Low carbon scenarios for Belgium: insights from a tri-regional energy system model

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1 Introduction[1]

The European Union (EU) targets to be climate neutral by 2050 leading to net-zero greenhouse gas emission. As an EU member state Belgium is also employing economy-wide strategies to meet the long-term climate targets. Belgium is one of the most densely populated and energy intensive countries in Europe. Belgium also houses large industrial clusters. Industry and transport together constitute around 70% of its total energy and non-energy final consumption. Belgium relies mostly on the import of energy carries which poses a risk of long-term energy supply. Geographical location and size of Belgium constraint its access to higher quality renewable energy resources. Innovation in industrial technologies opens the door of reducing carbon intensity of Belgium industry clusters. Thus, there is a need of developing optimal long-term strategies considering the whole energy sector of Belgium.

To project future GHG emissions and to support climate policy, many climate-economy models using different modelling approaches have been developed in the past decades. The scenarios produced by those modelling tools can give various insights to policy makers. They provide information on the optimal timing of emissions reductions, on the carbon price, on the costs of the energy transition and on the necessary investments in renewable technologies for instance. More specifically, models also give recommendations regarding how fast each energy sector should reduce its GHG emissions or which specific technologies we should invest in. Developing models, producing low-carbon scenarios and defining optimal emissions trajectories are all crucial to inform climate policy.

There are many different types of models. Nikas et al. (Goldstein et al., 2016) identify 4 main classes of climate-economy models or "Integrated Assessment models (IAMs)": partial equilibrium models, optimal growth models, computable General Equilibrium models and macroeconometric models.

Partial equilibrium models focus on a particular sector, as opposed to general equilibrium models which include the whole economy. Partial equilibrium models include energy system models which are often used to help determining optimal (least-cost) climate policies in many countries. Such models are technologically detailed, sector by sector, and can give valuable outputs to decision makers. Energy models are often built at the national or multi-national level. The "TIMES" model generator belongs to this category (Goldstein et al., 2016) (Loulou et al., 2005a) (Loulou et al., 2005b). Note that many countries have their own national TIMES model (e.g., Ireland (Glynn et al., 2019), Canada, Pakistan (Ur Rehman et al., 2019)). There are also more global TIMES models (e.g., ETSAP-TIAM modelling 15 regions of the world (Labriet et al., 2008) and JRC-EU-TIMES, a European model (Simoes et al., 2013)).

In the EPOC[2] project we develop a Belgian energy system model using the TIMES modelling framework. The EPOC project combines the expertise of thirteen Belgian institutes to provide a consistent calculation for the long-term energy future in Belgium.

[1] Part of the introduction comes from a PhD thesis (Coppens L., 2023).
[2] The EPOC project is under the Belgian energy transition fund.

TIMES models are usually built on an aggregated (national or European) level. In order to give insights to policy makers, industries and utilities in Belgium, an integrated energy system model is a very useful tool. In our case, it is also highly valuable to detail the three Regions of Belgium to consider local specificities and to inform policy makers, particularly because the Regions are legally competent in many policies related to energy transition and climate change. So far, there were no such detailed model of the three Belgium Regions energy system. We build on past modelling experiences of two partners of the consortium (ICEDD and VITO/EnergyVille) who have previously developed respectively a TIMES model for Wallonia and a single-region TIMES model for Belgium.

Besides, a lot of knowledge and expertise on energy modelling is present in the EPOC consortium. In fact, different models are used in the EPOC project, such as a generation dispatch model, an adequacy model, a transport model or a building model. One aim of the EPOC project is to combine the expertise of the Belgian research community by linking the different energy models, carefully discussing the input data used and applying them to the Belgian situation. This will support policy makers in their decisions with respect to the energy future in Belgium towards 2050. The overall approach of the project is a first-of-a-kind in the Belgian energy sector: never before have such a wide range of academic partners collaborated in one energy modelling research project[3]. Our TIMES model benefits from the knowledge and data of the consortium.

1.1 Objectives

The objectives of this modelling study under the EPOC project are as follows:

- Develop a tri-regional long-term energy system planning model of Belgium (TIMES-EPOC) with explicit regional definitions and recent database
- Link various models developed by the EPOC consortium to the TIMES-EPOC model
- Perform scenario analysis with the TIMES-EPOC model to analyse the energy transition pathways of Belgium

2 Methodology

2.1 The TIMES modelling framework[4]

The Integrated MARKAL-EFOM System (TIMES) is a model generator developed by the Energy Technology Systems Analysis Program, one of the longest Technology Collaborative Program of the International Energy Agency. A model generator as TIMES can customise models based on the choice of the reference energy system, input database and constraints defined by the user. There are four main inputs to a model: the energy services demands, the existing stock of technologies, the future technologies and the primary energy supply sources and potentials. In the TIMES framework, the "commodities" play a central role: they can be materials,

[3] The project is coordinated by EnergyVille, and the participating research institutes are VITO, Imec, KU Leuven, UHasselt, ICEDD, WaterstofNet, Transport & Mobility Leuven, Ugent, UMons, KMI (Het Koninklijk Meteorologisch Instituut van België), UCL, ULiege and ULB.

[4] This general introduction to the TIMES modelling framework comes from Coppens et al. (2022).

emissions, energy carriers and services. They can be produced and consumed via many different processes (technologies). One key element of the TIMES modelling framework is the focus on a detailed set of technologies for each sector.

In TIMES, perfect foresight (i.e., all future events within the defined temporal horizon are known) and competitive markets are assumed. For the model to find an optimal solution, it must satisfy all energy services demands and constraints while maximising the net total surplus of consumers and producers (considering the whole temporal horizon). In our case, we did not assume any demand price elasticities, as in Vaillancourt *et al.* (Vaillancourt et al., 2014) for instance. We believe it makes more sense to keep the demands exogenous and to take into account specific assumptions about the evolution of the demands coming from regional (or national) studies instead of theoretical elasticities. As a result of the absence of demands losses, the optimisation is equivalent to a cost minimisation under the defined constraints.
The model consists of linear equations. Basically, the TIMES linear program without elastic demands can be written as (Loulou et al., 2005a):

$$\text{Min c} \times X \qquad (1)$$

$$\text{s.t.} \sum VAR_{ACT\,k,i(t)} \geq \text{DM}_i(\text{t})\,, \quad \text{i} = 1,2, \dots \text{I}; \text{t} = 1, \dots, \text{T} \qquad (2)$$

$$\text{and B} \times X \geq \text{b} \qquad (3)$$

Equation 1 expresses the fact that the discounted costs (vector "c") have to be minimized. "X" are the variables (e.g., new capacity of processes, quantity of commodity (e.g., energy) consumed, produced or stored, imports, activity level of technologies, etc.). Equation 2 implies that the exogenous demands ("DM") must be satisfied by the activity variables of end-use technologies ("VAR_ACTk") ("i" is the demands related index and "t" is the time index). Equation 3 expresses the fact that all the other constraints defined in the model must be satisfied[5].

2.2 Benefiting from the consortium expertise

Our tri-regional Belgian TIMES model is at the heart of the EPOC project. Fig. 1 shows how TIMES is linked to the different other models used within the consortium. Those links, interactions, exchanges of information among the consortium's partners (and their respective models) are the main added value to our Belgian TIMES model. We present below the main inputs received from consortium's partners during the modelling task:

- Waterstofnet, which is a hydrogen knowledge centre, provides us with detailed data on hydrogen technologies coming from the most recent studies. Moreover, we build our hydrogen module in TIMES in collaboration with them in order to get a consistent, most-realistic representation of a potential future hydrogen economy, which is adapted to Belgium.

[5] Please refer to the documentation (Loulou *et al.*, 2016, 2005) for more details on the equations: there is a great number of different variables and equations that are taken into account but the above system gives a general view on the optimisation program.

- A dispatch model (PLEXOS) from UGENT, based on TYNDP2020 scenarios input data, produces import/export possibilities curves which are fed into TIMES.
- Travel profiles and transport activity data, among other transport information, come from TML (a research office specialised in traffic, passenger, and freight transport) and their transport model.
- The building model's team provides us with detailed information on renovation measures (detailed analysis of costs and benefits of such measures), a building typology, data on the building stock as well as the calibration of heat demand and fuel breakdown.
- Alongside with VITO/EnergyVille and ULB, several meetings with the different industrial Belgian federations were organised to ask and validate data for industrial consumptions, future demand, new technologies parameters and their availability.

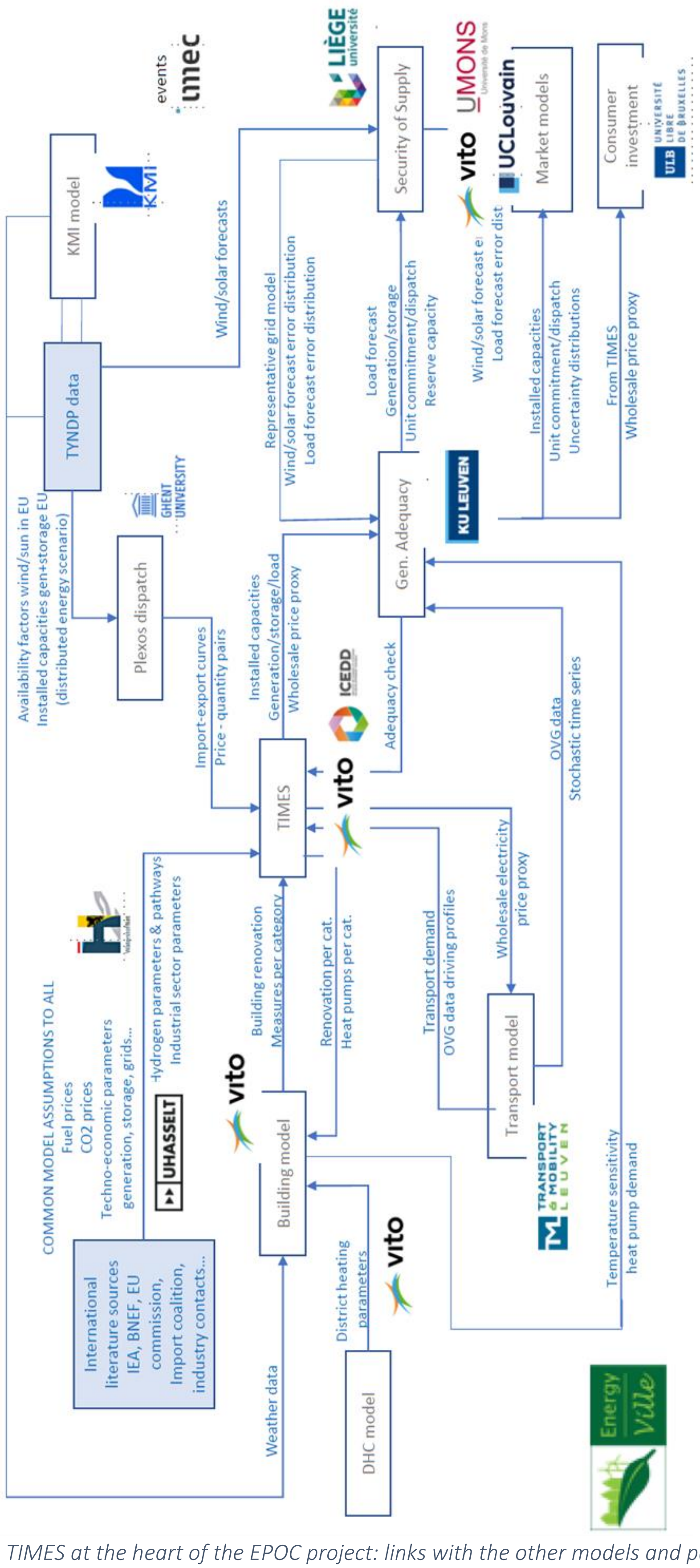

Figure 1: TIMES at the heart of the EPOC project: links with the other models and partners

2.3 General structure of the model and main assumptions

2.3.1 Spatial and temporal resolution

The model is tri-regional, considering the Walloon Region, the Flemish Region and the Brussels-Capital Region. The base year is 2018, which is the last year with a complete set of data in the regional energy balances. After the base year, and until the end of the time horizon (2050), optimisation is carried out over periods of 5 years length, which have 2020, 2025, 2030, 2035, 2040 and 2050 as milestone years. To reflect both seasonal and infra-day fluctuations on both demand and supply sides, especially in the power sector, each milestone year is reproduced through 10 representative days, with a bi-hourly resolution, for a total of 120 so-called time-slices. The 10 representative days are chosen through an optimization algorithm, which, once a set of time-series relevant to the choice has been defined, minimizes the sum of the errors between the complete, and reduced time-series referring to representative days (Poncelet et al., 2017) (Poncelet et al., 2016).

Table 1: Representative days, and calendar days to which they correspond

Rep. day	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10
Calendar day	19.01	06.02	21.04	02.05	09.06	26.07	28.08	30.10	18.11	29.12

2.3.2 Model structure

The model is composed by several modules, each representing one specific sector within the energy system. In the figure below, an extremely simplified representation of the structure is provided.

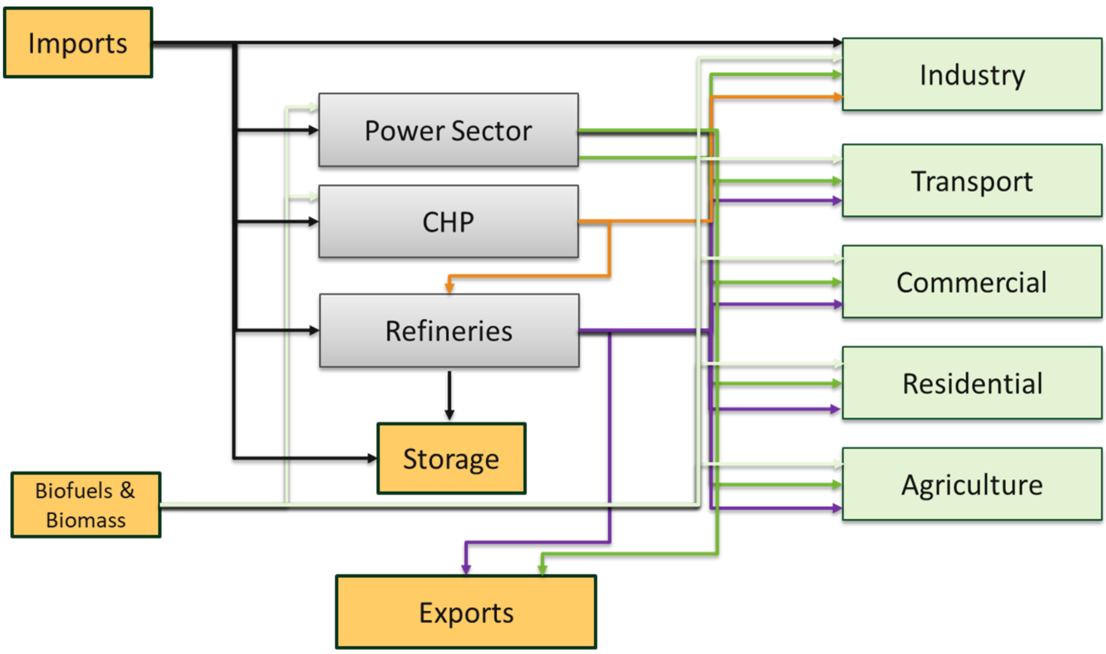

Figure 2: Simplified representation of the TIMES-EPOC model structure

The sectors representation here is to be read from the left to the right, following the conventional path from the energy supply to the final consumption (end sectors). All the sectors, from the supply ones to the end demands, are described with a high level of detail for the base year (calibration procedure), while for the future periods, the model is free to invest in new technologies, choosing from a set of available ones, for which all techno-economic parameters are provided. More details on the technologies available in each sector are reported in the sectors description.

2.3.3 Macro-economic assumptions

Accurate demand projections play a critical role in informing energy system models, given the significant transformations that the future energy system will undergo, and TIMES-EPOC distinguishes between different types of demands:

- Service demands (e.g., space heating, passenger-km transportation)
- Product output (e.g., steel, cement, paper) – for industrial sectors
- Energy demands

Each type of demand described here can be either linked to drivers, which will then impact their future trends, or can be derived from more detailed sector-specific models. Here are the main assumptions used for future sector demands:

- Industry: The throughput of products in 2050 is projected to remain at the same level as in 2020
- Transport: Demand for passenger-km, tonne-km, and energy is derived from the results of the TREMOVE model developed by TML.
- Residential: Final energy services demand is driven by population growth, projected to increase from 11.5 million in 2020 to 12.4 million by 2050.
- Commercial: Final energy services demand is influenced by economic growth projections based on the Federal Planning Bureau.
- Agriculture: Energy demand in the agricultural sector is assumed to remain at the same level as today, as it has shown stability over the past 20 years. Non-CO2 greenhouse gas emissions, such as methane and N2O, are not considered.
- Transformation: The transformation sector, encompassing refineries and the power sector, adapts to changes in demand sectors. Refineries, in particular, are expected to follow the downward trend in crude intake projected by CONCAWE as a low boundary for their activity.

In TIMES-EPOC, all costs of the energy system are discounted to a selected year. The discount rate is employed to calculate the annualized payment of investment costs for each process. The model allows for different discount rates to be assigned to each process or sector, although currently, it is defined at system level, with a value of 3%. Non-technical factors such as taxes and subsidies are not considered in the model, including green certificates and social tariffs. This deliberate choice ensures an unbiased view of the energy system, free from politically motivated influences on costs.

2.4 Description of the supply and transformation sectors

In this section, the transformation sectors will be presented: starting from the energy supply, with the modelling of resources availability and trade, and continuing with transformation, of fossil fuels (refineries), molecules (with a special focus on hydrogen) and of power.

2.4.1 Energy (non-power) trade

Since Belgium is highly dependent on commodity trade (only 21% of the total supply is produced internally, according to the Eurostat Energy Balance for 2018), in TIMES-EPOC the energy trade is made available for a variety of commodities.

In the table below, the import prices for energy commodities are reported; exports are also possible, at the same price levels, with a deflation factor of 0.9.

Table 2: Import price for key energy commodities

Fuel group	Fuel	Unit	2018	2030	2040	2050	Source
Solid Bioenergy	Wood Chips	€/MWh	32.7	35.8	39.1	42.7	HRM-EU[6]
	Wood Logs	€/MWh	42.6	46.6	50.9	55.6	
	Wood Pellets	€/MWh	42.0	56.0	61.1	66.7	
	Biomass	€/MWh	16.2	16.9	18.0	18.0	
Biofuels	Biodiesel	€/MWh	71.0	69.0	69.0	69.0	IEA Bioenergy – Advanced Biofuels[7]
	Bioethanol	€/MWh	104.5	96.5	85.3	74.0	
	Biogas	€/MWh	80.0	69.0	60.5	52.0	
Coal	Coal	€/MWh	15.8	10.8	11.2	11.2	IEA – WEO 2021[8]
Oil Products	Crude Oil	€/MWh	41.9	31.7	30.2	28.8	
	Diesel	€/MWh	42.2	41.1	39.2	37.4	Adapted from IEA – WEO 2021
	Gasoline	€/MWh	44.6	38.8	37.0	35.3	
	Fuel Oil	€/MWh	22.8	23.1	22.1	21.0	
	Kerosene	€/MWh	48.1	52.6	50.2	47.8	
	LPG	€/MWh	43.8	44.3	42.3	40.3	
	Naphtha	€/MWh	37.6	34.2	32.7	31.1	
Natural Gas	Natural Gas	€/MWh	34.7	37.2	35.0	35.0	EnergyVille assumption
Nuclear Fuel	Nuclear Fuel	€/MWh	1.7	1.7	1.7	1.7	ENTSO-E[9]
eFuels	H_2 - Gaseous	€/MWh	41.6	26.9	24.4	21.9	H_2 Import coalition results
	H_2 - Liquid	€/MWh	50.3	35.7	33.1	30.6	
	eMethane	€/MWh	31.4	25.1	23.5	21.9	
	Methanol	€/MWh	25.8	21.9	20.8	19.7	
	Ammonia	€/MWh	23.1	19.2	17.9	16.6	

2.4.2 Maximum resources availability

Many of the key resources in order to achieve an energy transition have a limited availability.

[6] https://heatroadmap.eu/wp-content/uploads/2020/01/HRE4_D6.1-Future-fuel-price-review.pdf
[7] https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf
[8] https://prod.iea.org/reports/world-energy-outlook-2021
[9] https://2020.entsos-tyndp-scenarios.eu/fuel-commodities-and-carbon-prices/

One key example is represented by RES, especially in a relatively small territory as the Belgian one. The technical potential for renewable energy sources, such as rooftop PV and onshore wind in Belgium, has been assessed as part of the Energy Transition Fund BREGILAB project[10], utilizing the Dynamic Energy Atlas[11] for Belgium. This comprehensive evaluation considers solar irradiation and wind speeds at a provincial level, resulting in estimates of the technical potential for rooftop PV (103.3 GW) and onshore wind (20.5 GW). For the offshore wind, the Belgian offshore platform[12] assumption has been used, with a resulting maximum availability growing from the current 2.26 GW to 4.6 GW in 2030 and 8 GW from 2040 onwards. These figures are included in the TIMES-EPOC model as upper limits across the full time-horizon; however, this constraint would not reflect alone the public acceptance for a large expansion of the use of such technology across the country: for this reason, also a growth constraint has been introduced for onshore wind (250 MW of new installation per year until 2030).

Biomass, biofuels and waste availabilities have also been constrained, following one common assumption: the maximum historical availability levels should not be exceeded. This limiting assumption impedes the resources, which often possess considerable value also in non-energy applications and remain subject to evolving policies, from assuming a disproportionately influential role within the country's prospective energy system.

Table 3: Biomass, biofuels and waste maximum resource availability

Subsector	Category	Unit	2018			2050		
			BR	FL	WA	BR	FL	WA
Solid biomass	All, aggregated	TWh/y	0.28	14.17	8.89	0.28	14.17	8.89
Biofuels	Bioethanol	TWh/y	0.07	0.96	0.49	0.07	0.96	0.49
	Biodiesel	TWh/y	0.16	4.46	2.05	0.16	4.46	2.05
	Biogas	TWh/y	0.06	1.32	1.35	0.06	7.92	8.08
Waste	Municipal solid waste	TWh/y	1.32	5.49	1.66	1.32	5.49	1.66
	Industrial sludge	TWh/y	0.11	1.61	1.61	0.11	1.61	1.61

Important to note here is that in this study, only focus is on the scope 1 emissions of Belgium. The international bunker fuels are not taken into account, but could present additional markets for liquid biofuels. This aspect will be further worked out in the ETF PROCURA project.

2.4.3 Refineries

In Belgium, there are four refineries with a combined crude oil intake capacity of 776 kbbl/Cd. TIMES-EPOC represents the high complexity of refineries with a single, flexible process that utilizes heat, electricity, and some fossil fuels to convert crude oil into refined products such as gasoline, diesel, and naphtha. Onsite, certain by-products like refinery gas are utilized to generate heat and electricity. Refineries in Belgium not only meet local demand but also export a substantial volume of refined products: as a matter of fact, in the

[10] https://www.energyville.be/en/research/bregilab-support-research-development-renewable-energy-belgian-electricity-grid
[11] https://www.energyville.be/en/bregilab-renewable-energy-belgium
[12] https://www.belgianoffshoreplatform.be/en/

TIMES-EPOC model's base year (2018) Belgium exported 381 TWh of petroleum products. The model incorporates the export process for each product at specific prices to reflect the societal benefits derived from such exports (see the part above on energy trade). As the demand for diesel, gasoline, and other fuels produced by refineries diminishes, the refineries are anticipated to increase their focus on exporting these products and producing feedstock for the chemical sector, such as Naphtha and LPG. In terms of carbon dioxide (CO_2) emissions, refineries contribute to emissions primarily through furnaces and boilers, utilities, catalytic crackers, and hydrogen production: in total, they are responsible for approximately 4.5 MtCO2 emissions from fossil fuel utilization and around 3.9 MtCO2 from process emissions. To address these emissions, the primary option for emission reduction in the existing refinery installations is the adoption of Carbon Capture, Utilization, and Storage (CCUS) technologies.

2.4.4 Hydrogen and e-molecules

Concerning the hydrogen module, one partner (Waterstofnet) shared with us detailed data on hydrogen technologies coming from the most recent studies. We started from the structure of the hydrogen module of JRC-EU-TIMES (Bolat and Thiel, 2014a, 2014b; Ruiz et al., 2019; Sgobbi et al., 2016) and adapted it to Belgium. We consider centralized and decentralized distribution (as well as storage). Concerning centralized distribution, we compute a cost (euros/GW) for the pipelines network needed in Belgium to distribute hydrogen to the main industrial end-users. 230 kms of new pipelines are needed and 410 kms of pipelines should be repurposed (Waterstofnet provided us with differentiated data for those two types of pipelines). We only consider distribution routes to the industry, electricity generation sector and transport sector. Concerning the production technologies, we define different types of electrolysers (alkaline, proton exchange membrane (PEM), and solid oxide electrolysers (SOE)) and steam methane reforming options (with or without CCS). We also consider imports, terminals and cracking/regasification for several molecules: NH_3, MeOH, LH_2, LCH_4: import prices are reported in the energy trade section.

2.4.5 Power sector

The power sector plays a crucial role in the future energy system. Ensuring a reliable power sector becomes vital not only for meeting the electricity demand required to achieve climate goals but also for enhancing energy security, also under scarce renewable production conditions.

In the TIMES-EPOC model, the power sector is represented to determine its future requirements. The model optimizes the sector to meet the electricity demand resulting from changes in demand patterns, such as the introduction of electric vehicles, heat pumps, electric furnaces, and other energy-consuming technologies. TIMES-EPOC incorporates the existing power generation capacity categorized by technology and assigns a decommissioning profile, enabling the model to identify the optimal technology choices that minimize system costs while considering electricity demand and hourly profiles.

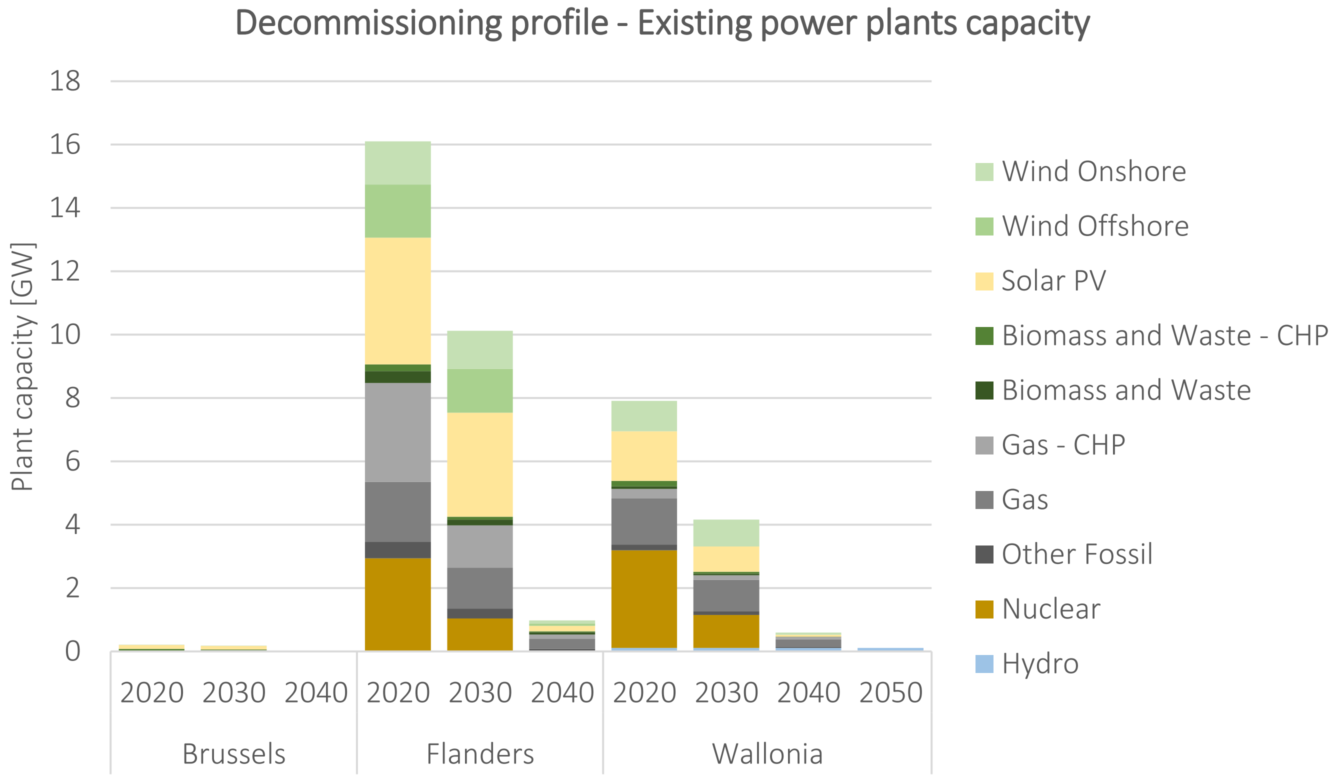

Figure 3: Decommissioning profile for existing power plants capacity in TIMES-EPOC model

The available portfolio of technologies in the model includes gas turbines, biomass plants, Combined Heat and Power (CHP) systems, solar photovoltaic (PV), onshore and offshore wind, hydrogen turbines (starting from 2030), existing nuclear reactors, and nuclear small modular reactors (available from 2045). Renewable energy sources are available up to a constrained level, discussed already in the Maximum resource availability section.

However, it is equally crucial to consider the representation of the broader regional context surrounding Belgium to obtain a more realistic assessment of the decarbonization potential of the Belgian power system. To address this, an innovative approach has been adopted to incorporate the power market dynamics with neighbouring countries. This approach entails the utilization of a European-level dispatch model, incorporating several key assumptions. Firstly, the interconnection capacity has been aligned with the Ten Years Network Development Plan (TYNDP) published by ENTSO-E in 2022[13], taking into account the projected developments in renewable capacity and electricity demand across other European nations. In the European-level dispatch model, developed by Universiteit Gent, Belgium is substituted with an ideal power sink, whose power consumption level is varied in increments of 1 GW. By simulating different power consumption levels, the model enables the assessment of the corresponding electricity price for imports at each level. This price is assumed to be equal to the rate at which neighbouring countries are willing to export electricity to Belgium.

Table 4: Interconnection capacity, for both power import and export, per region

Interconnection capacity	2018	2030	2050

[13] https://2022.entsos-tyndp-scenarios.eu/

	BR	FL	WA	BR	FL	WA	BR	FL	WA
Import	-	3.25	3.25	-	3.40	5.48	-	6.73	6.30
Export	-	3.25	3.25	-	3.40	4.48	-	6.73	4.80

The outcomes of this model were subsequently integrated into the TIMES-EPOC framework, enabling the representation of the availability and pricing of imported electricity during each time period (time-slice).

In addition to the generation capacity, the power sector also relies on the transmission and distribution (T&D) grid's ability to accommodate peak demand. However, the TIMES-EPOC model does not include the complete representation of the network topology for these grids. Instead, it employs three distinct voltage levels (high, medium, and low) to establish connections between electricity supply and demand. To account for future grid reinforcement requirements, the current low voltage grid capacity has a decommissioning profile, and an investment cost is assumed for new capacity.

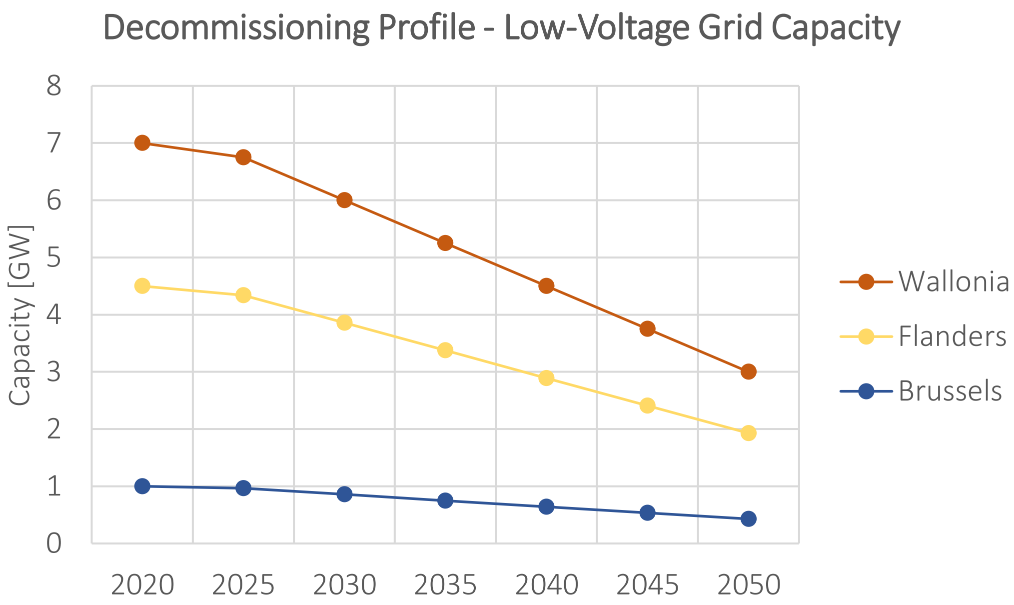

Figure 4: Decommissioning profile for the current Low-Voltage grid per region, stacked graph

The TIMES-EPOC model adopts a simplified approach known as the "copper plate" concept to depict the flow of electricity within the grid. While this simplification ensures energy balance across all time periods (time-slices) and provides information on the quantity of electricity transmitted at each voltage level, it does not specifically assess the flow balance or potential congestion within the grid. Consequently, the model does not provide an explicit evaluation of grid flow and congestion. Nonetheless, it accurately maintains energy balance and offers valuable insights into the distribution of electricity across voltage levels.

2.5 Description of the demand sectors

2.5.1 Industry

Regarding the industry, we consider 9 sectors and 27 different demands (see Table 4). We include the most common and energy-intensive sectors such as cement and iron and steel production as well as highly specific Belgium industries, such as milk powder, sugar, or processed potatoes production. Meetings with the different industrial Belgian federations were organized in the past years to ask and validate data for industrial consumptions, future demands as well as new technologies parameters and their availability. Following those meetings, we took the assumptions that the industrial demands will remain constant in the future. Each industrial subsector has a different structure and include several processes. Following is a brief description of some of the key industrial sectors modelled in the TIMES-EPOC.

In the cement sector, there are different types of kilns which produce heat. This heat is then used to produce clinker (either via wet or dry processes). Clinker is also partly imported. Finally, clinker is used to produce cement and to meet the exogenously defined regional demands for this subsector. In the future, the model can invest in a new technology to electrify the finishing process. To decarbonise the clinker production, the model can invest in CO_2 capture. As to the CO_2 capture, we define two different methods in the industrial sector: post-combustion treatment and oxycombustion. Prof. P. Hendricks (from ULB) provided us with valuable information on specific industrial issues (e.g., validation of our assumptions on oxycombustion). Note that we also consider the need to produce oxygen when an oxycombustion technology is chosen by the model.

In the steel sector there are currently two different ways to produce steel i.e., Blast Furnace – Basic Oxygen Furnace (BF-BOF) and Electric Arc Furnace (EAF). We model various intermediate steps of steel making from procurement of scraps/ iron ore to finishing. We model various technological options to make the transition of the steel industry sector towards net zero emissions. Fuel replacement by H_2 and biomass respectively in the blast-furnace and the electric arc furnace are considered. Use of H_2 for direct reduction (DRI) and H_2-based heat for finishing are modelled. Refurbishing of existing technologies e.g., basic oxygen furnace, sinter plant, blast furnace, electric arc furnace, with carbon capture are modelled. Investment into new technology options like gas based DRI and electric arc furnace integrated with carbon capture units are also considered.

For the chemical sector we model the production of seven final products namely ammonia, BTX, C4, chlorine, Ethylene, Ethylene Oxide and Propylene. For ammonia sector the primary emission reduction route is steam methane reforming with carbon capture for producing hydrogen. It is also possible to use imported hydrogen or hydrogen produced by grid electricity, for ammonia production. High value chemicals like ethylene, propylene, BTX and C4 are produced by naphtha steam cracker. Primary decarbonization option are electrification of the cracker and carbon capture. Usage of methanol to produce olefins (MTO), aromatics (MTA) and propylene (MTP) are also modelled as disruptive technological options in the future. For other chemicals decarbonization options are hydrogen and electricity-based heating.

In the food sector we model the production of potatoes, milk, sugar, and other products explicitly. For each food type two processes are modelled, one representing heat production and other the production of the actual product itself using electricity, heat, and other raw materials. For the decarbonization of the heat production in the future we model electrification and usage of biogas.

Table 5. Industrial subsectors demands.

Sector	Product	Unit	BR	FL	WA
Chemicals	Ammonia	Mt		0.73	0.25
Chemicals	BTX hydrocarbons	Mt		0.67	
Chemicals	C4-hydrocarbons	Mt		0.71	
Chemicals	Chlorine	Mt		0.81	0.16
Chemicals	Ethylene	Mt		0.83	
Chemicals	Ethylene Oxide	Mt		2.02	
Chemicals	Other chemicals	TWh	0.06	14.87	5.83
Chemicals	Propylene	Mt		1.65	
Chemicals	Other chemicals non-Energy use	TWh	0.29	9.71	0.37
Food	Milk	Mt		0.12	0.11
Food	Other food	TWh	0.13	9.68	2.18
Food	Transformed potatoes	Mt		1.45	1.54
Food	Sugar	Mt		0.25	0.46
Iron and steel sector	Finished Steel	Mt		3.27	4.33
Non-Energy Use in Industry Sectors	Non-Energy Use (other than Chemical)	TWh		2.52	
Non-ferrous metals Industry	Copper	Mt		0.39	
Non-ferrous metals Industry	Other Non-ferrous Metals	TWh	0.03	2.08	0.18
Non-ferrous metals Industry	Zinc	Mt		0.25	
Non-Metallic Minerals	Cement	Mt		1.05	4.61
Non-Metallic Minerals	Glass Flat	Mt		0.1	0.67
Non-Metallic Minerals	Glass Hollow	Mt			0.24
Non-Metallic Minerals	Glass other	Mt		0.05	0.32
Non-Metallic Minerals	Lime	Mt			1.85
Non-Metallic Minerals	Other Non-Metallic Minerals	TWh		2.84	0.88
Other Industries	Other Industries	TWh	0.2	11.77	1.48
Pulp and Paper Industry	High Quality Paper	Mt	0.01	1.58	0.45
Wood	Wood	Mt	0.08		2.10

2.5.2 Transport

In 2019, the transport sector in Belgium was responsible alone for more than 25% of the country emissions[14]. In particular, the largest contribution was coming from the road transport, responsible for about 96% of the sector CO_2 emissions released within the country. This excludes the international transport, for the aviation and navigations subsectors, which is responsible for the consumption of 115 TWh (all the national transport amounts to a consumption of 103 TWh) (*Energy balance sheets*, 2020).

[14] https://klimaat.be/doc/nir-2023-15042023-final.pdf

In the TIMES-EPOC model, the transport sector encompasses both domestic and international transportation, covering passenger and freight services. It is worth noting that the Belgian greenhouse gas (GHG) inventory does not currently include emissions from international transport, thus excluding them from the national emissions considered in the TIMES-EPOC model.

The structure of the model aligns with the Eurostat energy balance and consists of the following subsectors: aviation, navigation, rail and road transport. In the TIMES-EPOC model, road transport is further subdivided into passenger cars, buses, freight, and motorcycles. The passenger car category is divided into two distinct groups based on driving habits, namely Commuting/Non-Commuting. The figure presented below illustrates the sector structure along with the available (drivetrain) technologies aimed at fulfilling the end demands. The underlined technologies are already present in the base year and, as a result, have undergone calibration.

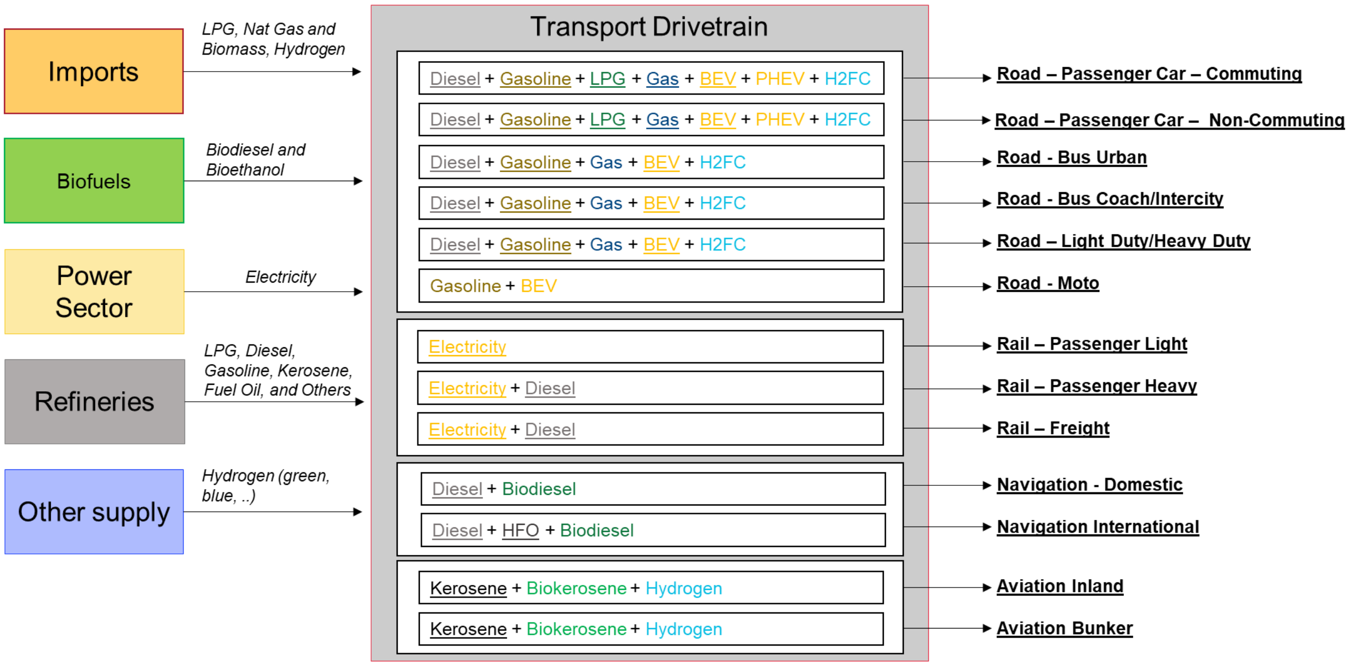

Figure 5: Sector structure, with all end demands (on the right), and full list of technologies available (Transport Drivetrain)

All the sector's techno-economic data come from the TREMOVE transport model by TML[15], as well as the vehicles use profiles: in fact, while all the other end demands are modelled only at annual level, passenger cars are characterized by a typical usage profile. This is realized with the aim of better representing the impact of the uptake of EVs on the power system. For this reason, the EVs are modelled as shown in the picture below, with processes representing EV chargers in both residential and commercial buildings, with a variable availability. They can charge the car batteries, which in turn power the car process, accordingly with the satisfaction of the specific end-demand. Vehicle-to-grid systems are not allowed in the current model.

[15] https://www.tmleuven.be/en/navigation/TREMOVE

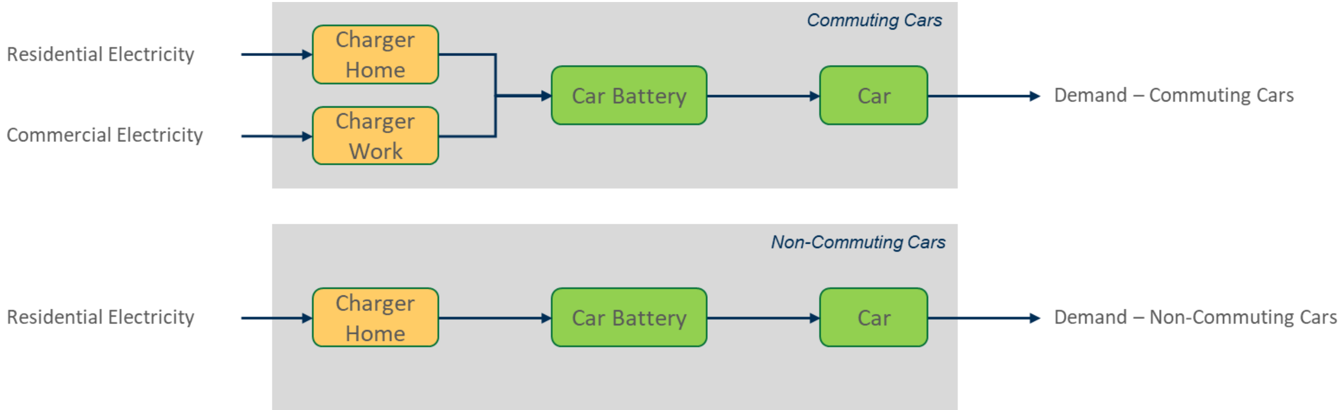

Figure 6: Scheme of charging options for EVs in TIMES-EPOC

Other assumptions have been used when building this sector:

- All internal combustion engine cars (ICEs) can use, with a share up to the 20%, biofuels to be powered
- All cars have been assumed of medium size for the techno-economic parameters
- Being the demand split between the different modes, no modal shift is accounted

End demands are defined and quantified in two different ways: for the navigation and aviation they are based purely on energy demand, while for road and rail transport in TIMES-EPOC are measured in billion passenger-kilometres (for passenger transport demands) and in billion ton-kilometres (for freight transport demands). Demand projections for 2050 are derived from TML's TREMOVE model, which predicts an expected increase in demand of approximately 8-13% for all road transport subsectors, while rail transport is projected to experience a growth of nearly 30%.

Table 6: Transport sector demand definitions and projections

Subsector	Category	Unit	2018			2050		
			BR	FL	WA	BR	FL	WA
Aviation	International aviation	TWh	-	49.96	22.45	-	71.08	31.94
	Domestic aviation	TWh	-	0.10	0.15	-	0.14	0.21
Navigation	Inland navigation	TWh	0.03	4.83	0.65	0.03	4.83	0.65
	International bunkers	TWh	-	393.4	-	-	393.4	-
Road	Bus - Coach/Intercity	Pkm*10^9	0.57	4.19	2.64	0.44	5.08	2.87
	Bus urban	Pkm*10^9	0.56	4.80	2.81	0.50	5.80	2.81
	Car – Commuting	Pkm*10^9	3.20	42.38	22.80	1.65	39.74	28.85
	Car – Non-Commuting	Pkm*10^9	2.52	33.30	17.91	1.30	31.23	22.67
	Freight – Heavy Duty	Tkm*10^9	0.10	8.16	4.07	0.09	10.27	4.76
	Freight – Light Duty	Tkm*10^9	0.79	10.99	6.76	0.51	11.48	7.85
	Motorcycles	Pkm*10^9	0.06	1.20	0.84	0.03	4.83	0.65
Rail	Rail Freight	Tkm*10^9	2.59	6.40	4.59	4.26	10.53	7.55
	Passengers Light	Pkm*10^9	0.29	0.65	0.50	0.32	0.71	0.55
	Passengers Heavy	Pkm*10^9	2.78	7.39	5.04	3.07	8.15	5.56

2.5.3 Residential

As to the residential sector, we use a detailed typology of buildings for each region. In the base year, our residential sector is divided in 12 different categories depending on the Region and on the number of facades. For each category, the surfaces (m^2) of buildings and the net needs (PJ/m^2) for space heating and DHW are differentiated.
The base year is calibrated using the regional energy balances. For the future, the model can choose to invest in numerous different technologies and retrofitting options: e.g., we define different types of boilers, heat pumps, etc. There are many different types of renovations options, depending on what is renovated (walls, roofs, windows, floors), on the type of building (the number of facades) and on how old the building is (we consider 5 different periods of construction).

EnergyVille, a member of the consortium, uses many data sources (national cadaster, JRC IDEES 2015, Tabula, Statbel, regional energy balances, warmtekaart) in order to obtain the detailed data on surfaces and net needs which we feed into our TIMES model (see the Buildings task in the EPOC report for more details). Technical and economic data for four types of retrofitting options (for each of the building categories) also come from EnergyVille. Data on new technologies come from TIMES-Wal (Coppens et al., 2022).

The demand (in m^2) follows the projected evolution of the number of households (BFP and Statbel, 2020). We also consider a demolition rate of 0.075% in Brussel and of 0.2% in Wallonia and Flanders. The net needs of new buildings are defined as equal to the needs of buildings built in 2015 (according to the data from EnergyVille Building Energy Calculation Service). We consider a maximum annual rate of renovation of 4%.

Table 7. Building stock

	Building stock in 2018 (Mm²)			Building stock in 2050 (Mm²)		
	BR	FL	WA	BR	FL	WA
2 Facades (existing)	16	93.56	62.29	15.62	87.57	58.31
2 Facades (new)	0	0	0	0.7	33.76	4.56
3 Facades (existing)	2.26	83.63	56.09	2.21	78.28	52.5
3 Facades (new)	0	0	0	0.07	8.3	4.04
4 Facades (existing)	1	153.12	88.52	0.98	143.32	82.85
4 Facades (new)	0	0	0	0.03	8.27	6.45
Apartment (existing)	15.81	33.6	10.65	15.43	31.45	9.97
Apartment (new)	0	0	0	0.81	6.97	1.79

Table 8. Demand driver: expected evolution of the number of households (millions)

	2018	2020	2030	2040	2050
Brussels	0.54	0.55	0.56	0.57	0.57
Flanders	2.79	2.83	2.99	3.12	3.21
Wallonia	1.57	1.59	1.67	1.74	1.77

Table 9. Demand driver: GDP growth (with GDP standardised at 1 in 2018). Data come from regional projection (BFP et al., 2020) for the short term and from European projections (recommended parameters provided by the European Commission for the mandatory reporting of national GHG projections) for the medium and long term.

2018	2020	2030	2040	2050
1	0.91	1.09	1.25	1.42

2.5.4 Commercial

The commercial sector is divided into 6 subsectors: catering, hotels and shops, offices, education, health care, other services and datacentres. We define 3 main types of demand: space heating, space cooling and hot water for each subsector (except for the datacentres subsector where we only define an electricity demand). Moreover, we consider other generic demands (non-specific to subsectors) such as cooking and lighting. All the demands are expressed in energy terms (PJ).

Depending on the subsector, the evolution of the demand in the future is either driven by GDP expected growth or by the expected growth of the number of household (see Table 5 and 6). The resulting demands (in PJ) are presented in Table 9.

The base year consumptions are calibrated thanks to the regional energy balances and data on new technologies come from TIMES-Wal (Coppens et al., 2022). As in the residential sector, the model can choose to invest in numerous technologies: e.g., biomass, gas and oil boilers, different types of heat pumps as well as CHPs combined with heat exchangers. There are also 4 types of renovation options (walls, roofs, windows, floors).

We consider a maximum annual rate of renovation of 4%.

Table 10. Commercial demands.

	Demands	Unit	2018	2030	2040	2050
Catering, hotels and shops	Space cooling	TWh	3.7	4.1	4.6	5.3
	Space heating	TWh	6.5	7.1	8.1	9.3
	Water heating	TWh	1.5	1.6	1.8	2.1
Education	Space cooling	TWh	0.4	0.4	0.4	0.4
	Space heating	TWh	1.6	1.7	1.8	1.8
	Water heating	TWh	0.3	0.3	0.3	0.3
Health care	Space cooling	TWh	1.0	1.0	1.0	1.1
	Space heating	TWh	2.5	2.6	2.7	2.7
	Water heating	TWh	0.5	0.5	0.5	0.5
Offices	Space cooling	TWh	2.2	2.4	2.7	3.1
	Space heating	TWh	4.0	4.4	5.0	5.8
	Water heating	TWh	0.9	1.0	1.1	1.3
Other services	Space cooling	TWh	1.7	1.9	2.1	2.4
	Space heating	TWh	4.6	5.1	5.8	6.6
	Water heating	TWh	0.9	1.0	1.1	1.2
All commercial	Refrigeration	TWh	2.7	2.8	2.9	3.0

	Cooking	TWh	3.8	4.0	4.2	4.3
	Datacentres	TWh	1.8	1.9	2.2	2.5
	Lighting	TWh	25.9	28.3	32.3	36.9
	Other Electric	TWh	2.6	2.9	3.3	3.7
	Other Energy	TWh	0.2	0.2	0.2	0.2

2.5.5 Agriculture

The smallest demand sector is represented by agriculture, forestry, and fishing. It contributes to 2.2% of the country's CO2 emissions (2.2 Mt_{CO2})[16]. They come from the combustion of diesel and natural gas, which represent respectively 41 and 33% of the final energy consumption (*Energy balance sheets*, 2020), in the context of activities such as offroad transport and greenhouse heating (*Energy balance sheets*, 2020). To meet heat demand, Combined Heat and Power (CHP) systems partially cover the requirements and also generate a significant portion of the sector's electricity consumption. However, it is essential to note that TIMES-BE primarily focuses on energy-related emissions in the agriculture sector, excluding non-CO2 greenhouse gas emissions associated with land use and livestock from the scope of this study.

The sector's demand, coming from the Eurostat Energy Balance, has been split in four: electric appliances (representing the sector's total current electricity consumption), off-road transport (including the total national offroad transport demand), greenhouse heating and low-temperature heating. The demands are defined in energy terms. In the figure below, the sector structure is reported with the available technologies in order to meet the end demands: the underlined ones are already present in the base year, so they have been subject to calibration.

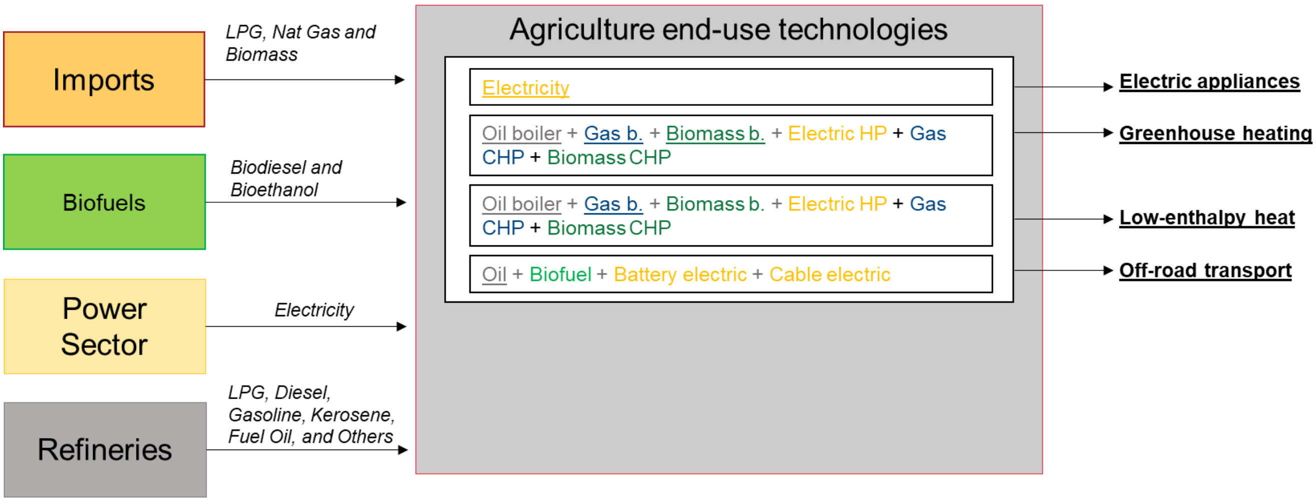

Figure 7: Sector structure, with all end demands (on the right), and full list of technologies available

The sector is described basing on the Eurostat energy balance, with some ad-hoc assumptions, as a flat consumption profile for electric appliances across day and night. The final demands are projected to be constant from the base year to 2050.

[16] https://klimaat.be/doc/nir-2023-15042023-final.pdf

Table 11: Agriculture sector demand definitions and projections

Demand	2018 [TWh]			2050 [TWh]			source
	BR	FL	WA	BR	FL	WA	
Electric appliances	-	1.02	0.06	-	1.02	0.06	Eurostat
Off-road transport	-	0.89	0.44	-	0.89	0.44	
Low-temperature heat	-	0.46	0.21	-	0.46	0.21	
Greenhouse heat	-	4.31	0.44	-	4.31	0.44	

2.6 Scenarios

The description of the model and assumptions provided until this point is valid for all the scenarios which have been studied in the framework of the EPOC project.

In order to study different possible pathways for a deep decarbonization of the Belgian energy system, a number of scenarios were carried out. In this section the assumptions that differentiate these scenarios from each other are stated, and then summarized in the table at the end of the section.

The defined scenarios represent a sensitivity analysis encompassing two primary dimensions. The first dimension involves the consideration of varying degrees of Dunkelflaute events (a German term referring to a period of low simultaneous availability of solar and wind energy production) within the timeframe under examination. This aims to establish a power sector that progressively enhances its resilience to such events. The second dimension pertains to the availability of high-flexibility nuclear reactor technology (SMR, Small Modular Reactor) by 2045, meeting the EU Taxonomy requirements for passive safety, minimal generation of long-lived waste, and non-proliferation.

Finally, a scenario without a climate target (the Business-As-Usual scenario), was included in the set for comparative purposes.

2.6.1 Central Scenario

In the Central Scenario, an increasing carbon tax has been assumed, and applied to all the CO_2 emissions (without a distinction between ETS and non-ETS).

Table 12. Exogenous carbon tax assumptions (all scenarios except the reference scenario).

	2018	2020	2030	2040	2050
Carbon Price [€/tCO_2]	25	50	150	250	350

In addition to this, a Net-zero constraint for 2050 has been applied. This translates into:

1. A target, for 2050, of 2 Mt_{CO2}/y total residual emissions, to allow the industry currently present on the Belgian territory to maintain the local production. In fact, even in the case of a very deep penetration of carbon capture use, more than 1.5 Mt_{CO2}/y would remain from fugitive process emissions. Compensating these emissions by carbon-negative technologies will be cheaper than switching to complete emmission – free production.
2. Absence of carbon-negative technologies such as Direct Air Capture: in fact, given the scarce availability of carbon storage capacity in the Belgian territory, the carbon removal from the atmosphere is more likely to happen in other European regions (e.g., Norway, Iceland). Belgium would then buy carbon credits from these countries. Also negative emissions through biomass are not considered in the model.

2.6.2 Dunkelflaute Scenario

The Dunkelflaute scenario, derived from the German words "Dunkel" meaning “darkness” and "Flaute" referring to a “period without wind”, explores the implications of an extended period of solar and wind scarcity within a fully decarbonized energy system. This scenario investigates the response of the system under conditions of severely reduced solar and wind energy availability. It aligns with the Central scenarios in terms of carbon pricing, emission targets, and the inclusion of carbon negative technologies.

To construct this scenario, a historical-based approach has been employed. Specifically, a past occurrence of one of the most severe Dunkelflaute periods, lasting for three weeks, has been considered. The Royal Meteorological Institute (RMI) has provided insights into this specific event. The capacity factors for solar and wind during this period have been estimated at 3.5% and 13.8% respectively. Additionally, the scenario assumes limited availability of power import from neighbouring countries, mirroring the prevailing conditions during the identified Dunkelflaute episode.

2.6.3 Dunkelflaute Extreme Scenario

The Dunkelflaute Extreme Scenario represents an even more extreme condition for the energy system. Unlike the regular Dunkelflaute scenario, which considers a prolonged period of reduced solar and wind resources, the Dunkelflaute Extreme Scenario assumes the complete absence of solar and wind resources for the designated period. This scenario explores the implications and challenges associated with a complete lack of solar and wind energy availability, pushing the energy system to its limits in terms of resource diversification and resilience.

2.6.4 Nuclear Scenario

In the Nuclear Scenario, investments are allowed in Small Modular Reactor (SMR) technology that complies with the stringent EU Taxonomy guidelines. These advanced reactors, with an average size of 300 Mwe, are assumed to be capable of flexible operation. A synthesized SMR plant, with a flexible operation capability, is assumed with an investment cost of 7500€/kW, encompassing waste management and risk insurance considerations.

Table 13: Nuclar SMR techno-economic assumptions

Starting year of operation	Capex [€/kW]	Fixed OPEX [€/kW/y]	Variable OPEX [€/MWh]	Technical Lifetime [y]	Efficiency [%]	Annual availability [%]
2045	7500	83.3	7.52	60	33	80

2.6.5 Nuclear + Dunkelflaute Scenario

In this scenario, the effect of the combination of the two conditions (limited resource availability for solar and wind, and possibility to invest in a flexible nuclear technology) are combined.

2.6.6 Nuclear + Dunkelflaute Extreme Scenario

In this case, the most extreme Dunkelflaute assumption is combined with the availability of Nuclear SMR from 2045.

2.6.7 Business-As-Usual Scenario

The Business-As-Usual (BAU) scenario, adopted for comparative analysis purposes, represents a no-action scenario in which no emission constraints are assumed. In this scenario, the carbon price is maintained at a constant level of 50€/t, reflecting the 2020 baseline, throughout the entire time horizon until 2050.

Table 14. Scenarios' resume

Scenarios	Emissions-related assumptions	Power sector assumptions
Central	• Exogenous and **increasing carbon tax (up to 350€/t in 2050)** on all sectors' emissions • Target of **2 Mt CO_2 emissions in 2050**	See "Power sector section"
Dunkelflaute	Same as Central	• **Reduced solar** and **wind availability** for 3 weeks period • **Limited availability** of **power import** during the same time
Dunkelflaute Extreme	Same as Central	• **No solar** and **wind availability** for 3 weeks period • **Limited availability** of **power import** during the same time
Nuclear	Same as Central	**Nuclear SMR available from 2045**
Nuclear + Dunkelflaute	Same as Central	Same as **Nuclear Scenario** + **Dunkelflaute Scenario**
Nuclear + Dunkelflaute Extreme	Same as Central	Same as **Nuclear Scenario** + **Dunkelflaute Extreme Scenario**
Business-As-Usual (BAU)	• A **constant carbon tax** of **50€/ton** • **No target on emissions**	Same as Central

3 Results

The Results section of this report is divided into two parts. The first part focuses on the Central Scenario and provides an overview of the general findings, followed by specific results for each end sector.

In the Central Scenario, the analysis reveals key findings that shed light on the overall decarbonization pathway. Then, by examining the sector-specific results, a deeper understanding of the implications for different industries and their contribution to the decarbonization efforts is attained.

The second part of the Results section focuses on the sensitivity analysis, which takes a comparative approach to assess a set of scenarios. Given the influential role of the power sector, the analysis primarily concentrates on this sector. This comparative analysis allows for a more nuanced evaluation of the robustness and adaptability of the power sector under different conditions.

3.1 Central Scenario Results

3.1.1 Global results

The results for the Central Scenario show a progressive decarbonization of the sectors, driven by the increasing carbon price. If comparing these results with the Business-As-Usual Scenario results, a great leap in the effort can be noticed already by 2030, when a 150€/t_{CO2} carbon price already pushes down the emissions from 99 to 54 Mt/y. One aspect to be highlighted is the role played by carbon capture in the transition: already in 2030, the model finds cost-optimal to capture ~15 Mt_{CO2}/y from industry, which slightly reduce towards 2050.

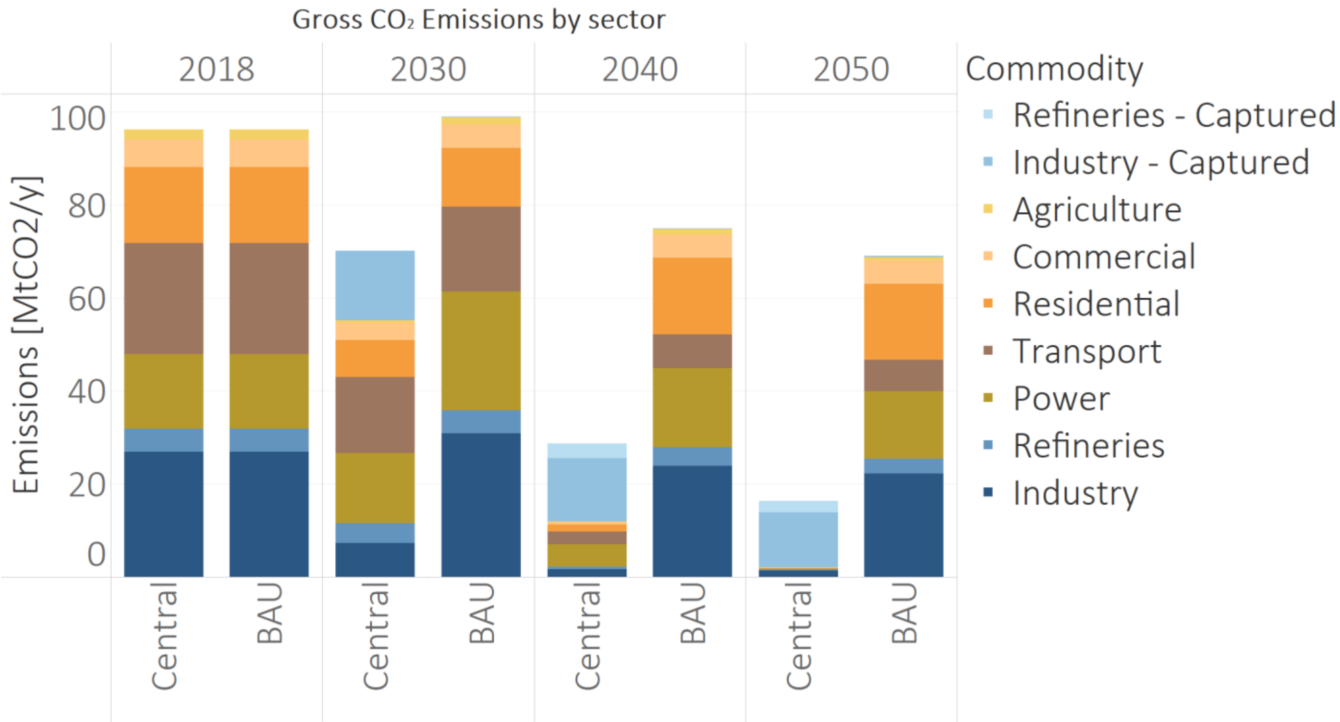

Figure 8: Gross (emitted + captured) CO2 emissions by sector

The cost-optimal solution also suggests a coordinated decarbonization effort across the three regions: in 2030, similarly to the base year, Flanders is responsible for ~70% of the total emissions, while Wallonia covers more than one fourth of the total, and Brussels the 3%. The tendency is confirmed in 2040, while in 2050 the higher concentration of hard-to-abate industries in Flanders determines higher residual emissions.

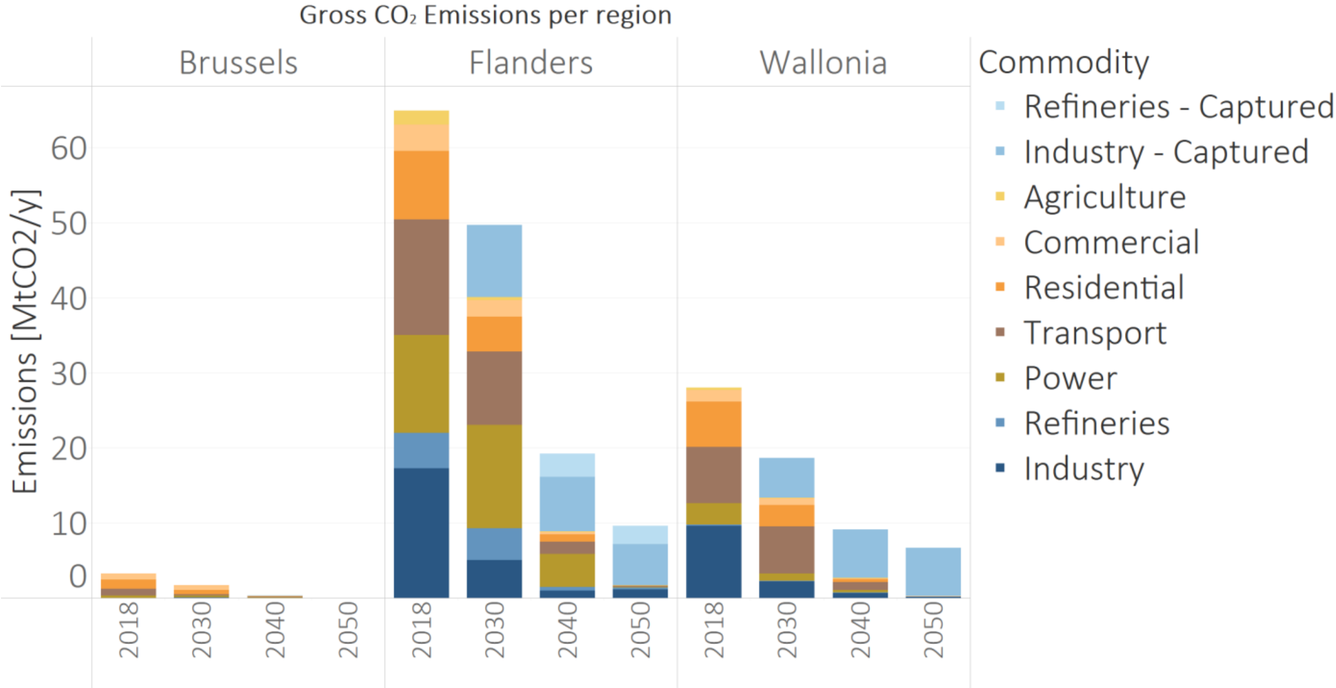

Figure 9: Gross (emitted + captured) CO2 emissions per region, Central Scenario

The analysis of final energy consumption reveals that the primary driver for decarbonization is a profound electrification of end-use sectors. The total electricity consumption doubles in just over twenty years, increasing from 83 TWh in 2018 to 165 TWh in 2040. In contrast, fossil fuel consumption is progressively reduced, and over the same period, it decreases by 80%, dropping from 279 TWh in the base year to 53 TWh.

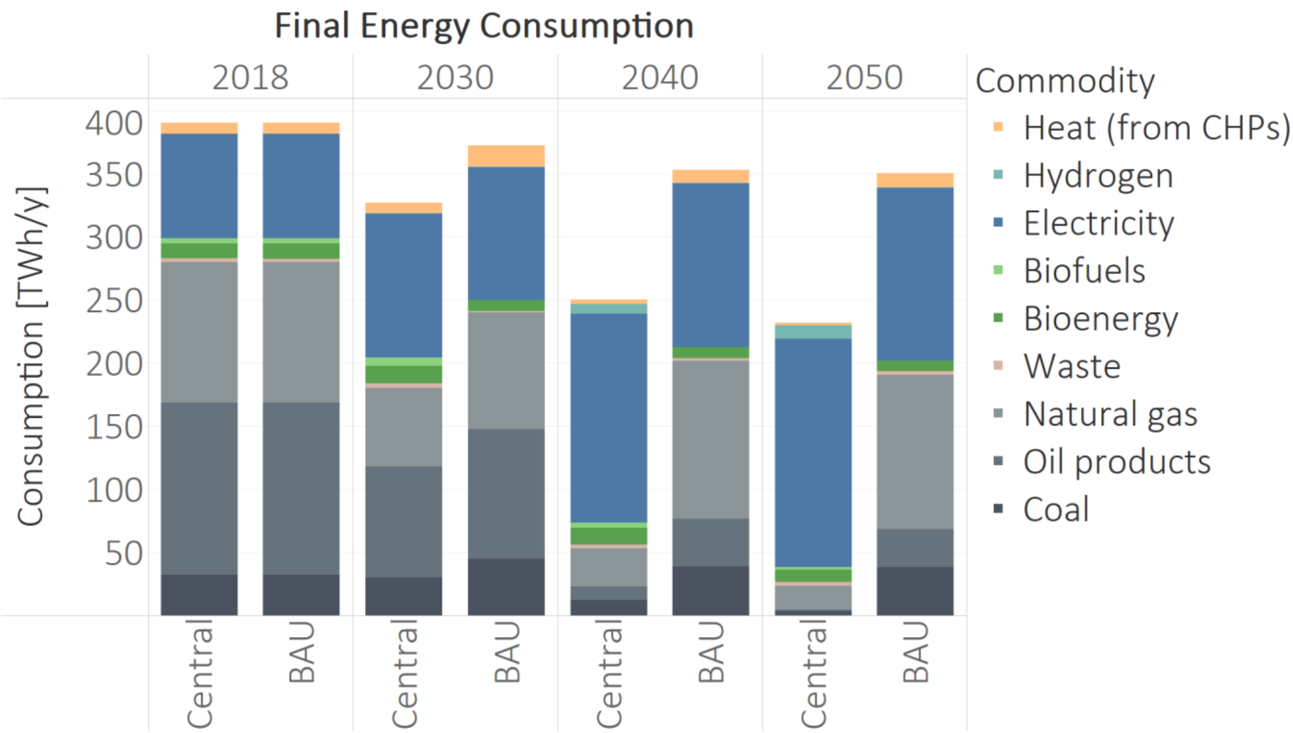

Figure 10: Final energy consumption by commodity
Note: excluding ambient heat

Finally, the system cost of the scenario is presented to provide a quantitative estimate of the economic effort required for its realization. Specifically, the system cost refers to the difference between the Central Scenario and the Business as Usual, expressed in million euros (M€). The cost is split in investments, operational (O&M costs) and energy trading (Flow costs). It can be observed that even in this decade, investments on the order of 2 billion euros per year are needed, along with corresponding operational costs and energy trading expenses. By 2050, these efforts are projected to increase to over 8 billion euros in annual investments, with approximately 1 billion euros in operational costs and another billion euros in energy trading expenses (mainly due to the increase in electricity and hydrogen imports, +7 b€, which are not fully compensated with oil products expenses reductions, -6 b€).

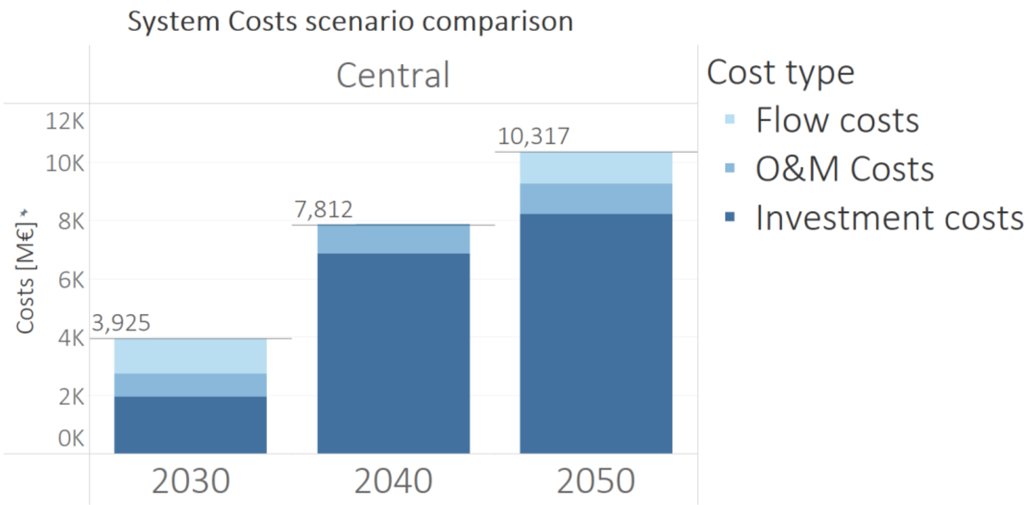

Figure 11: Total additional annual system cost, Central scenario (compared to BAU)

3.1.2 Sector-specific results

3.1.2.1 Industry

The industrial sector assumes a pivotal role in the decarbonization efforts of the Belgian energy system. An in-depth analysis of emission trends within the industrial sector and across different emission categories reveals a significant reduction trajectory by 2030 that aligns with cost optimization principles. This reduction is primarily facilitated by the widespread adoption of carbon capture technologies, playing a paramount role in reducing the emissions in sectors such as chemicals, steel, and non-metallic minerals. Subsequently, an even deeper decarbonization becomes optimal in the following decade, targeting sectors like Pulp and Paper and Other Industry. Nevertheless, in order to reach the emissions target by 2050, the model projects a substantial allocation of over 70% of the residual emissions (1.4 Mt) to the industrial sector, with a particular emphasis on addressing process emissions in the Chemicals and Steel domains.

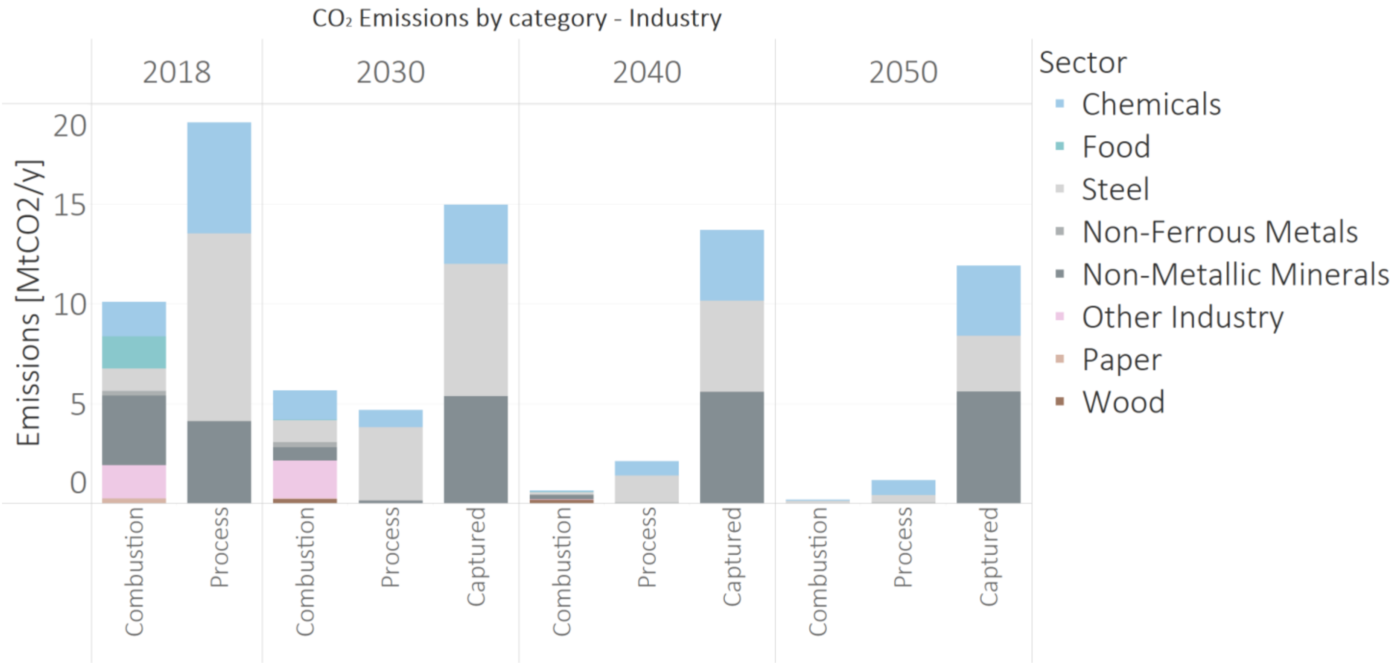

Figure 12: CO2 emissions by category, by industrial subsector, Central Scenario

Shifting our focus to the final consumption within the industrial sector, it becomes evident that the progressive electrification drive is primarily responsible for emissions reduction not attributable to carbon capture. Concurrently, this electrification trend contributes to an overall enhancement in sectoral efficiency, leading to a reduction of approximately one-third in total energy consumption by 2050. Nevertheless, a portion of fossil fuels continues to be utilized until 2050, predominantly in hard-to-abate sectors such as steel and chemicals, which are coupled with carbon capture technologies.

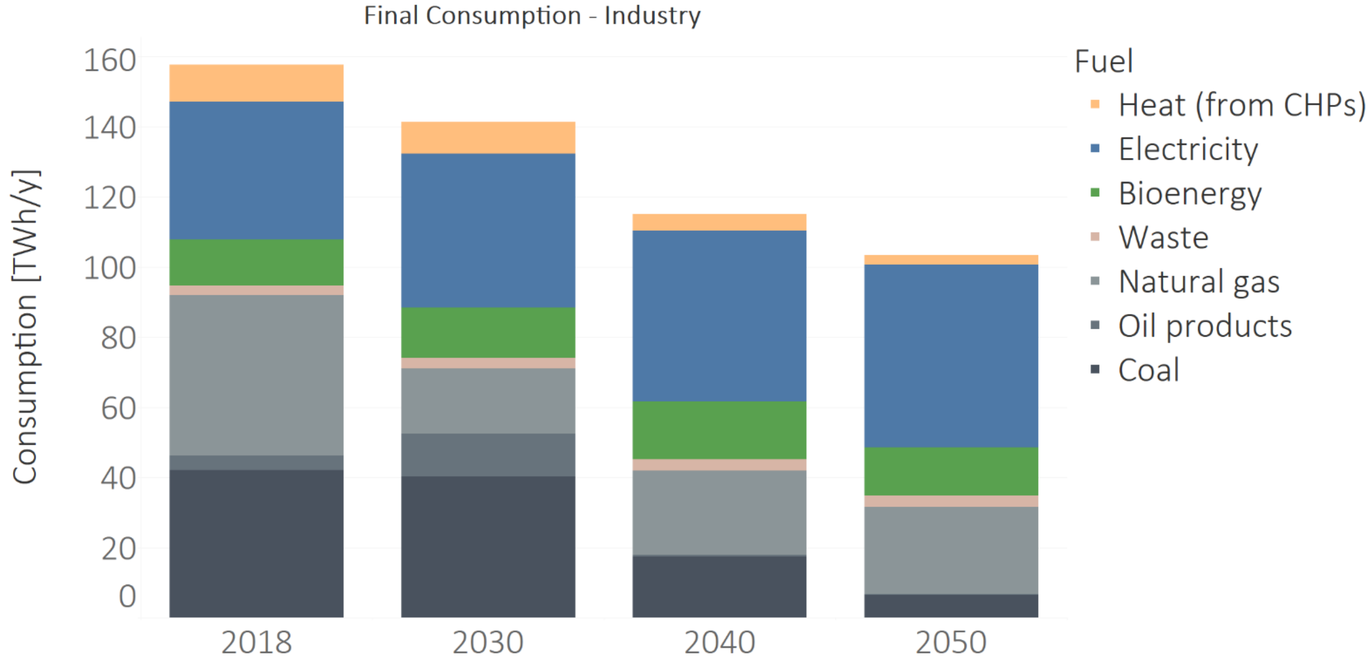

Figure 13: Final consumption (energy and non-energy) - Industrial sector, Central Scenario

3.1.2.2 Transport

The transportation sector emerges as the second-largest emitter in the Base Year, highlighting the significance of its decarbonization. As depicted in the accompanying graph, most domestic emissions originate from road transport (excluding bunkers encompassing international aviation and shipping). The cost-optimal solution proposed by the model entails decarbonization by 2030 for nearly all subsectors, except for road transport. Notably, within this timeframe, a significant leap in decarbonization is observed, particularly in passenger car transport and light-duty vehicles, primarily in the regions of Flanders and Brussels. Subsequently, by 2040, emissions are greatly reduced across all road usage categories, with residual emissions persisting solely in the case of heavy-duty vehicles.

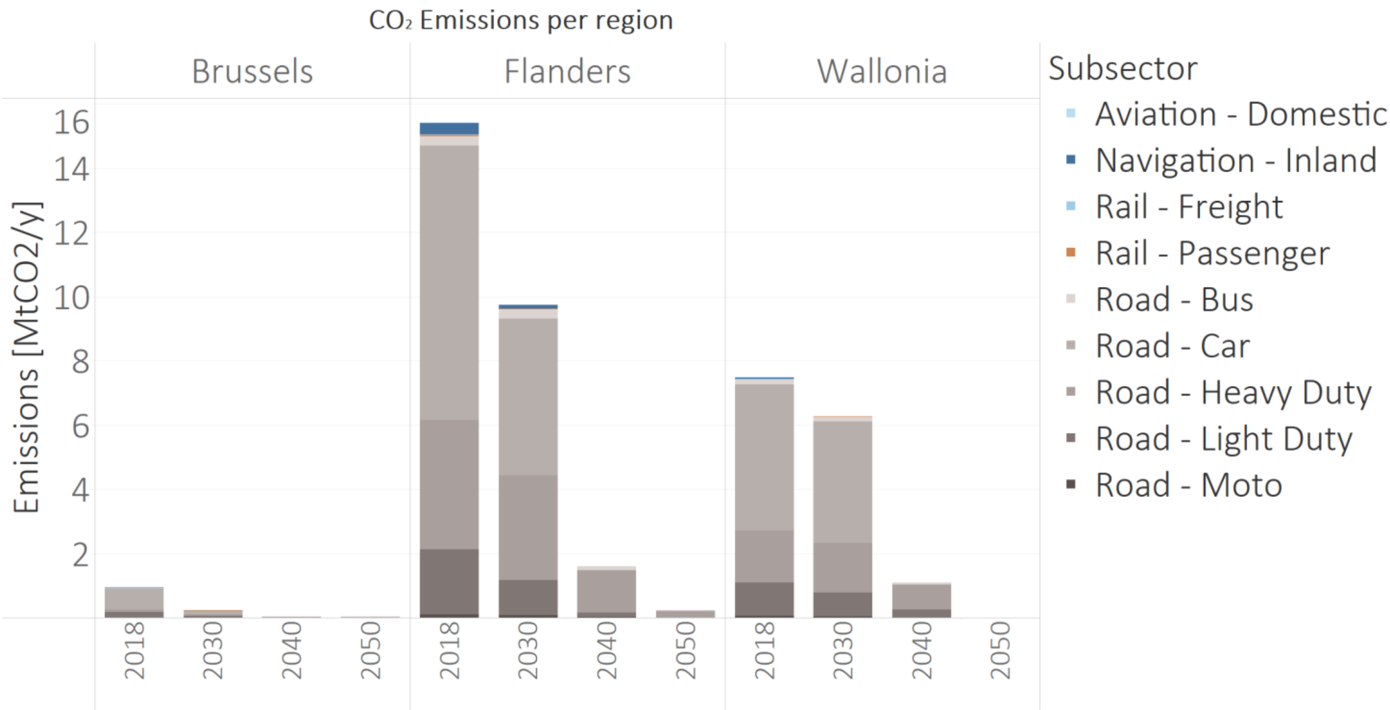

Figure 14: CO_2 emissions per region - Transport sector, Central Scenario

Shifting focus to final consumption, it is evident that the primary driver for decarbonizing road transport is electrification. Electricity consumption for road traffic is projected to reach 8.6 TWh in 2030 (approximately five times the current electricity consumption for rail transport) and 26 TWh in 2050 (exceeding the current electricity consumption in the entire commercial and public services sector).

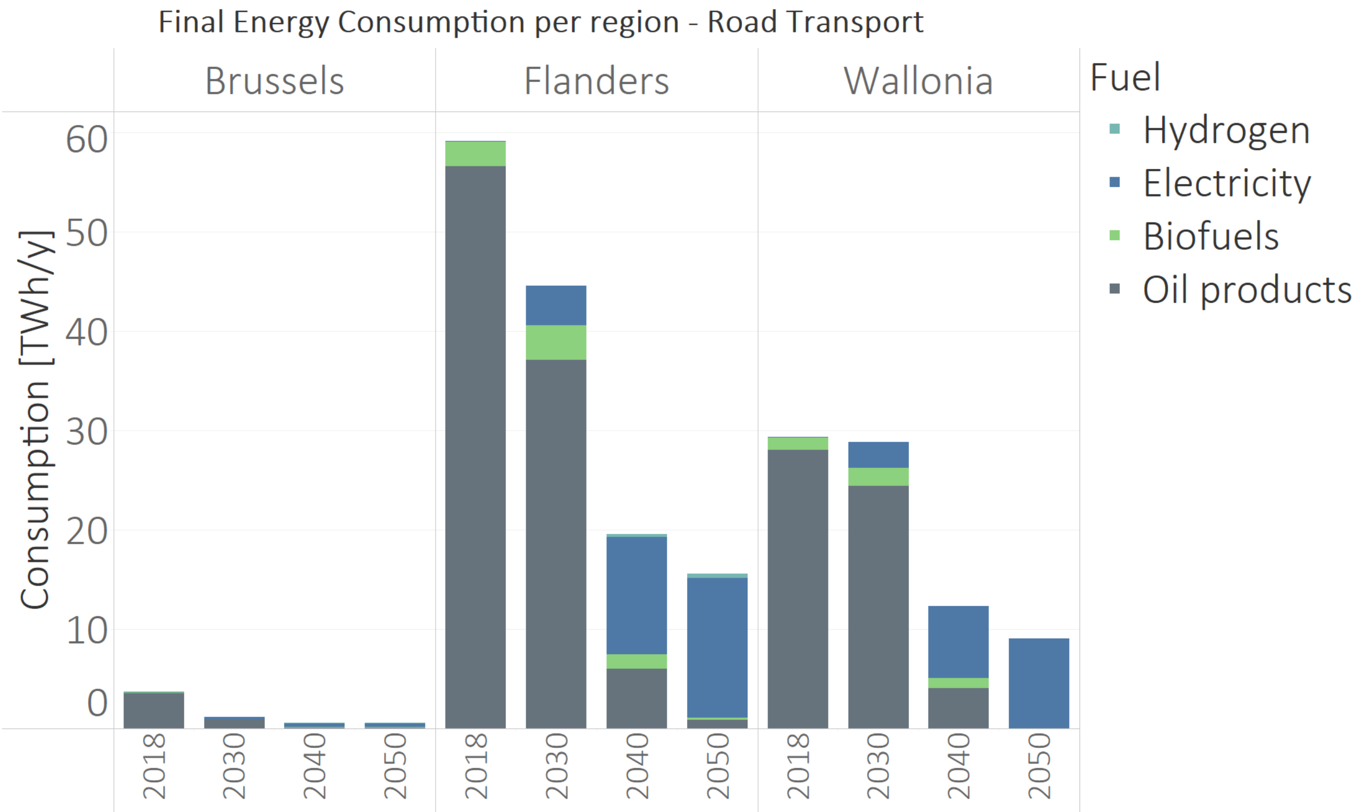

Figure 15: Final Energy Consumption - Road Transport, Central Scenario

The model achieves these targets through significant investments in the sector. For instance, focusing on passenger cars, the numbers projected for 2030 are highly challenging, with approximately 2.7 million electric vehicles (EVs) and 5 GW of EV charging infrastructure to be installed. The replacement of almost the entire current fleet with EVs would occur around 2040, with an estimated 5.5 million EVs and over 10 GW of EV chargers in place.

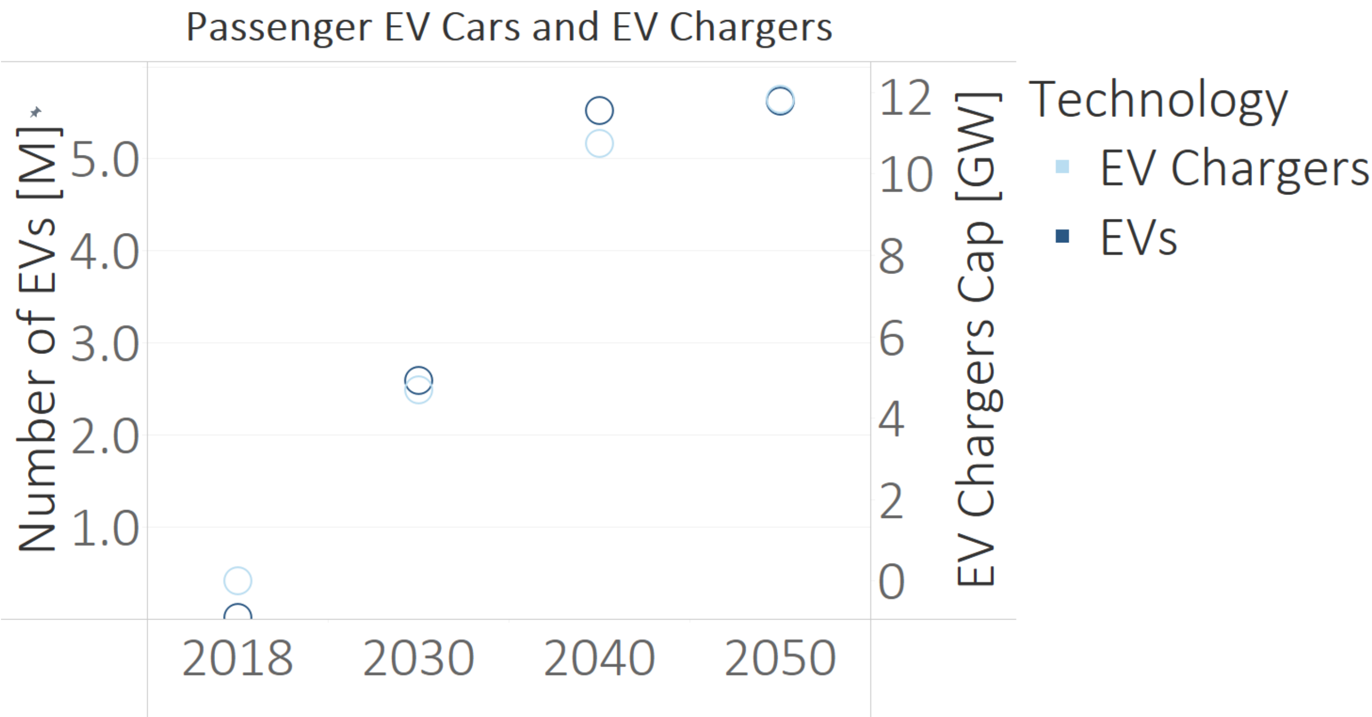

Figure 16: Passenger EV Cars and EV Chargers

3.1.2.3 Buildings

The combination of the residential and commercial sectors accounts for an annual energy consumption of nearly 150 TWh, serving various end demands. While some end uses, such as refrigeration, lighting, and space cooling, are partially electrified, the major energy-consuming applications still rely on fossil fuels. However, in the Central Scenario, a progressive electrification. A limited amount of biofuels may be present in locations where biogas is available via CHP and the waste heat is coupled to heat networks. This transition shows a significant reduction in the fossil fuel component by 2030 compared to current levels, particularly for oil products, which decreases by 45%. It is important to emphasize that the presented results pertain to the heat generation source and do not exclude the potential utilization of district heating networks, for heat transport, even on a large scale.

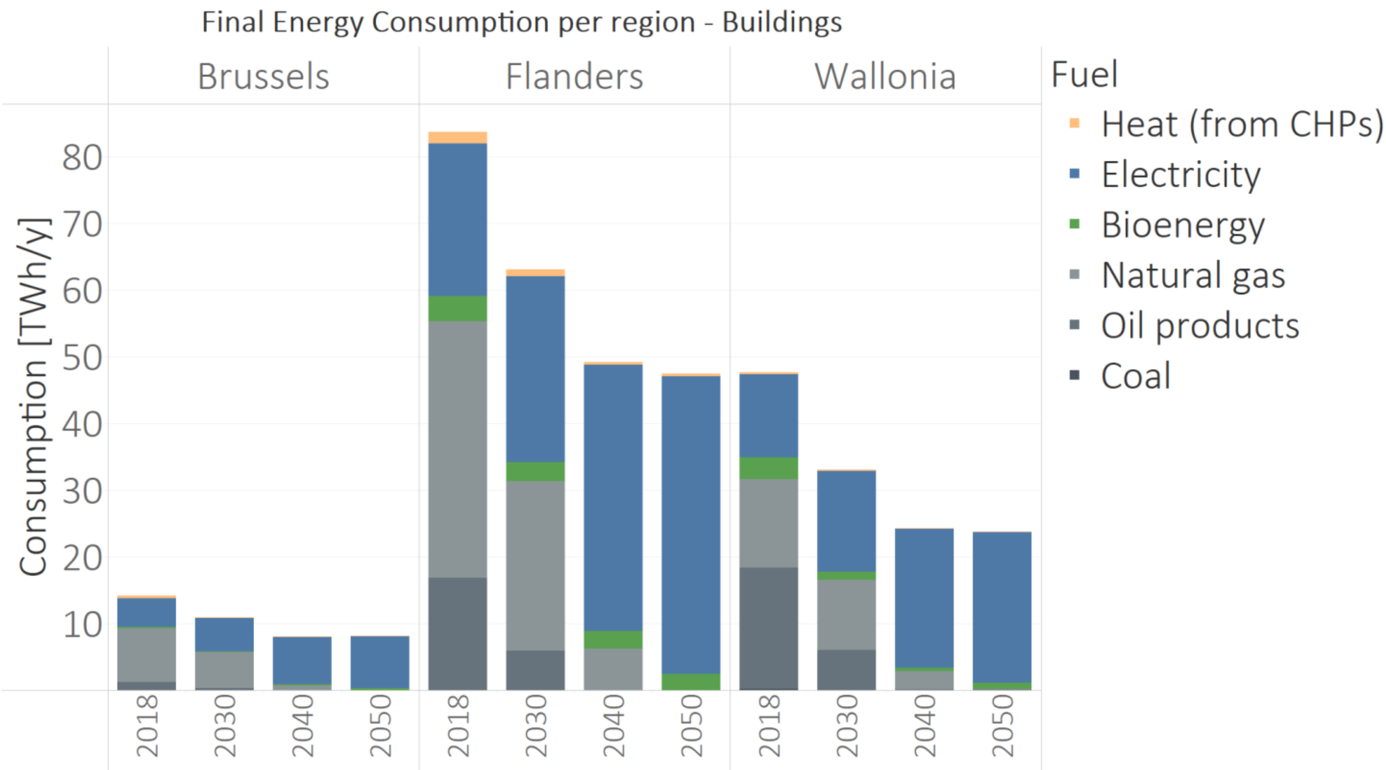

Figure 17: Final Energy Consumption in buildings, Central Scenario

The graph below illustrates the breakdown of emissions by end demand in buildings. It the significant role played by space heating, which was responsible for the majority of emissions in the base year. To address this issue, the primary strategies to be adopted are the widespread deployment of heat pumps and the implementation of energy efficiency measures.

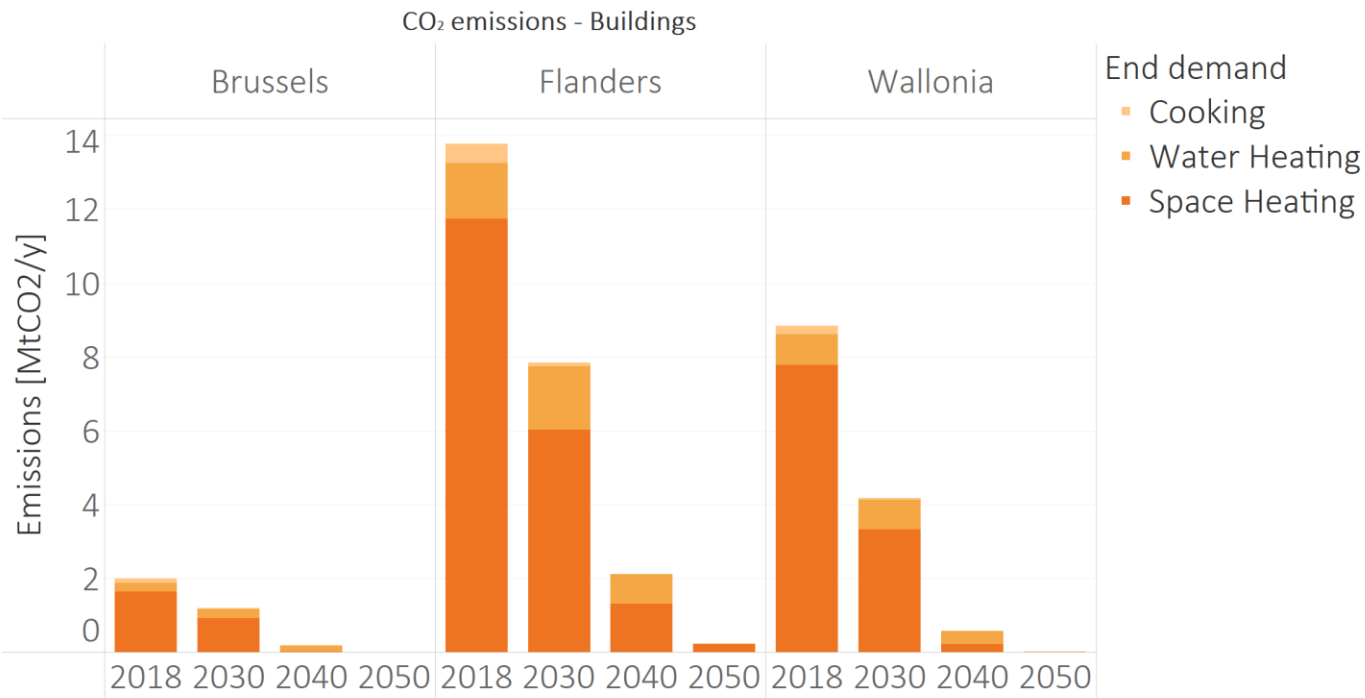

Figure 18: CO2 emissions in Buildings per end demand, Central Scenario

The final graph aims to address this particular aspect, revealing the share of space heating demand covered by energy efficiency savings and the portion met by heat pumps.

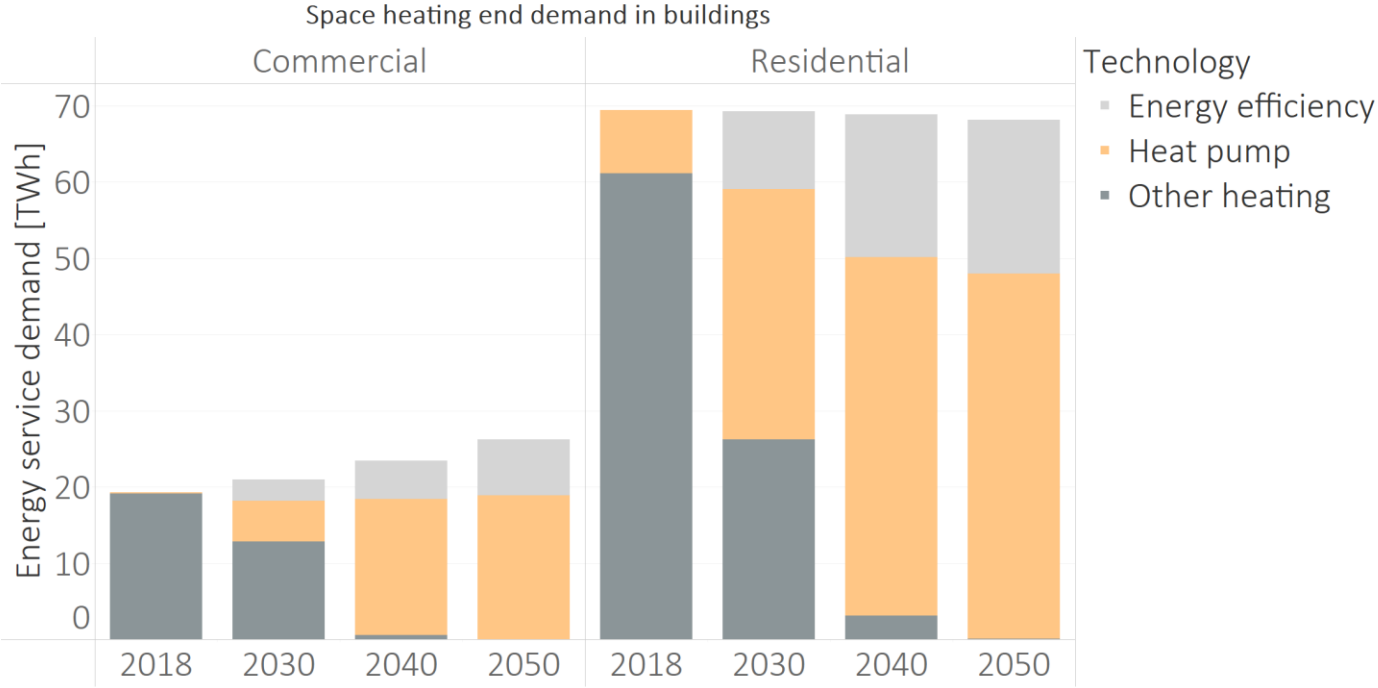

Figure 19: Space heating energy service demand per source, Central Scenario

3.1.2.4 Power

The decarbonization of the energy system heavily relies on the strengthening of the power sector. Summarizing the findings across different sectors, the electricity demand in end sectors is projected to nearly double by 2050 compared to 2018 levels. This trend is observed across all end sectors.

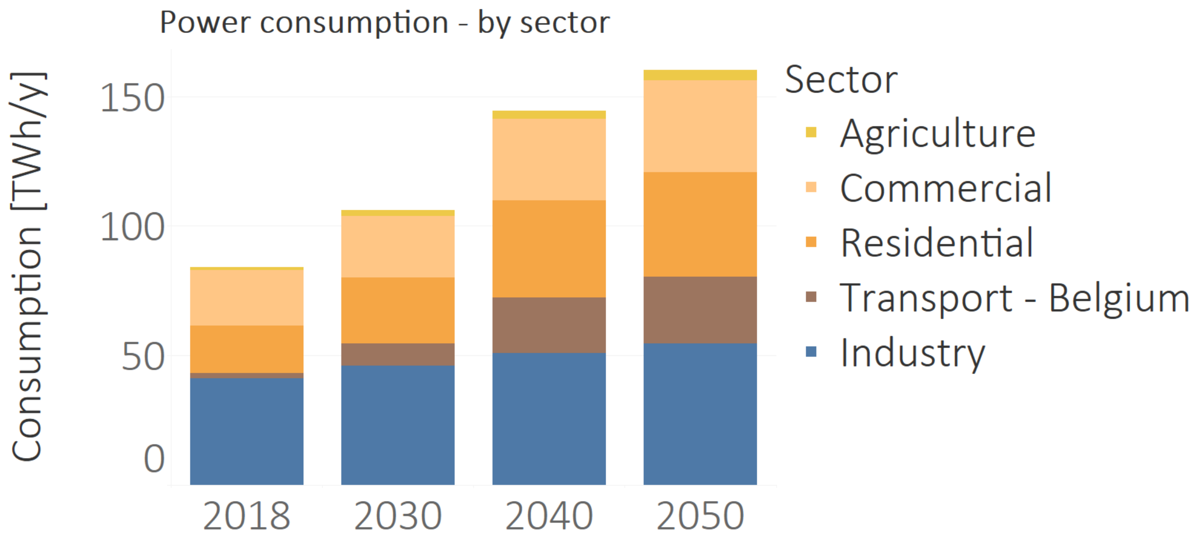

Figure 20: Power consumption - by sector, Central Scenario

Consequently, the power sector faces the challenge of meeting the increasing demand while considering the rising carbon price. The cost-optimal solution entails a significant upfront investment in renewable resources. Specifically, solar photovoltaic capacity expands from the current level of just over 5 GW to 29 GW by 2030, with a further leap to 60 GW by 2050. Similarly, both onshore and offshore wind power prove to be a "no regret" option as investments are made up to their maximum installable potential. New biomass plants, particularly combined heat and power (CHP) are installed (around 1.5 GW), along with 0.5 GW of waste incinerators. Most fossil-based power plants are phased out without replacement.

Starting from 2040, hydrogen turbines emerge as a viable option, with a peak capacity of over 7 GW installed by 2050. This diversification of the power sector with renewable energy sources and the introduction of hydrogen turbines contributes significantly to the decarbonization goals.

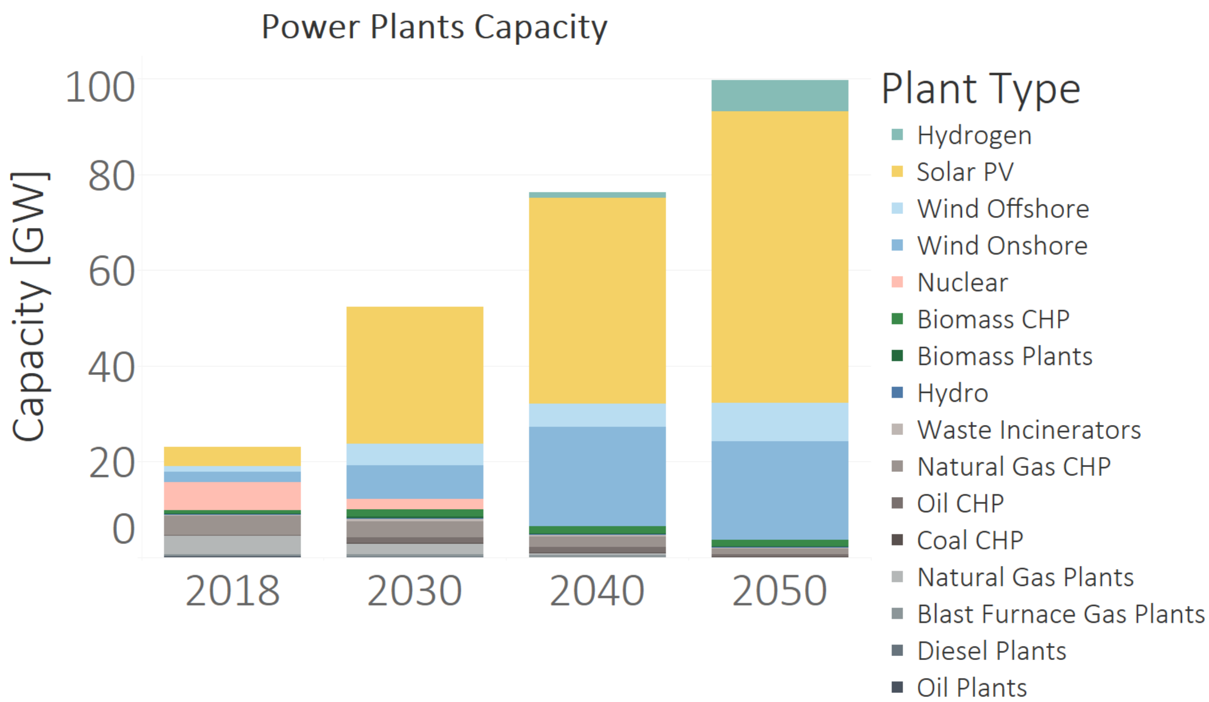

Figure 21: Power plants capacity, Central Scenario

Another crucial player in the power sector transition is energy storage. Specifically, grid-connected electrochemical batteries and electrolyzers emerge as key technologies in achieving the Net Zero target. Ambitious investments are directed towards installing over 7 GW of electrochemical batteries and 8 GW of electrolyzers. It is important to note that these numbers do not include automotive batteries, as they were excluded from the count due to the restriction on Vehicle-to-Grid utilization, mentioned in the Methodology section.

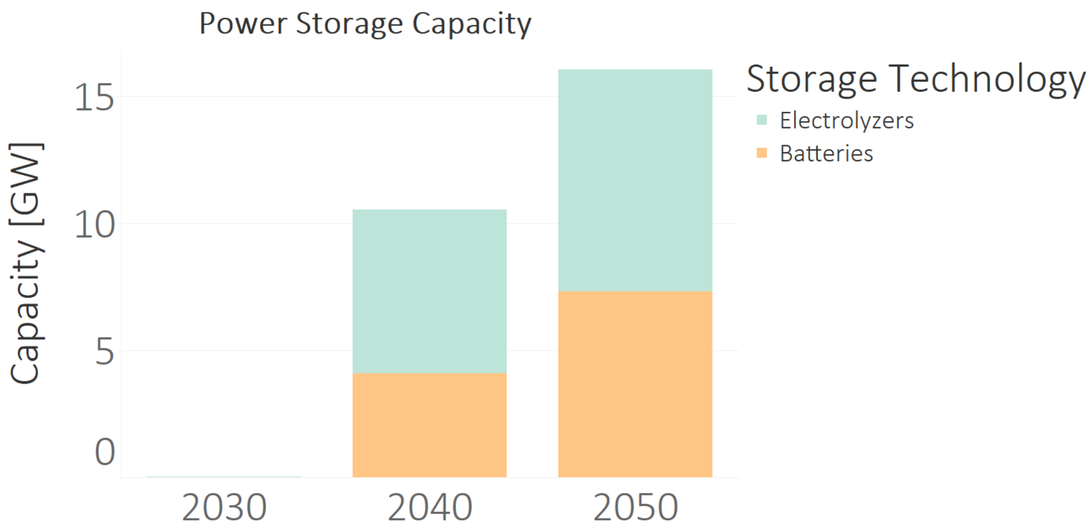

Figure 22: Power storage capacity, Central Scenario

The investments on new power plants and on new electricity storage capacity consequently lead to a substantial increase in domestic production, rising from approximately 77 TWh/year to over 105 TWh/year in 2030 and reaching 143 TWh/year in 2050. This growth is primarily driven by renewable sources, with solar PV accounting for 28 TWh/year of production in 2030 and 56 TWh/year in 2050 (compared to just 4 TWh/year in 2018), and wind power increasing from 8 TWh/year to 30 TWh/year in 2030 and 70 TWh/year in 2050. Biomass also contributes significantly, generating around 10 TWh/year of electricity.

Hydrogen plays a significant role in balancing the system, especially as the power system becomes net zero. In 2050, 21 TWh/year is absorbed by electrolyzers, and hydrogen turbines also come into play, contributing 7 TWh/year.

However, it is important to highlight the significance of imports, which quadruple by 2050 compared to the numbers in 2018 and 2030 (which are roughly equivalent), reaching nearly 50 TWh/year.

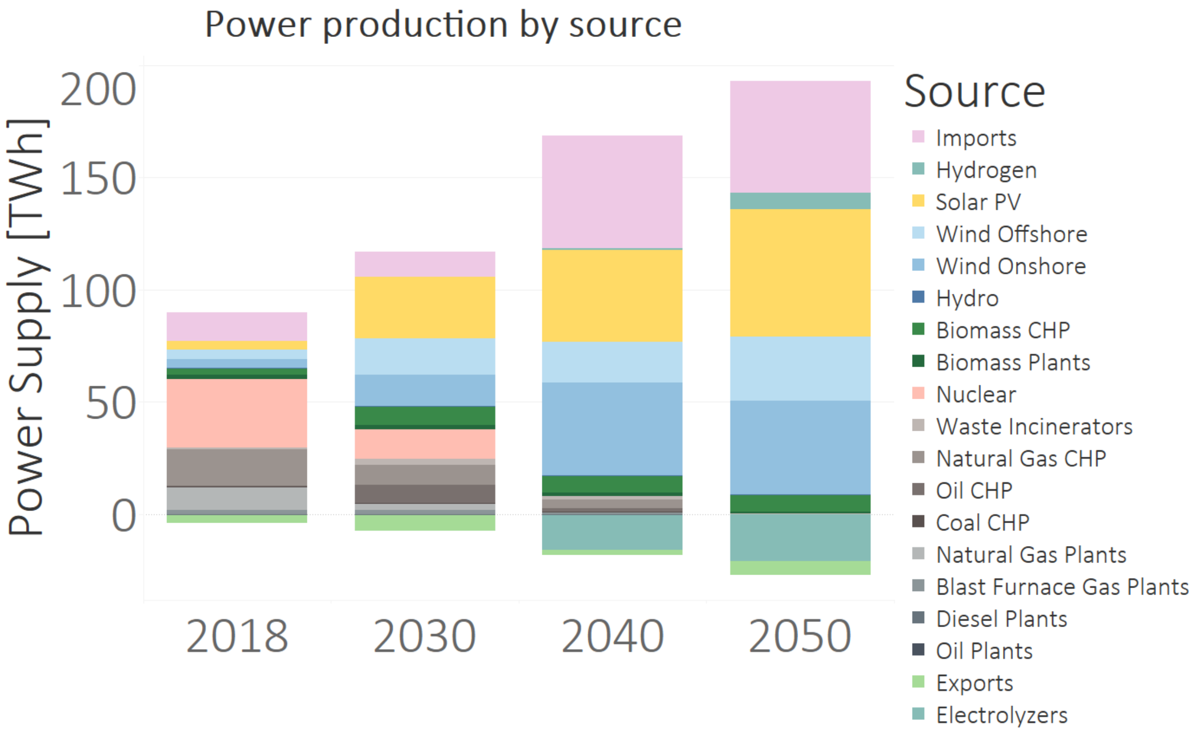

Figure 23: Power production by source, Central Scenario

It is also interesting to delve into the electricity dispatch at bi-hourly level to understand how the fully decarbonized power sector behaves under different climatic conditions and the varying availability of renewable resources. Four representative days from different seasons were chosen to illustrate these dynamics.

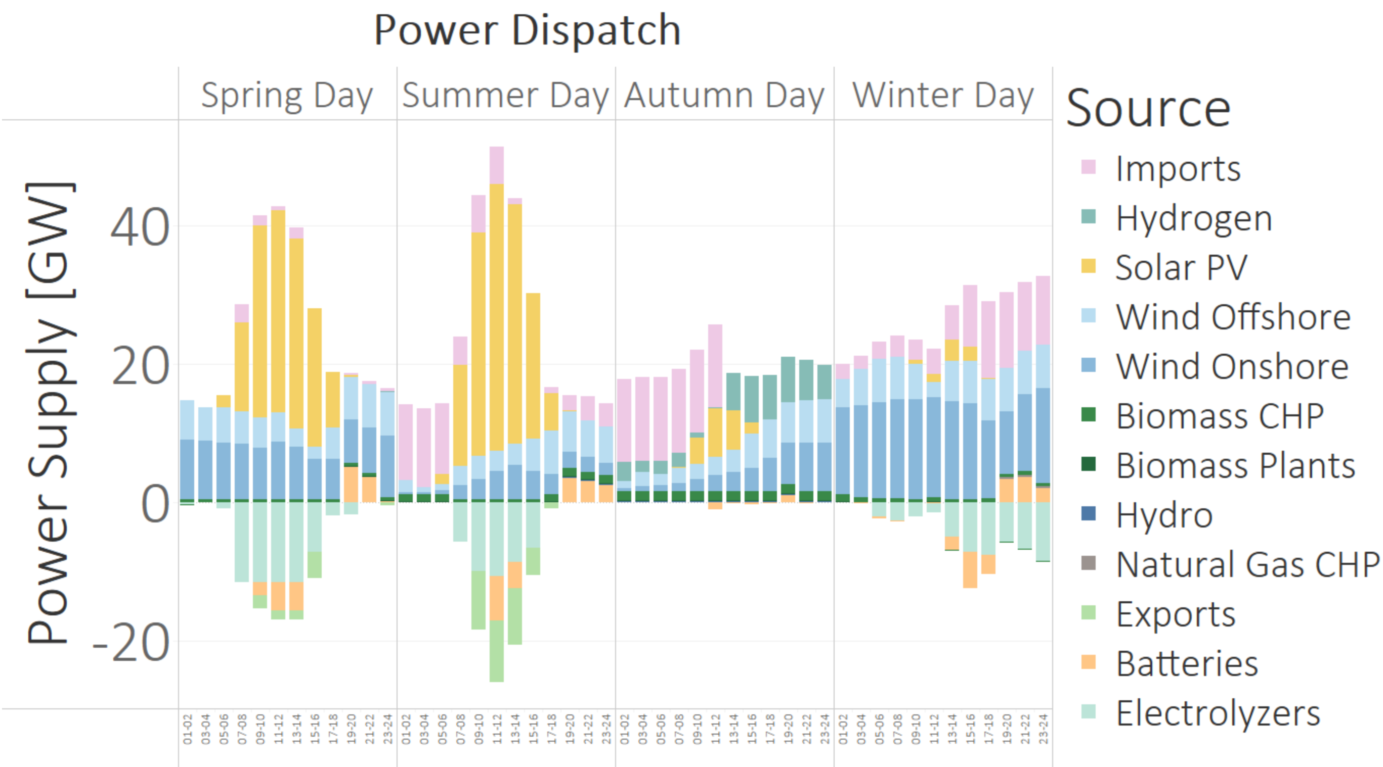

Figure 24: Power dispatch in four typical days, Central Scenario (2050)

On a spring day characterized by abundant availability of solar PV and wind, the surplus electricity is stored using batteries and electrolyzers. During a summer day with less wind but ample sunlight, the strategy involves importing electricity during night-time and storing the excess generated during the day using batteries (which are then discharged at night) and electrolyzers, or even exporting it. Autumn and winter days, with minimal solar production, require variable imports depending on the availability of wind energy, with the exception of the latter half of the autumn day when the hydrogen turbine comes into play.

3.1.2.5 Hydrogen

As it has been highlighted in the previous paragraphs, hydrogen plays a significant role within the results of the Central Scenario. In order to explicitly present the outcomes specifically related to this energy commodity, the following graphs depict the supply of hydrogen divided by source and the demand by sector. It becomes evident the crucial role of hydrogen imports (which would account for two-thirds of the supply in 2050) to meet the demands (mainly industrial until 2040, while one-third would be allocated to the power sector in 2050).

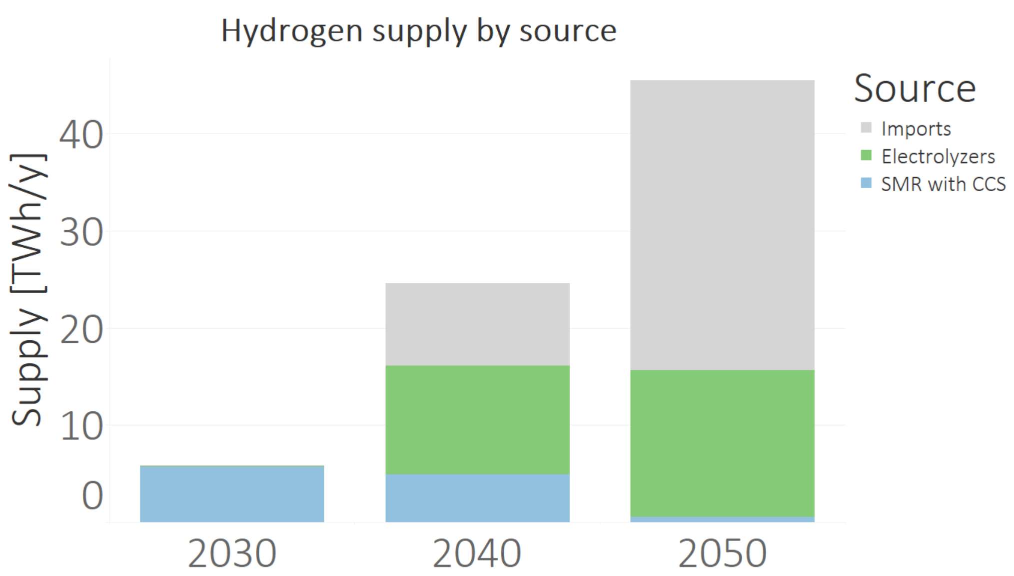

Figure 25: Hydrogen supply by source, Central scenario

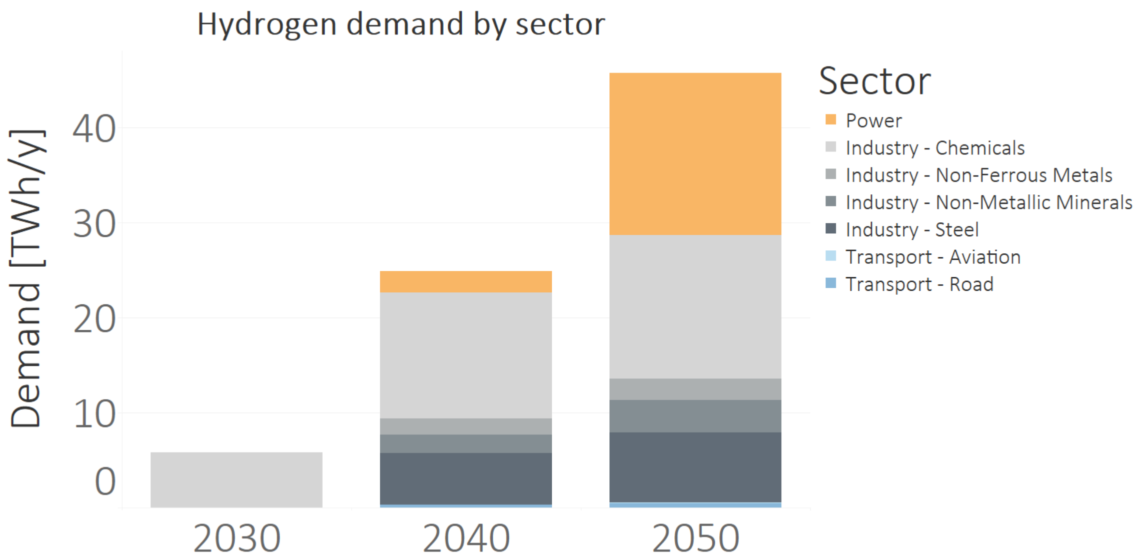

Figure 26: Hydrogen demand by sector, Central scenario

3.2 Power sector focus: sensitivity analyses

3.2.1 What if there is a remarkably long Dunkelflaute period?

The presence of a critical period in electricity production and dispatching due to the scarcity of renewable resources significantly influences the energy mix during that period. In both scenarios, the full capacity of flexible low-carbon resources is utilized. Specifically, in the Dunkelflaute Scenario, in addition to the reduced residual solar and wind energy production, the entire biomass capacity is employed, along with approximately 12 GW of hydrogen turbines operating continuously. In the Dunkelflaute Extreme Scenario, nearly 18 GW of hydrogen turbines are required to meet the demand.

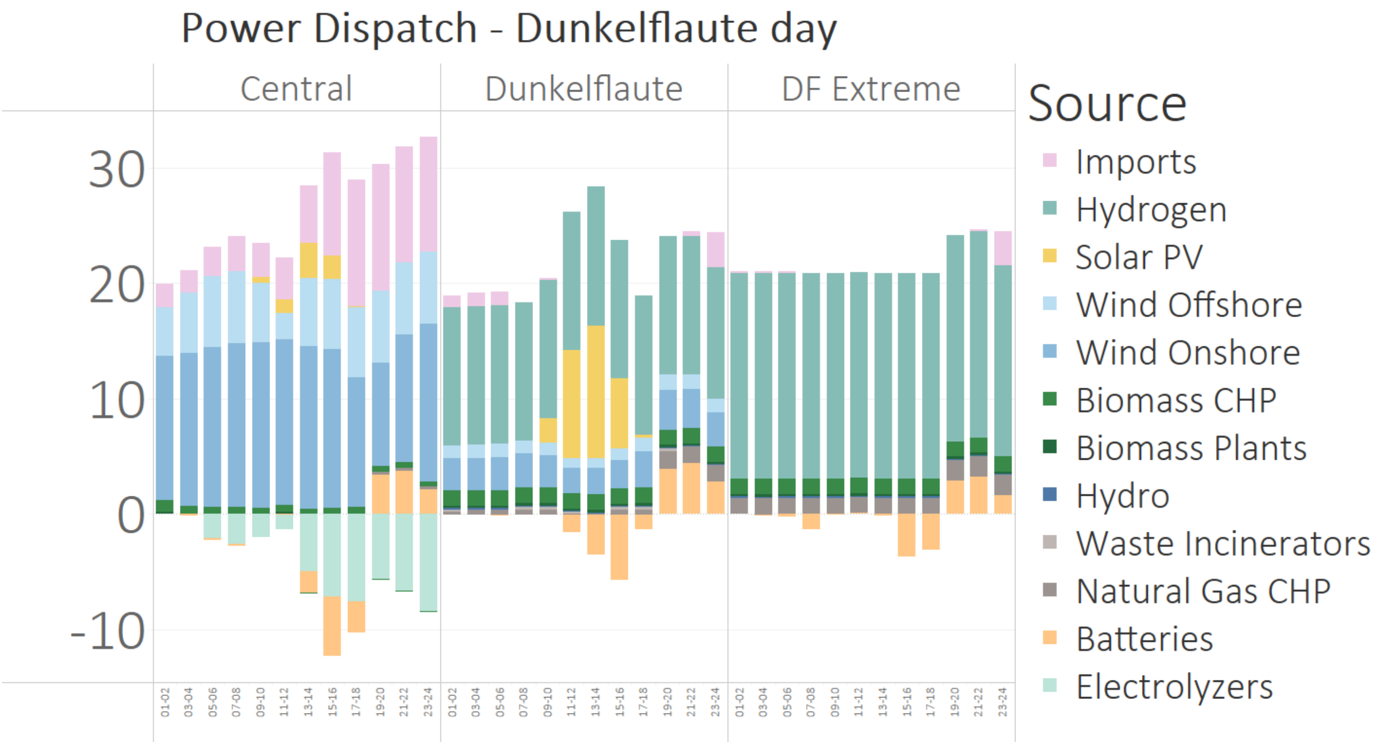

Figure 27: Power dispatch - Dunkelflaute day, scenario comparison

These changing conditions also impact investment choices, with solar PV being a key player. In the Dunkelflaute Scenario, given the non-zero capacity factor of solar potential during the Dunkelflaute day, an overinvestment of around 10 GW in PV is considered cost-optimal, along with the aforementioned 12 GW of hydrogen turbines (instead of 7 GW). In the Dunkelflaute Extreme Scenario, the significant change primarily lies in the quantity of installed hydrogen turbines compared to the Central Scenario, reaching nearly 18 GW.

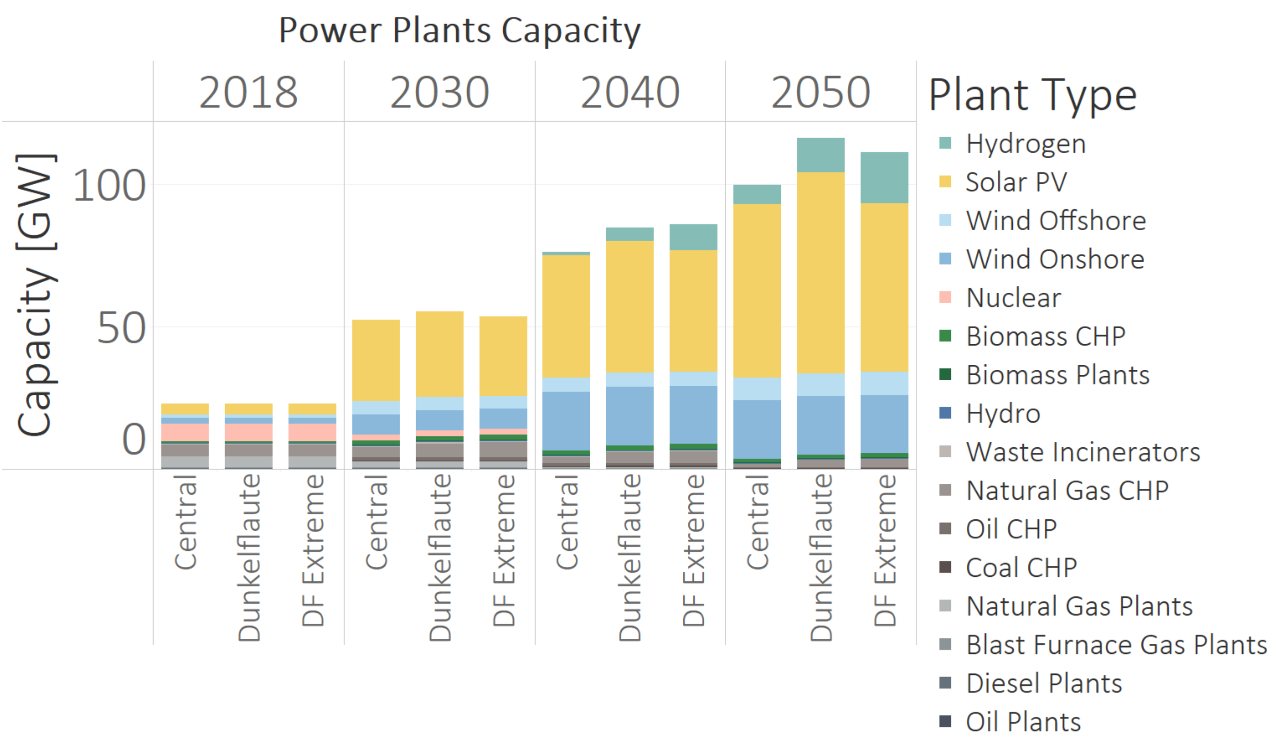

Figure 28: Power plants capacity, scenario comparison

3.2.2 Would Nuclear SMR availability change the picture in 2050?

In the Nuclear Scenario, the goal was to explore the potential of a flexible and low-carbon technology that would only be available in 2045. The results indicate that nuclear power could indeed play a significant role in achieving complete decarbonization of the sector. In this scenario, approximately 16 GW of nuclear capacity is installed, completely replacing the hydrogen turbines and reducing the need for additional PV installations. While the Central Scenario projects an increase of 18 GW in solar PV capacity between 2040 and 2050, with nuclear power available, the capacity actually decreases to levels similar to those of 2030.

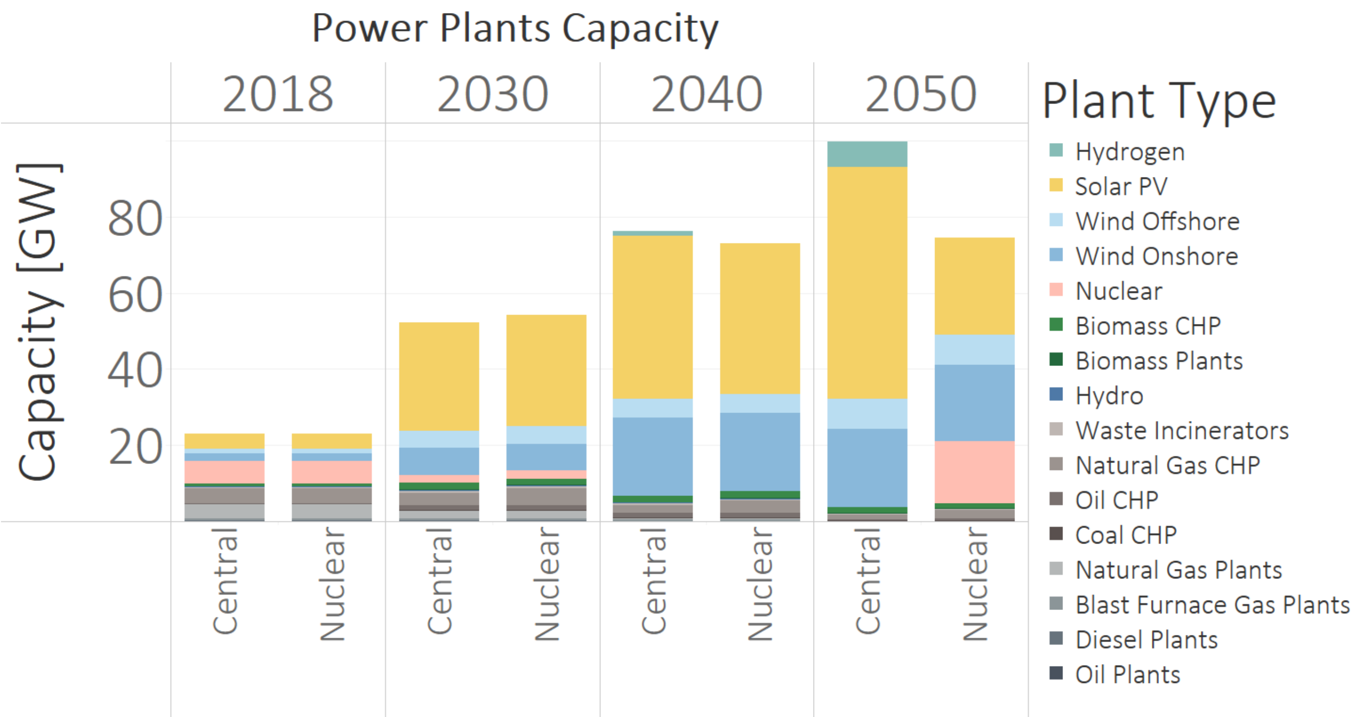

Figure 29: Power plants capacity, scenario comparison

Such a large-scale investment in nuclear power would result in a substantial contribution to the Belgian energy mix, generating 114 TWh of electricity. This would significantly reduce the need for imports (16.3 TWh instead of 50 TWh) and increase the export of low-carbon electricity.

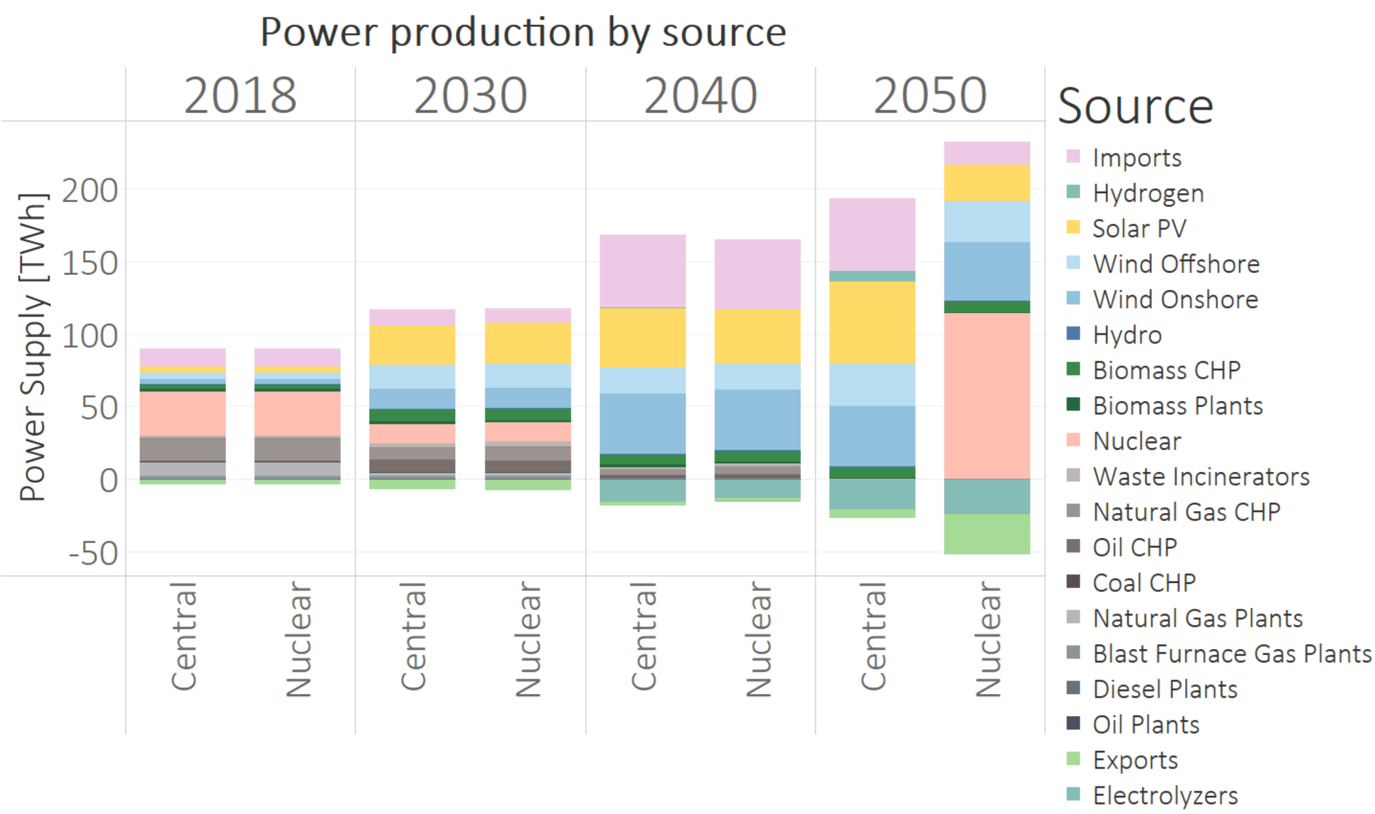

Figure 30: Power production by source, scenario comparison

3.2.3 Would nuclear SMR availability help in case of a Dunkelflaute period?

As observed in the Dunkelflaute and Dunkelflaute Extreme scenarios, when variable renewables are not available, flexible and low-carbon resources become crucial. Therefore, as expected, in the Nuclear + Dunkelflaute and Nuclear + Dunkelflaute Extreme scenarios, the impact of Nuclear SMRs becomes even more significant.

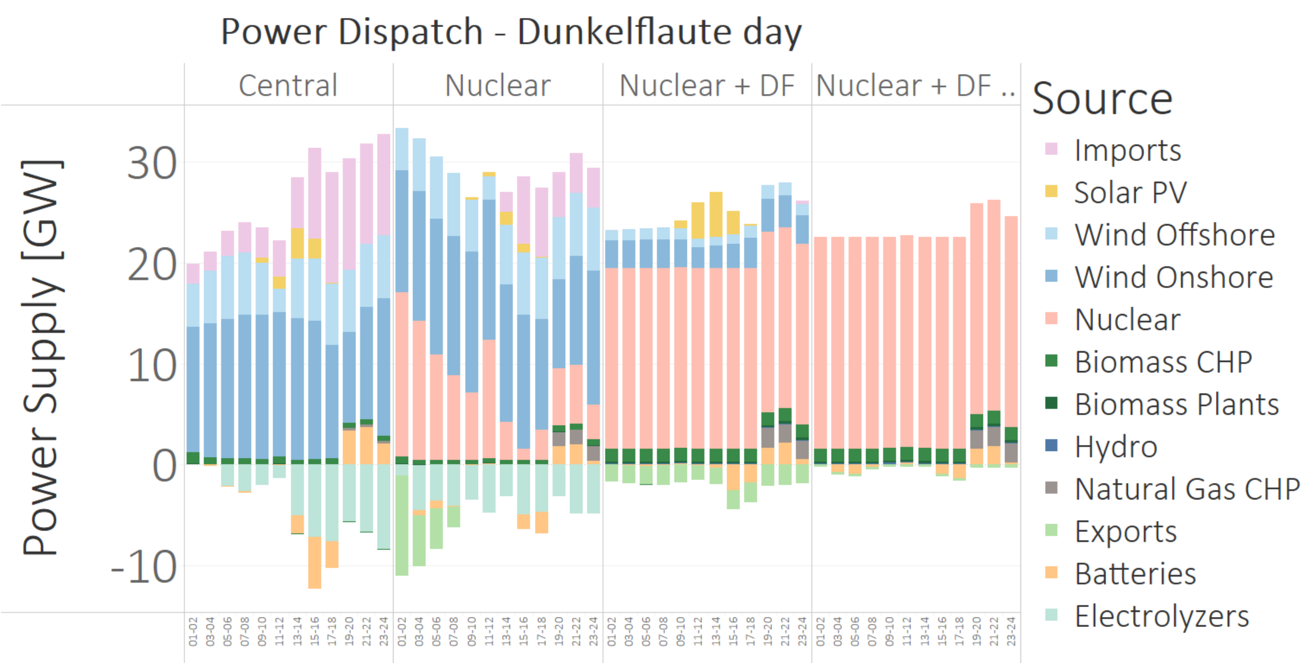

Figure 31: Power dispatch - Dunkelflaute day, scenario comparison

Indeed, in these scenarios, the cost-optimal installed capacity of Nuclear SMRs reaches nearly 18 GW and almost 21 GW, respectively. This capacity is over four times higher than the currently installed nuclear capacity. Once again, the decision to invest in this technology results in a reduction in solar photovoltaic investments. In the Nuclear + Dunkelflaute and Nuclear + Dunkelflaute Extreme scenarios, the solar photovoltaic capacity levels in 2050 are similar to the Nuclear scenario (25 GW). Moreover, in the Nuclear + Dunkelflaute Extreme scenario, given the very large amount of SMR installed, wind installed capacity is also affected (for the only time in all the scenarios analyzed), as it is not installed to its maximum potential, stopping at 17 GW onshore and 5 GW offshore.

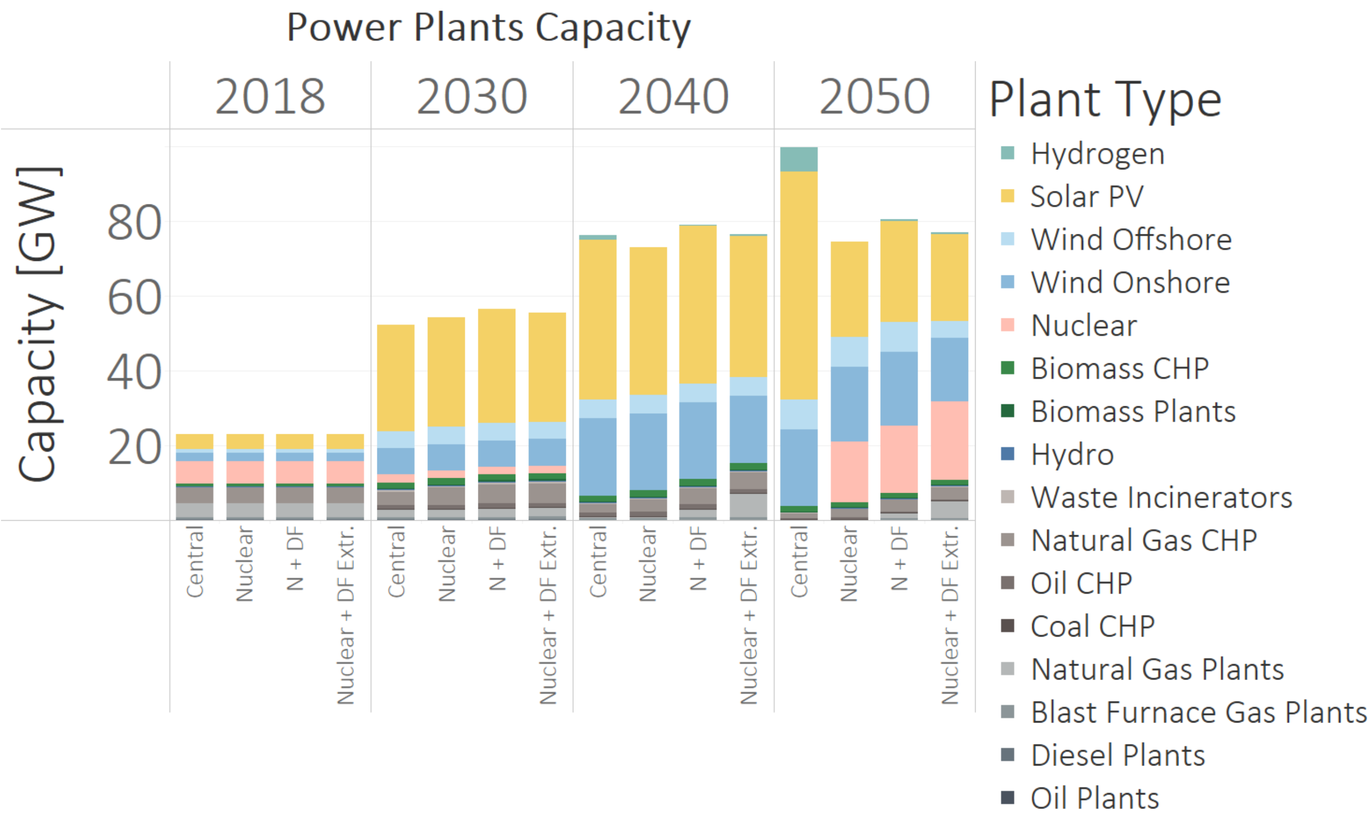

Figure 32: Power plants capacity, scenario comparison

In scenarios with nuclear availability, the SMR (Small Modular Reactor) technology is utilized as baseload power, as expected. The following graph is designed to illustrate the contrasting usage of two low-carbon and flexible technologies: SMRs and hydrogen turbines. To make a fair comparison, two scenarios are considered: Dunkelflaute and Nuclear + Dunkelflaute, under identical weather conditions, with a capacity of 12 GW for hydrogen turbines in the former and 18 GW for SMRs in the latter.

It can be observed that in the Dunkelflaute scenario, hydrogen turbines are utilized primarily as peaking capacity during periods of low renewable energy production (afternoon-night of the autumn day and Dunkelflaute). On the other hand, in the Nuclear + Dunkelflaute scenario, SMR reactors are employed as baseload power, operating almost constantly, except during periods of exceptionally high renewable energy generation, such as the midday hours in spring and summer. It should be noted, however, that start-up costs and ramp-up times have not been considered for either technology (although they are claimed to be very low).

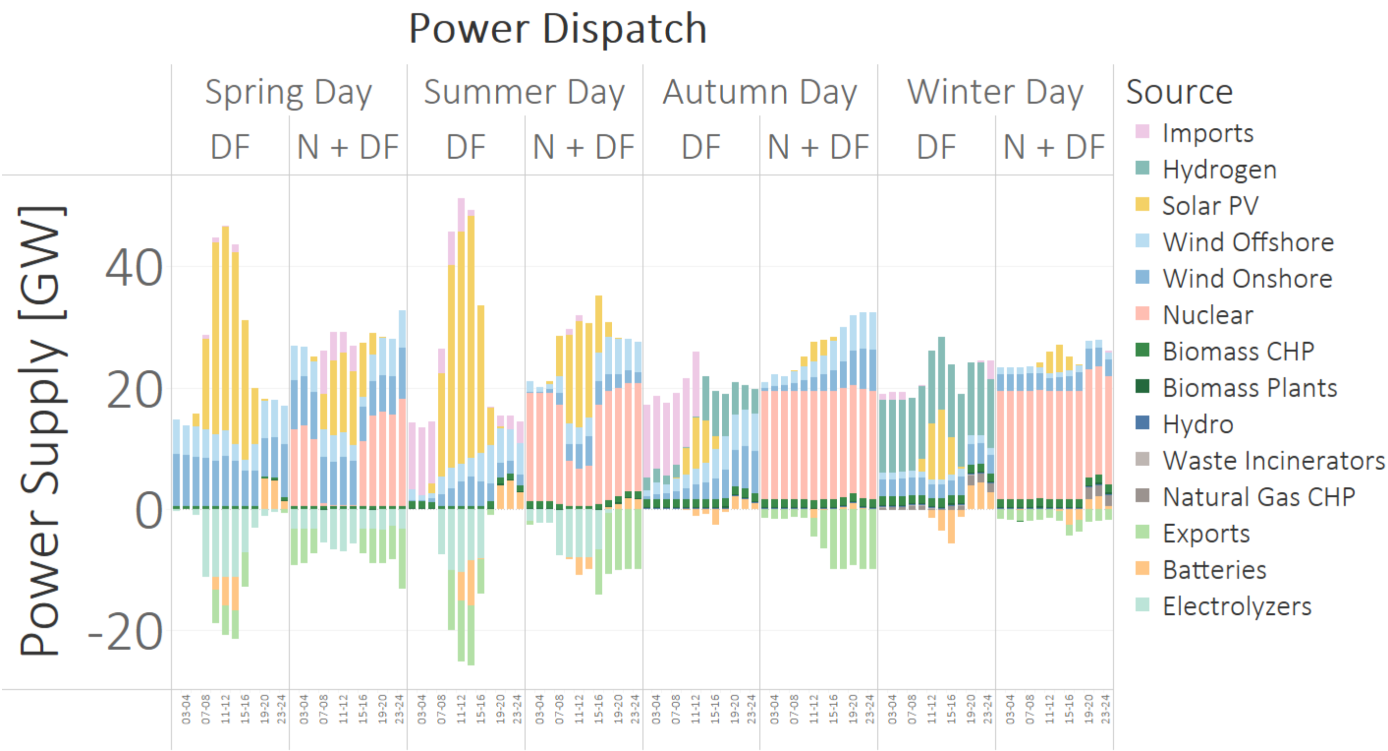

Figure 33: Power dispatch in four typical days, scenario comparison

3.2.4 Electricity price

It is highly interesting to examine the marginal prices of electricity in the various net-zero target scenarios. The graph below shows the electricity marginal prices in all time-slices (with the ones of the Dunkelflaute day highlighted in red), with a whisker highlighting the range of 1.5 the IQR. The average value is highlighted in yellow and with a label showing it. Once again, the six scenarios were taken into consideration. The following graph illustrates how decarbonization leads to an increase in electricity prices, peaking in 2040, where the Central Scenario shows an average price just above €110/MWh. During this period, all scenarios exhibit high price volatility, reaching values above €250-300/MWh. This pattern repeats in 2050 for all scenarios that do not include SMR availability, particularly on winter days with Dunkelflaute (highlighted in red dots). Conversely, in all Nuclear scenarios, prices below

€200/MWh are evident almost consistently throughout, regardless of the presence of a Dunkelflaute day.

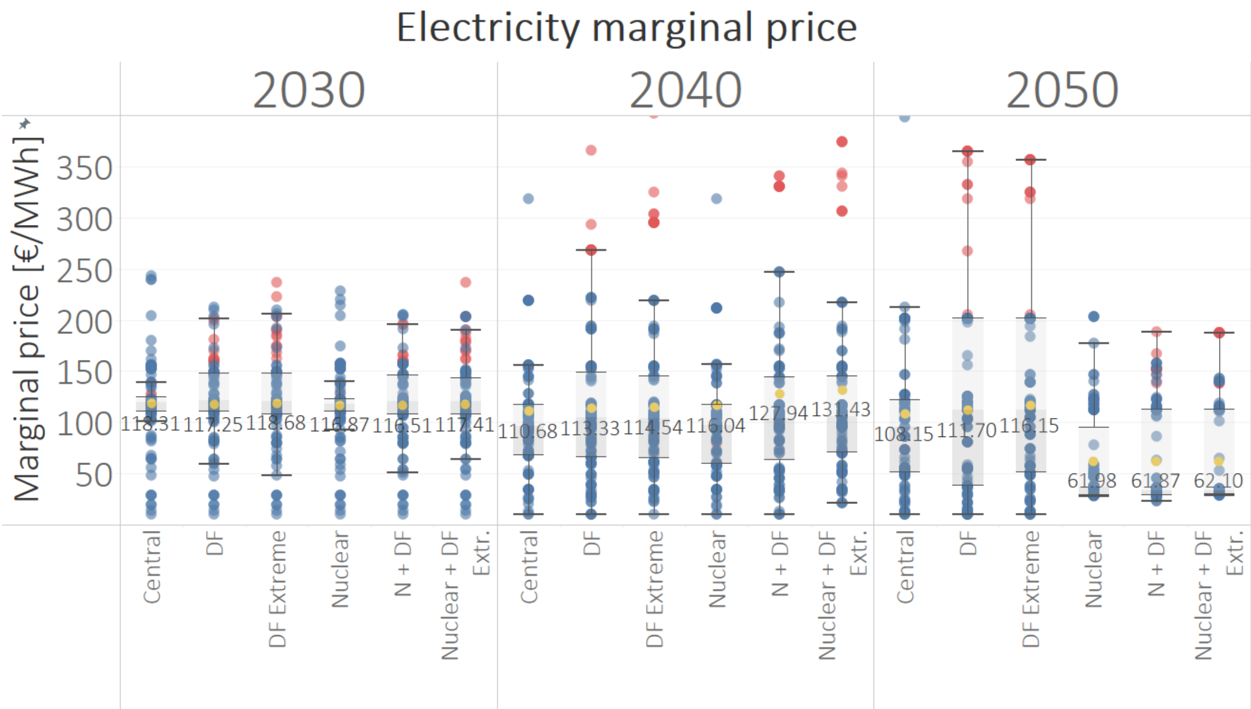

Figure 34: Electricity marginal prices, scenario comparison. In yellow and with label, average price. The red dots highlight prices in the Dunkelflaute day

3.3 System costs

In a similar manner to the general results section, this section compares the system costs across different scenarios, in the form of annual undiscounted total costs, with respect to the Business as Usual scenario. This means that the costs displayed below represent the cost difference between each of the scenario showed and the BAU one, i.e. a scenario without stringent climate goals. It is worth reminding that "Flow costs" contribution covers all the energy trading costs. The results show that the projected investments are quite similar across the different scenarios in 2030. However, when considering the year 2050, it becomes evident that building a resilient energy system capable of withstanding prolonged periods of renewable energy supply shortage entails significantly higher costs, particularly in terms of "Flow costs." The availability of a technology like nuclear SMR significantly increases investment costs (the projected 17 GW in the Nuclear Scenario would cost over ~2 billion euros annually), but it would lead to significant savings in energy imports (approximately 6 billion euros annually), resulting in lower total costs.

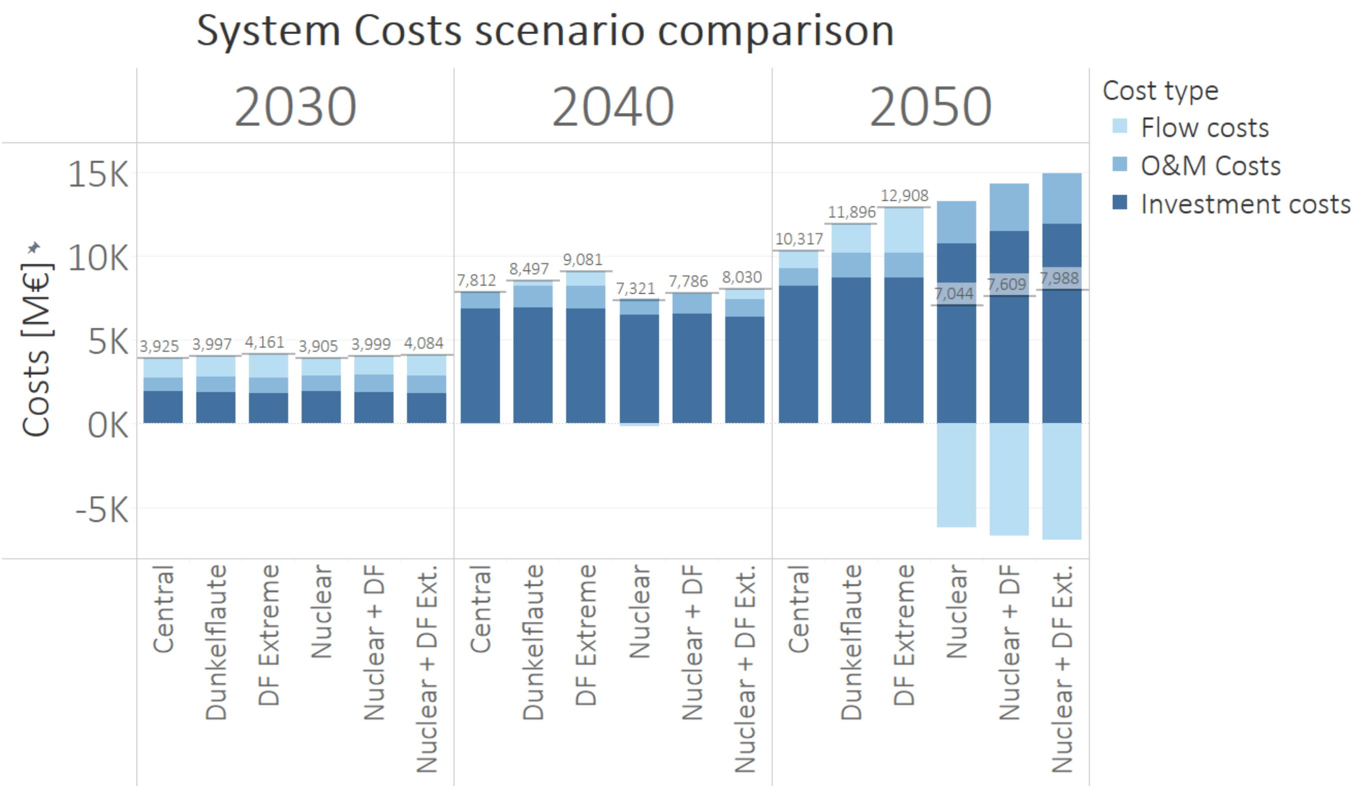

Figure 35: Annual undiscounted total cost of each scenario with respect to Business as Usual (BAU), in b€/y

4 Conclusions

The goal of the EPOC project is to offer insights to policymakers and stakeholders regarding the optimal path towards a low carbon society in 2050. To do so, a tri-regional Belgian model, has been developed, building on past modelling experiences in VITO/EnergyVille and ICEDD. The resulting TIMES model is at the core of the EPOC project, which gathers thirteen research institutes and benefits from the partners expertise. The TIMES model is being linked with five different models in order to improve its accuracy: a transport model, a buildings model, a dispatch model, and an adequacy model. This ensures the consistency of our results and improve the inputs used in TIMES. These interactions are meant to become iterative in some points: for instance, the electricity price computed endogenously in TIMES will be included in the transport model, which will then update the future transport demands used in TIMES. In this paper, an overview on the methodology used is given, together with a list of the key assumptions used to build the TIMES model and the EPOC scenarios.
Within the context of EPOC, seven scenarios were primarily analyzed, including six net-zero scenarios with key variables such as the presence (or not) of a period with limited solar and wind availability, and the possibility to invest in a new technology, the nuclear Small Modular Reactor (SMR). The final scenario takes the form of a Business-as-Usual Scenario, used as a reference to calculate decarbonization costs.

The results provided by the model demonstrate that a complete decarbonization of the Belgian energy system is feasible and requires a decisive push, particularly in terms of electrification and, temporarily, the deployment of carbon capture technologies. Carbon capture is cost-optimal at carbon prices of approximately €150/ton for certain industrial sectors and refineries, and it would contribute to achieving significant climate targets by 2030. However, this is contingent on the assumption of infinite storage capacity, which cannot currently be allocated to the national territory and would require collaboration with neighbouring countries. On the other hand, electrification is identified as the main driver for decarbonization, with disruptive effects expected in the transportation sector, as well as the building sector and certain industrial sectors. Hydrogen use is mainly limited to industrial sectors and power production.

Simultaneously, the power sector would undergo significant investments, especially in terms of renewable capacity. Fully harnessing the wind potential is deemed a no-regret choice in all scenarios, as is the installation of up to 25 GW of solar PV by 2030. However, this may not be sufficient to ensure a continuous supply of low-carbon electricity, considering the current nuclear phase-out and the increasing electricity demand. Therefore, in the long term (by 2050), depending on the scenarios considered, two solutions are proposed. One approach relies heavily on the import of electricity and the deployment of peaking plants, such as hydrogen turbines, to cover demand during periods of low renewable availability and high import prices. The other approach involves substantial investments in flexible baseload capacity, such as nuclear SMRs, and becoming net exporters, significantly reducing both electricity and hydrogen imports. The second solution is deemed cost-optimal based on the assumptions made in the scenarios considered.

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