecules industry that is being formed today.

5.2.1. Refineries

A refinery is a complex and expensive integrated process that converts crude oil into finished products by heating, pressure or a catalyst. All refineries can be divided into three basic steps: separation, conversion and treatment. In Belgium, there are 4 refineries with a crude oil intake capacity of 776 kbbl/Cd[103]. This is represented in TIMES-BE as a single, flexible process that requires heat, electricity, and some fossil fuels to transform crude oil into refined products (i.e.: gasoline diesel, naphtha). Some by-products such as refinery gas are used onsite to produce heat and electricity. Due to the geographical location of Belgium, the refineries are used to cover local demand as well as to export a big volume of refined products. In fact, in 2019, Belgium exported 378 TWh of petroleum products[104]. To represent the benefits for society of exporting such products, TIMES-BE includes the export process for each one at a given price. Moreover, as the demand for diesel, gasoline and other fuels produced by refineries phases out, the refineries will be used more to export such products and to produce the feedstock used in the chemical sector (i.e.: Naphtha, LPG).

Table 20. Minimum crude oil intake in refineries in TIMES-BE

	units	2014	2019	2030	2040	2050
Oil intake	TWh	432	403	339	281	222

The main sources of CO_2 in refineries are furnaces and boilers, utilities, catalytic crackers and hydrogen production[105]. The refineries in Belgium are responsible for 4.5 $MtCO_2$ emissions from the use of fossil fuels and approximately 3.9 $MtCO_2$

[102] https://asset-ec.eu/wp-content/uploads/2019/05/ASSET_CACM-FBMC_FinalReport.pdf
[103] https://www.concawe.eu/refineries-map/
[104] Eurostat Belgian energy balance 2019, Export- Oil and petroleum products.
[105] http://dx.doi.org/10.1016/j.egypro.2009.01.026

from process emissions. The main emission reduction option for the current refineries installations is the use of CCUS. However, alternative production routes such as Fischer-Tropsch (FT) synthetic fuels from green hydrogen or biomass are also modelled in TIMES-BE.

5.2.2.Molecules

In recent years the use of molecules, and in particular hydrogen, has been regarded as one of the pillars of the energy transition and a future carbon-neutral economy. Therefore, TIMES-BE was adapted to represent all the future molecules' value chains, from imports and local production up to the final use. In general, TIMES-BE covers four main molecules, namely hydrogen, e-methane, methanol and ammonia. The e-methane, methanol and ammonia can be imported as such through dedicated terminals or reconverted into hydrogen, which requires additional investments and considerable energy losses. Whereas, pure hydrogen can be imported through cross-border pipelines. There is a representation of the main hydrogen transport grid, which assumes the development of a hydrogen pipeline in Belgium according to the European hydrogen backbone study[106]. Large industrial hydrogen consumers and hydrogen turbines will be close to the main transport network. Conversely, other sectors (i.e.: transport, commercial) will see a higher transport cost value due to distribution infrastructure, which is then represented as an additional tariff in TIMES-BE.

Local hydrogen production, distributed and centralized, can take place through a traditional natural gas steam reformer (NG/SMR), possibly coupled to a carbon capture unit (blue H_2). Other production routes of hydrogen in the model are biomass gasification, electrolyzers (alkaline and PEM) and pyrolysis (plasma and reactor).

As hydrogen is the base for all molecules (see Figure 16), TIMES-BE includes the option to synthesize methanol, e-methane and Fischer Tropsch fuels to be primarily used in the chemical and transport sectors. To be able to produce these molecules, there is the need for a CO_2 source, which can be industrial captured CO_2 or from the Direct Air Capture Unit (DAC). Emissions can be reduced by capturing and using carbon (CCU) in products through Methanol To olefins, Methanol to Aromatics and Fischer Tropsch. To account for the storage part of the CCUS strategy, and since Belgium lacks CO_2 storage sites, all the CO_2 to be stored is assumed to leave the country by shipping it from the ports of Antwerp and Ghent at 13.6€/tCO_2[107]. To account for the fact that CO_2 must be transported to the ports, a CO_2 transport tariff (€1.5/tCO_2)[107] was included for sectors that are far from the ports such as cement and glass (less than 180 km).

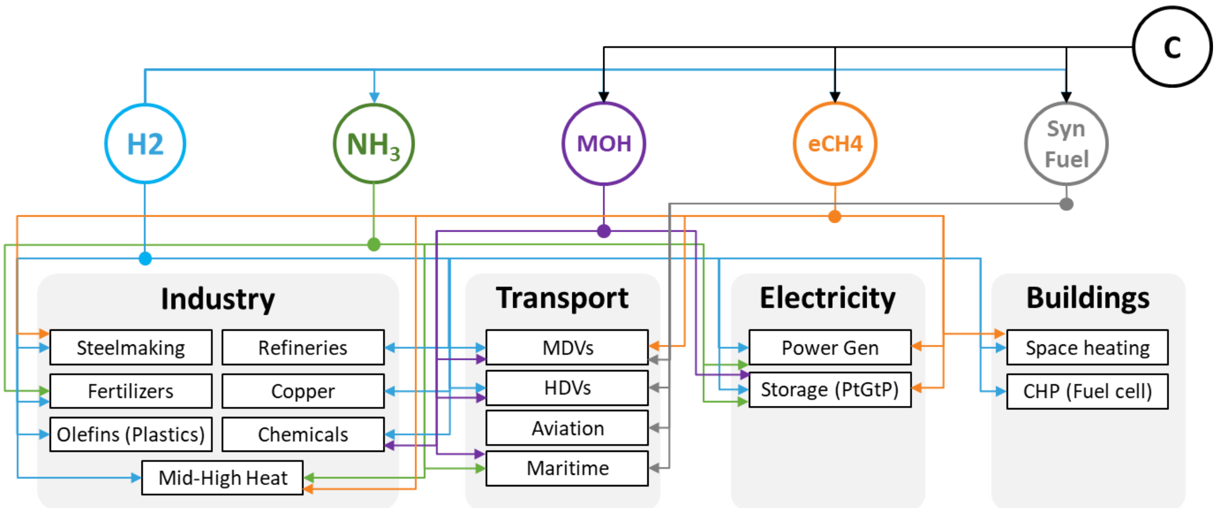

Figure 16. Simplified molecules network in TIMES-BE

[106] https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf
[107] The Costs of CO2 Transport Post-demonstration CCS in the EU (Table 2), ZEP. https://www.globalccsinstitute.com/archive/hub/publications/119811/costs-co2-transport-post-demonstration-ccs-eu.pdf

Conclusion

This document described the main assumptions of the BE-TIMES model which was performed to generate study results which are available in full detail on the 'Paths 2050' website https://perspective2050.energyville.be. The authors thank the Energy Transition Funds of the FPS Economy and Febeliec for funding part of the model development.

The document discusses the TIMES-BE model setup, the macroeconomic assumptions, and the fuel prices. The topic of resource and material availability is discussed. Taking into account limitations due to critical material availability will be worked out further in the ETF project Circec. For every sector, transport, residential & commercial, industry sector and power sector, this document describes in detail the assumptions, main parameters and processes behind the model results. In addition, possibilities of molecule import and electricity flows in Europe are modelled as well. The TIMES-BE model is able to capture cross-sector, cross-energy vector and cross-border flows of electricity and molecules and provides investment pathways towards a carbon-neutral society in 2050.

Annex A. Main techno-economic assumptions

Discount rate: 3%

Electricity generation

Technology	CAPEX [€/kW]			FIXOM [€/kW]			VAROM no fuel [€/MWh]			Efficiency	Lifetime [yr.]
	2030	2040	2050	2030	2040	2050	2030	2040	2050		
OCGT	568	568	568	19	19	19	-	-	-	42%	20
CCGT	855	855	855	20	20	20	-	-	-	59%	30
Biomass plant	2000	2000	2000	30	30	30	-	-	-	39%	40
Gas CHPs	1180	1180	1180	45	45	45				32%[108]	30
Bio CHPs	1000	1000	1000	50	50	50	-	-	-	14%	40
Residential PV	600	480	360	25	25	25	-	-	-	n.a.	25
Com/Ind PV	540	432	324	17	16	15	-	-	-	n.a.	25
Onshore wind	965	851	737	42	40	37	-	-	-	n.a.	30
Offshore wind	1750	1625	1500	65	57	50	-	-	-	n.a.	30
North Sea wind	2700	2575	2450	65	57	50	-	-	-	n.a.	30
H_2 turbine	568	568	568	19	19	19	-	-	-	43%	20
Nuclear SMR	7500	7500	7500	83	83	83	7.5	7.5	7.5	33%	60

KU LEUVEN vito imec UHASSELT

[108] Only makes reference to electricity efficiency. When heat is consider, efficiency goes up to 78%.