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Author(s)	Aleksandr Borzunov, Dmitrii Bogdanov, Yousef Pourjamal, Christian Breyer
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Contents

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Abbreviations

BNL	Benelux region
BPS	Best Policy Scenario
BPS_favourVPV	Best Policy Scenario with vertical PV
BPS_favourOE	Best Policy Scenario with high ORE
BPS_import	Best Policy Scenario with unrestricted imports of e-fuels
BPS_import50	Best Policy Scenario with limited e-fuel imports to a maximum of 50% of total demand
BPS_lowPV	Best Policy Scenario with low share of PV
BPS_noBPV	Best Policy Scenario with no bifacial PV
BPS_2040	Best Policy Scenario with carbon neutrality reached by 2040
Capex	Capital Expenditures
CO_2	Carbon Dioxide
EC	European Commission
EEZ	Exclusive Economic Zone
EU	European Union
FED	Final Energy Demand
FTL fuels	Fisher-Tropsch Liquids fuels
GHG	Greenhouse Gas
HDV	Heavy-Duty Vehicle
IEA	International Energy Agency
LCOC	Levelised Cost of Curtailment
LCOE	Levelised Cost of Electricity

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LCOFE	Levelised Cost of Final Energy and Non-energy Use
LCOH	Levelised Cost of Heat
LCOS	Levelised Cost of Storage
LDV	Light-Duty Vehicle
LUT-ESTM	LUT Energy System Transition Model
MDV	Medium-Duty Vehicle
NECP	National Energy and Climate Plan
NOAA	National Oceanic and Atmospheric Administration
Opex	Operational Expenditures
ORE	Offshore Renewable Energy
OSPV	Floating Offshore Solar Photovoltaics
O&M	Operation and Maintenance
PED	Primary Energy Demand
PV	Photovoltaics
RE	Renewable Energy
RES	Renewable Energy Sources
SDGs	Sustainable Developments Goals
TES	Thermal Energy Storage
TPED	Total Primary Energy Demand
UN	United Nations
WACC	Weighted Average Cost of Capital
WavEC	Wave Energy Centre

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WMO	World Meteorological Organization

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0. Executive summary

Offshore renewable energy (ORE) plays a pivotal role in the transition to a carbon-neutral energy system in the European Union (EU), especially in areas with high population density and limited area for onshore renewable energy (RE) development. In such RE constrained regions, it becomes increasingly important to overview multiple energy transition scenarios with special emphasis on the possible contribution of offshore wind power, wave power, and floating offshore solar photovoltaics (OSPV) to the development of Europe's future energy systems to unlock the full RE potential.

The purpose of this report is to assess the importance of ORE in the Belgium, the Netherlands, and Luxembourg (Benelux) regions' energy transition through detailed modelling of the regional energy system. The study aims to support the EU's energy transition by offering a clear vision of how different ORE technologies may impact the energy transition in different parts of Benelux: three regions of Belgium, including Brussels, four regions of the Netherlands, and Luxembourg. By applying a multi-node approach and high-resolution spatial and operational data in modelling, the report aims to analyse how offshore wind power, wave power, and OSPV interact with onshore electricity supply, influence system costs and grid demands, and contribute to defossilisation pathways up to 2050.

This report aligns with the European Green Deal's emphasis on increasing the shares of RE in the total energy supply of the EU.

This study expands the LUT Energy System Transition Model (LUT-ESTM) to incorporate ORE technologies, i.e., offshore wind power, wave power, and OSPV, to assess their role in achieving the European Green Deal targets. Leveraging high-resolution spatial (0.45°) and temporal (hourly) data, and validated techno-economic input from the EU-SCORES project, the model enables a comprehensive analysis of offshore energy resource potentials across the Benelux regions. Eight scenarios are developed, aligned with, above, and below the ambition of the Green Deal, to evaluate the systemic impact of ORE technologies and the broad diversity of photovoltaics (PV) technologies. The results provide insights into system operation, overall cost implications, and greenhouse gas (GHG) emission reductions, highlighting the relative importance of each ORE technology under various transition pathways.

Energy transition scenarios for the Benelux energy system were modelled using LUT-ESTM, a linear optimisation tool designed to create cost-optimised scenarios for the full energy-industry system. It features hourly resolution over a full year, a geographical multi-node structure, and methodologies for dispatch and investment optimisation. The energy transition across Benelux is explored through eight scenarios: (1) the reference Best Policy Scenario (BPS), aligned with the European Green Deal and the European Commission's ORE growth targets, (2) examining the effects of expanded ORE technologies, (3) with a lower role of onshore PV systems, (4) increased share of vertical bifacial PV systems, (5) with restricted bifacial PV systems, and (6) an accelerated pathway to carbon neutrality by 2040. Additionally, to better illustrate the importance of local ORE sources and

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compare a self-sufficient energy system with a system that allows e-fuel and e-chemical imports, two e-fuel and e-chemicals import scenarios were presented for the region: (7) with unlimited imports and (8) with imports covering not more than 50% of the respective e-fuels and e-chemicals demand.

The key findings of this report are that the scenario with favoured offshore wind power and OSPV slightly increases system costs compared to the baseline scenarios. However, this favoured ocean energy (OE) is not the most expensive in terms of annualised system cost and levelised cost of electricity. The main conclusion of this scenario is that in regions with limited onshore RE sources, such as Benelux, ORE is essential and the only possible solution to achieve self-sufficiency in carbon neutrality and a stable energy system without importing fuels into the region or installation of nuclear power plants. The favoured ORE scenario significantly improves the stability of the energy system by reducing the need for energy storage and hydrogen-based balancing, while grid reinforcement increases the role of transmission capacity and allows landlocked and area limited regions such as Brussels to benefit from ORE technology introduction. Technological diversity in solar PV, especially the use of OSPV, facilitates land use optimisation and improves system integration in the context of spatial constraints, which is the optimal cost-effective solution for landlocked regions and regions with access to the North Sea. In addition, the co-location of offshore wind power and OSPV enables significant infrastructure synergies, as OSPV can be deployed within existing offshore wind farms, allowing for the shared use of grid connections, offshore substations, vessels, and operation and maintenance infrastructure. This spatial and infrastructural coupling limits additional seabed occupation and accelerates deployment by leveraging already developed offshore energy hubs. The scenario with a lower share of PV technologies increases the total annualised. cost of the energy system by 1.5%, emphasising the importance of PV technologies in terms of optimal cost-effective solutions. Scenarios with e-fuel imports demonstrate the lowest annual and cumulative system costs due to a sharp reduction in domestic investments in electricity generation, conversion, and energy storage.

Shifting the energy system towards high levels of RE sources is a major strategy to reduce GHG emissions and prevent irreversible damage to planetary systems. This shift promises benefits that extend beyond merely reducing fossil fuel consumption and mitigating environmental impacts with ORE technologies playing a particularly important role. Offshore wind power, wave power, and OSPV offer a vast and underutilised resource potential, attractive electricity generation profiles, and strong complementarity with onshore RE, making them key enablers of a resilient, balanced, and fully defossilised Benelux energy-industry system.

This report covers the impact of ORE technologies in detail for all energy system components, their operation, the overall energy system cost and potential impacts on GHG emission reduction targets. The report emphasises how the impact changes during the transition.

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1. Introduction

Global climate change poses a serious threat to humanity. The effects of climate change are clear in the constant increasing of the global average surface temperature. According to the National Oceanic and Atmospheric Administration (NOAA) annual report [1] the global average surface temperature has reached 1.29°C above the 20th century average and 1.46°C above pre-industrial level. Moreover, the World Meteorological Organization (WMO) also noted that the global average temperature was above 1.55°C above the 1850-1900 average in 2024 [2], leading to a high frequency and intensity of extreme weather events. In accordance with the Paris Agreement [3], the global community committed to limit the increase of the average global temperature growth no more than 1.5°C above pre-industrial levels. However, observed trends indicates that the achievement of this goal is likely no longer possible on a direct trajectory, and humanity will have to consider more costly carbon dioxide removal options or adapt to the consequences of a temperature increase of levels permanently exceeding 1.5°C.

The temperature is rising particularly rapidly on the European continent, where the rate of warming is approximately twice the global average [4]. GHG emissions from the burning of fossil fuels remain the primary cause of climate change. With global average temperatures continuing to rise, the world can no longer focus solely on limiting this trend. Instead, the transition from fossil fuels to low-carbon energy sources, especially renewable energy (RE), has become not just a strategic choice but an essential measure to mitigate the worsening impacts of the climate crisis [5,6].

The long-term vision presented by the European Commission in the European Green Deal [7] provides possible scenarios for Europe's transition to a climate-neutral economy by 2050, in line with the goals of the Paris Agreement [3]. Among the key strategic objectives of the European Union (EU) are the reduction of GHG emissions by at least 55% by 2030 and the achievement of carbon neutrality by mid-century [8]. In March 2023, the EU stepped up its efforts to accelerate the deployment of RE sources, setting a target of bringing their share in total energy consumption to 42.5% by 2030, with an additional target of 45% [9]. To achieve these objectives, the EU and its member states play a leading role in the deployment of RE technologies, including offshore RE (ORE). Technologies such as offshore wind power, wave power, and floating offshore solar photovoltaics (OSPV) are seen as promising elements of future energy systems in European countries [10], especially in regions with limited land availability but a larger exclusive economic zone (EEZ) in the North Sea as well as high population density and energy demand as Benelux. The growing share of ORE in this region contributes to the resilience, security, and flexibility of the European energy system and could be the only cost-competitive solution [11,12].

The adoption of a more sustainable energy system based on clean technologies is a key indicator of a sustainable energy future. The transition towards a low-carbon energy system is already progressing in numerous countries. According

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to studies [13-16], this process both contributes significantly to climate change mitigation and generates considerable economic advantages. Many countries are already making progress towards low-carbon energy, and within the EU particularly the Benelux region with its favourable conditions for RE [17-19].

Solar photovoltaics (PV), one of the main and the fastest-growing RE technologies in the world [20,21] will play a significant role in achieving the EU's climate-neutral goal by 2050. It is the most cost-effective electricity source, with the capability to meet all final energy demand (FED) through sector coupling and power-to-X (PtX) technologies [22,23].Together with onshore wind power, PV has the potential to become the main energy source across Europe in near future [24,25]. However, to support flexibility and reliability of the system, and to supply energy where land and as a result PV and onshore wind power use is limited, ORE becomes an important part of the future energy mix [26,27]. ORE in general delivers a more stable electricity generation profile and has relatively high-capacity factors [28,29]. Moreover, in a region such as Benelux, wave power, offshore wind power, and OSPV could provide power to the landlocked regions, such as Brussels, where energy demand is high and available land area is limited. In addition, due to relatively stable electricity generation profiles, ORE could potentially reduce the need for energy storage in future energy systems and create more value than onshore RE technologies in the regions where the onshore PV and wind power potential is limited [30]. Moreover, in countries with limited land area and high population density, ORE represents the only RE alternative to achieve full defossilisation [31,32].

Europe holds a leading position in the offshore wind power industry [33]. The existing offshore wind power capacity in Europe can cover the region’s electricity needs, with demand projected to steadily rise in the years ahead. By 2024, Europe had around 37 GW of installed offshore wind power capacity connected to the grid [34]. Thereof, 2.6 GW was added in 2024, marking a 28% decrease compared to the 3.6 GW installed in 2023 [34, 35]. However, meeting the EU’s climate targets will require a significant acceleration in the pace of installation and, as a result, an increase in investments in offshore wind power projects. According to targets set by the EC [7], to reach climate neutrality by 2050, the offshore wind power capacity is expected to reach 160 GW by 2030 and 450 GW in 2050 thereof 212 GW in the North Sea (of which approximately 8 GW is planned to be installed in the Belgian EEZ [36] and 70 GW in the Dutch EEZ [37]), 85 GW in the Atlantic Ocean (including the Irish Sea), 83 GW in the Baltic Sea, and 70 GW in the Mediterranean and other Southern European waters [38]. The installed capacity figures for 2030 and 2050 provide the foundation for constructing offshore wind power scenarios applied in the energy transition modelling for Benelux in this report.

Thanks to favourable conditions for the development of offshore wind power and solar PV, the Benelux region has solid preconditions to transition towards 100% RE. In the first half of 2025, the Netherlands generated 48% of its electricity from RE sources [39], slightly less compared to 50.5% in 2024, while Belgium and Luxembourg remained below the EU average with a relatively low share of RE in their gross electricity consumption in 2024 with 31% and 20.5%, respectively [40].

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The share of wind-generated electricity in all three countries exceeds that of solar PV, underscoring the strategic importance of the wind resource for the region. By the end of 2024, the Benelux region generated 48 TWh of electricity from wind power (25% of total generation) and 30 TWh from solar PV (16% of total generation) [41]. These figures highlight both the rapid progress of RE deployment and the remaining potential for accelerating the clean energy transition across the region.

To reach Benelux's as well as all of Europe's full net zero emission target, ORE must be considered, developed, and evolved in the energy system [42]. The Benelux region has highly favoured conditions for the development of ORE, particularly offshore wind power, wave power, and OSPV [43]. The Netherlands aims to reach 21 GW of offshore wind power capacity by 2030, 50 GW by 2040, and 70 GW by 2050, while Belgium plans around 5.8 GW by 2030 and 8 GW by 2040 [44]. The development of ORE in the North Sea is increasingly supported by pilot initiatives and technology demonstration projects. In particular, the Oceans of Energy initiative [45] and the Wave Energy Centre (WavEC) [46] play a significant role in fostering innovation and collaboration in the field. SeaVolt gets ready for its first OSPV test platform to be installed in the Belgian part of the North Sea [47], and Oceans of Energy deployed the world's first OSPV farm integrated within an offshore wind farm [48], demonstrating the potential of hybrid energy platforms combining solar, wind, and wave resources. Meanwhile, WavEC and CorPower Ocean contribute to advancing wave power technologies through pilot deployments and research partnerships focused on improving the efficiency and reliability of wave energy converters. These initiatives collectively strengthen the technological and scientific base for ORE development in the Belgian and Dutch coastal areas, also demonstrate the growing technological diversity of ORE sources and prove that RE is an important part of the region's transition.

The wave energy potential remains moderate, with average wave power densities of approximately 2.8 kW/m for Belgium and 7.6 kW/m for the Netherlands [49]. These figures indicate that the North Sea has potential for wave power use [50]. This potential is enhanced by the presence of numerous existing wind farms and arising OSPV and wave power installations. These ORE capacities, with gradual expansion, could significantly reduce the capital and operating expenditures of future ORE projects [29], [42]. Although wave power and OSPV technologies are still in an early development stage, they could complement offshore wind power and enhance the flexibility and resilience of the Benelux energy system in the transition towards 100% RE.

Besides ORE, the solar resource potential has put both countries at the forefront of PV development in Europe. Solar PV capacity in the region has grown drastically, nearly doubling in two years, making it the second largest RE source [41], [51]. The Netherlands is global leader in solar PV, with approximately 25.4 GW of installed capacity as of 2024 [39], and a record 17% of its electricity generated from PV in 2023, reaching one of the highest per capital installations in the world [52]. Solar PV plays a crucial role in the country's climate goals, with a strong emphasis on electrification, integrating solar PV into various applications and prosumerism. Belgium, meanwhile, installed approximately 947 MW of new PV

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capacity in 2024, which pushed its cumulative installed capacity over 11.7 GW according to the Belgian grid operator Elia [53] and National Survey Report of PV Power Applications in Belgium [54]. The technical potential for residential solar PV in Belgium Flanders is estimated at 7.3 GW and Belgium Wallonia at 3.8 GW [55]. Luxembourg's cumulative installed solar PV capacity reached about 548 MW by 2024 and, as of the end of 2023, positions electricity generation from solar PV on the second place with 12%, after bioenergy [56].

The updated National Energy and Climate Plan (NECP) of Belgium [57] set a target to reduce GHG emissions by 35% by 2030 compared to 2005 levels and aims for a 17.4% share of RE in the gross final energy consumption. The Netherlands, in its revised NECP [58], commits to a 55% reduction in GHG emissions by 2030 relative to 1990 levels and outlines an ambitious strategy to achieve climate neutrality by 2050, with a strong focus on expanding offshore wind power and solar PV capacity. Luxembourg's updated NECP [59] set even higher ambitions, targeting a 55% reduction in GHG emissions by 2030 compared to 2005 and a 37% share of RE in its final energy consumption. Collectively, the Benelux NECPs emphasise accelerated defossilisation, large-scale deployment of solar PV and offshore wind power technologies to meet EU climate objectives.

Technological diversification within PV [60] and ORE enhances the flexibility, resilience, and efficiency of future RE-based systems [60]. In densely populated regions such as Benelux where available land is scarce [61], integrating multiple advanced PV technologies such as bifacial PV modules, single-axis tracking systems, and OSPV can deliver substantial benefits. Bifacial modules, capable of harnessing solar radiation from both front and rear surfaces, notably boost power output, particularly under high-reflectance surface conditions [62]. Furthermore, studies [60], [63] indicate that implementing single-axis tracking systems can enhance solar PV output by approximately 15-20% compared to fixed-tilted PV installations, while bifacial modules typically deliver more moderate improvements of up to 10%. These technologies contribute to more efficient land use, increased electricity generation density, and improved cost effectiveness. These advantages are particularly important in regions facing land constraints or high energy demand [64].

On the other hand, for Benelux, OSPV is particularly relevant along densely populated coastal areas where land availability is limited but grid access is favourable [62,63]. Combined with offshore wind power and wave power, OSPV contributes to a more balanced and stable RE mix, complementing wind energy and wave energy with solar energy patterns and reducing seasonal variability [67]. Moreover, OSPV can be deployed within existing and planned offshore wind farms, creating strong infrastructure synergies through the shared use of grid connections, offshore substations, marine space, and operation and maintenance infrastructure [68]. This co-location reduces additional spatial and environmental pressures, and enhances system efficiency, allowing Benelux to better exploit its full RE potential across both onshore and offshore domains. This technological diversification supports greater system reliability, reduces the need for storage

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and curtailment, and helps Benelux benefit from its full RE potential both onshore and offshore.

Combining PV technological diversity with ORE leads to a more resilient, regionally optimised and efficient system architecture [27]. The results of this combination support a strategic shift towards greater technological diversity in ORE and onshore PV diversity as a key driver for a sustainable energy transition in Benelux and entire Europe.

One of the objectives of this report is to assess the impact of ORE technologies in the energy system transition of Benelux through high-resolution regional energy system modelling and analyse their contribution to GHG emission reductions. The report aims to analyse how ORE technologies interact with onshore electricity supply, influence system costs and grid needs, and contribute to defossilisation pathways in Benelux within the broader European context up to 2050.

The report also examines techno-economical results of alternative energy transition pathways of the Benelux with a focus on the comparative advantages of ORE technologies (offshore wind power, wave power, and OSPV) deployment compared to a BPS as baseline with a cost-optimised PV expansion and in contrast the impact of importing e-fuels and e-chemicals versus the default self-sufficiency scenarios.

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2. Methodological approach

2.1. Methods for energy system modelling

The energy transition scenarios of the European energy-industry system were performed with the LUT Energy System Transition Model (LUT-ESTM) [13], [22], [24], a linear optimisation tool. For the given financial and technical assumptions and scenario, the model defines a cost-optimised transition pathway for the entire energy-industry system. LUT-ESTM operates in hourly temporal and multi-node spatial resolution. For each 5-year step of the transition pathway, LUT-ESTM defines a cost-optimal energy system structure and hourly dispatch to reach balance of supply and demand for all energy carriers for each hour of a given weather year. Power, heat, transport, and industry sectors, including desalination, are co-optimised to maximise synergy effects and reach maximum overall efficiency of the energy system. The model allows for different energy transition pathways to be explored. With its wide range of over 150 energy technologies across various sectors and uses, including transitional technologies, LUT-ESTM is ranked amongst the most sophisticated tools for the analyses of long-term energy transition pathways [69] and it is currently one of the most widely used tools for research on the transition to 100% RE systems [70], [71]. In the case of fuels, the model simulates the production of electricity-based e-fuels (gaseous and liquid) based both on green e-hydrogen and CO_2 from point source capture of sustainable CO_2 sources and direct air capture units, which are part of the PtX concept as an integral element of the arising Power-to-X Economy [72]. A description of how LUT-ESTM is designed in more detail with all sectors integrated and the key equations involved can be found in Bogdanov et al. [24]. The output of the model is a transition path optimised for a given scenario definition, considering factors such as CO_2 emission targets, shares of conventional and RE sources, technology costs in different transition years, implementation costs, and GHG emissions. Figure 1 shows the basic architecture of LUT-ESTM. The simplified scheme of a sector-coupled energy system as modelled with LUT-ESTM is shown in Figure 2 [22].

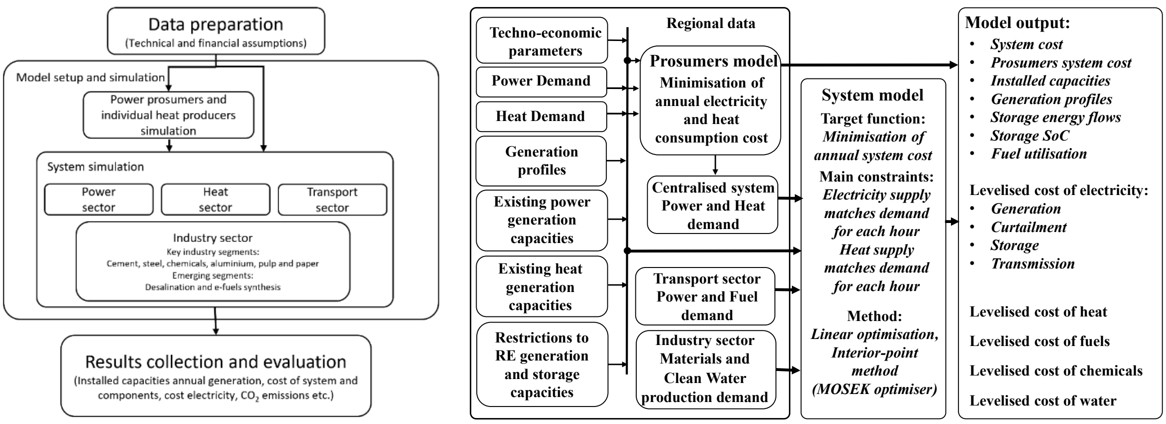

Figure 1 - Schematic representation of LUT-ESTM (left) and the model flowchart (right).

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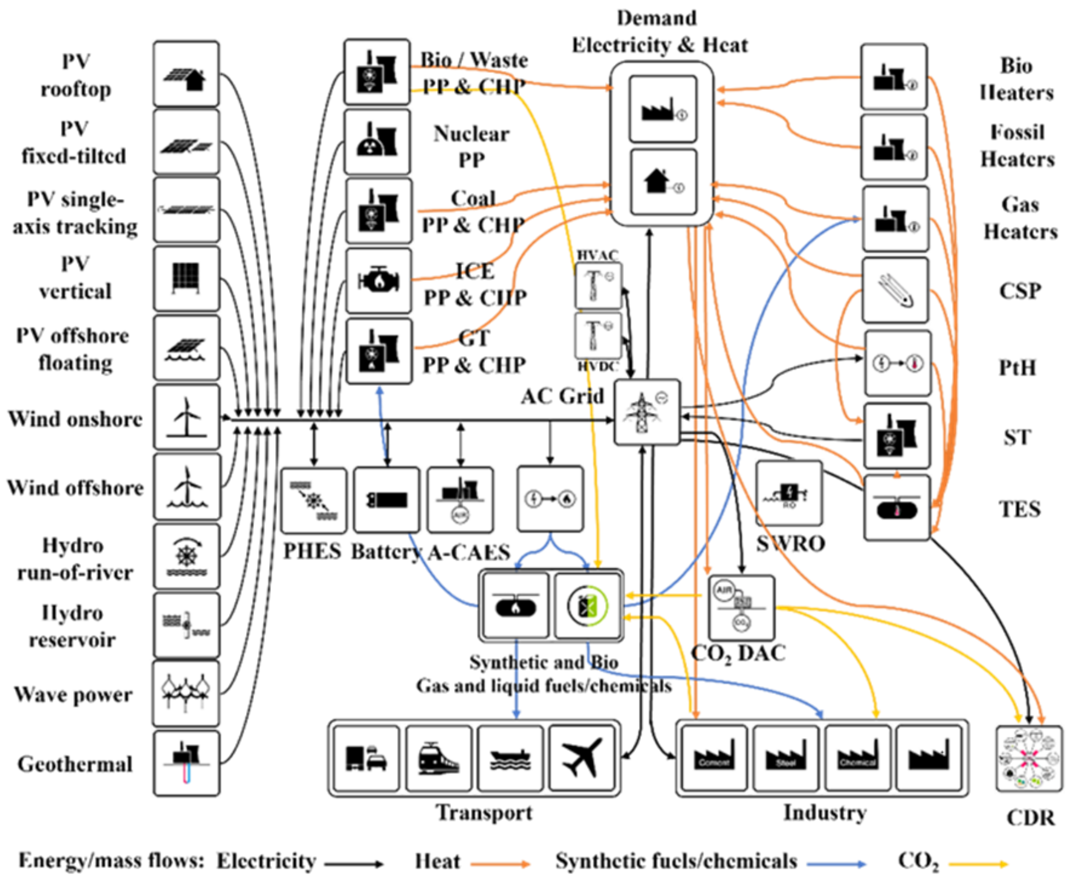

Figure 2 - LUT-ESTM integrated energy system structure scheme.

LUT-ESTM covers ORE technology, including offshore wind power (bottom-fixed and floating), OSPV, and wave power based on the respective potential, e.g. for wave power [28], and considers the electricity generation across the different technologies based on the installed capacities, and the respective energy yield following the applied scenarios. A diverse portfolio of generation and storage technologies, coupled with hourly resolution, facilitates the exploration of key insights into the optimal structure of future energy systems and the potential synergies among different generation and storage technologies. Moreover, the ability to model at an hourly resolution for an entire year allows for the uncovering of crucial insights on RE technologies operation. Grid connection capital expenditures (capex) are included in all power generation technologies, also for ORE. CO_2 emissions are priced at the point of emissions, such as for fossil fuel plants, industrial emitters, or transport vehicles.

The model target function is to minimise the total annualised cost of the entire energy system comprised of annualised capex, operational expenditures (opex), fuel costs, GHG emission costs, and ramping costs of all system elements. Respective parameters assumptions were made about future technological development, the use of different technologies, economic development, cost changes, and changes in consumer behaviour.

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The model guarantees that the energy demand for all sectors will be satisfied for all energy carriers and for each hour of a year. The inputs define electricity demand for general application, heat consumption for space heating, domestic hot water, and industrial process heat demand, transportation services demand, and demand for key industrial products. The model considers both energy and feedstock requirements for industries including cement, steel, chemicals, pulp and paper, aluminium, and others [22]. A crucial part of the transition is to divert from use of fossil fuels as feedstock and source of energy enabling the industry sector to rely entirely on renewable energy and feedstock. Transportation demand is derived across various modes, including road, rail, maritime (with inland waterways and international transportation), and aviation (with domestic and international transportation, for both passenger and freight transportation. The road segment is further divided into categories such as light-duty vehicles (LDV), two- and three-wheelers (2W/3W), buses for passenger transport, and medium- and heavy-duty vehicles (MDV and HDV) for freight transport. Demand for other transportation modes is estimated in passenger kilometres (p-km) for passengers and metric ton kilometres (t-km) for freight. Additional details regarding transportation demand, fuel shares, and specific energy demand are provided by Khalili et al. [73].

A detailed overview of the methodology along with the technical and financial assumptions that are considered in modelling the European power, heat, transport, and industry sectors are available in Bogdanov et al. [24]. These are based on the detailed description of the model applied to the global power sector in Bogdanov et al. [74] and all energy sectors in Bogdanov et al. [13], [22].

2.2. Regional structure of Benelux for energy system modelling

In order to achieve robust energy system analyses for Benelux in LUT-ESTM, the entire area is composed into eight regions with the power systems of the nodes being interconnected according to existing power grids. The region nodes follow the borders of 1 country, 6 regions and communities and 1 city: Brussels, Flanders, Wallonia, North Netherlands, East Netherlands, West Netherlands, South Netherlands, and Luxembourg (see Table 1 and Figure 3). The study covers territories connected to the power grid of Belgium, Netherlands, and Luxembourg of as January 2015.

Table 1. Description of the regional structure.

Node name	Autonomous community/ Region	Center of consumption	Area (km^2)
Brussels	Belgium: Brussels	Brussels	162
Flanders	Belgium: Antwerp, Limburg, East Flanders, Flemish Brabant, West Flanders	Antwerp	13,625
Wallonia	Belgium: Wallon Brabant, Hainaut, Liege, Luxembourg (Belgium), Namur	Charleroi	16,901

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Node name	Autonomous community/ Region	Center of consumption	Area (km²)
North Netherlands	Netherlands: Groningen, Friesland, Drenthe	Friesland	11,389
East Netherlands	Netherlands: Overijssel, Gelderland, Flevoland	Gelderland	10,970
West Netherlands	Netherlands: Utrecht, North Holland, South Holland, Zeeland	South Holland	11,894
South Netherlands	Netherlands: North Brabant, Limburg	North Brabant	7292
Luxembourg	Luxembourg	Luxembourg	2586

Figure 3 – Regional structure for the Benelux region.

2.3. Scenarios for energy system modelling

The energy transition across the Benelux region of Europe is explored in eight distinct scenarios with the following boundary parameters and conditions: The reference BPS sets the net-zero emissions target for 2050 according to the European Green Deal and follows the plans of the EC on ORE growth. Another scenario tests the impact of higher ambitions for offshore wind power, wave power growth, and the impact of OSPV introduction (favourOE). Three scenarios were designed to test the impact of PV technology diversity (low PV, noBPV, and favourVPV), and the sixth scenario tests the impact of an accelerated transition

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with carbon neutrality reached by 2040. Additionally, two import e-fuels and e-chemicals scenarios were designed to reflect the importance of local RE sources in particular ORE and to show the possible difference in energy system structure between the baseline BPS and the scenario with favoured ORE.

Best Policy Scenario (BPS): In this scenario, the Benelux energy system is set on a current ambition pathway. The climate neutrality vision for Netherlands, Belgium, and Luxembourg [54-56] by 2050 is achieved, as GHG emissions are net-zero by 2050 and reduced by at least 55% in 2030 below 1990 levels. No wave power is considered as a favoured capacity but build-out as part of a least-cost solution is allowed.

Best Policy Scenario with favoured ORE (BPS_favourOE): Follows the BPS targets, but with higher ORE capacities installed. The targets for offshore wind power, wave power, and OSPV introduction are increased. The offshore wind power capacity is set to reach 27 GW across Belgium and Netherlands shores by 2030, 77 GW by 2040, and 140 GW by 2050. Similarly, the wave power capacity for the coastal line of Benelux is set to 1.4 GW by 2030, 44 GW by 2040, and 94 GW by 2050. OSPV capacity are set to 11 GW in 2030, 73 GW by 2040, and 195 GW by 2050, following insights of upgrading offshore wind power with OSPV.

Best Policy Scenario with vertical bifacial PV (BPS_favourVPV): follows the BPS targets, the offshore wind power and wave power capacity are on the same level as in the BPS, however, additional vertical bifacial PV capacities are introduced to trace which changes follow a higher VPV share in the energy system. The VPV capacities for each 5-year interval are set to be 10% of the PV capacity built. VPV capacities are set to 12 GW in 2030, 46 GW by 2040, and 79 GW by 2050.

Best Policy Scenario with blocked bifacial PV (BPS_noBPV): Follows the BPS targets, but bifacial PV technology is excluded from the energy mix. The focus is on evaluating the impact of this exclusion on overall PV penetration and the energy supply mix to better highlight the value of the new default PV module technology.

Best Policy Scenario with reduced PV share (BPS_lowPV): This scenario reduces the share of solar PV in the overall energy supply mix compared to the standard BPS. The reduction share is set to 55% for 2030, 53% for 2035 and 50% for 2040-2050 years. It assesses the implications of relying less on solar PV and compensating with other RE sources, such as wind power, hydropower, bioenergy, and ORE.

Best Policy Scenario with Unlimited e-Fuel Imports (BPS_import): This scenario allows for unrestricted imports of e-fuels and e-chemicals to meet energy and industry feedstock demand. It explores the potential for heavy reliance on imported e-fuels and its effects on the domestic RE deployment and energy security.

Best Policy Scenario with Limited e-Fuel Imports 50%(BPS_import50): This scenario limits e-fuel and e-chemicals imports to a maximum of 50% of its total

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demand. The scenario aims to balance the local RE mix with a moderate level of imports, analysing how this affects the energy mix and security of supply.

Accelerated Best Policy Scenario 2040 (BPS_2040): This scenario accelerates the transition timeline, completely phasing out fossil fuels by 2040 instead of 2050. It explores the challenges and potential benefits of a faster transition, such as increased RE deployment, earlier emissions reductions, and technological advancements. In this scenario, the Benelux energy system is set on an accelerated energy transition pathway. Increased efforts to drive the RE share in FED to 56% in 2030 and 100% by 2040 is envisioned. This scenario enables energy-related CO_2 emissions reduction of at least 65% compared to 1990 levels, which is compatible with the climate target of limiting temperature rise to below 1.5°C as defined in the Paris Agreement.

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3. Results

Significant transformations are required for transition in key sectors: electricity, heat, transport, and industry to a sustainable and efficiently integrated energy system. The results of the Benelux region's energy transition for the period 2020–2050 presented in this report demonstrate that energy demand can be met by locally available sustainable RE sources. This approach allows for a proper assessment of the role of ORE in achieving a carbon-neutral energy system in 2050. Furthermore, to more realistically assess the potential evolution of the energy system, scenarios with fuel imports are also presented in addition to the baseline self-sufficiency scenarios.

This section analyses trends in final and primary energy demand, changes in the installed capacity of electrical and thermal power plants, the structure of electricity and heat supply, and the dynamics of the transition of the transport and industry sectors. The final subsections compare energy costs and CO_2 emissions across all scenarios considered, highlighting regional differences.

3.1. Final energy demand

All scenarios, apart from the accelerated scenario (BPS_2040), use the same assumptions regarding energy and service demand. Despite the expected growth in transportation services and industrial demand, electrification and improved overall energy efficiency led to a significant reduction in final energy demand (FED) in the baseline BPS. A sustained and significant decline in FED is observed between 2020 and 2050. The remaining scenarios, except for the BPS_2040, demonstrate similar trajectories of FED reduction. The BPS_2040 is the most ambitious and includes advanced policies across all sectors, from accelerated building renovation and changes in mobility patterns to accelerated electrification of transportation and industry. Implementation of such measures can lead to an even more rapid decline in final energy consumption.

The FED in 2020 is just over 1390 TWh. As shown in Figure 4, the transport sector has the maximum share of 42% with 585 TWh, followed by the industry sector with a share of 32% at 449 TWh. By the end of the transition in all scenarios, due to the efficiency improvement of the power system, the FED decreases in all sectors, from a total of 1159 TWh in the BPS and its variations to 1146 TWh in BPS_2040. The main change is the decrease in FED in the transport sector by 25% for the BPS from 585 TWh in 2020 to 434 TWh in 2050.

In the different scenarios such as the BPS, BPS_favourOE, BPS_noBPV, and BPS_lowPV, the FED shows the same slight downward trend compared to 2020, with transport sector demand declining from 585 TWh to 423 TWh in 2040 despite growth in the aviation and maritime segment as the largest sea port in the world measured by the freight turnover is located in this region. The FED in the transport sector is due to the high share of electric vehicles in transport, which leads to efficiency gains, as well as a shift towards greater use of electrified rail. The industry sector demand declines from 449 TWh to 436 TWh. Notably, in the accelerated transition scenario, total demand stabilises at a slightly lower level than in the other scenarios, around 1146 TWh. Power sector and heat sector

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demands remains stable in all scenarios. The industry sector dominates in 2050, while other sectors are more evenly balanced.

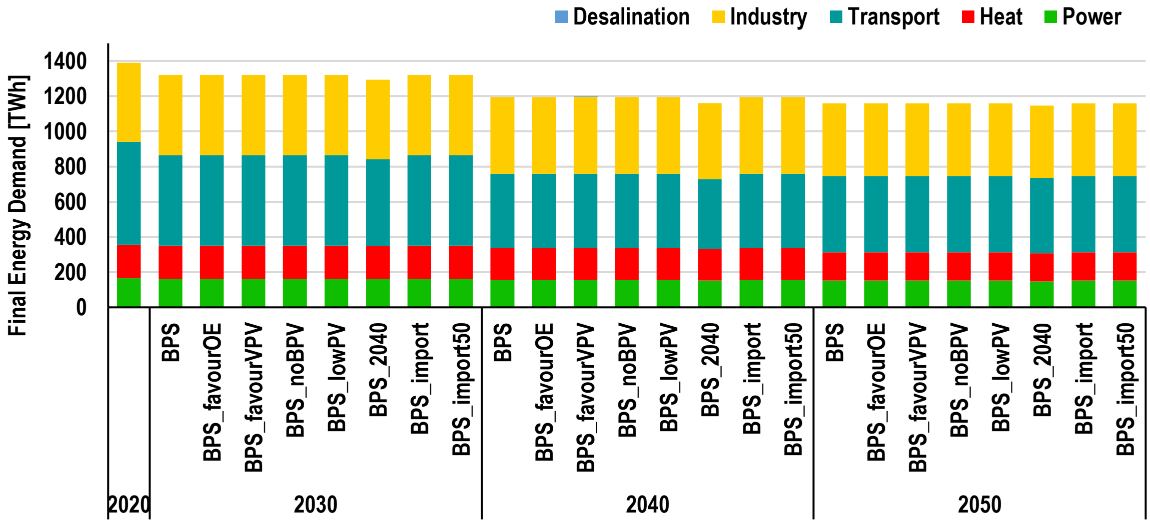

Figure 4 - Final energy demand by sector across scenarios during the transition in Benelux.

3.2. Primary energy demand

Electrification, as the core process of the energy transition, and the increasing volume of renewable electricity use across all sectors are significantly changing the structure of primary energy demand (PED) in the Benelux countries. As electricity consumption increases, heating, transport, and industry become increasingly reliant on electric technologies. This growth is most noticeable in the transport and industry sectors, as shown in the FED structure. Affordable electricity from solar PV systems, coupled with onshore and offshore wind power, makes the electrification of industrial processes even more competitive, which, in turn, increases the need for new generation capacity. Thus, renewable electricity accelerates the displacement of fossil fuels from the region's energy mix.

At the beginning of the transition, the Benelux energy system is dominated by fossil fuels with a small share of RE. The TPED for Benelux (including primary energy consumption and non-energy use) in 2020 was around 1782 TWh, including fossil fuels 1530 TWh (86%), nuclear energy 120 TWh (7%), and RE contributing with 132 TWh (7%) (see Figure 5). By 2050, in the BPS, the TPED stabilises at around 1750 TWh. Renewable electricity becomes the main source of energy in all scenarios with 1647 TWh (94%) in the BPS, 1653 TWh (93%) in the BPS_2040 and 1899 TWh (96%) in the BPS_favourOE. The remainder of the demand is covered by bioenergy and solar thermal energy and geothermal.

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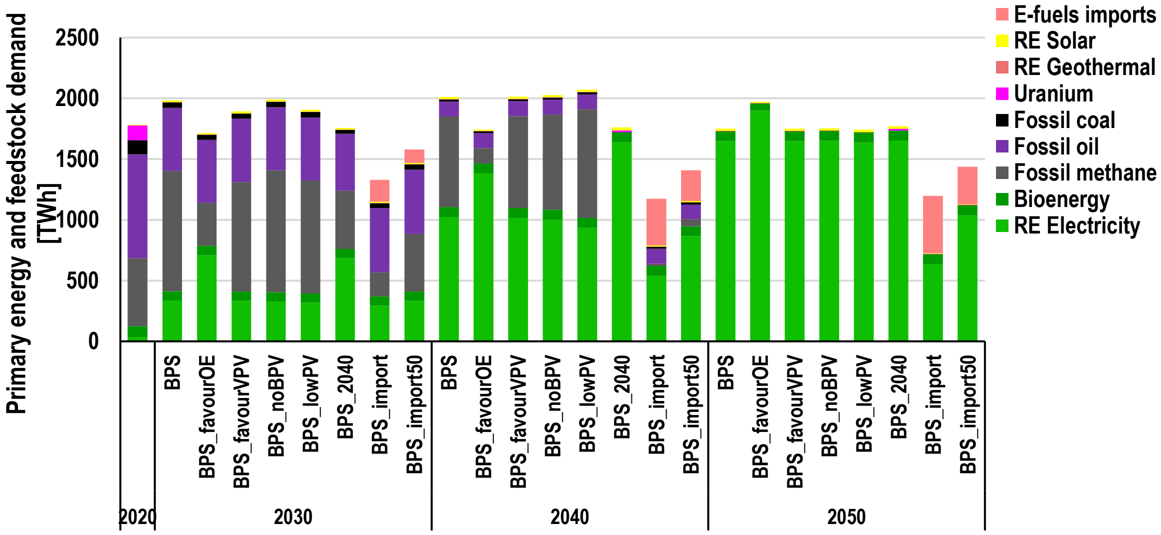

Figure 5 - Primary energy and feedstock demand in Benelux from 2020 to 2050 between all scenarios during the transition.

The shift towards RE becomes obvious as early as 2030, although fossil fuels continue to play a major role in the system. Scenarios show relatively the same TPED values around 1982 TWh. The maximum TPED values are observed for the BPS_lowPV at around 1905 TWh. By 2040, the BPS_2040 shows complete defossilisation, while in the other scenarios, RE sources cover a dominant part of Benelux's energy demand. Regardless of the presence or absence of ORE technologies, all scenarios show approximately the same level of RE penetration. In scenarios where PV technologies are limited (BPS_lowPV), the system is balanced by onshore RE technologies with a minimum TPED from renewable electricity of 412 TWh in 2030 and 1038 TWh in 2040.

By 2050, the structure of PED varies significantly depending on the chosen scenario of the energy system. The BPS_favourOE provides the maximum expansion of renewable electricity supply, 1899 TWh (96.3% of the total balance) with total energy consumption of 1971 TWh. A focus on offshore wind turbines, wave energy converters, and floating PV facilitates significant growth in the production of stable, high-density, year-round electricity. In turn, a high share of renewable electricity leads to a minimal demand for primary non-renewable energy sources and feedstock, as ocean and wind energy can cover electricity needs without additional conversion from fossil fuels or additional import of e-fuels. For comparison, the baseline BPS, with a 94% renewable electricity share and a total demand of 1750 TWh, demonstrates lower renewable power capacity and lower overall energy demand, while the scenarios with high e-fuel imports (BPS_import and BPS_import50) show a reduction in domestic production of 39.3% and 21.4% of demand, respectively, due to imports. Thus, the focus on offshore technologies in the BPS_favourOE both increases the volume of renewable electricity generation and minimises the consumption of other resources and feedstock. High reliability and scalability of ORE can cover the base

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and peak loads of the power system without additional use of energy storage systems or import e-fuels.

3.3. Electricity supply

The share of RE in gross electricity consumption in Belgium, the Netherlands, and Luxembourg continues to grow, indicating a positive trend in the energy transition to 100% RE. This fast growth trend is maintained in all scenarios with different levels of renewable electricity generation capacity, as shown in Figure 6. Electrification in all sectors leads to a required increase in electricity generation by almost 5 times by 2050 in all scenarios.

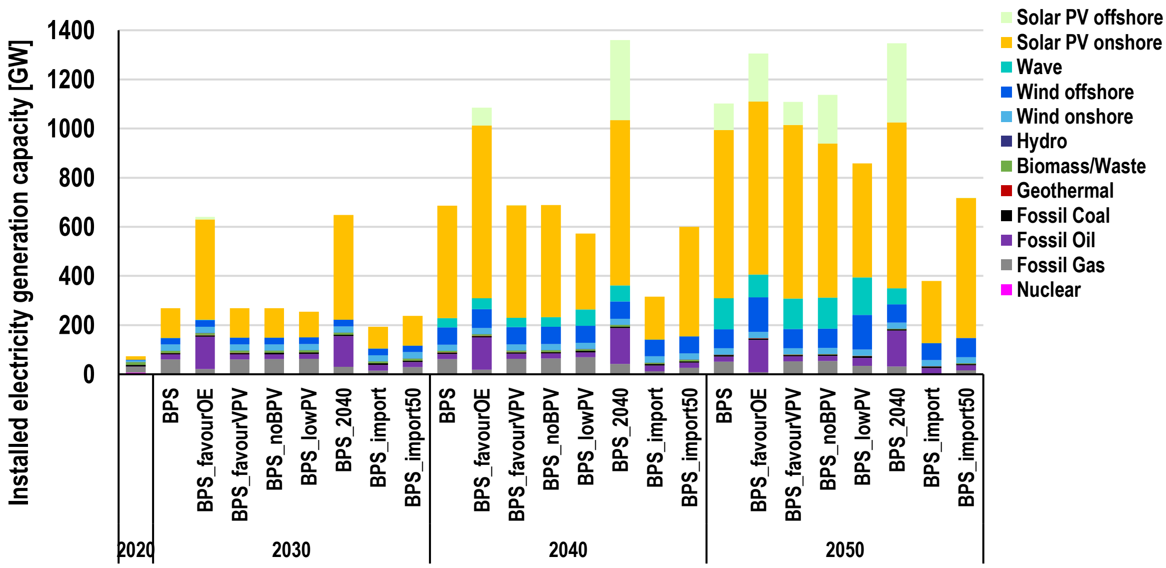

Figure 6 - Installed electricity generation capacities for all scenarios during the transition.

The energy transition in all presented scenarios is characterised by significant growth in installed electricity generation capacity. In 2020, total installed capacity in the region is approximately 73 GW, and the installed capacity structure still reflects the current dependence on fossil fuels. Gas, oil, and coal together account for a significant share (31 GW, or 43%). By 2025 offshore wind power grows to approximately 7 GW, onshore wind power to 10 GW, and wave power is absent. The largest RE technology is onshore solar PV, at approximately 41 GW, consistent with current observed trends of active PV growth. This is the starting point from which all energy transition scenarios are scaled.

By 2030, the differences between the scenarios become noticeable. Total capacity ranges from 237 GW (BPS_import50) to 649 GW (BPS_2040), and onshore solar PV remains the dominant technology, reaching 105-408 GW depending on the scenario. In the BPS_favourOE, offshore wind turbines steadily reach 27 GW, and wave power is introduced in the modeled volumes for the first time. Scenarios assuming no e-fuel imports require larger-scale deployment of local capacity, primarily PV, while the imported options demonstrate moderate growth in installed capacity due to external demand.

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By 2050, the system structure diverges radically between the scenarios: the total capacity is approximately 1103 GW in the BPS, 1305 GW in BPS_favourOE, 379 GW in BPS_import, and 718 GW in BPS_import50, representing increases of 9, 11, 3, and 6 times, respectively, relative to 2025. In the BPS, onshore solar PV continues to play a key role (up to 684 GW), along with OSPV (109 GW), which in this scenario plays a key role in preserving local sources. Offshore wind power capacity reaches 78 GW, which is in line with current government plans for offshore wind technologies development in the region by mid-century [37]. However, the most significant structural changes are observed in the BPS_favourOE, where the prioritisation of ORE technologies leads to a significant increase in offshore wind power (up to 140 GW) and wave power (up to 126 GW) capacity. This reduces the relative dependence on extreme scaling of onshore PV and creates a more balanced RE mix, which is logical given the high potential of the North Sea and the region's developed maritime infrastructure.

Fossil fuel-based power generation is phased out in all scenarios by 2050, except for the accelerated scenario where it ceases to operate by 2040. Nuclear power plants continue to operate until the end of their technical lifetime and all are decommissioned by 2030. However, nuclear power is recognised in all scenarios as being uncompetitive compared to low-cost renewable electricity and poses significant environmental and social risks, which are well documented in Europe and worldwide [75] and thus in many countries new investments have been blocked for overall societal reasons [76,77]. In the applied scenarios the system could install new nuclear power capacities, however, the model does not find new nuclear power capacities as part of a cost optimal solution in any scenario, which is in line with comparable results for Denmark [78], Sweden [79], and Finland [80], the latter of which is also considering small modular reactors [81].

The large-scale deployment of ORE technologies demonstrates a pronounced coastal distribution of installed capacity among the Benelux regions in the BPS_favourOE (see Figure 7). Northern Netherlands accumulates the largest wave power capacity (66.3 GW), while West Netherlands accounts for a significant share of both wave power (27.3 GW) and OSPV (109.3 GW). Offshore wind power is more evenly distributed but remains highest in Northern Netherlands (48 GW) and West Netherlands (55.2 GW), confirming the scenario's focus on the active exploitation of the North Sea's potential. The central and southern regions, Flanders, Wallonia, and East Netherlands, contribute primarily through onshore solar PV, particularly Flanders with 14 GW of prosumer PV and 91 GW of single-axis bifacial utility-scale PV, and moderate volumes of onshore wind power.

By 2050, North and West Netherlands will become the two main production hubs, providing more than half of the region's offshore electricity generation. This creates a fundamentally different spatial structure compared to the BPS, where onshore PV sites remain dominant, and is particularly different from the import scenarios, where coastal zones play only a secondary role.

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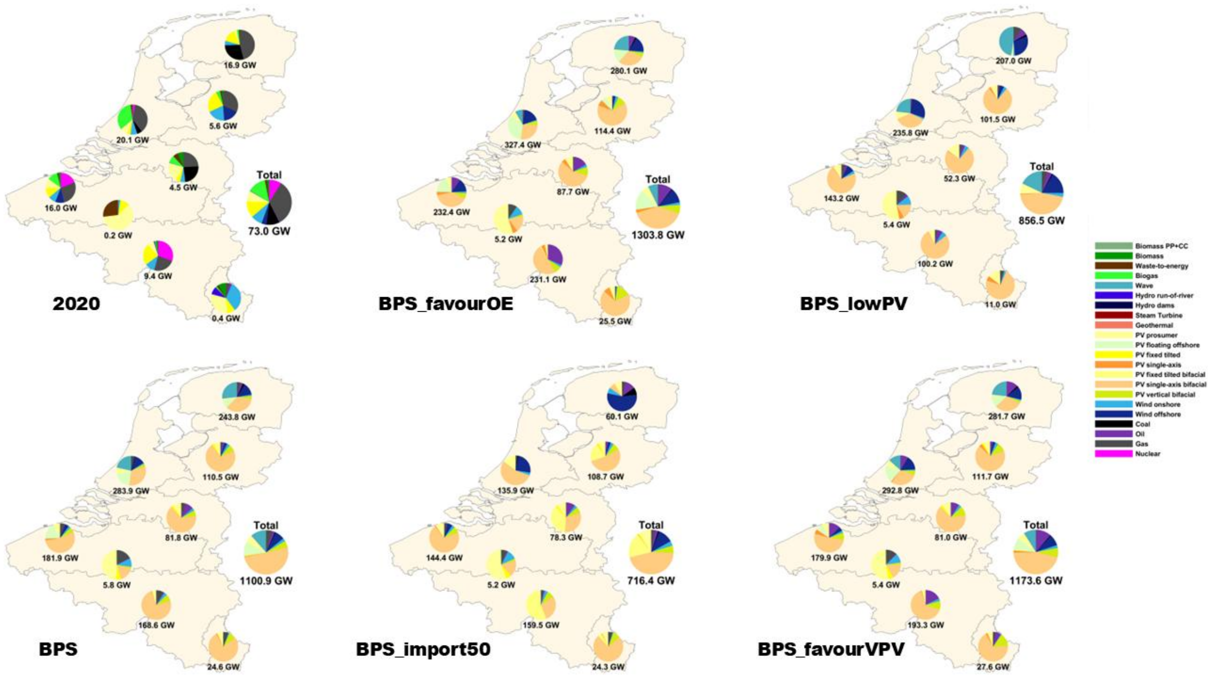

Figure 7 - Regional electricity generation capacities in different scenarios in 2020 and 2050.

The electricity generation follows the same trends. The electricity generation mix through the transition for given scenarios is presented in Figure 8.

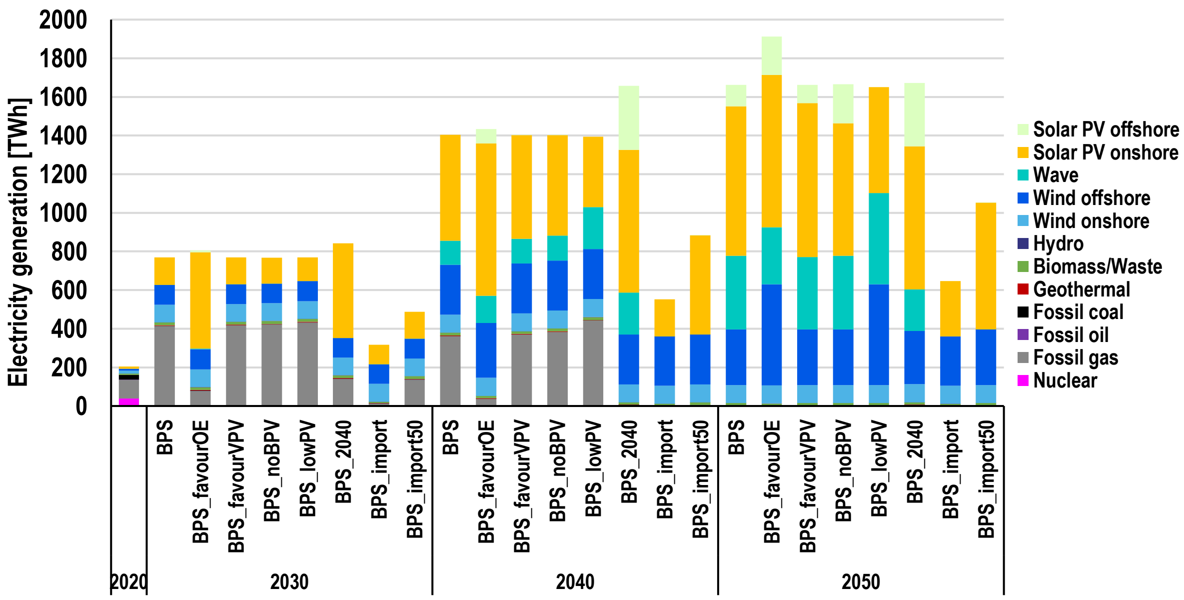

Figure 8 – Electricity generation for all scenarios during the transition.

By the end of the transition, electricity generation from offshore wind power ranges from 254 TWh in the BPS_import to 523 TWh in BPS_favourOE, keeping the position of the largest source of electricity generation among the ORE technologies. In the same scenario, wave power adds 293 TWh and OSPV generates 198 TWh, which, together with offshore wind power, contributes 1016

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TWh of generation from ORE technologies, approximately 53% of the total electricity generation in the BPS_favourOE.

Similar to the electricity generation capacity, a higher share of offshore wind electricity generation is observed in Northern and Western Netherlands (see Figure 9), while a higher share of solar PV generation is concentrated in Wallonia and Luxembourg. The highest electricity generation is observed in the BPS_favourOE (1903 TWh), where the maximum deployment of ORE technologies creates a productive and diversified system, compensating for the limited land mass in the Benelux region and ensuring high resilience through a three-component maritime balance. The lowest generation is recorded in the BPS_import (643 TWh). Large-scale e-fuel imports reduce the need for domestic RE, replacing domestic e-fuels production with external supplies and thereby limiting the electricity demand for synthesis and development of new infrastructure, especially offshore. In the baseline BPS, electricity generation is 1651 TWh, reflecting realistic growth. e-Fuel imports reduce domestic generation by redistributing production outside the region, while in the BPS_favourOE scenario, the opposite logic, maximising the use of North Sea resources, increases the generation specifically in offshore technologies.

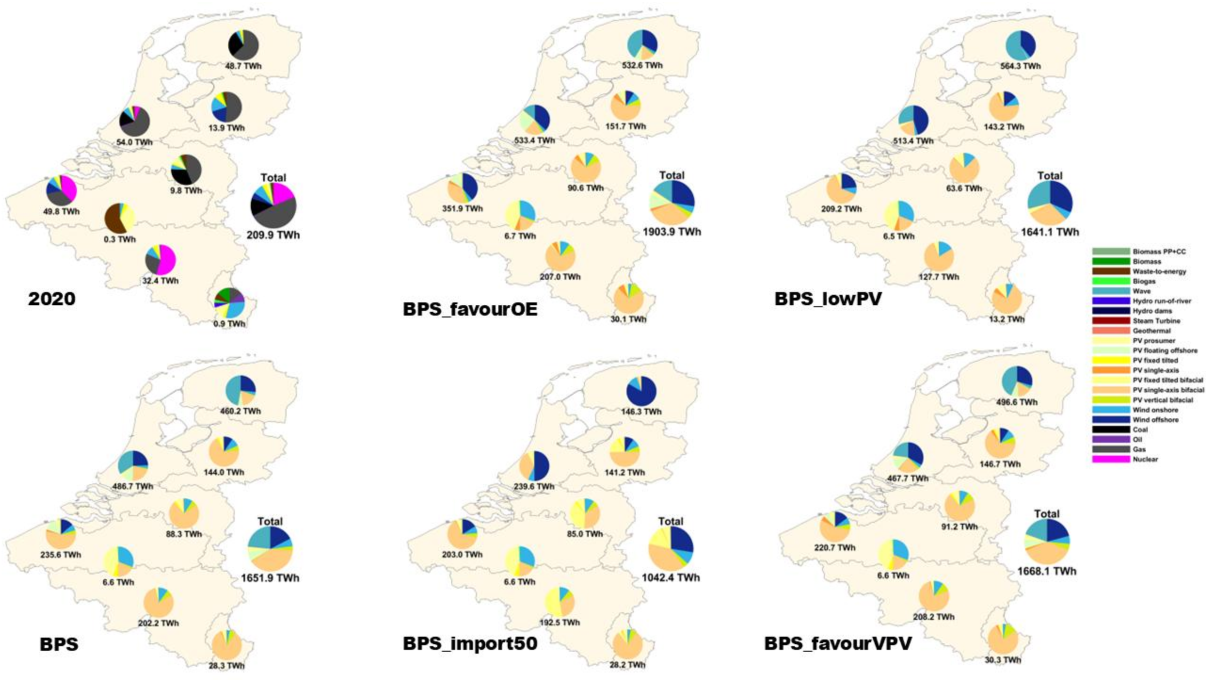

Figure 9 – Electricity generation by technologies during the transition in 2020 and 2050 in different scenarios.

In the BPS_favourOE, compared to the BPS, the installed electricity storage capacity decreases from 400 GWh_{cap} (BPS) to 394 GWh_{cap} (BPS_favourOE) see Figure 10, with most of the storage built in the densely populated coastal areas. The total storage throughput is around 59 TWh (Figure 12). This reflects lower reliance on onshore solar PV, and lower daily and seasonal variability of electricity supply. This effect is achieved through more stable generation from ORE, namely,

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offshore wind power, wave power, and OSPV, which together provide a more stable supply of electricity and reduce the demand for storage capacity.

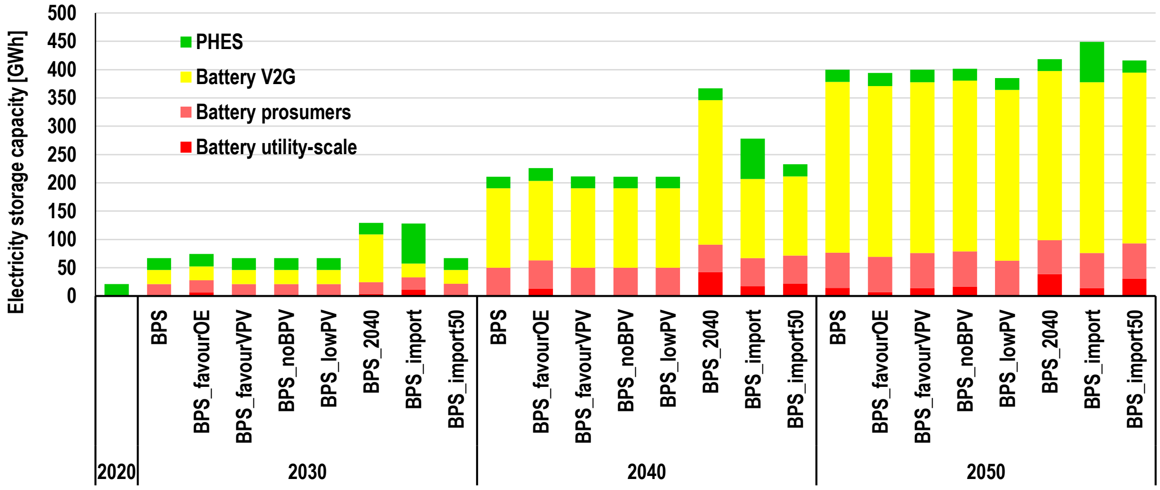

Figure 10 – Electricity storage capacity for all scenarios during the transition.

In 2050 in the BPS, the total storage capacity reaches 400 GW with an output of 58.7 TWh, mostly in the coastal regions (see Figure 11). The structure is dominated by V2G batteries (302 GW, about 75% of the capacity) and a large segment of prosumer batteries (62 GW), while utility-scale batteries account for about 14 GW and pumped hydro energy storage for 22 GW. In the BPS_favourOE, the total capacity is close (394 GW) and the total output from storage is almost identical to the BPS (58.6 TWh), but the internal structure is different. The role of utility-scale batteries is smaller (about 7 GW), while V2G and prosumer batteries remain comparable in scale to the BPS. This reflects the fact that intensive offshore wind and wave power smooth out the seasonal generation structure but increase the demand for system flexibility.

The BPS_import and BPS_import50 demonstrate an alternative trajectory. By 2050, they reach a total storage capacity in these scenarios of approximately 449 GW and 416 GW, respectively, and total output of 66.9 and 68.2 TWh, respectively (Figure 12 and Figure 13). This difference is 15–25% higher than in the BPS and BPS_favourOE. The difference appears due to the high share of e-fuel imports and the corresponding load distribution between electrolysers, synthetic e-fuels, and electric storage. The BPS_favourOE avoids the massive growth of storage infrastructure, relying on a more balanced and correlated electricity profile of offshore wind and wave power.

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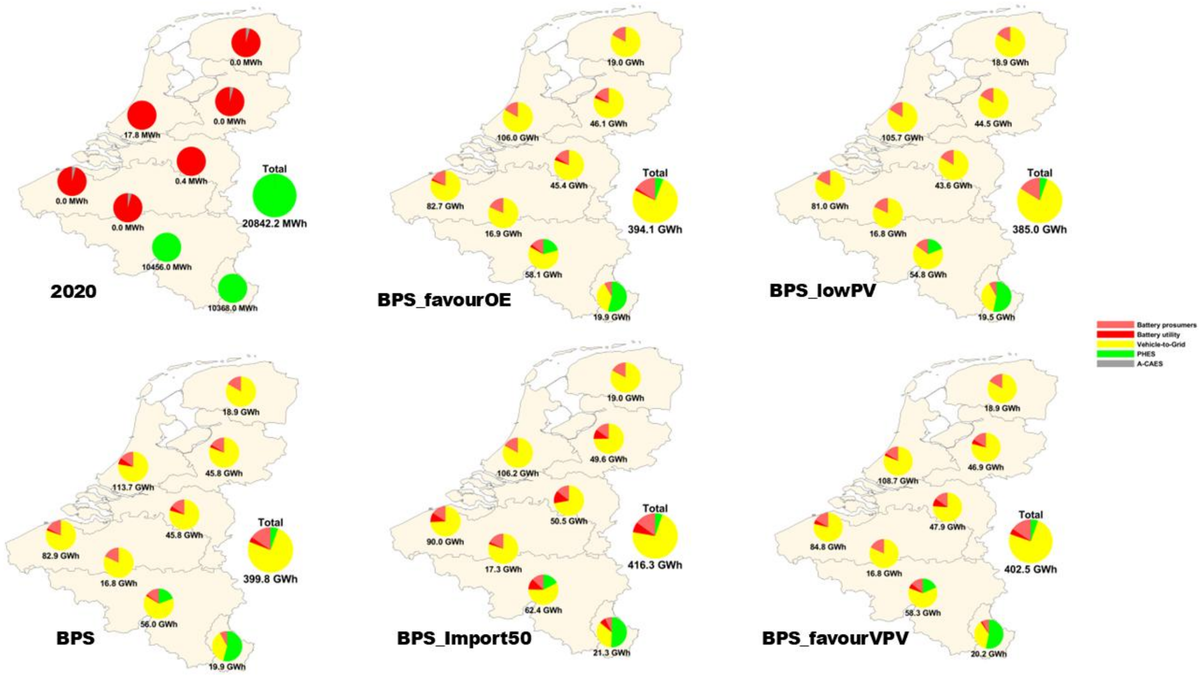

Figure 11 – Regional electricity storage capacities across different scenarios in 2050.

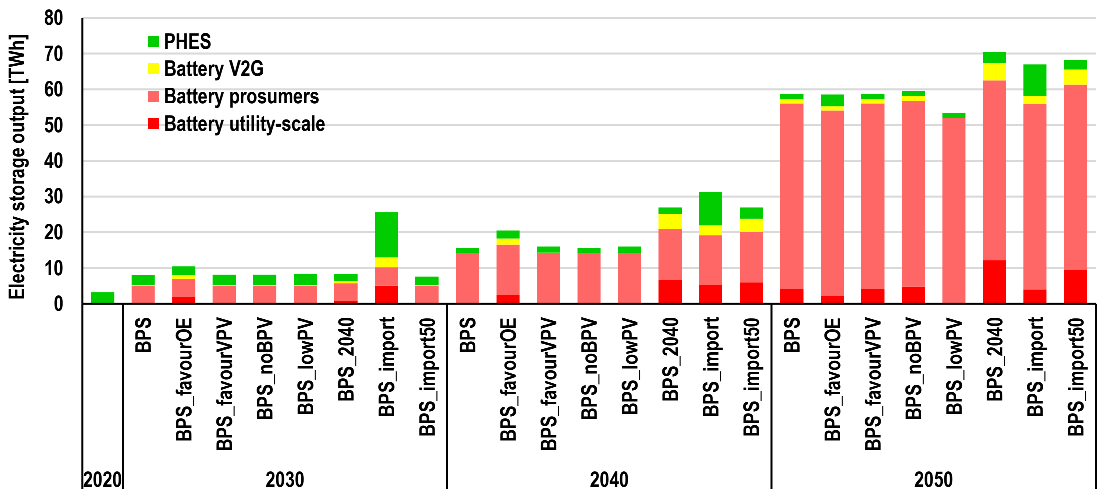

Figure 12 – Electricity storage output for all scenarios during the transition.

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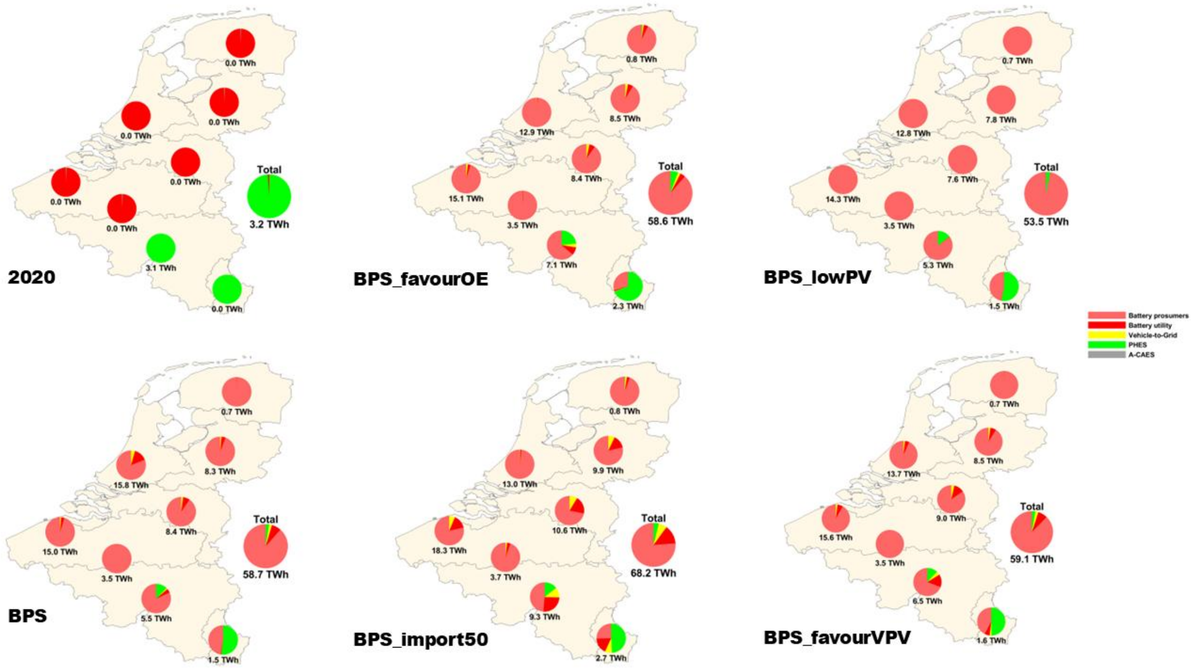

Figure 13 – Regional electricity storage output capacities across different scenarios in 2020 and 2050.

3.4. Heat supply

The heat sector plays a significant role in achieving Benelux's carbon neutrality during the energy transition. More than 15% of the region's FED comes from the heat sector, including space heating, domestic hot water, and industrial heat. Results for installed heat capacity and generation during the transition (see Figures 14 and 16) reflect the shift from fossil fuels to heat pumps as the primary heat generation source. In 2025, gas remains the primary heat source for Benelux, with 24 GW of installed capacity, accounting for a third of the heating infrastructure. Heat pumps account for approximately 19 GW, and electric heating for 9 GW. By 2030, heat pump capacity already exceeds gas installations in most scenarios.

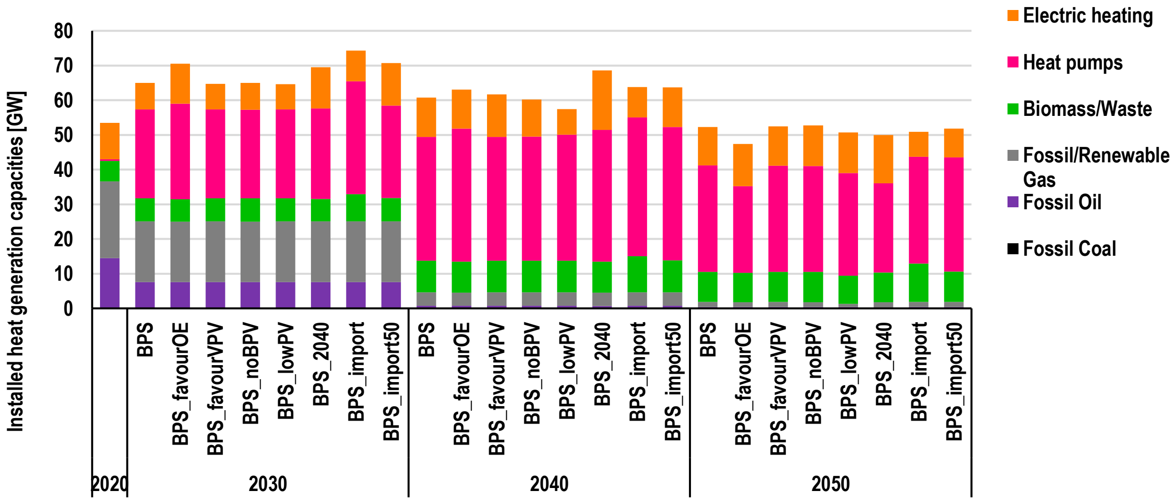

Figure 14 – Installed heat generation capacities in all scenarios during the transition.

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By 2050, the composition of installed heat capacity tangibly changes in all scenarios. Heat pump capacity becomes dominant (31 GW), completely excluding fossil fuels. Electric heating increases in most scenarios to 11–14 GW, reflecting deep electrification. Total capacity in 2050 declines compared to 2025 (from 70 GW to 50 GW), reflecting the increasing energy efficiency of buildings and industry: less installed capacity is required per unit of heat.

For the regional distribution of installed capacities, the largest systems are Flanders (13.9 GW) and Western Netherlands (15.2 GW) (see Figure 15) due to high population density, developed industry, and a significant volume of buildings requiring heating. Both regions have high heat pump capacities (6.35 GW and 7.48 GW, respectively), consistent with the projection of full heat electrification by 2050.

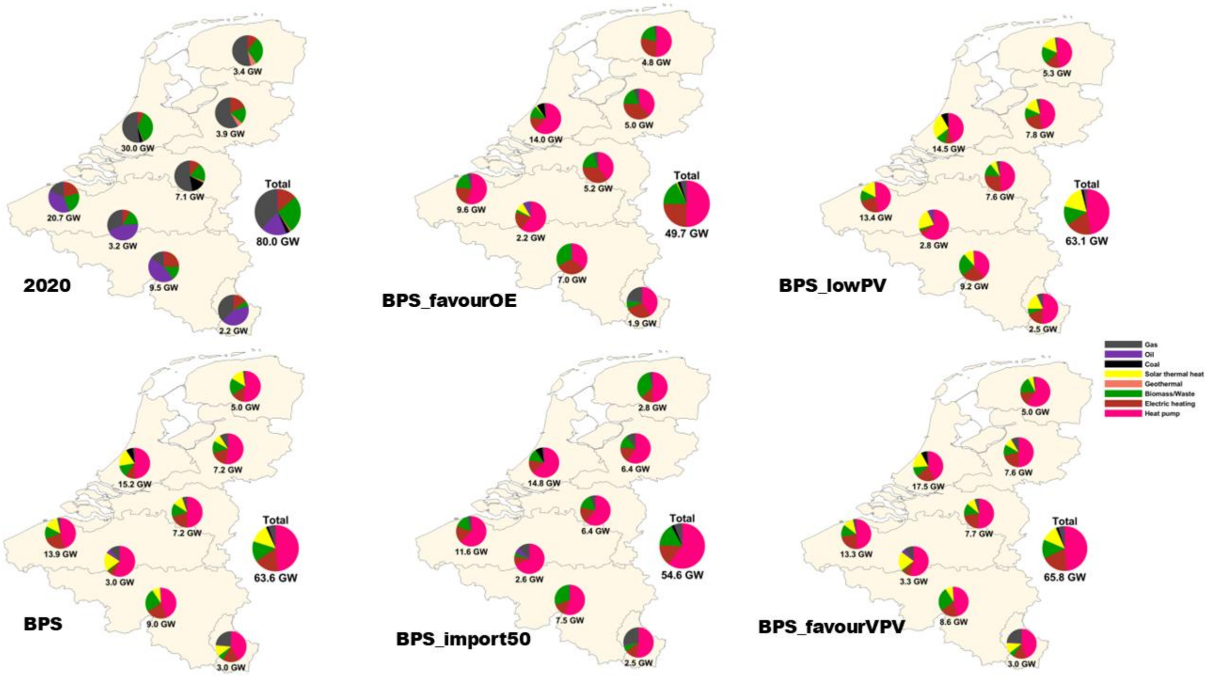

Figure 15 – Regional heat capacities across different scenarios in 2020 and 2050.

Heat generation in 2050 demonstrates a shift towards electrification. Heat pumps generate 123-180 TWh, electric heating increases to 9-68 TWh, and biomass and waste generate approximately 20 TWh. In the BPS_favourOE, heat pumps generate 123 TWh, which is lower than in the baseline BPS. This difference occurs as ORE provides a more stable power generation profile and reduces peak loads. Therefore, part of the heat generation in this scenario comes from electric heating (68 TWh, compared to 9 in the BPS). Conversely, import-dependent scenarios show a less stable heat structure. Lagged electrification leads to greater use of direct electric heating (up to 32 TWh) and a lower share of heat pumps.

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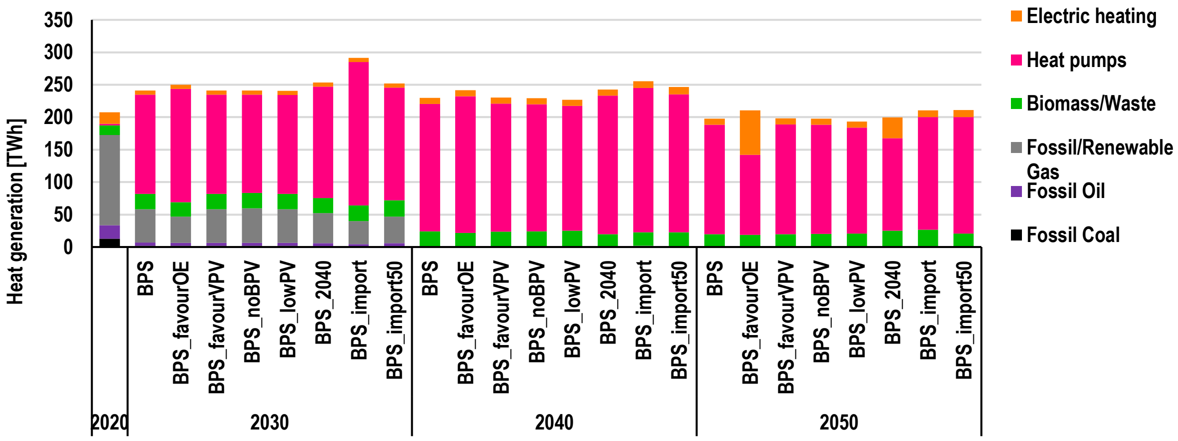

Figure 16 – Heat generation mix in all scenarios during the transition.

In the Benelux heat sector, by 2050, hydrogen storage will begin to play a key role, becoming the main mechanism for seasonal heat balancing. Hydrogen storage is used across the entire energy-industry system and is especially relevant for balancing e-fuels and e-chemicals production. Hydrogen heat storage capacity in the baseline BPS reaches 15 TWh, in BPS_favourOE 17 TWh, and in BPS_2040 it reaches 27 TWh, as these systems experience a larger seasonal gap between generation and heat demand (Figure 17). In contrast, in import-oriented scenarios, the capacity declines to 4-8 TWh, as some fuels for heat are imported from external markets. Short-term thermal energy storage (TES HT/DH) grows significantly more slowly and remains a supporting element, providing daily load leveling, while methane storage remains as residual infrastructure in the accelerated BPS_2040.

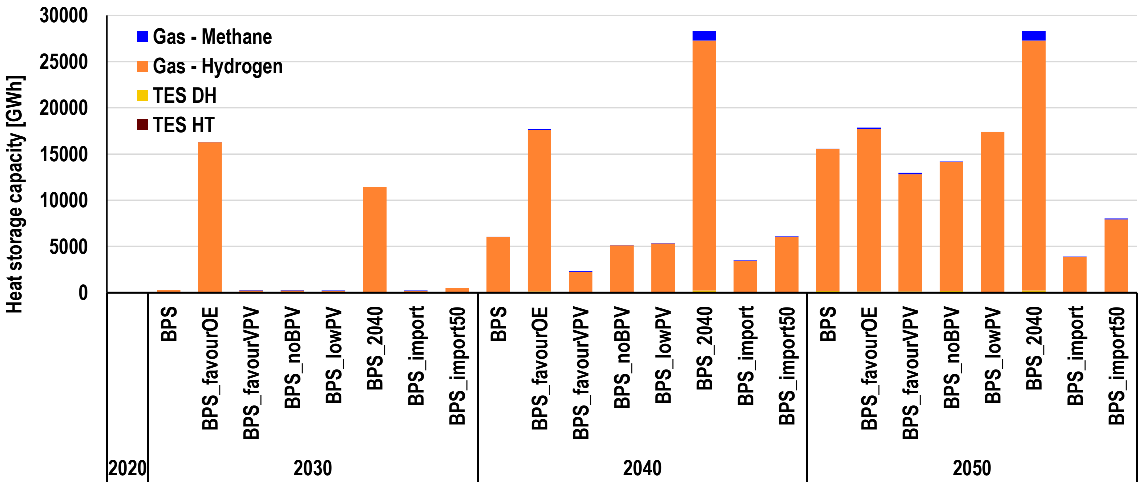

Figure 17 – Heat storage capacity in all scenarios during the transition.

The regional distribution of heat and gas storage (Figure 18) shows a strong concentration in Northern and Eastern Netherlands with 4 TWh and 3.3 TWh, where geology and existing gas infrastructure allow for the deployment of large hydrogen caverns. Industrial regions such as Wallonia and the port areas of

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Western Netherlands also have high levels of storage, while urban areas, such as Brussels, rely almost entirely on TES and grid flexibility.

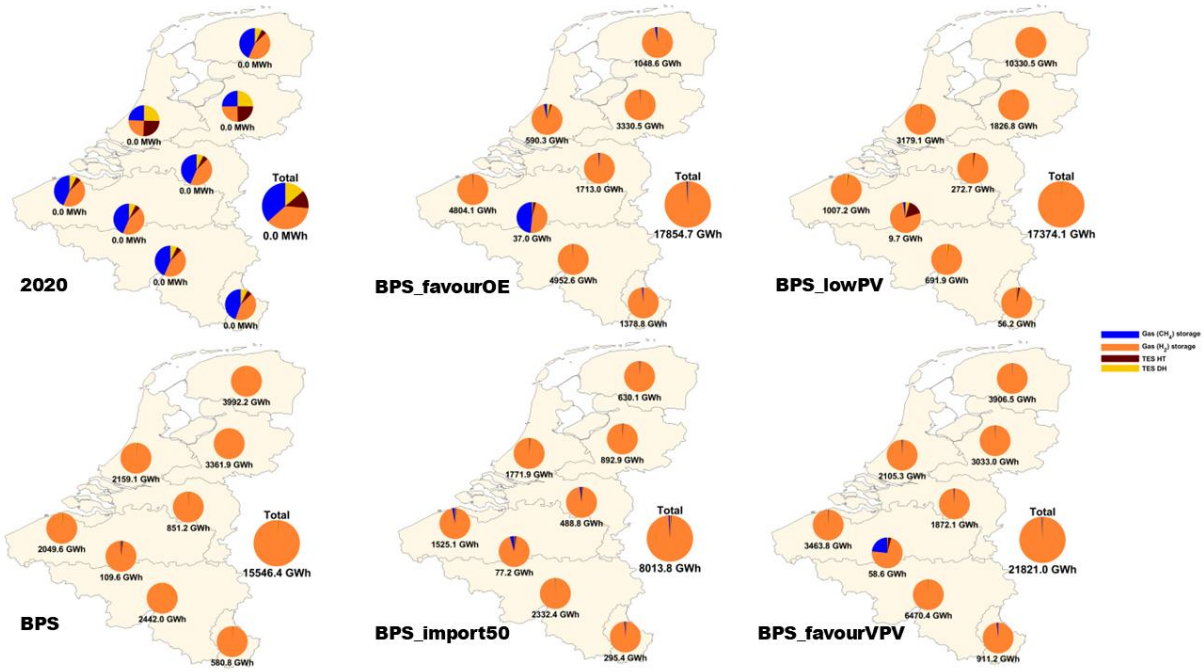

Figure 18 – Regional heat storage across different scenarios in 2020 and 2050.

The throughput of the heat and gas storage facilities follows the same trend with substantially higher throughput of storage in low ORE capacity scenarios and lower reliance on storage in scenarios with significant installation of ORE (Figure 19). The share of heat and gas storage in total throughput is much higher than the share in storage capacities, as, unlike gas storage, heat storage capacity operates in daily cycles resulting in much higher throughput for the same capacity.

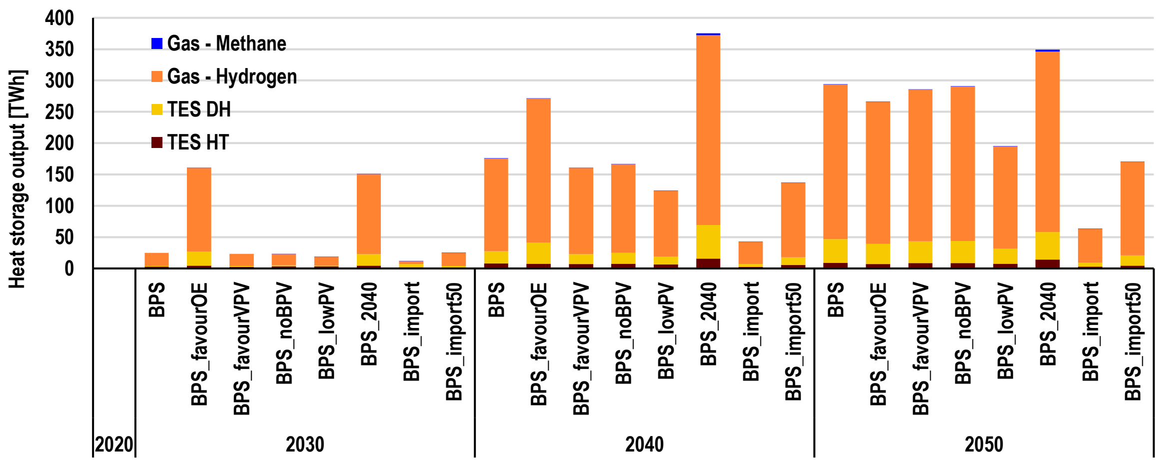

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Figure 19 – Heat storage output in all scenarios during the transition.

3.5. Transport, industry, and e-fuels

The transport sector plays a key role in the energy transition of Benelux and is undergoing significant changes. With the largest freight maritime port in the world, more that 40% of FED comes from the transport sector. Electrification and the sharing economy are rapidly changing the FED picture. Figure 20 shows the FED in the different segments of the transport sector, divided into road passenger and freight transport, rail passenger and freight transport, maritime passenger and freight transport, and aviation passenger and freight transport. The road segment has the highest level of electrification. In all scenarios, the FED for road passenger and freight transport decreases by more than five times (from 279 TWh to 75 TWh). Maritime freight transport is the most energy intensive and continues to consume the largest share of energy in all scenarios starting from 235 TWh in 2025 and 246 TWh in 2050 for all scenarios. Aviation passenger transport has a growing FED in all scenarios from 62 TWh in 2025 to 99 TWh by 2050, as the additional expected demand for transport services cannot be offset by efficiency gains. At the same time, the transport FED shifts from a fossil fuel-dominated mix to a more balanced energy mix, with electricity accounting for over 40% and the remaining share distributed between various e-fuels and sustainable biofuels, although the biofuel share does not exceed 5% due to limited feedstock.

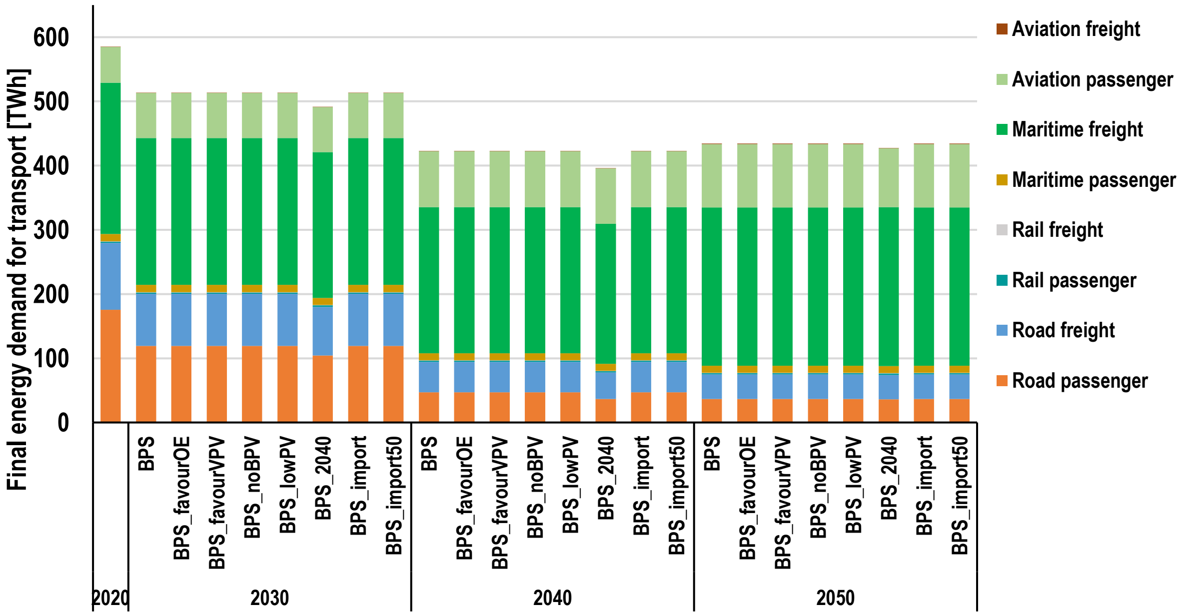

Figure 20 – Final energy demand for the transport sector across all scenarios from 2020 to 2050.

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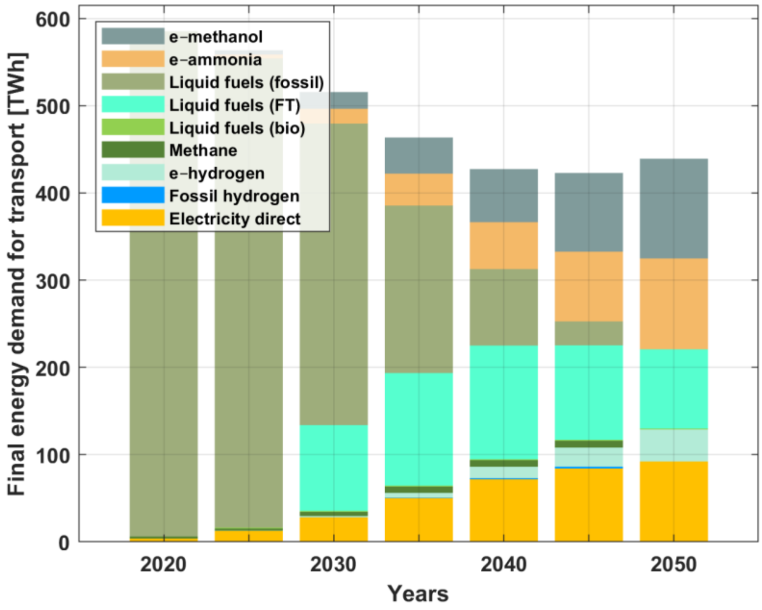

Figure 21 – Final energy demand for the transport sector by fuel during the transition for the BPS.

Benelux countries host a well-developed energy-intensive industrial base, including cement production, which substantially contributes to CO_2 emissions due to the continued reliance on fossil fuels and feedstock for energy supply and materials processing. The energy transition is accompanied by rising energy-related feedstock demand in the chemical industry (see Figure 22), driven by the growing need for hydrogen-based chemicals. By 2030, the combined energy and feedstock demand of the chemical sector reaches 294 TWh, accounting for approximately 65% of total industrial energy demand in the BPS. By 2050, the role of electrolysers in the industry sector increases markedly. The chemical industry becomes a major energy consumer, particularly to produce e-ammonia and e-methanol derived from e-hydrogen as a non-energy feedstock, enabling a shift towards sustainable chemical production.

The most significant reduction in energy demand is expected in the steel and cement industries, where processes become increasingly electrified, supported by growing shares of secondary steel and blended cement. Across all scenarios, energy demand in the steel industry is projected to decline by nearly half, from 51 TWh to 23 TWh. Meanwhile, energy demand in cement, aluminium, and other industries remains relatively stable throughout the transition period across all scenarios.

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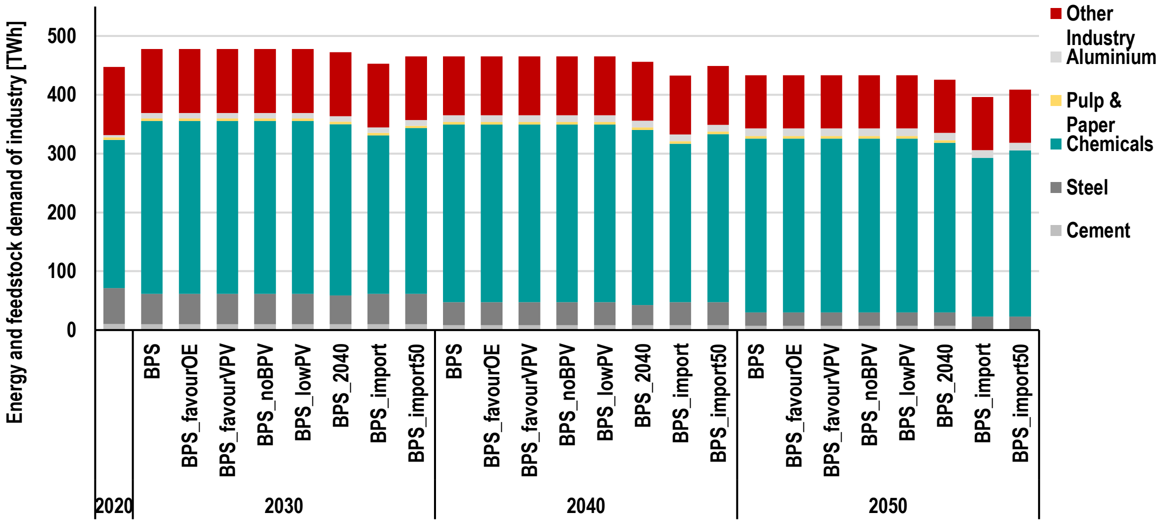

Figure 22 – Energy and feedstock supply for energy-intensive industries across the scenarios from 2020 to 2050.

Fuel conversion capacity in the Benelux countries is primarily driven by electrolyser expansion, which increases in all scenarios between 2025 and 2050 (see Figure 23). In the BPS, installed electrolyser capacity increases from 5 GW in 2025 to 261 GW by 2050, driven by the need to meet domestic e-hydrogen production for the chemical, synthetic e-fuels, and industrial segments. In the BPS_favourOE, electrolyser capacity reaches 241 GW by 2050. In the BPS_import, the need for domestic fuel production is lower, resulting in electrolyser capacity of 47 GW, while in the BPS_import50 it is 141 GW, reflecting increasing reliance on imported e-fuels. Hydrogen-based fuel synthesis processes, i.e., ammonia, methanol, and Fischer–Tropsch liquids, also scale differently depending on domestic hydrogen production volumes. By 2050, the highest methanol synthesis capacity is observed in the BPS_favourOE (41 GW) and in the BPS (44 GW), while the BPS_import50 is limited to 24 GW, highlighting the decline in domestic synthetic e-fuel production with high imports. Fischer-Tropsch capacity is highest in scenarios with large hydrogen production volumes (20–24 GW) but drops to 0 GW in the BPS_import scenario due to minimal domestic demand.

In the self-sufficient scenarios, the e-fuel production system is most developed, ensuring large-scale domestic production of hydrogen and e-fuels. The BPS represents a balanced system with large volumes of domestic production. The BPS_import50 and especially the BPS_import exhibit the lowest e-fuel production capacity, as e-fuel imports replace local production. This result demonstrates the greater the availability of renewable electricity, the greater the scale of domestic hydrogen and synthetic e-fuel production, while increased imports lead to a reduction in national infrastructure and shift the balance of the energy system towards external supply chains.

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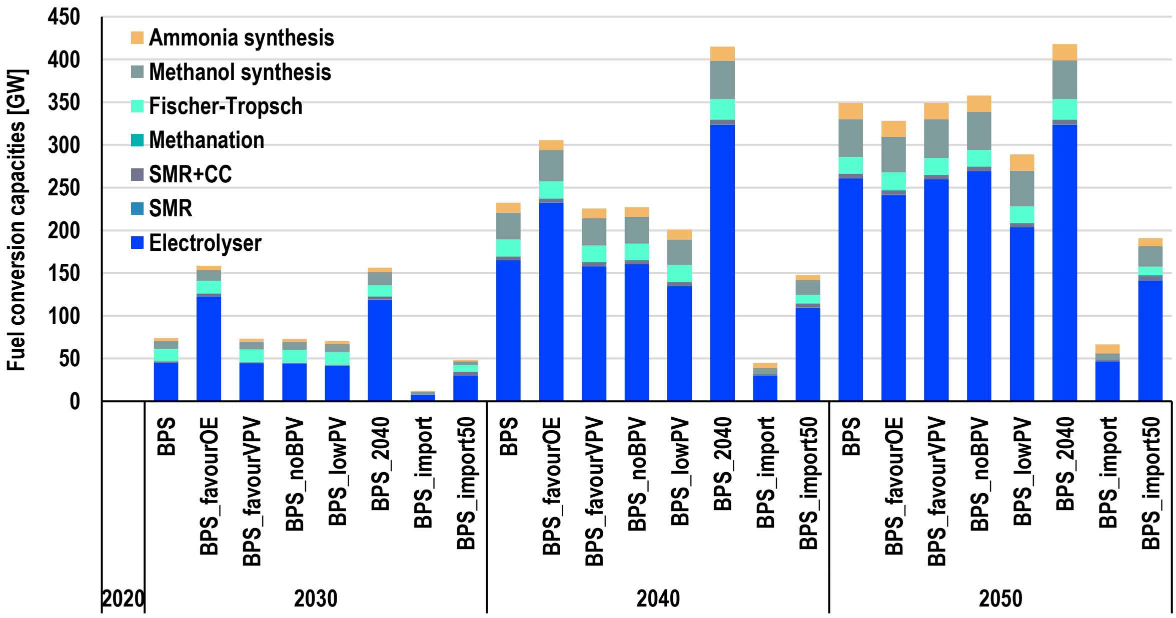

Figure 23 – Fuel conversion capacities across the scenarios from 2020 to 2050.

3.6. Sector coupling and flexibility in the energy system

The coupling of the different sectors of the energy system is the main key to reduce GHG emissions. This is due to the interaction between different sectors, types of energy use, and technological solutions. Energy flows depicted in Figure 24 and Figure 25 clearly demonstrate this impact. Figure 24 shows the energy flows in the Benelux system in 2020, when the sectors remained largely isolated from each other. In turn, Figure 25 shows the energy flows in the BPS by 2050, where system integration is more pronounced. In 2020, it is the power sector that is characterised by the greatest diversity of energy sources, while transport, especially road, maritime, and aviation, is almost entirely dependent on petroleum products. The heat sector shows moderate diversification but still relies heavily on fossil gas. This indicates that the current energy structure continues to suffer from limited flexibility, high fragmentation, and a significant dependence on fossil fuel imports.

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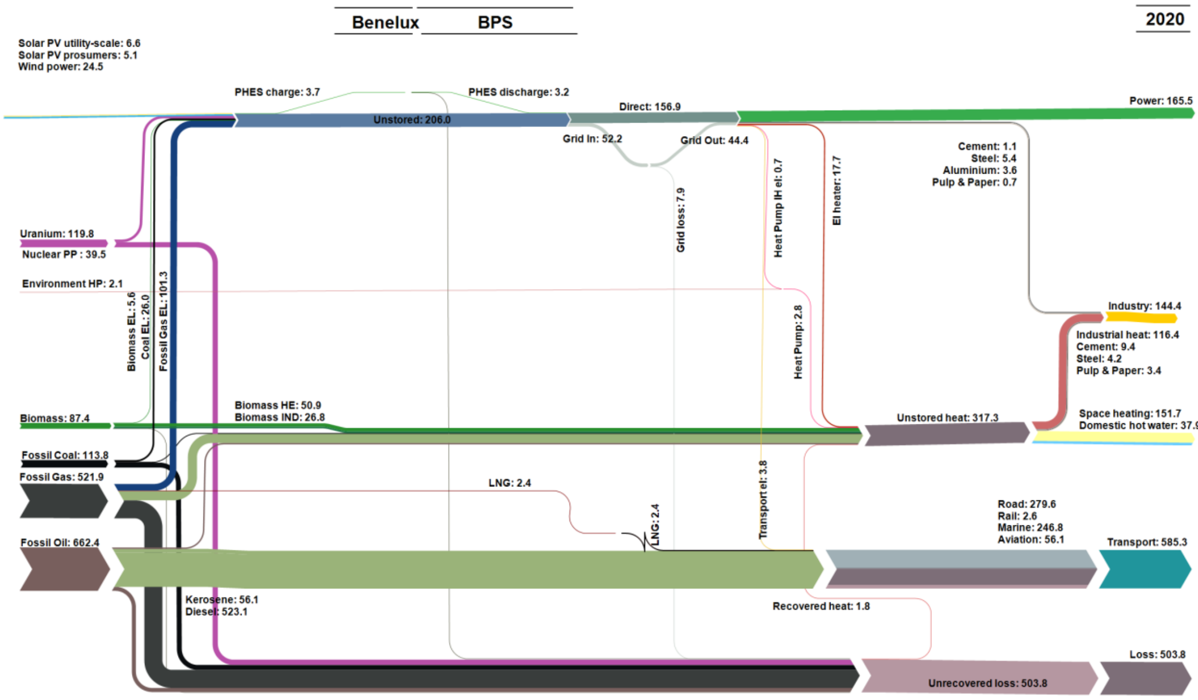

Figure 24 – Energy flows of the Benelux energy system in 2020.

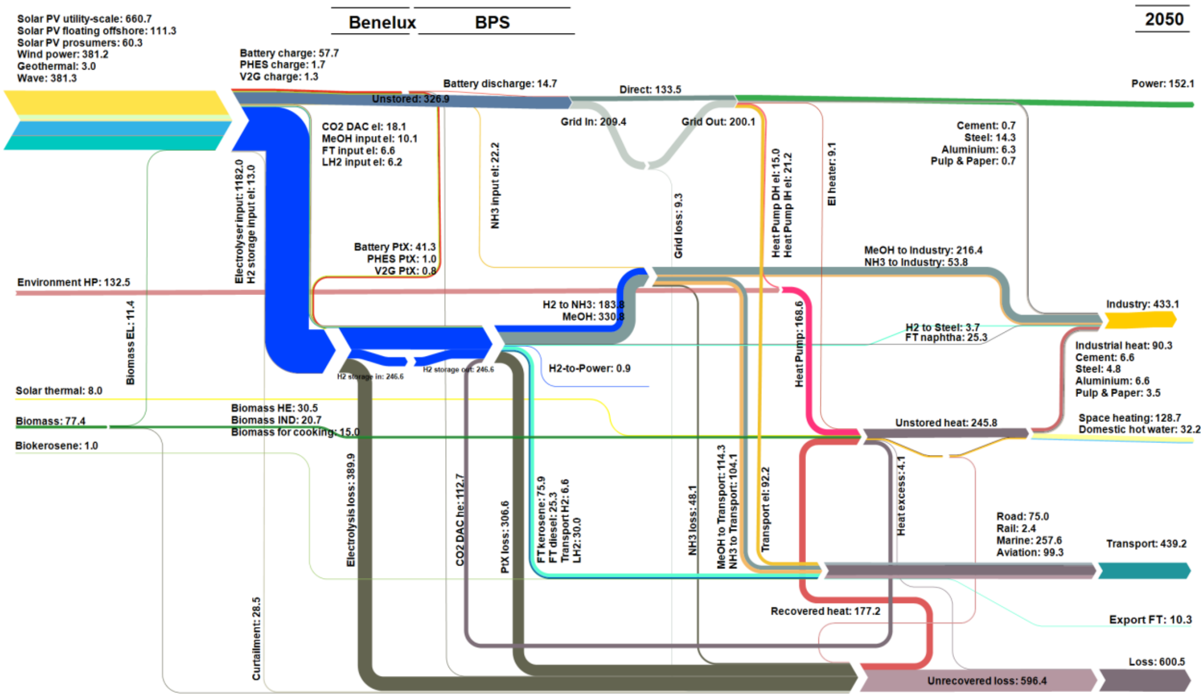

Figure 25 – Energy flows of the Benelux energy system in 2050 for the BPS.

The energy transition in the BPS and other scenarios results in a more interdependent and integrated energy system by 2050. The main characteristic of this system is the high share of diversification of the power, heat, transport, and industry sectors. The energy system is dominated by solar PV and wind electricity generation capacities. Onshore solar PV provides 661 TWh, complemented by OSPV 111 TWh, prosumer PV 60 TWh. Onshore wind power

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provides 381 TWh, wave power 381 TWh, and geothermal electricity generation 3 TWh. A significant contribution to final energy consumption is made by heat pumps, with additional environmental heat extraction of 132 TWh, as well as biomass (77 TWh, including 30 TWh for heating buildings, 20 TWh in industry), and solar thermal energy (8 TWh). Much of the electricity is used directly in the region of generation (direct: 133 TWh) whereas others are transmitted to neighbouring regions (Grid in: 209 TWh with Grid out: 200 TWh), with grid losses amounting to 9 TWh.

The largest use of electricity is the production of hydrogen and synthetic e-fuels: 1182 TWh is fed to electrolysis, of which a portion (246 TWh) is sent to hydrogen storage to balance supply and demand and thus provide the system more flexibility for reduced overall system cost, and converted into ammonia (H_2 to NH_3: 184 TWh), methanol (331 TWh), and Fischer-Tropsch liquids (FT kerosene: 76 TWh, FT diesel: 25 TWh). Additionally, these e-fuels syntheses result in 307 TWh losses, from which 179 TWh can be recovered in form of low temperature heat and used for district heating purposes. The final consumption is distributed among three main sectors. Industry uses 433 TWh, including industrial heat (90 TWh), as well as energy consumption in the cement (7 TWh), steel (5 TWh), aluminium (7 TWh), and pulp and paper (3 TWh) industries. Transport uses 439 TWh and the power sector demands 152 TWh, and remaining 161 TWh used for heating.

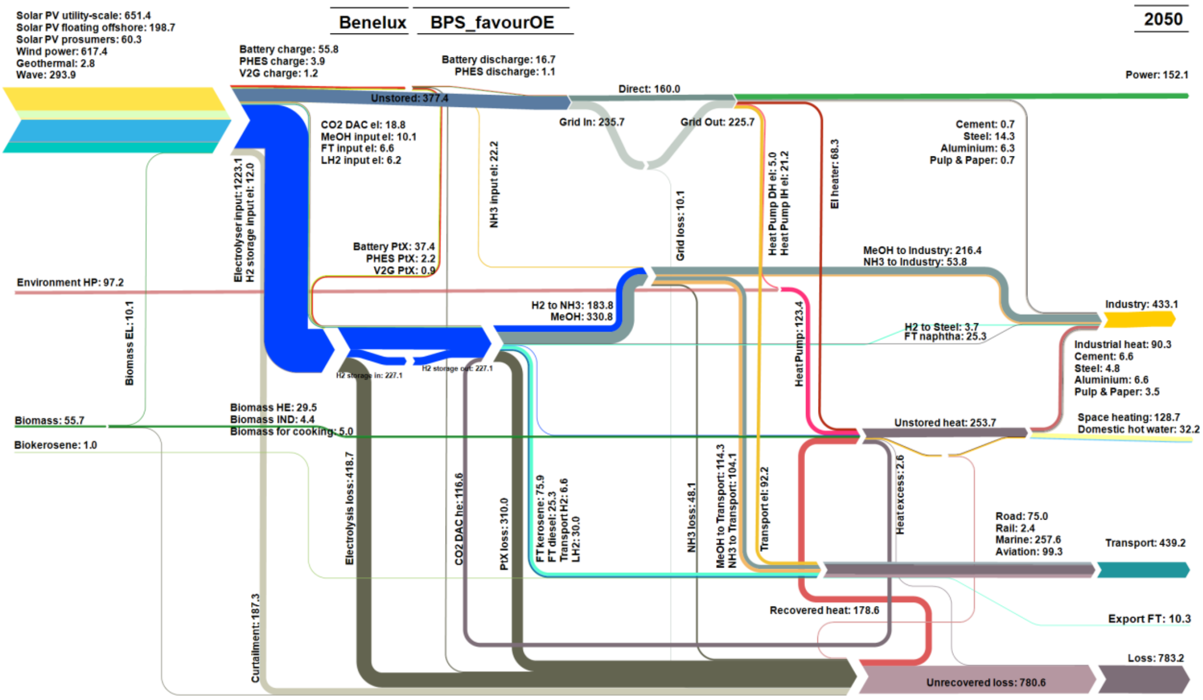

Figure 26 – Energy flows of the Benelux energy system in 2050 for the BPS_favourOE.

Figure 26 shows the energy flow of the Benelux region with increased ORE capacity. Renewable electricity flows are similar in their structure to the BPS, but their source shifts towards the ORE sources. Onshore solar PV generation provides 651 TWh (versus 660 TWh in the BPS), OSPV provides 199 TWh (versus 111 TWh in the BPS), and prosumer PV remains at 60 TWh. Onshore wind power

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produces 617 TWh (versus 381 TWh in the BPS), and wave power provides 294 TWh (versus 381 TWh in the BPS), while geothermal energy provides 3 TWh. The reduction in wave power in the BPS_favourOE is explained by strict government plan-based limits on offshore wind power capacities applied in the BPS. With limited offshore wind power capacities, to balance electricity supply and demand the system had to invest more in wave power after all lower cost alternative were fully utilised. When offshore wind power limits are relaxed in the BPS_favourOE, the system prioritises offshore wind power deployment and consequently invests less in wave power.

The key difference between the BPS_favourOE and the baseline BPS is not in the structure of the FED, but in the profile and excess of supply. The higher full load hours per installed capacity of ORE, in particular of offshore wind and wave power, provides a significantly greater influx of renewable electricity, which increases the full load hours on electrolysers and grid networks, but also leads to a slight increase in curtailment.

3.7. Energy system cost and emissions

Energy costs are a key factor in the implementation of energy transition scenarios. Renewable electricity, along with heat storage technologies and e-fuels production, become key components for Benelux and the European energy system as a whole.

The costs of the energy transition in Benelux show clear differences between the scenarios, particularly between scenarios focusing on the development of local renewable electricity generation and scenarios shifting towards e-fuel imports. These differences in approaches for energy system development leads to a significant variance in investment structures and long-term system costs. In the BPS, the system follows a balanced internal transition trajectory. Capex increases rapidly by 2030 (240 b€), after which they gradually decline as the large-scale deployment of RE stabilises, resulting in cumulative capex reaching 1012 b€ by 2050. Annual system costs decrease after a peak in 2035 (109 b€) and amount to 96 b€ in 2050, while their cumulative value reaches 2860 b€ (see Figure 27). The BPS_favourOE requires significantly higher early-stage investments due to the accelerated deployment of offshore wind power, wave power, and OSPV. Capex peaks in 2030 (389 b€), making this scenario the most capital-intensive. Although cumulative capex becomes the highest among all scenarios (1112 b€ by 2050), annual system costs in 2050 remain comparable to the BPS (104 b€). This demonstrates that the high investment burden does not lead to a proportional reduction in operating costs but rather reflects a long-term strategy of maximising the use of domestic resources.

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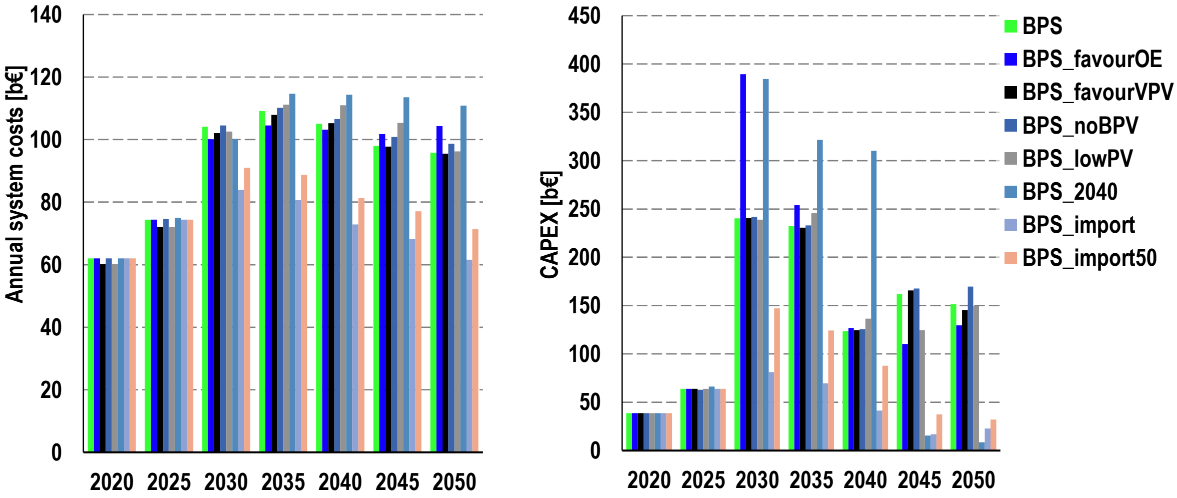

Figure 27 – Annualised energy system cost and capex across the scenarios from 2020 to 2050.

In contrast, the BPS_import demonstrates the lowest structural costs, as the widespread use of imported e-fuels dramatically reduces the need for domestic infrastructure development. Capex remains extremely low across all decades, increasing only to 23 b€ by 2050, and cumulative capex reaches 334 b€, almost three times lower than in the BPS. Annual system costs steadily decline from 2025 onward, reaching the lowest level among all scenarios of 62 b€ in 2050, due to the absence of large domestic production capacities. However, total annual costs are still significant (2272 b€). Despite lower annual payments, dependence on the global e-fuel market creates a significant long-term financial burden. The BPS_import50 occupies an intermediate position. Capex remain moderate (32 b€ in 2050), cumulative capex reach 531 b€, and annual system costs decrease to 71 b€ by 2050, higher than with full imports in the BPS_import but lower than in the other domestic self-supply scenarios. Thus, the BPS_import50 combines cost savings with increased energy security compared to full imports, while avoiding the high capital intensity of the BPS_favourOE.

The LCOE dynamic (Figure 28) shows a clear divergence between the local RE resource development scenarios and the scenarios relying on imported e-fuels. In the baseline BPS, the cost of electricity consistently declines from 88 €/MWh in 2025 to 73 €/MWh by 2030 and to 44 €/MWh by 2050, reflecting the scaling effect of solar PV and wind electricity generation and the disappearance of fuel costs and CO_2 emissions costs. The BPS_favourOE, despite the high capital intensity of ORE technologies, demonstrates a similar trajectory. In 2050, the LCOE for this scenario falls to 46 €/MWh. This reflects the fact that the accelerated development of offshore wind power and OSPV does not reduce electricity costs below the BPS level, as increased capex offset the benefits of high and stable generation.

On the other hand, the BPS_import provides the lowest long-term electricity cost of 33 €/MWh by 2050 among all scenarios. This is a direct consequence of the absence of domestic fuel costs and CO_2 emissions costs. The BPS_import50 also

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provides a low cost (34 €/MWh in 2050), positioning the import scenarios the most advantageous in terms of LCOE. Thus, dependence on external supplies of e-fuels minimises domestic costs at the cost of losing autonomy of the energy system.

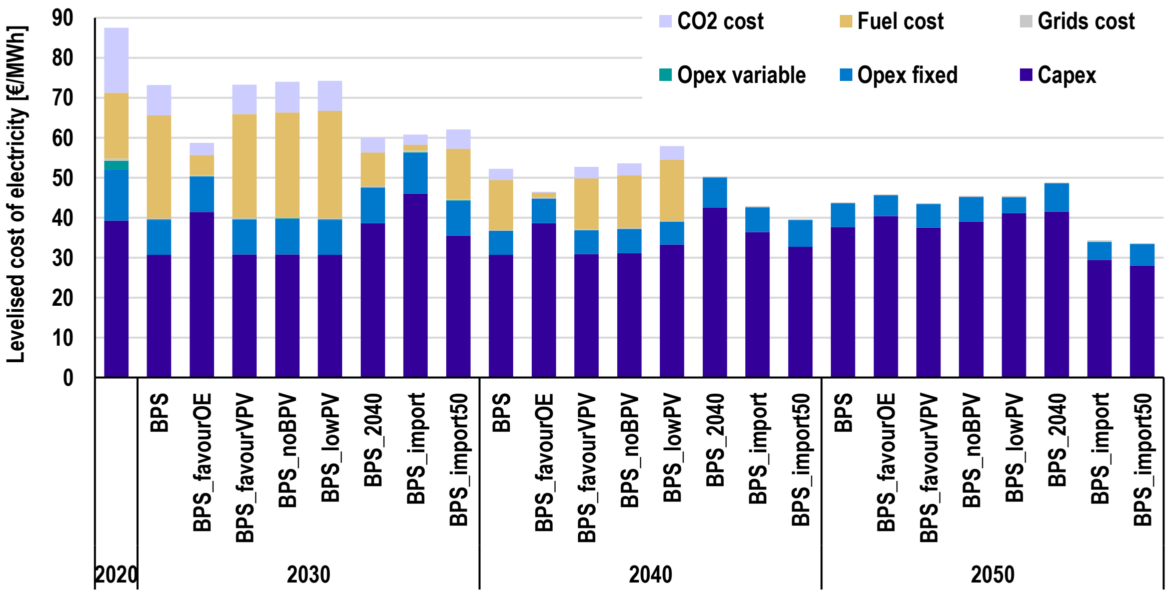

Figure 28 – Levelised cost of electricity across the scenarios during the transition.

The levelised cost of heat (LCOH) trajectories (Figure 29) follow a similar structure. The baseline BPS and BPS_favourOE maintain heat prices in the range of 27 €/MWh and 29 €/MWh. In 2030, they reduce to 22 €/MWh and 24 €/MWh. By 2050, due to the reduction of fossil fuel costs in the heat sector, they drop to 19 €/MWh and 25 €/MWh, respectively. The BPS_favourOE offers no additional gain in heat cost, as the heat sector is indirectly linked to offshore electricity generation and is largely determined by the development of heat pumps and electric heating. Compared to the other scenarios, the imported options stand out due to a sharp increase in heat cost in 2030 (up to 37 €/MWh), as the reliance on imported energy increases costs at the beginning of the transition. However, by 2050, the heat cost in the BPS_import and BPS_import50 drops again to 22 €/MWh and 26 €/MWh, respectively, remaining only slightly above the baseline BPS. This demonstrates that the import scenarios do not provide advantages in the heat sector but rather create an additional cost burden in the early stages of the transition.

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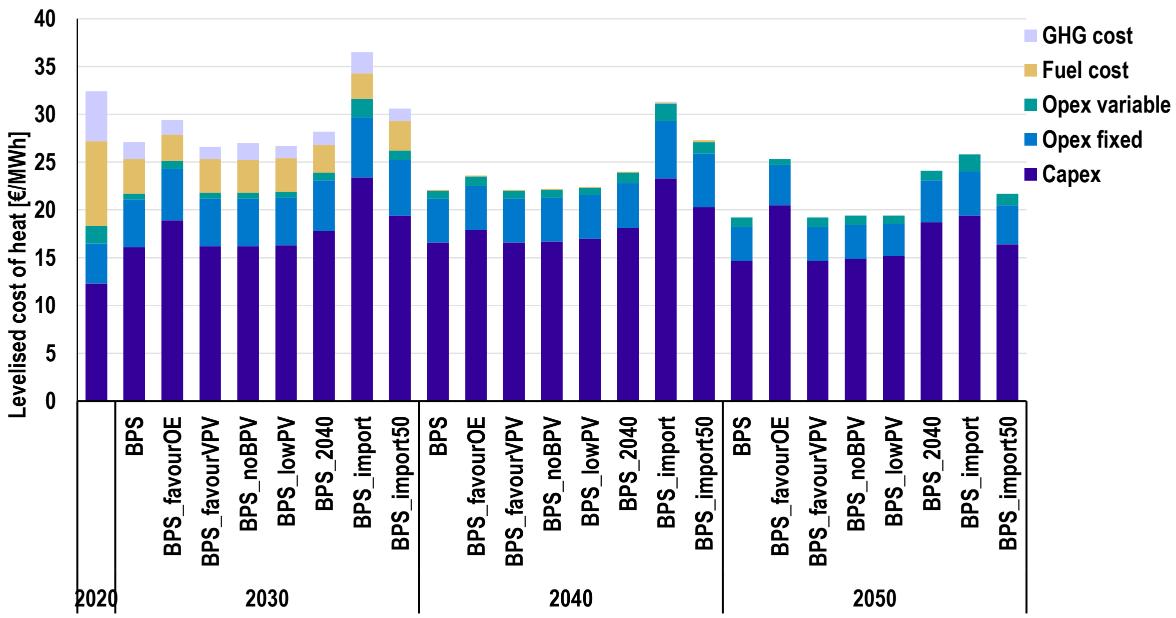

Figure 29 – Levelised cost of heat across the scenarios during the transition.

The levelised cost of final energy and non-energy use (LCOFE) (Figure 30) demonstrate the most significant differences between the scenarios. In 2030, the LCOFE in the BPS remains at 76 €/MWh, in BPS_favourOE it drops to 74 €/MWh, while in BPS_import and BPS_import50 it drops to 62-76€/MWh, respectively, due to a cheaper fuel mix. By 2050, the differences become even more pronounced. The BPS stabilises at 83 €/MWh, while BPS_favourOE leads to the highest cost of 90.5 €/MWh, due to the higher capital intensity of offshore infrastructure. In contrast, the BPS_import reaches a minimum of 53 €/MWh, and BPS_import50 reaches 62 €/MWh, making the import scenarios the clear leaders in reducing the LCOFE. This confirms the structural conclusion that increased domestic production of green e-hydrogen and e-fuels increases costs due to the higher domestic LCOE, while the import scenarios offset these costs by shifting them to foreign markets.

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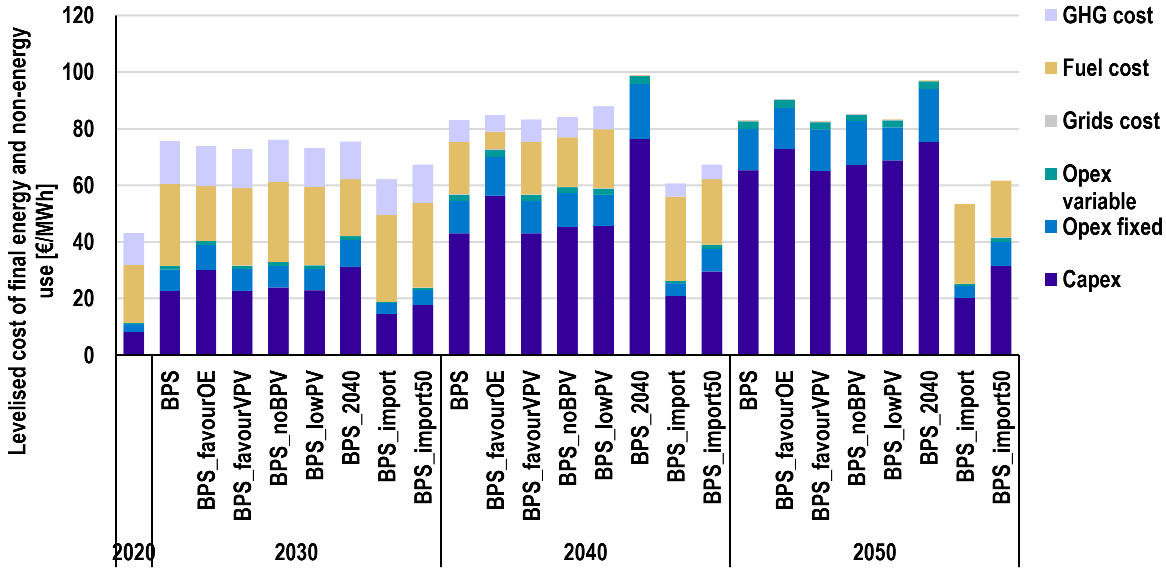

Figure 30 – Levelised cost of final energy and non-energy use across the scenarios during the transition.

The results of the energy transition demonstrate a sharp decline in CO_2 emissions across the power, heat, transport, and industry sectors in all scenarios by 2050, as shown in Figure 31. In 2020, CO_2 emissions from the power sector were over 66 $MtCO_2$, however, they experience a rapid decrease to zero by 2040 in the BPS_2040 and by 2050 in the other scenarios. In 2030, the lowest emissions occur in the BPS_import with 163 $MtCO_2$ and second lowest in the BPS_favourOE with 192 $MtCO_2$. The transport sector, which accounts for the highest emissions in 2020 of around 177 $MtCO_2$, achieves zero emissions by 2040. In other scenarios, emissions from the transport and industry sectors persist but remain minimal. Overall, emissions across all sectors experience an accelerated reduction to zero by 2040 in the relevant scenario, and a steady decline to zero by 2050 in other scenarios.

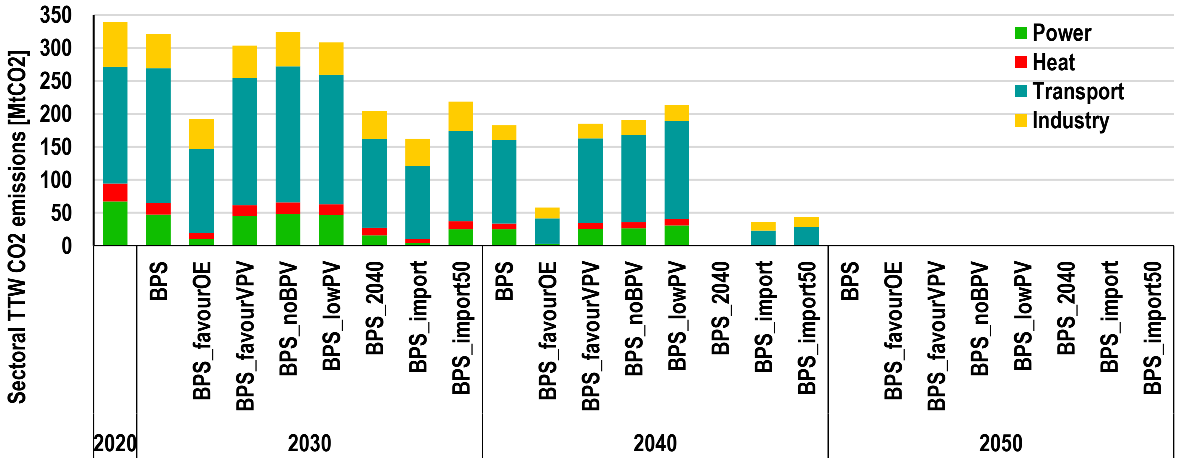

Figure 31 – Sectoral annual CO_2 emissions across the scenarios during the transition.

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4. Complementary impacts

4.1. The role of offshore renewable energy in achieving Benelux's energy targets

Limited land resources in the Benelux countries are a key structural challenge to large-scale defossilisation. Dense development, intense competition for land in urban agglomerations such as Brussels and Amsterdam, and a developed industry sector severely limit the potential for locating large-scale onshore RE facilities, particularly onshore wind farms and solar PV plants. Similar to the island regions described in studies of the Maldives and Hawaii [27], [82], the Benelux region faces the need to relocate electricity generation offshore, so that pressure on land resources can be reduced. In this situation, ORE technologies become not just an additional element of the energy system, but a system-forming element of the transition to carbon neutrality, as reflected in the results of both the main baseline BPS and the BPS_favourOE, and confirmed by similar studies [30], [42], [83].

The results of the BPS for Benelux confirm that a high share of offshore electricity generation significantly reduces the need for energy storage. The high share of ORE in the BPS also highlights that ORE technologies are the only solution for a self-sufficient energy system for the constraint of restricted land availability. Current offshore wind power targets of Belgium and the Netherlands adopted in the BPS seem to be inadequate to satisfy the energy demand of the region and result in an accelerated upscaling of wave power capacities. These findings are consistent with the conclusions of studies on the complementarity of offshore and onshore energy sources, which show that a stable seasonal wave power profile and high offshore wind performance smooth out variations in solar PV generation throughout the year [42], [84]. For the Benelux, where electricity generation from solar PV has a pronounced seasonal pattern and drops sharply in winter, such complementarity is particularly important. Electricity generation from offshore wind power reaches its maximum output during the colder months, which stabilises the system during periods of peak heating demand, where heat pumps and electric heating are the main sources. Results of cost comparisons highlight a key trade-off. The large-scale development of domestic ORE sources in the BPS_favourOE provides high energy autonomy but requires significantly higher initial investments. Conversely, import-based scenarios minimise capital requirements and reduce annual system costs; however, they increase the dependence on international e-fuel markets and risks to long-term sustainability. High initial investments can be partially mitigated through the co-development of OSPV with existing offshore wind farms and through the development of hybrid offshore PV-wind farms. The co-utilisation of offshore wind power and OSPV enables a reduction in grid connection costs due to the strong complementarity between wind power and PV generation profiles, as discussed earlier. In addition, hybrid offshore wind and OSPV power plants can reduce the area required for capacity expansion within the limited EEZs of Belgium and the Netherlands in the North Sea. Furthermore, wave power, with its high predictability and low intra-day variability, provides additional value in the form of

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diversification of the RE mix and reduced energy storage requirements. Model results for the Benelux region confirm these findings. BPS_favourOE demonstrates reduced requirements for storage and flexible gas units compared to the baseline BPS.

The increase in ORE capacities leads to an important political-economic consequence. The widespread use of ORE technologies can avoid the construction of new nuclear power plants. As literature shows, countries with limited land area often face difficulties in installing nuclear power generation facilities, ranging from intense competition for land to a lack of public consensus [77], [85]. A distinctive feature of the Benelux region is that offshore wind power offers high capacity and stable generation, which can compensate for the absence or decommissioning of nuclear power units, allowing climate goals to be met without increasing the share of nuclear power.

Therefore, the role of ORE technologies in the Benelux strategy goes beyond simple diversification. Offshore wind power primarily reduces the pressure on limited onshore RE resources, creates a more stable seasonal profile, and reduces the need for storage and hydrogen balance. The high share of ORE technologies makes it possible to avoid increasing nuclear power generation and is a self-sufficient and efficient energy system without dependence on imported e-fuels.

4.2. The role of e-fuels imports in achieving Benelux’s energy targets

A sustainable regional energy-industry system by 2050 requires significant volumes of energy-intensive synthetic e-products, particularly for the chemical industry, which is the main consumer of hydrogen and e-molecules. Research [86], [87], [88] confirms that in regions with a shortage of RE resources, imports of e-fuels are becoming a key tool for achieving climate goals.

The BPS results demonstrate that by 2040-2050, the share of electricity generation allocated to e-fuel production significantly increases, even in scenarios with limited RE potential: low PV capacity limit and limited offshore electricity generation growth. The BPS_import50 shows that importing up to 50% of the e-fuel demand reduces the pressure on the domestic hydrogen production infrastructure and reduces local electricity demand for electrolysers.

Thus, strategic e-fuel imports play a dual role. They reduce the systemic burden on hydrogen production and RE infrastructure within the region, increase the economic efficiency of the transition, and compensate for territorial limitations typical of the Benelux region. However, energy sovereignty is reduced with dependence on international e-fuel markets and outflow of financial means.

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5. Summary and key messages

This report explores the projections of Benelux's energy system from 2020 to 2050 across multiple scenarios, highlighting the impacts of offshore renewable energy sources deployment, solar photovoltaics diversity on sectoral defossilisation strategies on greenhouse gas emissions and introducing scenarios with different shares of possible import of e-fuels. One of the core findings is the consistent and significant reduction in final energy demand, which drops by 16% in most scenarios despite increasing activity in the transport and industry sectors. This reduction is primarily driven by enhanced energy efficiency and widespread electrification. The accelerated scenario especially achieves even greater savings through more ambitious policies and technological uptake, leading to earlier and deeper declines in energy use.

The drop in final energy demand in combination with the switch to renewable energy supply results in a substantial reduction of primary energy demand. In 2020, fossil fuels dominate the supply mix, whereas by 2050, renewable electricity becomes the main energy source across all scenarios. This transition drives the primary energy demand down from 2034 TWh to as low as 1773 TWh in the most ambitious scenario, with the integration of offshore renewable energy technologies contributing to this efficiency gain.

Electrification of the energy system requires a fast growth of electricity generation capacities. The electricity generation capacity dramatically expands over the period, growing from about 73 GW in 2020 to 268 GW in 2030 and to nearly 1102 GW by 2050. Solar photovoltaics and wind power emerge as the leading technologies, with solar photovoltaics exceeding 793 GW of installed capacity and up to 884 TWh of electricity generation in baseline scenarios. Offshore wind power also becomes increasingly important, particularly in the favoured offshore renewable energy scenario, reaching 140 GW in capacity and up to 524 TWh in electricity generation. Nuclear power generation is entirely phased out by 2030.

Energy storage systems scale up rapidly to accommodate the variability of renewable energy. By 2050, prosumer batteries and vehicle-to-grid systems exceed 53 TWh of output, playing critical roles in system flexibility. While the import scenario achieves the highest total storage deployment accounting 449 GW, scenario relies more on decentralised solutions, such as prosumer batteries, as well as more centralised pumped hydro energy storage, reflecting its early transition towards renewable energy. Other flexibility sources such as smart charging of electric vehicles and heat storage options also contribute to the system stability.

The industry sector shows a moderate overall energy demand growth, with chemicals and other industry segments expanding, while steel and cement decline due to material efficiency and substitution. In the transport sector, energy use for road transportation drops significantly with the uptake of electric vehicles, while aviation becomes the largest single transport energy consumer by 2050 due to limited direct electrification options. To supply sustainable fuels for industry, aviation, and shipping, e-fuels and e-chemicals conversion capacities,

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especially electrolysers, expand from nearly zero to over 260 GW, alongside a steady growth in methanol and Fischer-Tropsch liquids synthesis. Scenarios with imports limit domestic electrolysis capacity to 47-141 GW accordingly, offsetting demand through imports. The levelised cost of electricity in 2050 decreases to 44 €/MWh in scenarios with a high share of offshore renewable electricity generation. For imports scenarios it declines further to 33-34 €/MWh.

The baseline scenario is characterised by high investment during the period of active infrastructure deployment. Annual capital expenditures peak at approximately 240 b€ by 2030, and cumulative capital expenditures exceed 1000 b€ by 2050. Annual system costs stabilise at 96 b€ in 2050, reflecting a balance between investment, operating costs, and reduced fuel and carbon costs. The favoured offshore renewable energy scenario requires higher investment in the early stages of the transition, with a peak in capital expenditures of approximately 389 b€ in 2030 but demonstrates comparable and even slightly lower annual system costs in the long term, reaching approximately 104 b€ in 2050. The system cost can further decrease considering the benefits of co-utilisation of grid infrastructure by emerging offshore photovoltaics-wind farms, and more stable electricity supply profiles due to complementarity of wind and PV generation profiles.

Scenarios with imported e-fuels demonstrate a fundamentally different cost structure. In the scenario with unlimited import, capital expenditures are significantly lower, with accumulated capital expenditures amounting to only 334 b€ by 2050, almost three times less than in the scenarios with domestic e-fuel production. This is accompanied by the lowest annual system costs of around 62 b€ in 2050, with cumulative annual costs decreasing to 2272 b€ over the period up to 2050. The scenario with import of e-fuels covered 50% of demand occupies an intermediate position. Limiting imports to 50% increases capital expenditures and annualised cost compared to unlimited imports, but they remain significantly lower than in baseline and favoured offshore renewable energy scenarios. However, the lower system costs in the import scenarios come at the expense of increased dependence on external supplies, which is not directly reflected in cost figures but is critical for energy security and system resilience. Scenarios with e-fuel imports demonstrate the lowest annual and cumulative system costs due to a sharp reduction in domestic investment in generation, conversion, and energy storage. However, these savings come at the cost of high dependence on external e-fuel supplies. Minimising system costs does not determine the optimality of the energy transition. The scenario with a priority on offshore renewable energy technologies provides a more reliable, balanced, and strategically sustainable path to carbon neutrality with only moderately higher investment requirements.

As a result, the scenario with favoured offshore renewable energy sources enhances the spatial resilience of the Benelux energy system by redistributing electricity generation offshore, reducing the pressure on limited land, aligning regional differences in storage, and import needs. This resilience is a key advantage for a compact and densely populated region. The favoured offshore renewable energy scenario creates the most balanced and sustainable energy

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system in the Benelux. The combination of advanced offshore renewable energy technologies with limited and targeted e-fuel imports reduces system risks, reduces the need for energy storage, and improves system stability with modest additional investment. This confirms that technological diversity in offshore electricity generation is key to successfully and reliably achieving carbon neutrality in the region by 2050.

The main results and conclusions of this study highlight that the integration of floating offshore solar photovoltaics and wave power into the Benelux energy system leads to moderately higher total system costs compared to scenarios without them, but for the benefit of a higher system diversity and lower reliance on energy storage and transmission. The scenario with a lower solar photovoltaics share is the most expensive in terms of annual system cost, emphasising the economic importance of having a considerable solar photovoltaics share in the system.

Results show that an accelerated or limited scaling of offshore renewable energy and floating offshore solar photovoltaics only has modest effects on direct energy related greenhouse gas emissions, indicating that cross-sectoral policies and system-level strategies play a far greater role in determining defossilisation outcomes.

In conclusion, although the offshore renewable energy favouring scenario results in slightly higher capital expenditures and also annualised system costs, it offers a more resilient, regionally optimised and efficient system architecture. These results support a strategic shift towards greater technological diversity in offshore renewable energy as a key driver for a sustainable energy transition in Benelux.

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