European Scalable Offshore Renewable Energy Source (EU-SCORES)

D2.1 White paper on GHG emission reduction paths supported by offshore renewables (especially solar & wave) for achieving the European Green Deal targets

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Contents

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Abbreviations

AUH	Austria-Hungary
BNL	Belgium, Netherlands, and Luxemburg (Benelux)
BFOW	Bottom-Fixed Offshore Wind
BKN-E	Balkan-East
BKN-W	Balkan-West
BLT	Baltic
BPS	Best Policy Scenario
BPS-2040	Best Policies Scenario with carbon neutrality reached by 2040
BPS_FPV	Best Policy Scenario with OSPV
BPS_highOE	Best Policy Scenario with high ORE
BPS_highOE_FPV	Best Policy Scenario with high ORE and OSPV
BPS_lowOE	Best Policy Scenario with low ORE
BRI	British Isles
Capex	Capital Expenditure
CC	Carbon Capture
CH	Switzerland
CO_2	Carbon Dioxide
CRS	Czech Republic and Slovakia
DE	Germany
DK	Denmark
EC	European Commission
EEZ	Exclusive Economic Zone
EPBD	Energy Performance of Buildings Directive

EU	European Union
FI	Finland
FPV	Floating Photovoltaics
FR	France
GHG	Greenhouse Gas
HDV	Heavy-Duty Vehicle
IBE	Iberian Peninsula
IEA	International Energy Agency
IEA-PVPS	International Energy Agency - Photovoltaic Power Systems Programme
IRENA	International Renewable Energy Agency
IS	Iceland
IT	Italy
LCA	Lifecycle Assessment
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Heat
LDV	Light-Duty Vehicle
LUT-ESTM	LUT Energy System Transition Model
MDV	Medium-Duty Vehicle
NO	Norway
NOAA	National Oceanic and Atmospheric Administration
OSPV	Offshore Solar Photovoltaics
Opex	Operating Expenditure
ORE	Offshore Renewable Energy

PL	Poland
PtX	Power- to- X
PV	Photovoltaics
RE	Renewable Energy
RES	Renewable Energy Source
SDG	Sustainable Development Goal
SE	Sweden
SMR	Steam Methane Reforming
TES	Thermal Energy Storage
TR	Türkiye, Cyprus
TTW	Tank- to- wheel
UA	Ukraine-Moldavia
UN	United Nations
V2G	Vehicle-to-Grid
WEC	Wave Energy Converter

0. Executive summary

One of the most important issues confronting the present is greenhouse gas (GHG) emissions induced climate change, which has already had a sensible negative impact on economic activities and environmental sustainability, and the impact is expected to further grow in future. Activities such as energy consumption, industrial processes, transportation, agriculture, and deforestation are the main source of anthropogenic GHG emissions. A transition to low carbon energy sources and increase of energy efficiency is one of the main sources to curb anthropogenic GHG emissions. Renewable energy (RE) plays a major role in the defossilisation of the energy supply and the role of offshore renewable energy (ORE) in global climate efforts is growing. In order to direct sustainable development in the sector, it is crucial to comprehend the emission impacts of all major and emerging ORE technologies, such as offshore wind power, wave power and offshore floating solar photovoltaics (PV) systems. Several energy transition scenarios for ORE are studied to examine ORE technologies' impact on an optimal energy system structure, energy costs, and GHG emissions pathways, assessing potential mitigation strategies.

The results underscore how crucial multi-source ORE systems will be in determining the structure of renewable energy portfolios in the future. By sharing infrastructure, such as export cables and substations, these systems lower carbon intensity, increase overall efficiency, and foster the development of emerging technologies including wave power and floating offshore solar PV (OSPV). One important tactic to lower GHG emissions and prevent irreparable harm to our planet is to transition the energy system to a high proportion of RE sources, which demands area and can be challenging in densely populated coastal areas. Benefits from this change go beyond just lowering the use of fossil fuels and lessening their effects on the environment. As energy increasingly connects with environmental, economic, and social priorities, having a variety of technical and economic analysis methods for energy systems becomes crucial for thorough planning and well-informed decision-making.

Therefore, a structured approach was chosen to guarantee a thorough analysis, building upon the study's significance and stated objectives. The methodology was developed using relevant data sources, analytical frameworks, and computational tools to align with the objectives of the investigation. Data accuracy, model efficiency, and scenario reliability were important factors in the methodological design, which ensured that the results were reliable, applicable to real-world situations, and provided a reliable understanding of the energy policies and their effects. Detailed methods and techniques used in this study are described in the next section.

The LUT Energy System Transition Model (LUT-ESTM), a linear optimisation tool intended to create cost-optimised energy transition scenarios for the entire energy system, was used to model energy transition scenarios for the European energy-industry system. LUT-ESTM is applied in an hourly resolution for the entire year, a geographical multi-node structure, and investment and dispatch optimisation techniques. Six different scenarios are used to examine the energy transition in Europe: the reference Best Policy Scenario (BPS), aligned with the European Green Deal and the European Commission's (EC) ORE growth targets, as well as scenarios examining the effects of reduced or expanded offshore wind power and wave power implementation (lowOE and highOE scenarios), effects of OSPV implementation (FPV scenarios), and an accelerated pathway scenario with carbon neutrality reached by 2040 (BPS_2040).

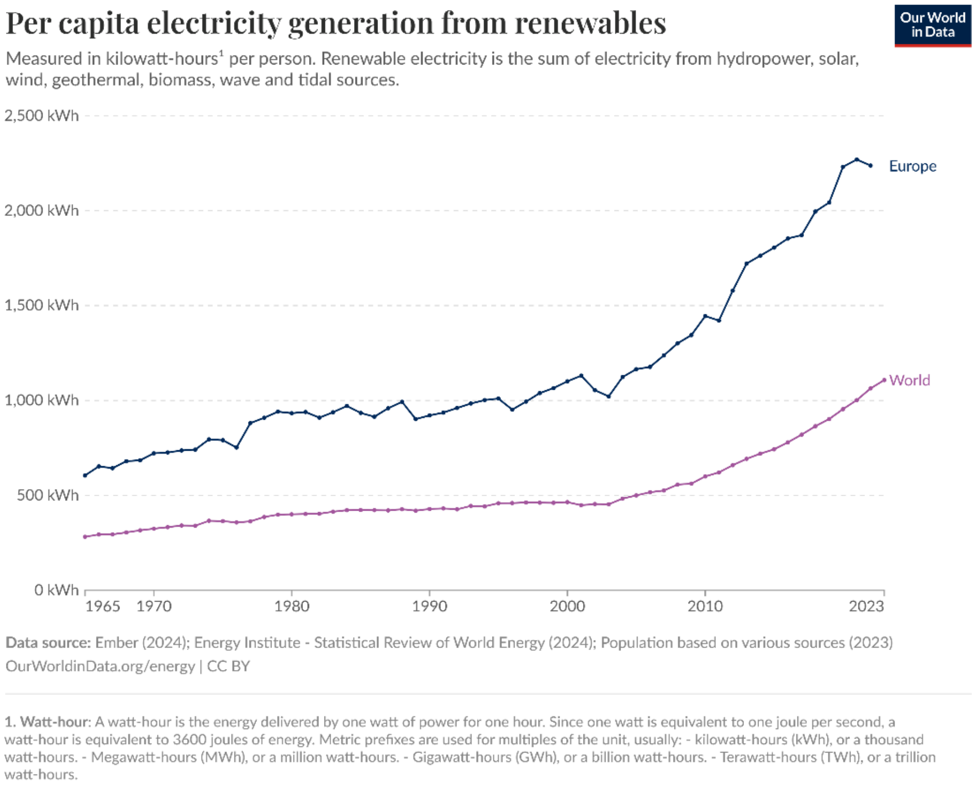
This report discusses GHG emission reduction as a key measure of the contribution of ORE technologies to the European energy landscape. The analysis shows a strong downward trend in CO_2 emissions across all modelled scenarios from 2020 to 2050, with reductions seen in the power, heat, transport, and industry sectors. Emissions start around 3270 $MtCO_2/a$ in 2020, led by transport (~1494 $MtCO_2/a$), and decline to roughly 2835 $MtCO_2/a$ by 2025. By 2030, most scenarios converge around 1775 $MtCO_2/a$, while the most ambitious scenario (BPS_2040) shows an earlier drop to 1621 $MtCO_2/a$. Notably, this scenario continues to decarbonise rapidly, reaching about 600 $MtCO_2/a$ in 2035, compared to 877–894 $MtCO_2/a$ in the others. By 2040, emissions in most scenarios range between 364–386 $MtCO_2/a$, whereas the fastest defossilisation path reaches near-zero levels, particularly achieving zero in transport and industry. Full defossilisation is achieved across all scenarios by 2050. Differences in technology choices, such as between offshore and onshore RE, do not significantly affect CO_2 emissions, as they primarily replace each other rather than fossil fuel sources. Cumulative CO_2 emissions from the power sector are largely locked in before 2040, with coal and gas remaining the dominant contributors. This highlights the long-term impact of early fossil fuel use and emphasises that rapid decarbonisation before 2040 is critical to reduce total CO_2 emissions and align with climate targets. However, results show that accelerated or limited scaling of ORE and OSPV has only modest effects on direct energy related CO_2 emissions, indicating that cross-sectoral policies and system-level strategies play a far greater role in determining defossilisation outcomes.

1. Introduction

In recent years, there has been a growing discussion about the critical climate situation caused by a significant increase in extreme weather events, such as droughts and wildfires in some parts of the world and constant rains and floods in others [1], [2]. The highest global temperature recorded by the National Oceanic and Atmospheric Administration (NOAA) occurred in 2023, when the average temperature across the Earth's land and ocean surfaces was 0.6°C warmer than the average from 1991 to 2020 and 1.48°C warmer than the pre-industrial level from 1850 to 1900 [3]. Additionally, sea levels have been gradually increasing globally as a result of climate change, mostly due to the melting of ice shields and glaciers as well as the thermal expansion of seawater. According to [4], between 1901 and 2018, there was an approximate 20 centimetre increase in the global mean sea level, with the rate of rise accelerating in recent decades. Sea level rise is projected to be further accelerated by ongoing greenhouse gas (GHG) emissions, possibly reaching 290 to 1100 millimetres by 2100, depending on future emission scenarios. Sea level rise is a crucial consideration in climate impact assessments and adaptation planning because it threatens low-lying communities, infrastructure, and coastal ecosystems [5]. These are yet more indisputable indications from nature that, in the absence of climate change mitigation measures, the trend of adverse extreme weather impacts will only worsen, putting ecosystems and human health at risk.

The creation and execution of climate change mitigation strategies are largely the responsibility of governments. However, current actions to decrease GHG emissions are not sufficient, as its impact is limited to a slow shift away from conventional methods in the power, heat, transport, industry, and agriculture sectors and towards the adoption of cutting-edge climate technologies across the board [6]. The Paris Agreement [7] and the United Nations (UN) Sustainable Development Goals (SDGs) [8] have created a clear picture of a future that calls for immediate climate action and addressing social and environmental aspects of sustainable development. In order to meet the Paris Agreement's 1.5°C temperature limit, the UN report [9] recommends reducing GHG emissions by 7.6% annually between 2020 and 2030. Another report published by the UN [10] also suggests a 28% reduction in projected 2030 GHG emissions for the 2°C pathway and a 42% reduction for the 1.5°C pathway.

Reaching carbon neutrality with the key target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels is the main goal of the European Green Deal program [11]. This objective is at the heart of the European Green Deal and in line with the European Union’s (EU) commitment to global climate action under the Paris Agreement [7], [12], [13]. The main objectives of the plan are to diversify energy sources, encourage energy efficiency, lessen the EU's dependency on imported energy, and greatly boost the use of renewable energy (RE) technologies. In recent years, European countries have been leading the deployment of RE technologies, driven by their vast RE resource potential and the extensive utilisation of RE sources (Figure 1). To fulfil the terms of the Paris Agreement, the EU has set goals for decarbonising buildings by 2050, phased out fossil fuel boilers, and encouraged refurbishment through the Energy Performance of Buildings Directive (EPBD) [14]. Additionally, it has established goals to defossilise aviation and shipping. Europe is making rapid progress in improving the sustainability of its energy systems in order to meet these objectives [14].



Per capita electricity generation from renewables

Measured in kilowatt-hours[1] per person. Renewable electricity is the sum of electricity from hydropower, solar, wind, geothermal, biomass, wave and tidal sources.

Data source: Ember (2024); Energy Institute - Statistical Review of World Energy (2024); Population based on various sources (2023)
OurWorldinData.org/energy | CC BY

1. **Watt-hour**: A watt-hour is the energy delivered by one watt of power for one hour. Since one watt is equivalent to one joule per second, a watt-hour is equivalent to 3600 joules of energy. Metric prefixes are used for multiples of the unit, usually: - kilowatt-hours (kWh), or a thousand watt-hours. - Megawatt-hours (MWh), or a million watt-hours. - Gigawatt-hours (GWh), or a billion watt-hours. - Terawatt-hours (TWh), or a trillion watt-hours.

Figure 1. Electricity generation from renewables per person for Europe and World [15].

Recent trends in a number of sectors show that the EU is seeing an increase in the growth of RE [15], electrification [16], and efficiency measures [17]. However, these developments are not happening quickly enough to reach the carbon neutrality level that will guarantee RE energy dominance and climate change mitigation. The heat, transport, and industry sectors must be heavily electrified in order to being integrated with the power sector; however, this will lead to an increase in the amount of electricity consumed. To accelerate the energy transition, rapid growth in electricity generation from low-cost RE sources, mainly solar photovoltaics (PV) and wind power will be needed. Deployment of solar PV and wind power capacities may be challenging in the densely populated regions with energy-intensive industry, especially, in coastal areas, where on the contrary ocean RE (ORE) technologies may play a substantial role. The EU recognises that accomplishing the required energy transition depends on the efficient and successful deployment of ORE. The effective use of marine areas can be improved by the adoption of cutting-edge ORE technologies, especially offshore wind power, wave power, and OSPV. ORE technologies can also help reduce costs when combined to multi-

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source ORE systems, typically in combination with offshore wind power and its infrastructure that is already in place.

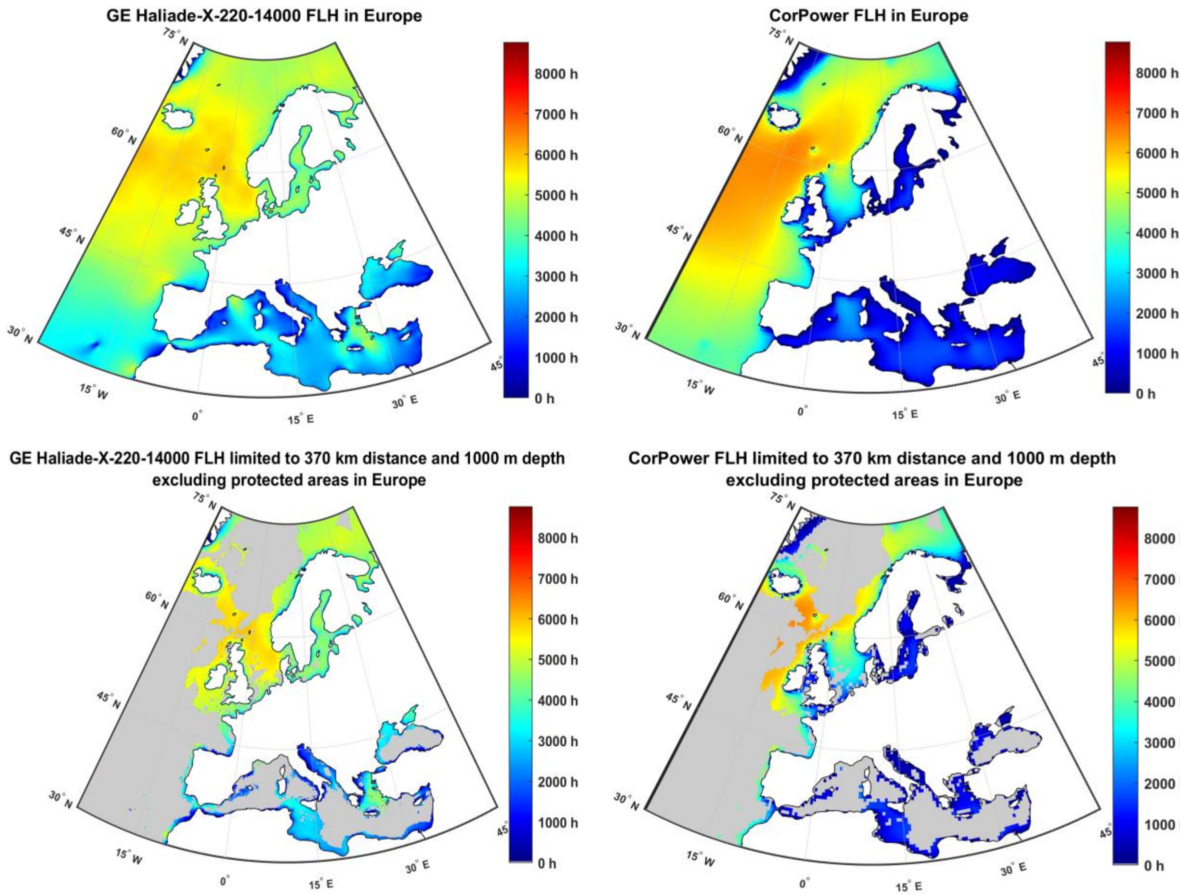

Figure 2 illustrates the potential of offshore wind power and wave power in Europe. The overall theoretical potential is shown as well as the projected technical potential with latest available ORE technologies and expected accessible distances and depths in the decades to come [18], [19]. Theoretical resource potential maps show that offshore wind power and wave power are widely and consistently available across northern and western Europe, with both technologies exceeding 5000 full load hours in many areas and occasionally reaching around 7000. Although technical constraints reduce the accessible areas, substantial resource potential remains.

Regarding wave energy, for point absorber type devices the wave power density reaches 14.8 MW/km^2 [19]. Figure 3 also includes the wave power profiles for selected regions in Europe. If 15% of exclusive economic zone (EEZ) area are used for wave energy converters, the technical potential for wave power in Europe may reach up to 7200 GW in capacity and a total electricity generation potential of up to 13,000 TWh [19]. According to this variation, combining several ORE technologies can improve system performance and dependability overall and offer supplementary advantages over using each technology separately.

Growing onshore RE capacity may encounter obstacles in densely populated areas, impeding advancement. Furthermore, ORE sources might be the only workable

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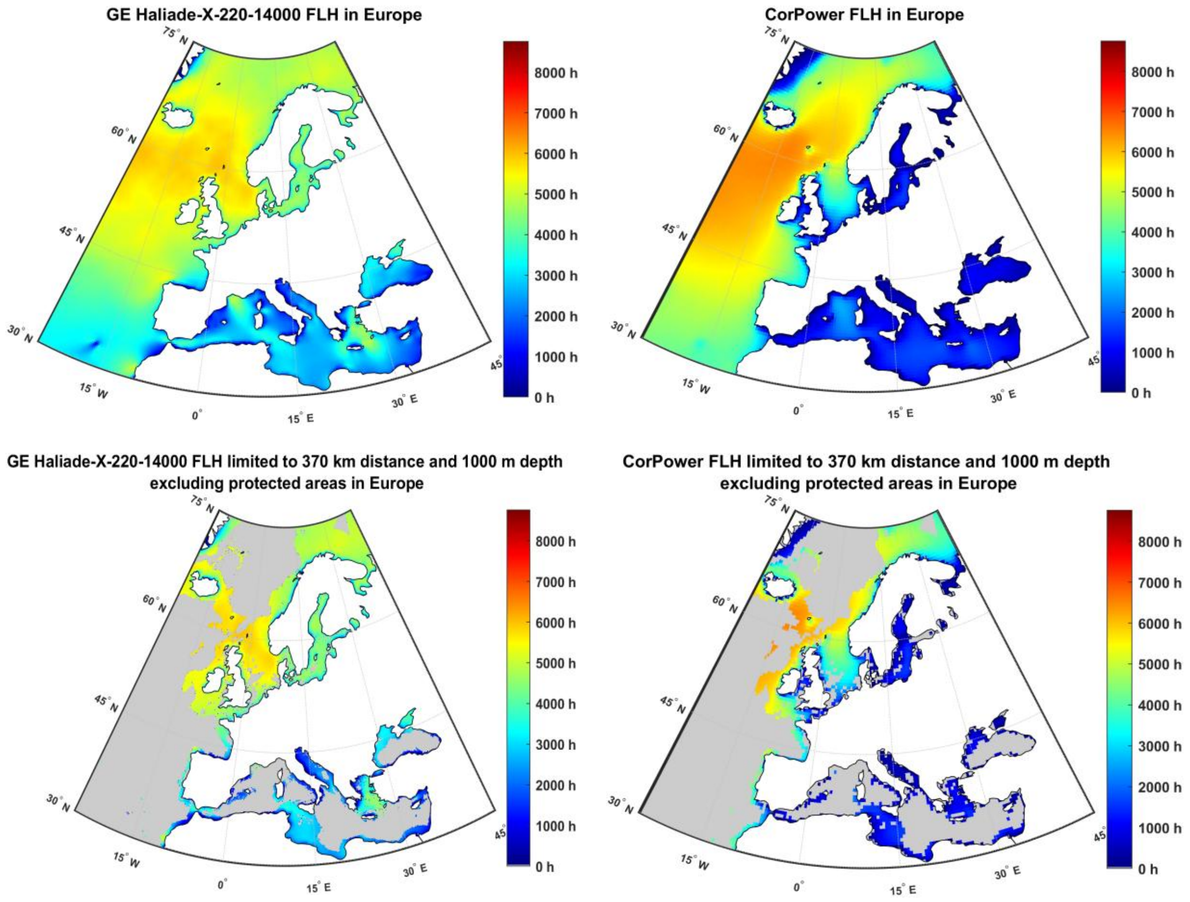
way to improve energy self-sufficiency and decarbonise the energy system in places where onshore RE resources are not enough to meet demand. A major player in this endeavour is the EU-SCORES project, which seeks to maximise the use of offshore space, provide a dependable, affordable energy system, and fortify the business case for investment.


GE Haliade-X-220-14000 FLH in Europe

CorPower FLH in Europe

GE Haliade-X-220-14000 FLH limited to 370 km distance and 1000 m depth excluding protected areas in Europe

CorPower FLH limited to 370 km distance and 1000 m depth excluding protected areas in Europe

Figure 2. Potential for offshore wind power (left) and wave power (right) for theoretical considerations (top) and technical limitations (bottom) measured in full load hours per year for Europe. Data sources: [18], [19].

Figure 3 illustrates the hourly capacity factor profiles for wave energy converters in chosen locations across Europe. The wave power generation profiles reach a maximum in winter months correlating with peak energy demand in northern Europe.

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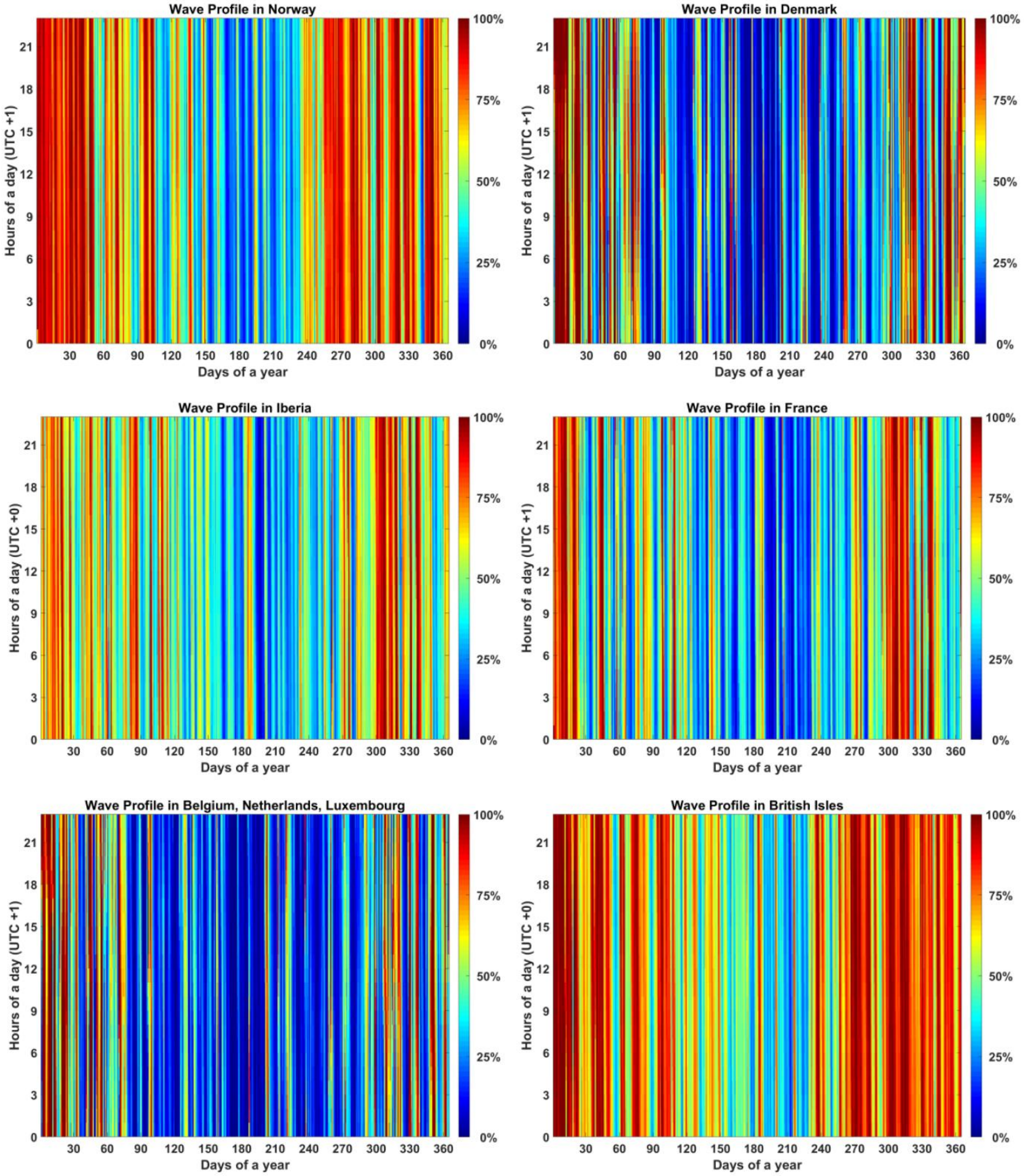
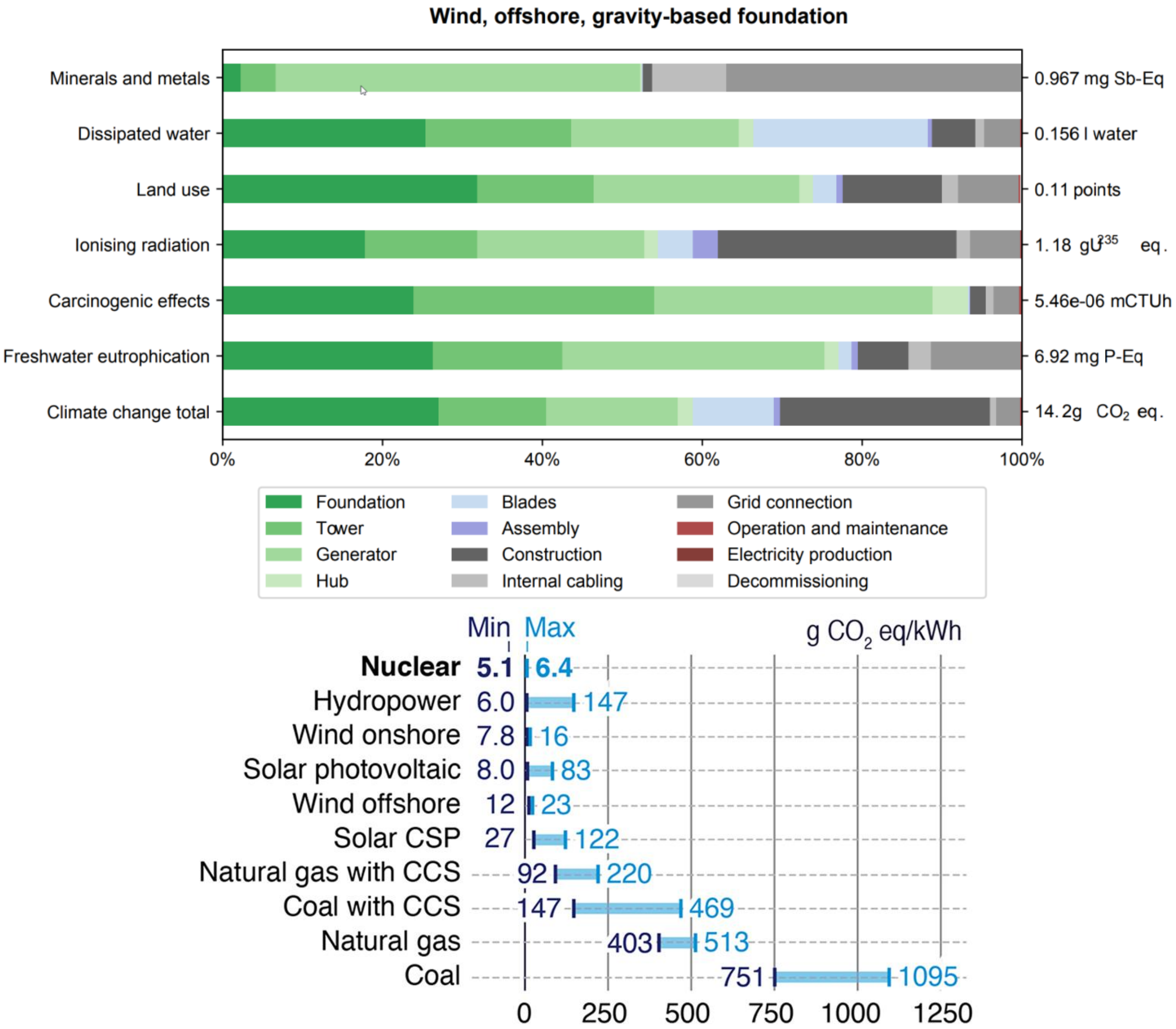


Figure 3. Wave power profiles in Europe [19].

Furthermore, ORE technologies may be more efficient for GHG emissions mitigation due to lower lifecycle emissions. For offshore wind power technologies (see Figure 4) life cycle GHG emissions are estimated at 14.2 gCO$_2$eq/kWh. Figure 4 also indicates the breakdown of the total emission based on the components in an offshore wind turbine [20]. This value can vary in different projects and regions which are mostly caused by differences in methodological decisions like the boundaries established in lifecycle assessments (LCA), system performance such as capacity factors, and contextual factors such as the availability of wind energy resources, technological maturity, and end-of-life strategies [21].



Source: based on data from UNECE (2022). Note: CSP — concentrated solar power; CCS — carbon capture and storage.

Figure 4. Life cycle impacts from 1 kWh of offshore wind power generation by structure components (top) [20] and in comparison with other technologies [22].

On the other hand, wave power technologies show a promising potential for low-carbon electricity generation, with life cycle GHG emissions typically ranging from 20-80 gCO_2eq/kWh, well within the range of RE technologies, though some technologies may exceed this due to design complexity, materials, and low technology readiness levels of some applications [23]. While still in early development phases compared to other RE, their environmental performance varies significantly by design and scale. Table 1 includes the different technologies and projects deployed in wave power with their installed capacities and global warming impacts.

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Table 1. Global warming impact of different technologies of different WEC [23].

Wave Energy Converter (WEC)	Installed capacity [MW]	GHG impacts [gCo$_2$eq/kWh]
LiftWEC	100	32
MegaRoller	1	33.8-75.1
ISWEC	0.1	31.5-62
CorPower C4	10	25-42
Oyster 1	0.315	79
Oyster 800	0.8	57
Pelamis	0.75	20
OBREC	0.03	37-86
Wave Dragon	7	28
Wavestar	1	47
Seabased	20	32-152

Regarding OSPV systems, life cycle GHG emissions are comparable to or slightly higher than traditional ground-mounted PV systems, primarily due to additional materials and anchoring requirements. However, their placement on water bodies can enhance performance through natural cooling effects, potentially offsetting some of the increased emissions. Table 2 exhibits the GHG impact of diverse PV systems. The numbers indicate that OSPV systems are a viable low-carbon energy solution, especially in regions where land availability is limited such as Benelux [24]. There are only very limited studies on life-cycle aspects of OSPV. One study [25] did such an analysis, however, with a PV technology that exited the market 10-15 years ago. Therefore, that study is not appropriate for a solid discussion, especially since the efficiency of that technology (a-Si PV) is around 60% lower than present day technology, which would lead to highly distorted results.

Table 2. Life cycle GHG emissions of onshore FPV systems.

System Type	GHG impact (gCO$_2$eq/kWh)
Floating PV (Benelux/Germany)	49-55 [24]
Foam-based FPV	28-102 [24]
Utility-scale PV (general)	26.2 [26]

While offshore wind power is an almost mature technology with 21 GW total installed capacity and 62 TWh electricity generation in 2024 and with fast growing installed capacity, projected to reach 48 GW with 180 TWh of annual generation in 2030 in EU-27 [27], some of the newer ORE technologies are still in the earlier stages of development. The extent of their contribution to Europe's energy transition will ultimately depend on the rate of development, associated costs, and practical installation rates, especially in densely populated areas such as the Benelux region, where spatial constraints make offshore solutions especially crucial. A variety of

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ORE technologies can be deployed in the marine environment. Combining these technologies in a complementary and coordinated way is the most cutting-edge strategy. It is possible to balance the variability of individual resources and produce a smoother overall power output by combining various sources, such as offshore wind power, OSPV, and wave power. Additionally, the shared use of costly transmission infrastructure can be made possible by this synergy. Offshore wind power can be combined with wave power and OSPV technologies to greatly expand installed capacity in a shorter amount of time. Lower levelised cost of electricity (LCOE), more effective use of offshore space, more reliable electricity generation, and higher revenue potential are just a few advantages of co-locating these systems. These benefits will promote quicker adoption and enable each technology to achieve cost savings through quicker learning curves. Together with enhanced planning models and developments in enabling technologies, including autonomous robotics and offshore electrical hubs, this integrated approach will solidify Europe's position as a leader in ORE.

In a nutshell, the various uses of ORE technologies are essential to a sustainable energy transition, significantly influencing system durability and optimising space usage. These technologies reduce downtime and increase overall system stability and reliability by requiring more precise diagnostics and real-time monitoring of offshore energy components. Nowadays, most reliable robots can monitor and perform some maintenance activities in ORE with higher quality. Grid operators can better understand the capabilities and features of the system by implementing new technologies. These technologies lower the LCOE and improve overall system performance. Using digital twins for diagnostics and predictive maintenance enhances system availability by decreasing downtime and improving reliability. To sum up, ORE technologies are a crucial way to achieve the energy transition objectives and lower GHG emissions in Europe.

To evaluate the impact of ORE technologies on the energy transition and GHG emission reduction paths, the transition was modelled using LUT Energy System transition model (LUT-ESTM) [27] for six different scenarios considering different speeds of ORE introduction in the system.

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2. Contextualising

Ocean energy has emerged as a promising RE source with the potential to significantly reduce GHG emissions as the global energy system undergoes a significant transition towards sustainability. The search for sustainable and dependable alternative energy sources has been fuelled by the growing urgency to mitigate climate change, which has been reinforced by international agreements like the Paris Agreement. ORE sources like wave power, offshore wind power, and OSPV systems are still underused resources that could supplement current onshore RE by offering a more reliable and varied power supply, even though onshore solar PV and wind power have made significant progress in decarbonising power systems.

As part of the energy transition associated with the European Green Deal, the impact of ORE capacities implementation on the European energy system and its related GHG emissions is one of the most significant indicators of the value of ORE capacities for the European energy system.

Offshore wind farms, wave power, and OSPV systems are the main types of ocean-based RE. To generate electricity, each of these technologies uses various aspects of the marine environment. Large-scale electricity generation is made possible by the abundance of space provided by the ocean's vast surface for offshore wind power and OSPV installations, which also lessen land-use conflicts. On the other hand, wave power provides a highly concentrated and coherent source of electricity that can increase grid stability and reduce the need for large-scale energy storage solutions. Because of stronger and more reliable wind energy and wave patterns, these ORE technologies can achieve higher capacity factors than conventional onshore wind power and solar PV plants.

Despite its high potential, ORE faces several challenges that have hindered its large-scale deployment. Limited infrastructure, high initial capital expenditures (capex), and wave power's technological immaturity have all hindered commercialisation efforts. Furthermore, transmission technology advancements and strategic planning are needed to integrate ORE sources into current power grids. Environmental issues also demand careful thought and mitigation techniques, such as the effects of offshore wind farms on marine ecosystems and the structural robustness of OSPV systems. All these issues must be resolved in order to fully realise ORE's potential and establish it as a significant contributor to the RE mix.

RE from offshore sources may offer a chance to accelerate the reduction of fossil fuels use and respective GHG emissions. Moreover, in locations with favourable RE resources and bathymetry the use of offshore wind power, wave power, and OSPV mix may significantly increase energy yields while optimising costs. These technologies complement each other by using different marine resources at varying times and ensure a more continuous and reliable power output and to better use available power infrastructure. While wave power devices can generate electricity even at lower wind speeds and thus also smaller waves carrying less energy, offshore wind farms benefit from strong and steady wind speeds. In turn, OSPV systems can work alongside offshore wind farms, sharing infrastructure and lowering capital investment, and they can take advantage of open ocean space without land constraints. When these technologies are used together, they can maximise energy capture and reduce overall operating and maintenance costs, making ORE a more attractive option than fossil fuel-based power generation and other RE resources.

ORE's contribution to defossilisation initiatives can be strengthened by its possible integration with other low-carbon technologies, such as energy storage and off-grid hydrogen production. As a key energy carrier for producing synthetic e-fuels for a range of industrial and transportation uses, green hydrogen could be produced through electrolysis using excess electricity from offshore wind and wave energy farms. Such sector coupling solutions could speed up the adoption of ORE projects and increase their economic viability.

This study aims to contribute to the growing body of research on ORE through six distinct simulations considering its impact on GHG emissions. The feasibility and efficacy of ORE as a climate mitigation strategy are examined in this study by analysing multiple deployment scenarios and evaluating emission reductions under various circumstances. The findings in the sections that follow will provide a data-driven understanding of how offshore wind power, wave power, and OSPV can contribute to the larger shift to sustainable energy. These analyses are essential to better understand and manage critical aspects to enhance a more sustainable RE industry.

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3. Methodological approach

3.1 Methods of energy system modelling

The energy transition scenarios of the European energy-industry system were performed with the LUT-ESTM [28], 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 the exploration of different energy transition pathways. With its wide range of over 150 energy technologies across various sectors and uses, including transitional technologies is ranked amongst the most robust tools for the analyses of long-term energy transition pathways and it is currently one of the most widely used tools for research on the transition to 100% RE systems. 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 Power-to-X (PtX) concept as an integral part of the arising Power-to-X Economy [29]. 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. [30] and updated in Satymov et al. [31]. 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 5 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 6 [32].

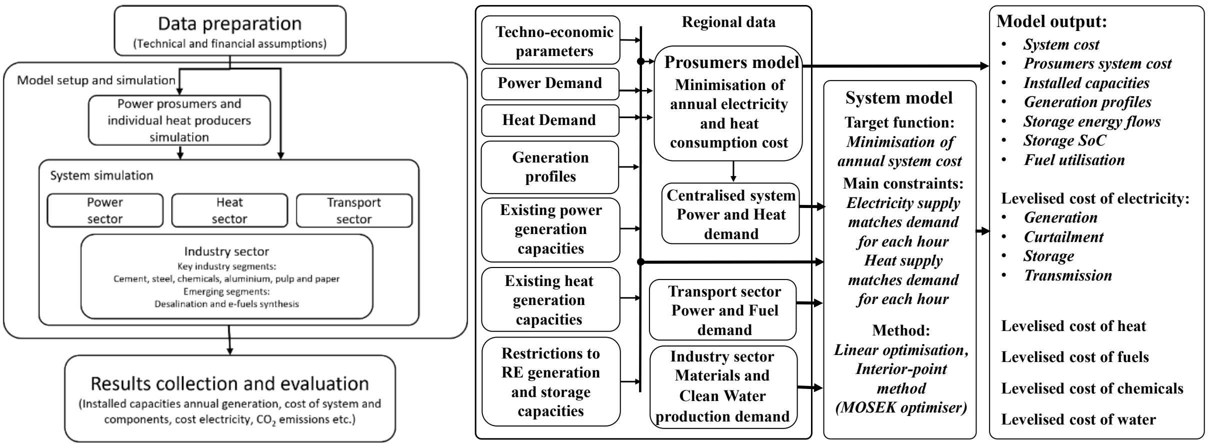

Figure 5. Schematic representation of LUT-ESTM (left) and the model flowchart (right).

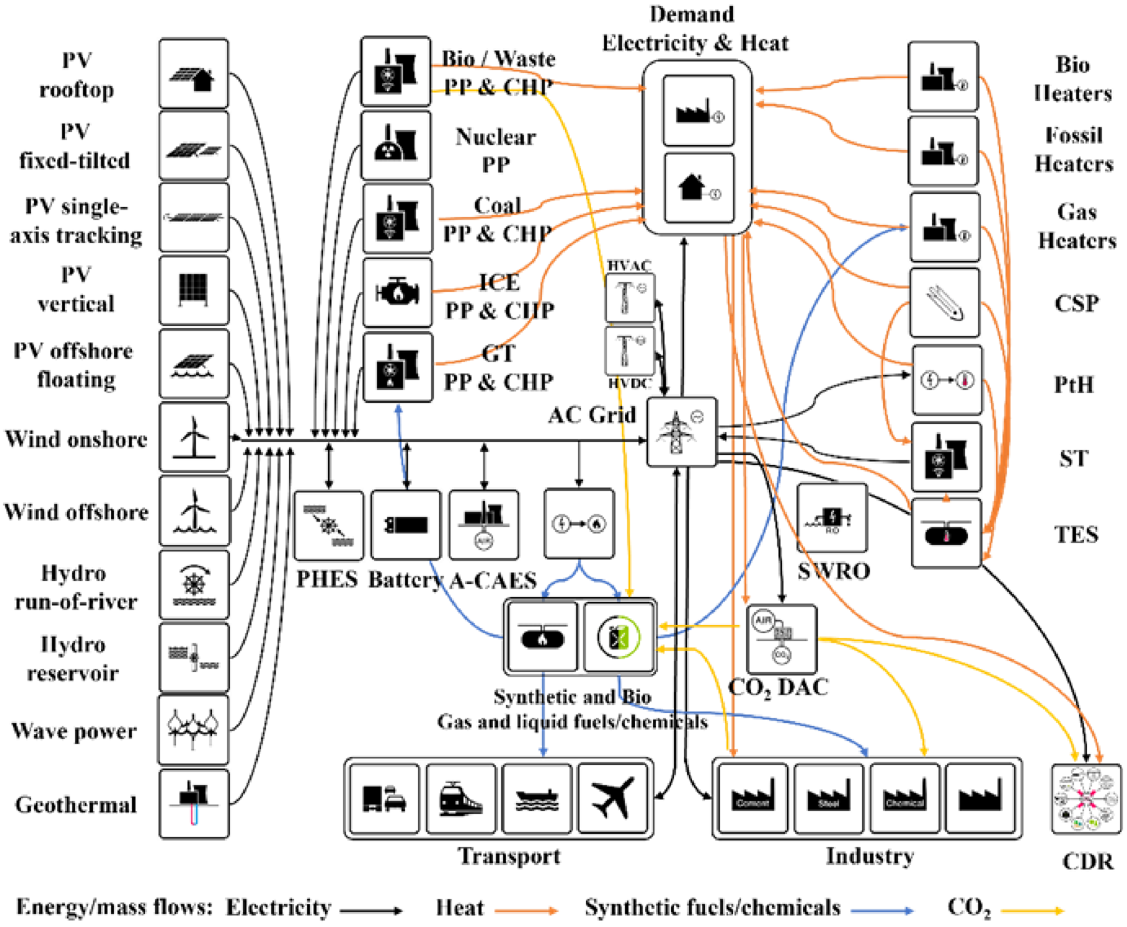

Figure 6. LUT-ESTM integrated energy system structure scheme.

LUT-ESTM covers ORE technology, including offshore wind power (both bottom fixed and floating), OSPV, and wave power based on the respective techno-economic potentials, e.g. for wave power [19], 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 crucial insights on RE technologies operation to be uncovered. Grid connection capex is 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 or industrial emitters so that also embedded CO_2 is finally priced, however, at the point of the actual emissions.

The target function of LUT-ESTM is to minimise the total annualised cost of the entire energy system comprised of annualised capital expenditures, operational expenditures, fuel costs, GHG emission costs, and ramping costs of all system elements. Respective parameter assumptions were made about future

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technological developments, the use of different technologies, economic development, cost changes, and changes in consumer behaviour.

The model guarantees that the energy demand for all sectors will be satisfied for all energy sectors 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 industrial demand for industrial processes. The model considers both energy and feedstock requirements for industries including cement, steel, chemicals, pulp and paper, aluminium, and others [33]. A crucial part of the transition is enabling the industry sector to rely entirely on renewable energy and feedstock. Transportation demand is derived across various modes, including road, rail, marine (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 (LDVs), two- and three-wheelers (2W/3W), buses for passenger transport, and medium and heavy-duty vehicles (MDVs and HDVs) for freight transport. Demand in 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 energy requirements are provided by Khalili et al. [34]. The optimisation aims to minimise the total cost of the energy system.

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. [35]. These are based on the detailed description of the model applied to the global power sector in Bogdanov et al. [36] and all energy sectors in Bogdanov et al. [29].

3.2 Regional structure of Europe for Energy system modelling

In order to achieve robust energy system analyses for Europe and correspondingly for the 27 EU member states, a two-step modelling approach is adopted [37]. The first step represents the hierarchical approach to energy system optimisation. The second step enables further disaggregation of the regional results to retrieve the country-specific results for representative energy transition pathways.

STEP 1: Europe is categorised into four macro regions, which are Nordic, West, Central, and Southeast as shown in Figure 7 [38]. Energy transition pathways in six distinct scenarios are simulated for these interconnected macro regions of Europe and the results serve as a guiding reference for the next step. The four macro regions are further comprised of 19 regions across Europe. Iceland is not connected to the integrated European power grid and, thus, modelled as an energy island. The composition of the four macro regions and the corresponding 19 regions of Europe plus Iceland are as follows:

Nordic: Norway, Denmark, Sweden, Finland, and a Baltic region that includes the countries of Estonia, Latvia, and Lithuania.

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West: Iberian peninsula region with Portugal, Spain, and Gibraltar, France together with Monaco and Andorra, Italy together with San Marino, Vatican, and Malta, British Isles region comprised of the UK and the Republic of Ireland, Benelux region comprising Belgium, the Netherlands, and Luxembourg.

Central: Germany, Poland, a region comprising the Czech Republic and Slovakia, a region with Austria and Hungary, a region with Switzerland, and Liechtenstein.

Southeast: A region that includes the Western Balkan countries of Slovenia, Croatia and Bosnia and Herzegovina, Serbia, Montenegro, Macedonia, Kosovo and Albania, a region including Eastern Balkan countries of Romania, Bulgaria and Greece, a region with Ukraine and Moldova, a region with Türkiye, and Cyprus.

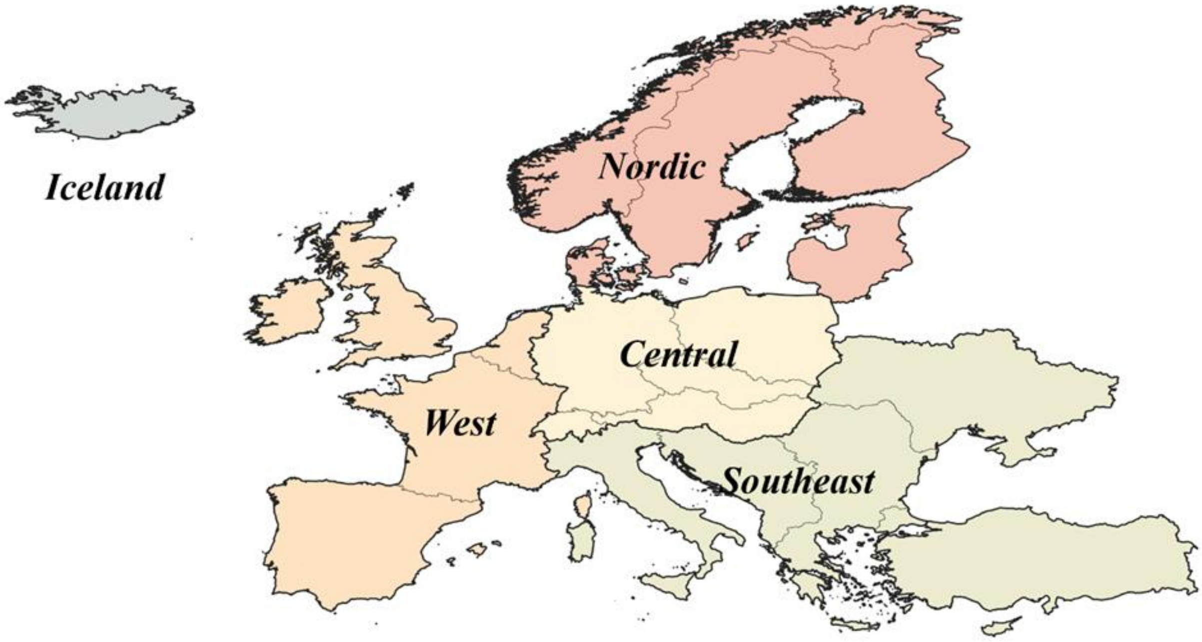

Figure 7. Europe's four macro-region division.

STEP 2: The spatial resolution is further increased from the four macro regions to 19 regions across Europe, plus Iceland wherein some of the smaller countries have been merged with larger countries to form sizeable local regions. This reflects the highly interconnected energy infrastructure across Europe, as the energy transition is envisioned on a regional basis. The energy system transition is simulated for the whole of Europe, which is structured into 20 interconnected regions. These interconnections follow the interconnected patterns of the five macro regions (the four continental ones plus Iceland), as electricity is predominantly exchanged within regional electricity pools. The 20 regions are interconnected with optimised transmission networks, e-methanol and Fischer-Tropsch fuels can be exchanged between regions and, Iceland remains as an isolated region. Cost-optimised transition pathways for an integrated European energy system are modelled for three distinct scenarios.

3.3 Scenarios for energy system modelling

The energy transition across Europe is explored in six distinct scenarios with the following boundary parameters and conditions: The reference Best Policy Scenario (BPS) sets the net-zero emissions target for 2050 according to the European Green Deal and follows the plans of the European Commission (EC) on ORE growth. Other scenarios test the impact of lower and higher ambitions of offshore wind power and wave power growth (lowOE and highOE scenarios variations) and the impact of OSPV introduction (FPV scenarios variations), and the sixth scenario tests the impact of an accelerated transition with carbon neutrality reached by 2040.

Best Policy Scenario (BPS): In this scenario, the European energy system is set on a current ambition pathway. The climate neutrality vision of the EC [39] by 2050 is achieved, as GHG emissions will be net-zero by 2050 and reduced by at least 55% in 2030 below 1990 levels. The offshore wind power capacity is set to reach 90 GW across Europe by 2030, 180 GW by 2040, and 270 GW by 2050. Similarly, the wave power capacity for Europe is set to reach 1.5 GW by 2030, 15 GW by 2040, and 60 GW by 2050. No OSPV is considered as a favoured capacity, though build-out as part of a least-cost solution is allowed.

Best Policy Scenario with low ORE (BPS_lowOE): Follows the BPS targets, but no ORE technologies are favoured, only the existing offshore wind power capacities are considered, and new capacity installations are decided by the model on the basis of system cost optimisation.

Best Policy Scenario with high ORE (BPS_highOE): Follows the BPS targets, the targets for offshore wind power and wave power introduction are increased. The offshore wind power capacity is set to reach 90 GW across Europe by 2030, 225 GW by 2040, and 450 GW by 2050. Similarly, the wave power capacity for Europe is set to 1.5 GW by 2030, 20 GW by 2040, and 100 GW by 2050. No OSPV is favoured, and new capacity installations are decided by the model on the basis of system cost optimisation.

Best Policy Scenario with high ORE and floating OSPV (BPS_highOE_FPV): follows the BPS_highOE targets, however, additional OSPV capacities are introduced. Most OSPV is set to be installed in Western Europe in the North Sea, reflecting the area deficit in the region. OSPV capacity for Western Europe and all Europe is set to 1 GW and 1.5 GW in 2030, 20 GW and 30 GW by 2040, and 100 GW and 150 GW by 2050, respectively.

Best Policy Scenario with floating OSPV (BPS_FPV): follows the BPS targets, the offshore wind power and wave power capacity are on the same level as in the BPS, however, additional OSPV capacities are introduced. Most of the OSPV capacity is set to be installed in Western Europe in the North Sea, reflecting the area deficit in the region. OSPV capacity for Western Europe and all Europe is set to 1 GW and 1.5 GW in 2030, 20 GW and 30 GW by 2040, and 100 GW and 150 GW by 2050, respectively.

Best Policies Scenario - 2040 (BPS_2040): In this scenario, the European energy system is set on an accelerated energy transition pathway. Increased efforts by all member states to drive the RE share in final energy demand across the EU 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. The offshore wind power capacity is set to reach 90 GW across the EU and across Europe by 2030 and 270 GW by 2040. Similarly, wave power capacity for all Europe is set to 1.5 GW by 2030 and 60 GW by 2040. No OSPV is considered.

3.4 Upper and lower limits in the RE capacities

Lower and upper limits were established for RE sources, including offshore wind power, OSPV, and wave power. The lower limits represent the installed capacities as of 2020 of the energy system and are set for 2020 and 2025. These limits were determined using data on existing installed capacities across the 20 regions, sourced from the "Global Data" database, IRENA, and IEA-PVPS reports [40], [41], [41]. The lower limits for 2020 and 2025 for key RE technologies are detailed in Table 3. The upper limits for PV and wind power plants are determined by land use constraints and capacity density. Offshore wind power expansion is controlled following the EC targets.

Table 3. ORE technologies' lower limits considered in the model for 2020 and 2025.

Region	**Offshore solar PV [GW_{DC}]**		**Offshore wind power [GW]**		**Wave power [GW]**	
	2020	**2025**	**2020**	**2025**	**2020**	**2025**
NO	0	0	0	0	0	0
DK	0	0	1.7	2.2	0	0
SE	0	0	0.2	0.2	0	0
FI	0	0	0.1	0.1	0	0
BLT	0	0	0	0	0	0
PL	0	0	0	0	0	0
IBE	0	0	0	0	0	0
FR	0	0	0	0.5	0	0
BNL	0	0	2.5	6.2	0	0
BRI	0	0	9.9	14.6	0	0
DE	0	0	7.6	8.4	0	0
CRS	0	0	0	0	0	0
AUH	0	0	0	0	0	0
BKN-W	0	0	0	0	0	0
BKN-E	0	0	0	0	0	0
IT	0	0	0	0	0	0
CH	0	0	0	0	0	0
TR	0	0	0	0	0	0
UA	0	0	0	0	0	0
IS	0	0	0	0	0	0

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4. Main findings

The transition from the 2020 system comprised mostly isolated the power, heat, transport, and industry sectors to a fully integrated energy system capable of fulfilling the EU's energy and raw material demands without use of fossil energy necessitates profound structural and technological shifts but can be accomplished by 2050. This study models fast growth of RE use in the system and progressive increase in sector coupling over the 30-year horizon, ultimately resulting in a sustainable, highly effective, and interconnected energy system of Europe.

The scenarios considered in this research encompass a range of assumptions regarding system efficiency improvements, the fast reduction of energy imports from outside of Europe, and the deployment levels of emerging technologies. Scenario variations aim to reflect the impact of ORE technologies on the European energy transition pathways: energy demand in the system, electricity and heat supply structure, industry, transport and e-fuels production, energy cost, and GHG emissions reduction trajectories.

4.1 Final energy demand

All scenarios, except the BPS_2040, share the same energy and services demand assumptions. Despite expected growth in transportation services and for some of the industrial product demand, electrification and overall increase of efficiency lead to a substantial reduction of final energy demand (FED) from 2020 to 2050 revealing a clear and consistent trend of declining total energy use. Five of the scenarios, except for BPS_2040, share identical FED reduction pathways. The BPS_2040 is the most ambitious scenario assuming advanced policies in all sectors including accelerated buildings retrofitting, modal shifts in transportation, and accelerated electrification in transport and industry. These policies implementation is expected to lead towards even faster reduction of FED.

In the BPS, total FED drops steadily from 16,345 TWh in 2020 to 13,206 TWh in 2050 (Figure 8 left). This overall FED reduction of around 20% is primarily driven by a sharp decrease in demand for fuels, which nearly halves over the period. In 2020, fuels and chemicals account for over 7700 TWh, but by 2050, this figure falls to just under 3850 TWh. This dramatic decline reflects a significant shift away from fossil fuels and conventional chemical feedstock in favour of cleaner, more efficient alternatives. The transition suggests strong efforts in decarbonising industry and heavy transport and includes the uptake of new energy carriers such as e-fuels, e-chemicals, and some sustainable biofuels.

At the same time, electrification across all sectors drives electricity demand growth. Electricity demand in FED starts at 2869 TWh in 2020 and rises steadily to 4317 TWh by 2050, representing a growth of nearly 50%. Overall electricity generation including PtX processes grows from 3329 TWh in 2020 to 15,365 TWh in 2050. The electricity demand trend in FED is strongest after 2030, reflecting the ramping of policies and technologies favouring electric solutions over fuel-based ones. Heat demand, on the other hand, declines only slightly over the same period.

From 5736 TWh in 2020, it decreases gradually to 5040 TWh by 2050, suggesting that modest gains in building insulation and industrial heat recovery are partially compensated by increased standards of living.

The BPS_2040 introduces a more accelerated transition (Figure 8 right), particularly from 2030 onwards. It results in a more ambitious reduction in total FED, which drops to 12,625 TWh by 2050, about 600 TWh lower than in the other scenarios. This indicates a more ambitious policy direction focused on both demand-side efficiency and earlier shifts in technology and fuel use.

In the BPS_2040, electricity demand continues to increase but at a slightly moderated pace, reaching 4219 TWh in 2050. The slower growth compared to the BPS scenario reflects earlier deployment of demand-reducing technologies. Heat demand declines more sharply in this scenario, falling to 4653 TWh by 2050, compared to 5040 TWh in the other pathways. This deeper reduction points to more improvements in building efficiency, industrial heat use, and potentially behavioural changes. The fuels and chemicals demand again sees the largest cut, falling to just 3752 TWh by 2050, about 100 TWh less than in the other scenarios. This highlights the impact of earlier and more decisive action to move away from fossil fuels and fossil fuels-based chemical feedstock.

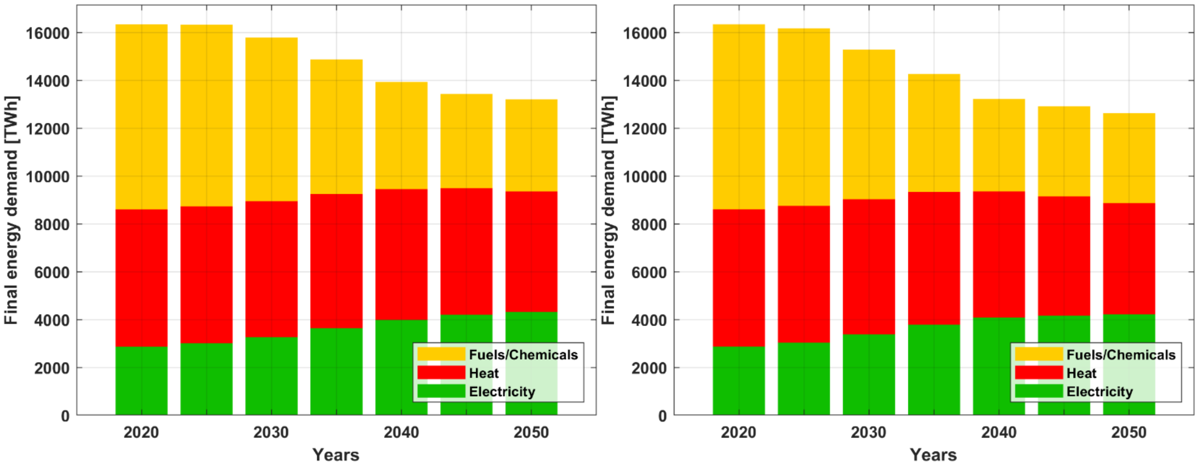

Figure 8. Final energy demand in the BPS (left) and the BPS_2040 (right).

Overall, the key insights from this comparison show that electrification is a key measure for the increase in energy efficiency across all scenarios, electricity FED increases, while the use of fuels declines sharply, leading to an overall FED decrease. Heat demand reduces more moderately, but deeper reductions are possible under more ambitious frameworks.

Importantly, the decline in FED occurs despite growing demand in some sectors, particularly transport and industry. In BPS assumptions, European passenger transport demand increases from around 7960 billion p-km in 2020 to over 14,800 billion p-km in 2050, and freight transport rises from 17,300 billion t-km to more than 24,200 billion t-km in the same period (see Table 4). However, the FED for transport significantly decreases, falling from 5634 TWh in 2020 to just 3676 TWh in 2050. This trend clearly illustrates the impact of improved energy efficiency and technological advancement. More efficient vehicles and electrification contribute to reducing energy consumption even as energy service demands increase. The BPS_2040 scenario demonstrates what further decline can be achieved with more proactive policies, including a more substantial reduction in FED and a faster shift toward clean energy use, largely enabled through efficiency gains across sectors.

Table 4. Transport demand increase versus transport FED decrease.

	2020	2025	2030	2035	2040	2045	2050
Transport passenger, billion [p-km]	7959	8704	9615	10,632	11,909	13,328	14,842
Freight demand billion [t-km]	17,296	17,875	18,583	19,500	20,686	22,225	24,217
FED for transport [TWh]	5634	5551	5032	4256	3700	3579	3677

4.2 Primary energy demand

Figure 9 shows global primary energy and feedstock demand (PED) from 2020 to 2050 under several energy transition scenarios. The demand is categorised by energy source and highlights the shift from fossil fuels to RE over time.

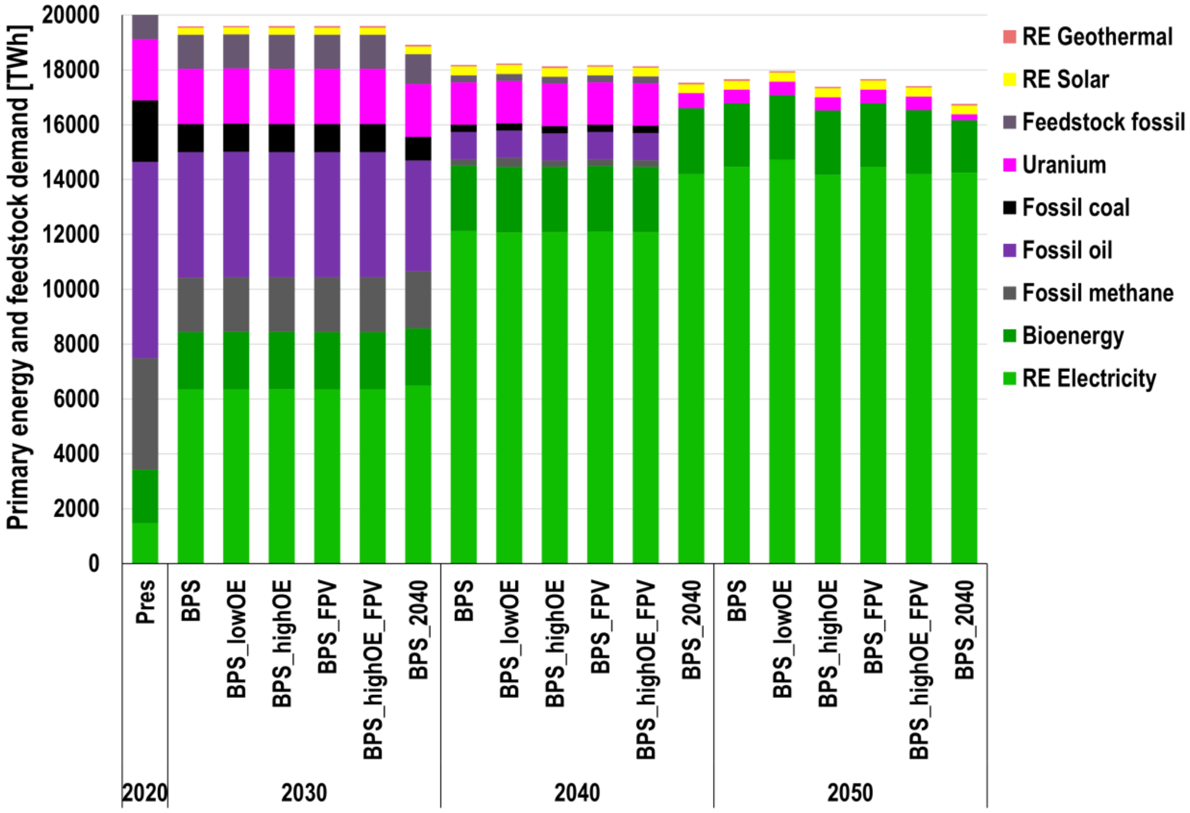

Figure 9. Primary energy and feedstock demand in Europe from 2020 to 2050 among all energy transition scenarios.

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In 2020, total PED is about 20,634 TWh, dominated by fossil fuels. Fossil oil (7164 TWh) and fossil methane (4056 TWh) are the largest contributors, followed by coal (2243 TWh), and uranium (2227 TWh). Renewable electricity is still minor at 1475 TWh, with bioenergy at 1952 TWh, and solar thermal and geothermal contributing only 94 TWh and 25 TWh, respectively.

By 2030, renewable electricity increases significantly to over 6300 TWh across all scenarios, in the BPS fossil oil and methane drop to about 4568 TWh and 1990 TWh, respectively. Coal demand is reduced by more than half to 1024 TWh and bioenergy rises slightly above 2090 TWh. Overall, the total PED in the BPS slightly drops to around 19,540 TWh.

In 2040, the shift accelerates. Renewable electricity more than doubles to over 12,000 TWh (reaching 14,205 TWh in the BPS_2040), becoming the main energy source. Fossil fuel use drops sharply, fossil oil and coal fall below 1000 TWh, and methane reduces to 224–336 TWh. Bioenergy grows to around 2380 TWh and fossil feedstock is almost phased out. Total PED falls further to about 18,125–18,849 TWh, and 17,475 TWh in the BPS_2040.

By 2050, renewable electricity dominates the mix, reaching 14,465 TWh in the BPS. Fossil fuels are completely eliminated in all scenarios. Only uranium and bioenergy remain as secondary contributors. Solar thermal grows gradually to around 330 TWh, and geothermal remains small but stable at 52–57 TWh. Total PED declines further, down to 17,330-17,900TWh in the BPS variations, and 16,700 TWh in the BPS_2040.

The PED across scenarios reflects the influence of RE deployment strategies, particularly the role of ORE and OSPV. While overall PED remains relatively stable across most scenarios, those with higher integration of ORE, such as the BPS_highOE and BPS_highOE_FPV, tend to show slightly lower PED values by 2050. On the other hand, the BPS_lowOE with reduced offshore wind power and wave power capacity results in increased PED. Thus, the differences in PED by 2050 among scenarios are a result of both the quantity and type of RE deployed, with high ORE pathways offering a marginal but meaningful reduction in overall energy demand through efficiency improvements.

4.3 Electricity installed capacity, generation, and storage

This section presents a power sector analysis between 2020 and 2050, based on different scenarios of energy system transition. The focus is on installed electricity capacity and generation, and storage systems, with attention to the evolving technology mix and trends across renewable and fossil energy sources.

4.3.1 Electricity installed capacity, and generation

Over the transition, total installed electricity generation capacity increases dramatically, driven primarily by the rapid growth in solar PV and wind power technologies (see Figure 10). In 2020, the total installed capacity was relatively modest, with onshore solar PV at 177 GW, onshore wind power at 183 GW, offshore wind power at 22 GW, and hydropower at 200 GW. The fossil fuel-based power generation still represents a major share of the power plants fleet with 2006 GW of mainly coal-based generation capacity and gas turbines capacity of 244 GW. Nuclear power also held significant shares at 132 GW.

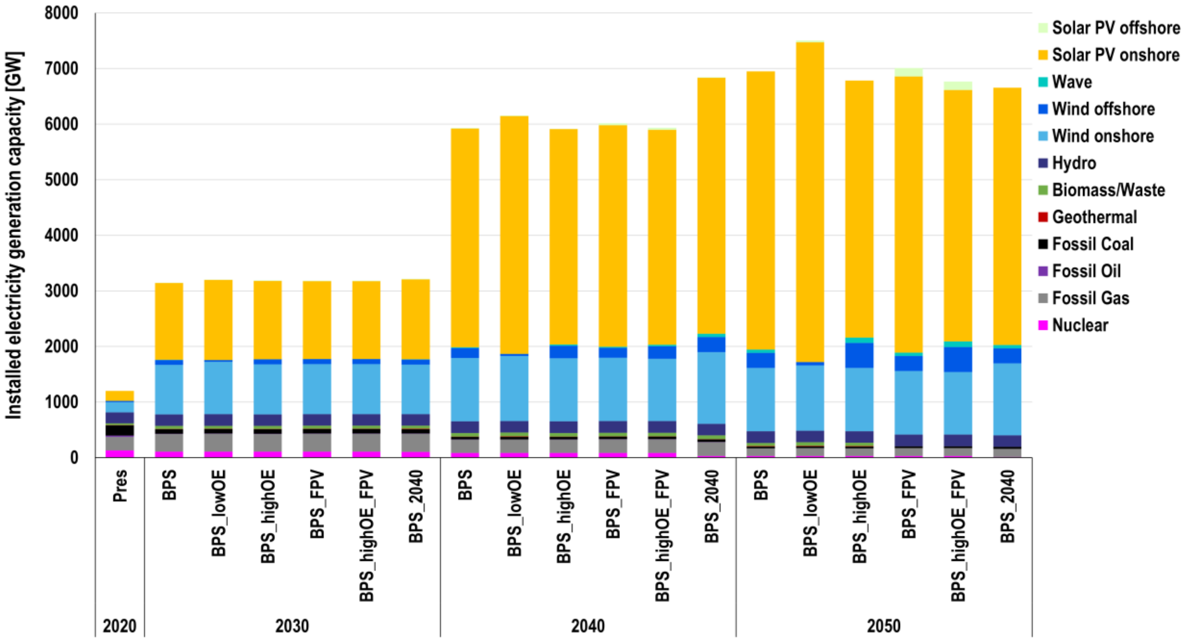

Figure 10. Installed electricity generation capacity by source from 2020 to 2050 among all energy transition scenarios.

By 2030, solar PV capacity jumps significantly to about 1400 GW across all scenarios, with the highest being 1440 GW in the BPS_lowOE. Onshore wind power also sees strong growth, reaching up to roughly 940 GW (BPS_lowOE). Offshore wind power increases to around 91 GW in most cases, while hydropower remains steady just above 208 GW.

Further acceleration is seen by 2040. Solar PV capacity reaches over 4600 GW in the BPS_2040, nearly 11 times the 2020 level. In the BPS_highOE and BPS_highOE_FPV offshore wind power reaches 225 GW, at the same time, the accelerated increase of offshore wind power leads to a reduced installation of solar PV, while the onshore wind power capacity stays at approximately the same level.

In 2050, the solar PV capacity further increases exceeding 5000 GW in the BPS scenario. In the BPS_highOE and BPS_highOE_FPV, offshore wind power reaches 450 GW, leading to slightly lower solar PV capacity compared to the BPS. In the BPS_lowOE, the offshore wind power and wave power capacity is limited resulting in higher capacities of onshore wind power and most importantly solar PV to compensate the lack of ORE capacities. Onshore wind power maintains a strong role across all scenarios, with values around 1140 GW, peaking at 1293 GW in the BPS_2040.

Wave power, bioenergy, and geothermal grow modestly, with wave power capacity reaching up to 100 GW in the BPS_highOE scenarios, reflecting their emerging role in the future mix.

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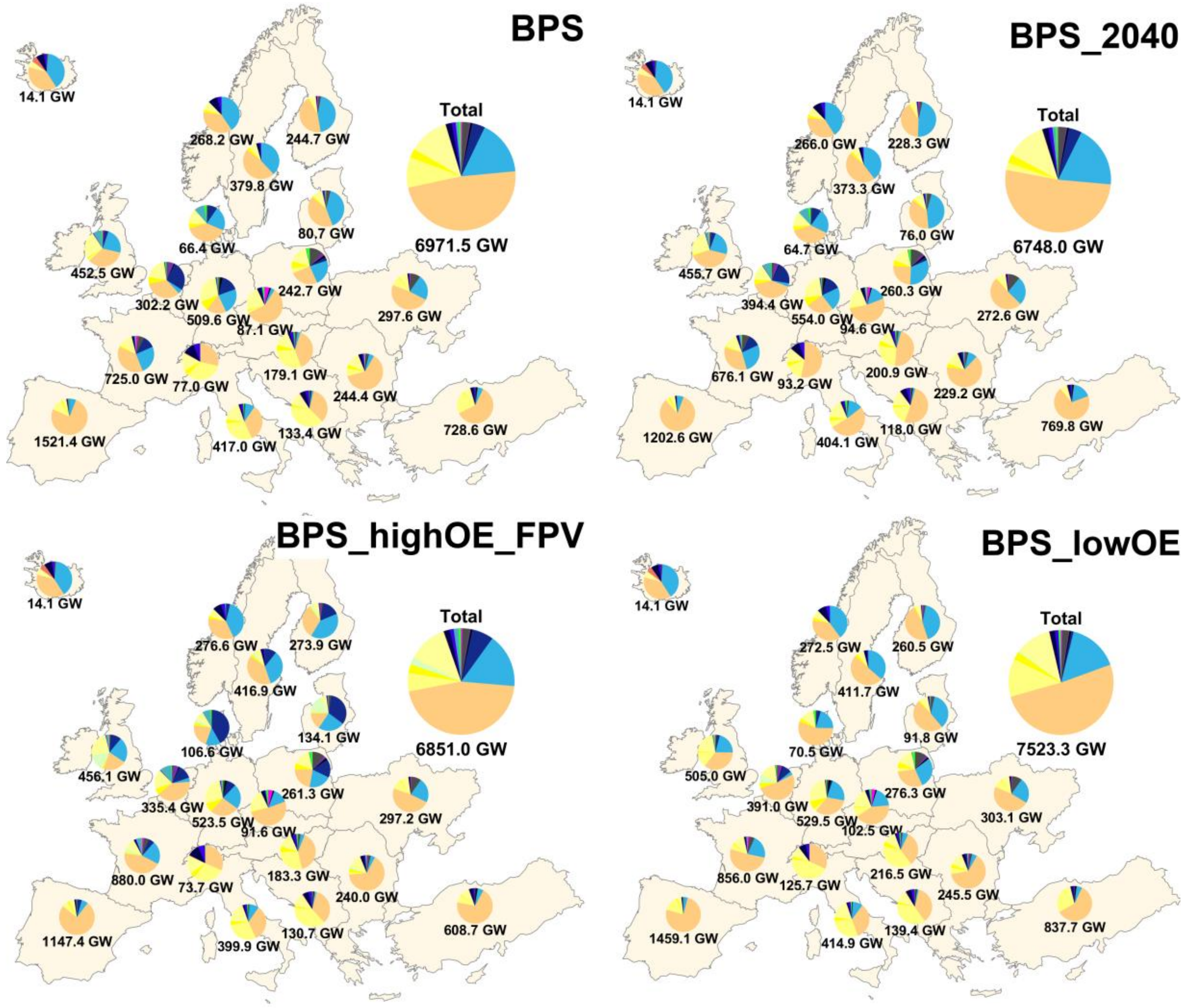
Nuclear power capacity declines, falling to 12 GW in the BPS_2040 by 2050. Fossil thermal power capacities shrink sharply. Coal power plant capacity drops from 184 GW in 2020 to 35 GW by 2050, and oil falls to zero GW in almost all scenarios. Fossil gas power plant capacity declines but remains present, falling from 244 GW to about 139–148 GW by 2050, depending on the scenario.

Figure 11 represents the regional outlook of the electricity generation capacity transition from 2020 to 2050 for the chosen scenarios. In 2020, the dominant sources are fossil fuel-based power plants, with coal and gas plants prominent in the pie charts of countries including Germany, Poland, and parts of Southern and Eastern Europe. Nuclear power also contributes significantly, especially in France and several central European countries. RE sources such as onshore and offshore wind power, hydropower, and various PV technologies play a smaller but growing role.



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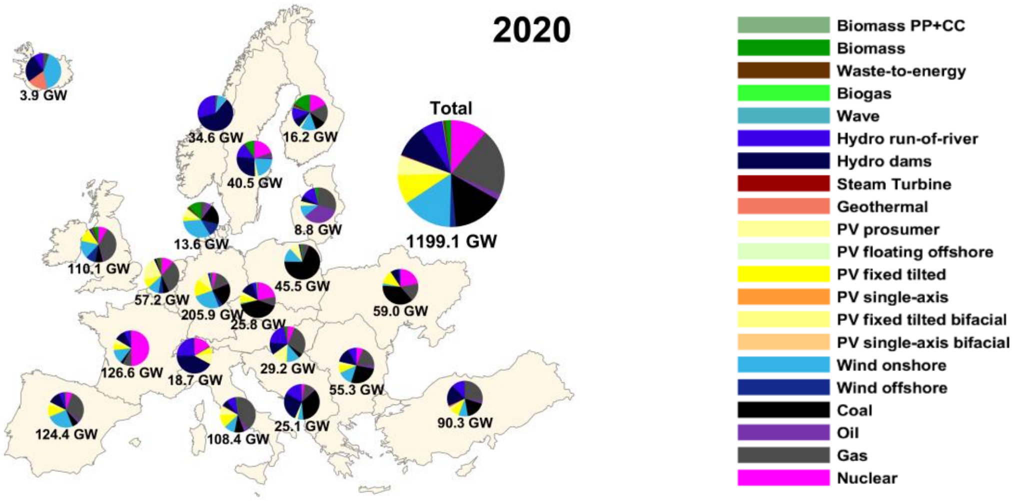


Figure 11. Electricity installed capacity by technologies in different scenarios in 2020 and 2050 across Europe.

By 2050, every scenario projects a steep increase in total installed capacity, with total values ranging from 6748 GW to 6971 GW. This nearly sixfold increase reflects the anticipated electrification of many sectors and the transition towards a zero-emission energy system and lower capacity factors of renewable electricity generation capacities compared to conventional power plants. Across all scenarios, the most noticeable trend is the dramatic expansion of solar PV technologies. In the projections, PV dominates in all regions, particularly in countries with high solar energy potential such as Spain, Italy, Greece, and parts of Eastern Europe. In the BPS, Spain alone grows to over 1500 GW, with PV being the largest contributor.

Wind power also continues to expand significantly, especially in regions with favourable wind energy conditions. Onshore and offshore wind power remain critical components in Northern and Western Europe. In the UK, Denmark, and the Netherlands, wind power represents a substantial portion of installed capacity across all scenarios in 2050. In the BPS_lowOE use of ORE technologies is not favoured, resulting in a substantial reduction of these technologies' capacities. Lack of support for ORE technologies results in a decrease of local generation capacities and increase of imports in the area-limited Benelux region. The system still installs offshore wind power and OSPV capacities in the Benelux region but as part of the cost-optimised solution. While solar PV still dominates in southern regions, wind power maintains a stronger presence in Central and Northern Europe. The BPS_2040 shows a slightly lower total capacity of 6748 GW but retains the overarching shift towards RE. It exhibits a relatively more conservative expansion of solar PV compared to the BPS_highOE but still shows strong reliance on solar PV. The electricity generation structure during the transition follows respective trends (Figure 12 and Figure 13). In 2020, fossil fuels and nuclear power still provided a large share, with nuclear power producing 740 TWh, coal power plants contributing 549 TWh, and fossil gas plants 405 TWh. Solar PV and wind electricity generation were much smaller at 223 TWh and 576 TWh, respectively, for solar PV and wind power.

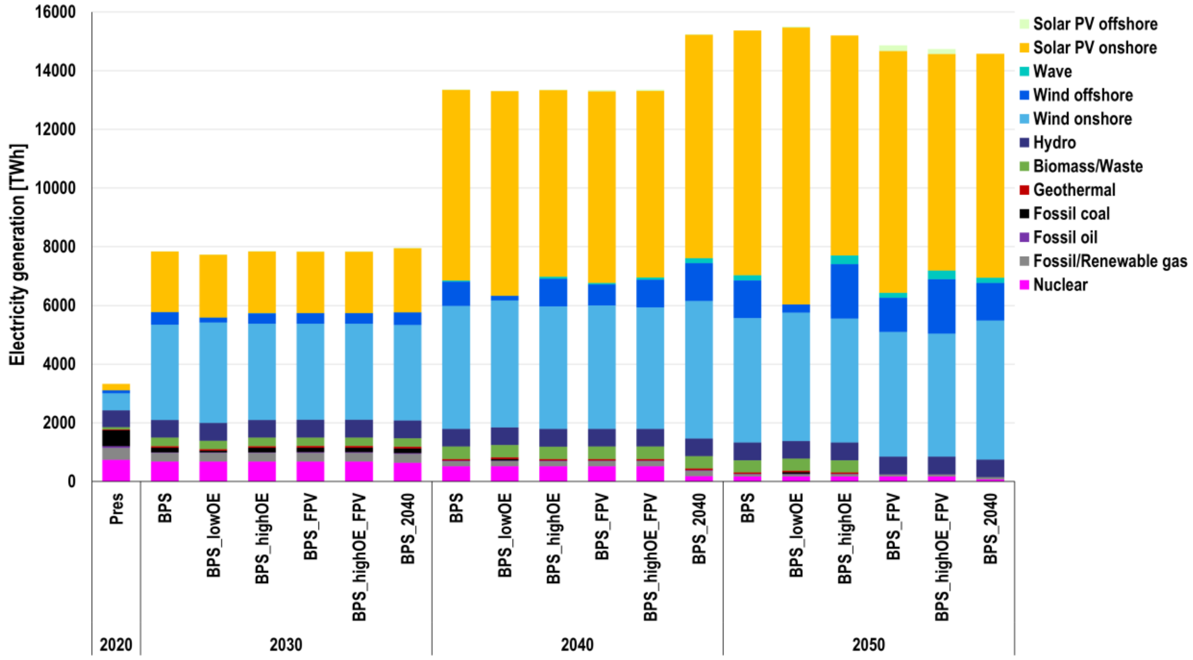
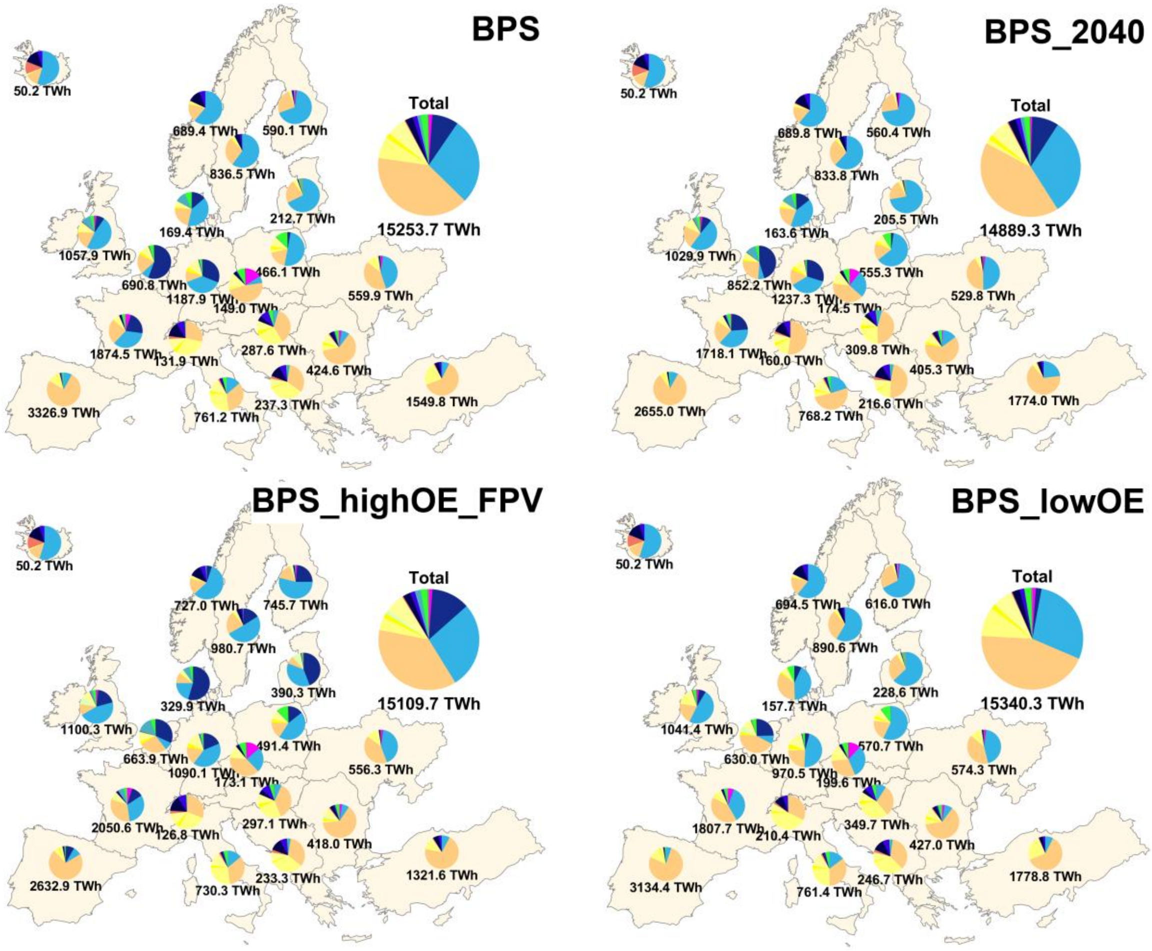


Figure 12. Electricity generation by resource from 2020 to 2050 among all energy transition scenarios.



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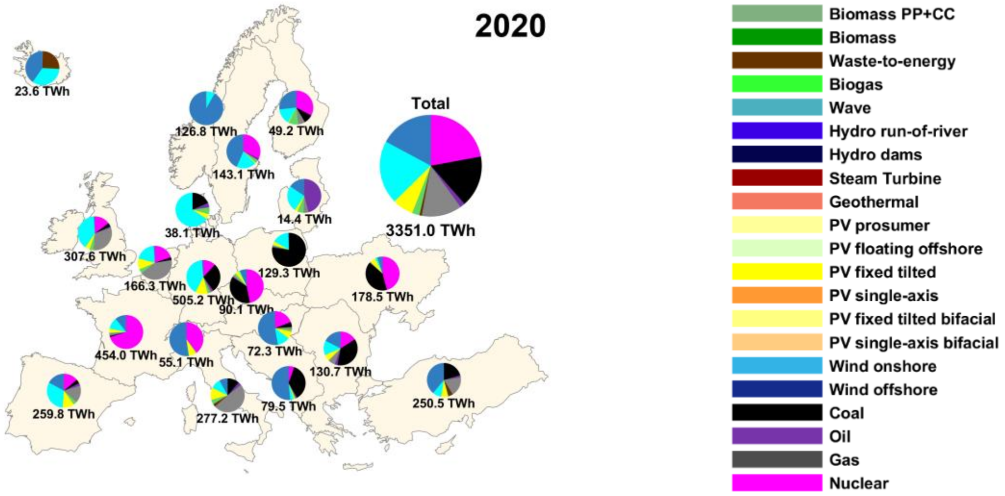

Figure 13. Electricity generation by technologies in different scenarios in 2020 and 2050 across Europe.

By 2030, solar PV generation increases almost tenfold to about 2100 TWh, while onshore wind power exceeds 3200 TWh, close to total electricity generation in 2020. Offshore wind power also starts to grow, reaching up to 358 TWh in the BPS_highOE. At the same time, fossil coal and gas power generation drops significantly to around 159 TWh and 294 TWh, respectively. Nuclear power generation remains stable at 676 TWh in most scenarios.

In 2040, the share of RE will become dominant. Solar PV rises to about 6300-7000 TWh, and onshore wind power continues to contribute between 4142-4690 TWh across scenarios. Offshore wind power becomes a major player, with about 1000 TWh supplied in the BPS_highOE and BPS_highOE_FPV scenarios.

In 2050, solar PV is the dominant source of electricity with 8335 TWh generated in the BPS and 9444 TWh in the BPS_lowOE. Onshore wind power generation stabilises around 2040 levels, while offshore wind power reaches 1861 TWh in both BPS_highOE and BPS_highOE_FPV.

Electricity from fossil fuels drops to negligible levels by 2040 and by 2050, coal and oil are phased out completely in all scenarios, while gas turbines still operate using biomethane, e-methane, and e-hydrogen, providing 66–71 TWh depending on the scenario. Nuclear power falls sharply to 172 TWh, and in the BPS_2040 down to only 75 TWh.

Hydropower stays relatively constant, around 602 TWh, while biomass/waste generation grows modestly to 425 TWh by 2040 but then slightly decreases to 340 TWh in the BPS_2040 by 2050. Geothermal also grows steadily, though still contributing a smaller share overall. Despite the fast growth, the share of wave power in the 2050 total electricity supply is limited to 176 TWh in the BPS and 293 TWh in the BPS_highOE and BPS_highOE_FPV.

4.3.2 Electricity storage

The deployment of electricity storage systems will grow significantly between 2020 and 2050, playing a critical role in supporting variable RE sources such as wind power and solar PV. This growth is evident not only in installed capacity in Figure 14 but also in the substantial rise in stored electricity output in Figure 15, which enhances system flexibility and reliability.

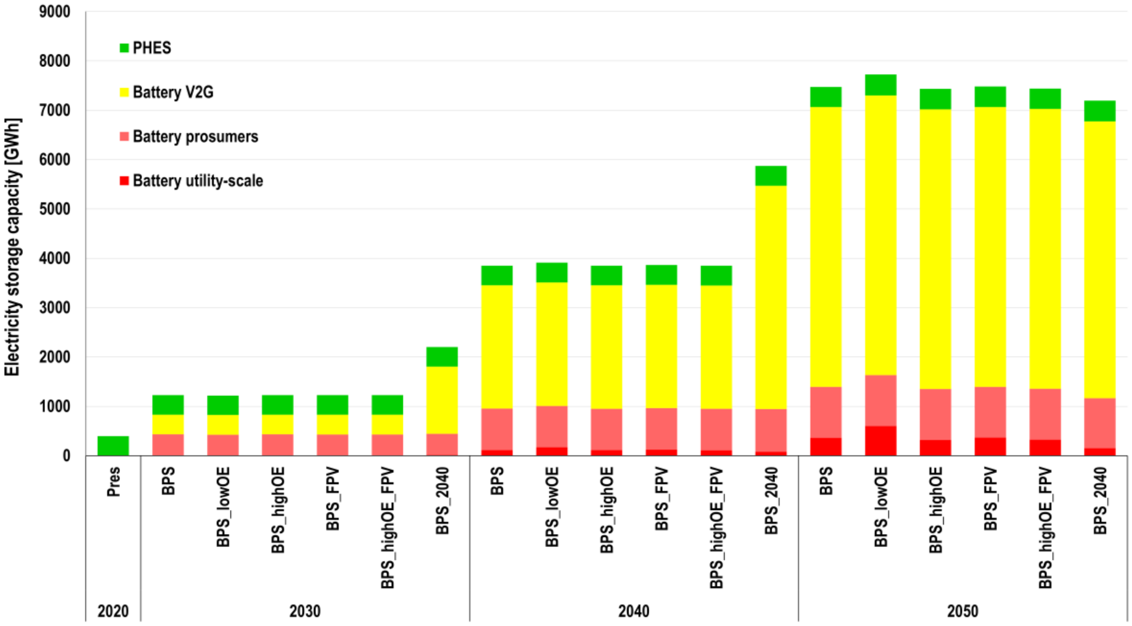

Figure 14. Electricity storage capacity from 2020 to 2050 among all energy transition scenarios.

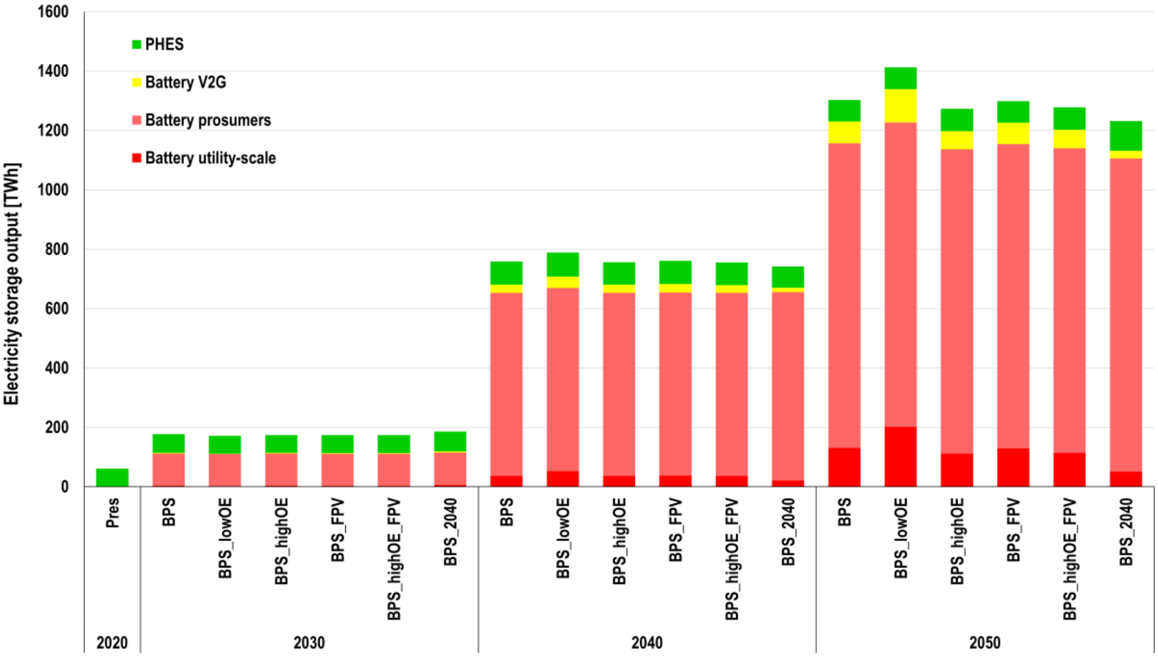

Figure 15. Electricity storage output from 2020 to 2050 among all energy transition scenarios.

Among the scenarios, the BPS_lowOE stands out with the highest total storage capacity by 2050, including 601 GWh_{cap} of utility-scale batteries which is the largest across all pathways. Combined with 1031 GWh_{cap} from prosumer batteries and 5670

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GWh_{cap} from vehicle-to-grid (V2G) systems, the BPS_lowOE achieves the highest electricity storage output, 202 TWh from utility-scale batteries, 1026 TWh from prosumer batteries, and 112 TWh from V2G. PHES also grows slightly, reaching 73 TWh in stored electricity output. This highlights the valuable role of ORE technologies in energy supply and demand balancing due to their smaller seasonal and daily variability.

On the other hand, the BPS_2040 reflects the earliest transition towards RE but with more modest utility-scale battery capacity (153 GWh_{cap}). However, it achieves the highest prosumer battery output at 1055 TWh and PHES output of 101 TWh, indicating a strong reliance on decentralised and utility-scale solutions.

Across all scenarios, prosumer batteries are the most consistently scaled technology, exceeding 1000 GWh_{cap} in capacity and 1000 TWh in output by 2050. V2G systems also emerge as a vital flexibility resource, reaching over 5600 GWh_{cap} and together with flexibility from smart charging of BEV substantially reducing the demand for utility-scale batteries. Utility-scale battery deployment varies more widely, with electricity output ranging from 51 TWh in the BPS_2040 to over 200 TWh in the BPS_lowOE.

PHES contributes consistently to storage across scenarios, despite only modest growth. The data highlights the critical role that distributed and diverse storage solutions play in preserving grid stability and optimising the integration of renewable energy, especially in high-renewable and electrification pathways.

4.4 Heat supply

The transformation of the heating sector between 2020 and 2050 is marked by a major shift away from fossil fuels toward electrification, RE-based heating, and large-scale storage systems. Figure 16 and Figure 17 show that across all scenarios, heat pumps emerge as the dominant technology, expanding from 27 GW in 2020 to around 470 GW by 2050, and generating nearly 2,900 TWh of heat annually. Electric heating also plays a growing role, with capacities reaching up to 265 GW, and generation rising as high as 660 TWh, especially in BPS_2040, which is the highest among all scenarios. Biomass maintains a stable role, contributing between 427–444 TWh in most cases.

Fossil fuel, particularly gas, use in heating declines sharply. By 2050, gas boilers capacity is projected to drop from 574 GW to just 5 GW, with oil and coal boilers almost entirely phased out. This marks a deep decarbonisation of the sector, especially in heat generation, where fossil-based contributions are nearly eliminated across all scenarios.

Heat storage systems expand significantly to support the new energy mix. Hydrogen storage has the most dramatic growth, reaching up to 41,900 GWh capacity in the BPS_lowOE and annual throughput of nearly 1920 TWh, the highest across all scenarios. Methane storage remains smaller in scale but grows in some scenarios to over 7000 GWh_{cap}. Thermal energy storage (TES) also sharply rises, reaching 640 GWh$_{cap}$ (high temperature) and 340 GWh$_{cap}$ (district heating) in the BPS_lowOE, supporting seasonal heat balancing with outputs of up to 208 TWh.

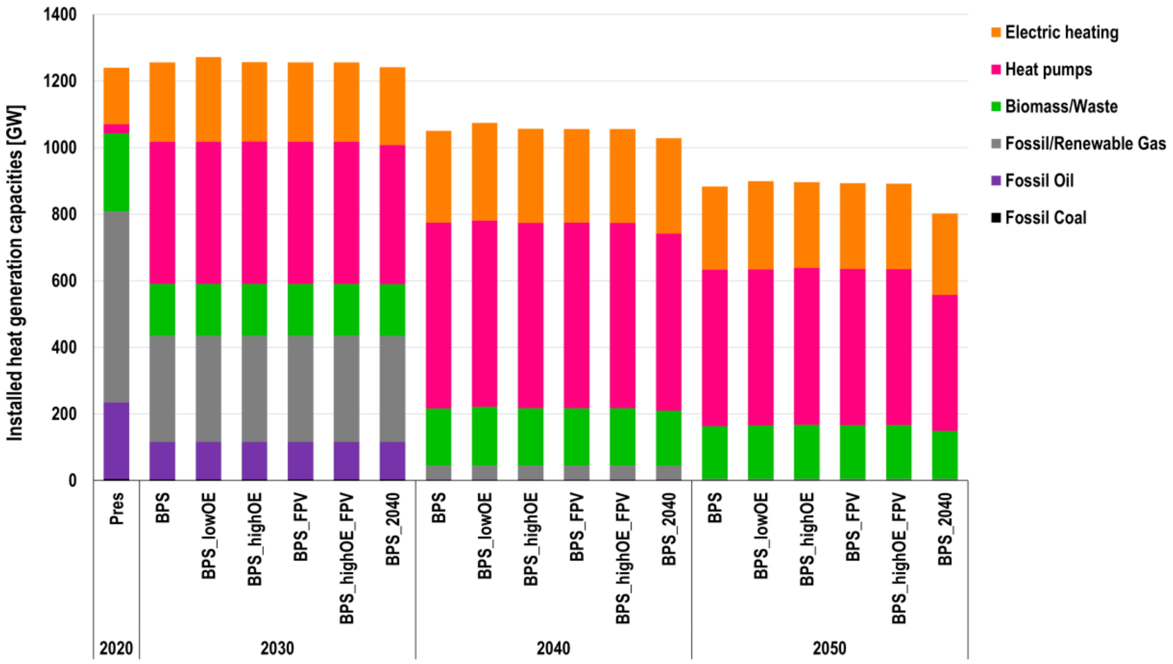

Figure 16. Installed heat generation capacities from 2020 to 2050 among all energy transition scenarios.

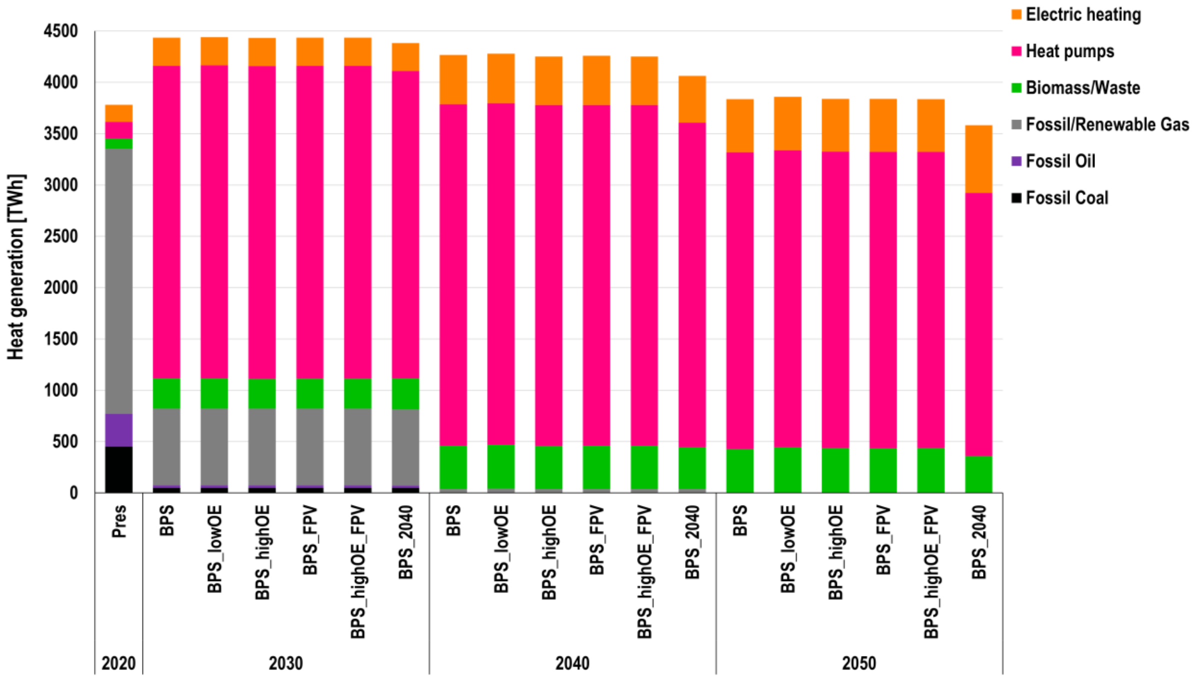

Figure 17. Heat generation by resources from 2020 to 2050 among all energy transition scenarios.

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A crucial insight from the analysis is the changing role of seasonal storage technologies depending on the RE mix. In scenarios such as the BPS_lowOE or those with high OSPV (e.g. BPS_FPV), the growing share of solar PV with higher seasonality, leads to increased reliance on long-term storage, particularly hydrogen, to manage summer-winter imbalances largely to cover a stable hydrogen supply for the e-fuels and e-chemicals synthesis units. In contrast, scenarios with a greater share of offshore wind power and wave power (such as the BPS_highOE) show reduced demand for seasonal storage, as these technologies provide a more stable year-round electricity generation, especially in winter months.

While the impact of electrification on the heat sector is strong, the seasonal dynamics of supply and demand become more complex, especially for industrial use and e-fuels and e-chemicals synthesis. Notably, the impact on residential heat is rather negligible, but industrial applications and e-fuels and e-chemicals production show vastly different storage needs, reinforcing the importance of longer term hydrogen storage for buffering variable hydrogen production for stable synthesis demand in deep defossilisation scenarios (Figure 18).

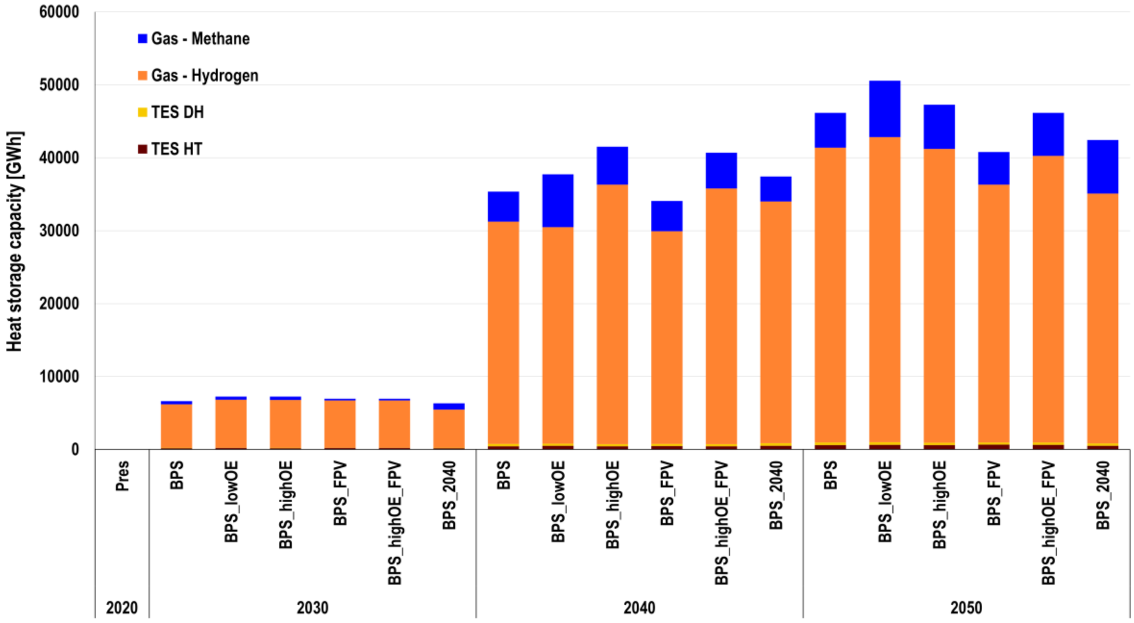

Figure 18. Heat storage capacity from 2020 to 2050 among all energy transition scenarios.

Therefore, the heat sector is rapidly decarbonising through widespread deployment of heat pumps, expanded use of electric heating, and continued bioenergy contribution. At the same time, large-scale storage systems, especially hydrogen and TES, which provide the seasonal flexibility both to the heat system and the whole energy system, allowing for flexible operation of electrolysers, which become a central component of the energy transition. Scenarios such as the BPS_lowOE and BPS_2040, with strong electrification and high RE shares, demonstrate the most intensive reliance on heat and gas storage (Figure 19), highlighting its critical role in maintaining stability and year-round supply.

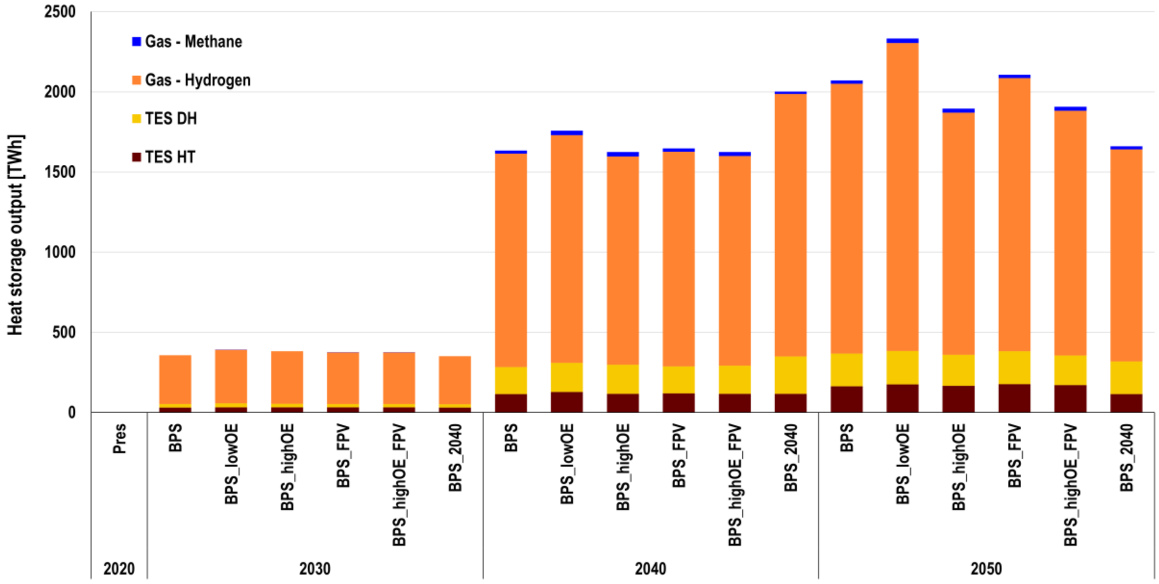

Figure 19. Heat storage energy output from 2020 to 2050 among all energy transition scenarios.

4.5. Transport, industry, and e-fuels

Figure 20 shows the FED for the transport sector between 2020 and 2050 across the scenarios. With the exception of the BPS_2040, which shows slight differences, all other scenarios remain very close to the BPS projection in each year.

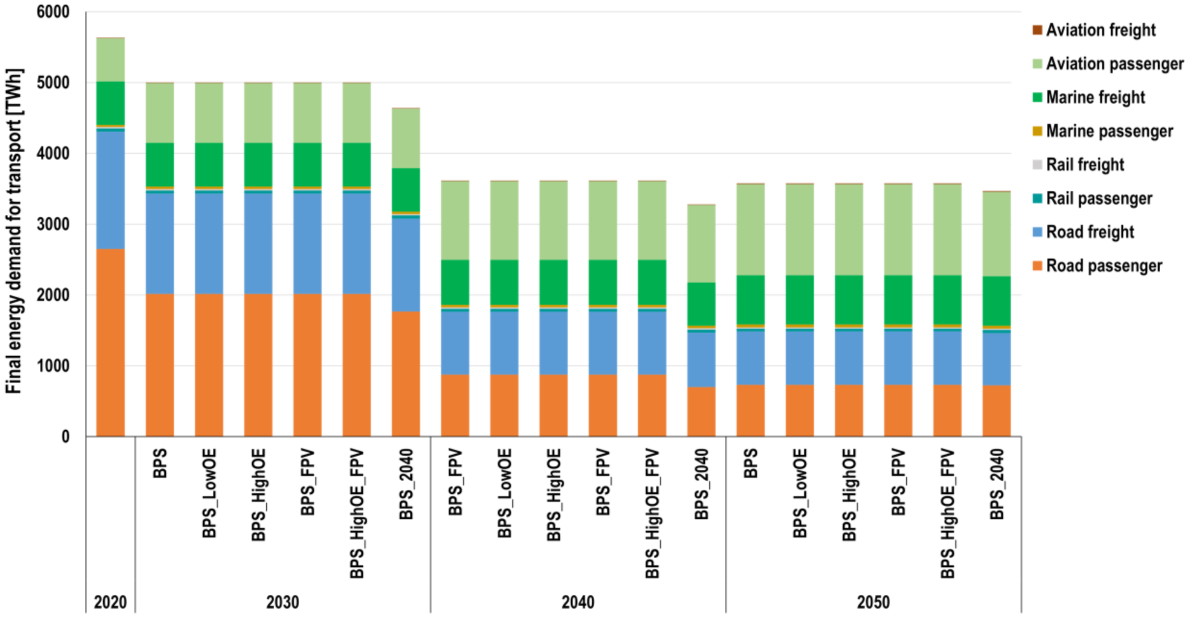

Figure 20. Final energy demand for the transport sector in segments from 2020 to 2050 among all energy transition scenarios.

In 2020, the total FED for the transport sector was around 5612 TWh. Road passenger transport dominated the sector with 2653 TWh, followed by road freight

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at 1656 TWh. Marine and aviation transport each accounted for 612 TWh, while rail had the smallest share with 43 TWh for passenger and 21 TWh for freight transport.

By 2030, the overall transport FED is projected to drop. Road passenger and freight transport decrease to around 2016 TWh and 1420 TWh, respectively. Aviation passenger transport rises to 845 TWh, overtaking marine freight, which remains stable at around 619 TWh. The rail and marine passenger segments remain minor contributors, with values just over 40 TWh and 33 TWh, respectively. Aviation freight increases only slightly, reaching about 6 TWh. These trends are consistent across all scenarios except for the BPS_2040, which shows a modest reduction in road transport compared to the BPS.

The change in transport FED is more noticeable by 2040 and 2050, although it stays mostly constant in both years. Road passenger and freight FED drop significantly to around 730–880 TWh due to substantial efficiency as consequence of direct electrification, and aviation passenger FED rises sharply to over 1100 TWh, becoming the largest single transport demand segment. Marine freight also grows steadily, reaching around 635–700 TWh. The rail and marine passenger segments remain minor and nearly unchanged. The BPS_2040 continues to show slightly lower values than the other scenarios, especially in the road and aviation segments. Overall, the transport FED transition from 2020 to 2050 indicates a major shift in energy demand from road to aviation and marine transport due to limited possibilities for direct electrification in aviation and marine transport. With minor deviations in the BPS_2040 pathway, the majority of scenarios exhibit a similar pattern, with a decline in demand for road transportation and an increase in reliance on aviation.

Figure 21 presents the energy and feedstock demand projections for key energy-intensive industries, namely cement, steel, chemicals, pulp and paper, aluminium, and other industries from 2020 to 2050 in the different scenarios. Except for the BPS_2040, the results across the other scenarios within each year are nearly identical.

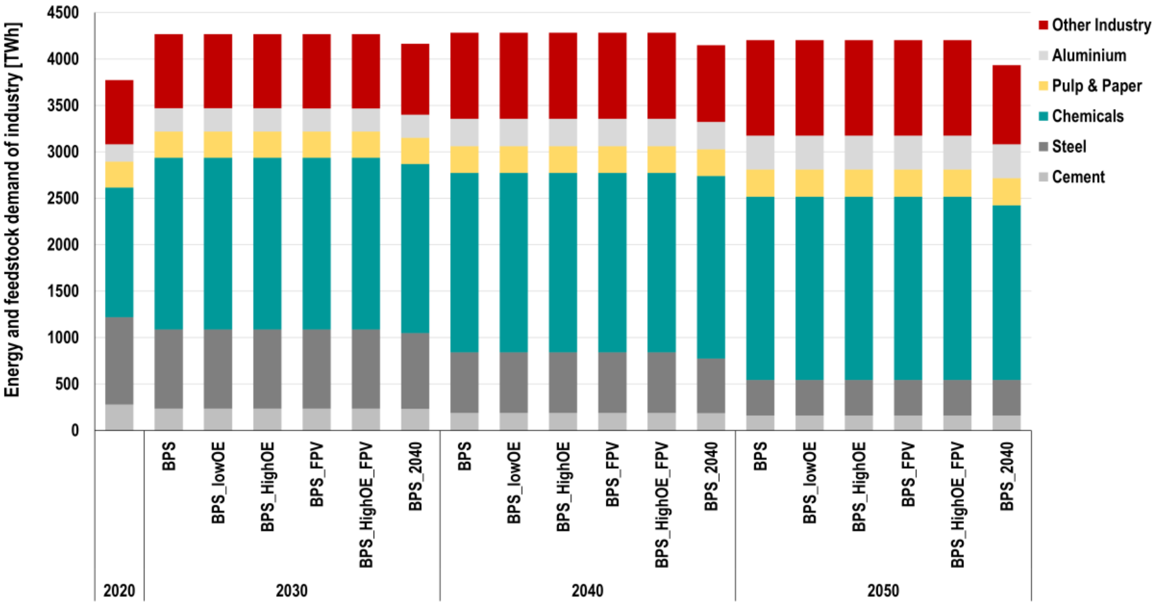

Figure 21. Energy and feedstock demand of different industries from 2020 to 2050 among all energy transition scenarios.

In 2020, the total industrial demand was around 3784 TWh. Chemicals had the highest consumption at 1397 TWh, followed by steelmaking at 938 TWh and other Industries at 691 TWh. The remaining industries (cement, aluminium, and pulp and paper) had considerably lower demands ranging between 189 and 281 TWh. By 2030, the demand increases significantly, reaching approximately 4270 TWh in the BPS. Chemicals see the largest increase, growing by over 30% to 1848 TWh. Other industries also rise to 799 TWh, though steelmaking drops slightly to 854 TWh and cement declines modestly to 235 TWh. All other scenarios for 2030 remain almost identical to the BPS.

In 2040, demand continues to rise slightly. Chemicals grow to 1934 TWh and other industries reach 927 TWh. Steelmaking and cement continue their downward trends, falling to 652 TWh and 189 TWh, respectively. The BPS_2040 diverges slightly from others, especially in the chemical industry, which decreases to 1820 TWh, roughly 115 TWh lower than in the BPS.

By 2050, considerable shifts happen, and chemicals reach 1974 TWh and other industries sharply jump to 1028 TWh. Aluminium continues its growth, doubling from 2020 to 366 TWh. Cement and steelmaking see significant reductions, down to just 160 TWh and 385 TWh, respectively, mostly due to efficiency gains or material substitution. Again, the other scenarios closely align with the BPS, while the BPS_2040 shows a slightly lower total demand, particularly due to reduced demands in chemicals and other industries.

To satisfy sustainable fuels and feedstock demand from industry, marine, and aviation transport, the system has to ramp e-fuels production capacities. Figure 22 illustrates the growth of fuel conversion capacities from 2020 to 2050 across different scenarios. These capacities include electrolysers, steam methane reforming (SMR), SMR with carbon capture (SMR+CC), methanation, Fischer-

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Tropsch, methanol, and ammonia synthesis. Across all the years, the general trend shows substantial growth in total capacity, especially driven by electrolysers. The differences between scenarios are relatively small, with the exception of the BPS_highOE scenarios, where electrolyser capacity is consistently lower.

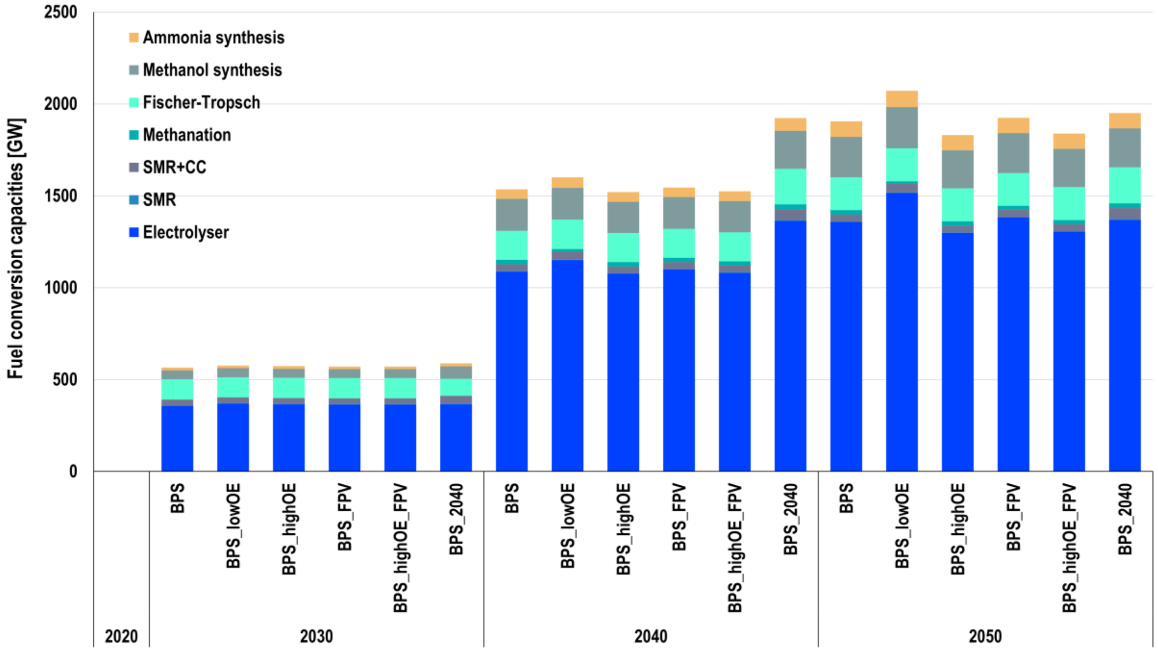

Figure 22. Fuel conversion installed capacities from 2020 to 2050 among all energy transition scenarios.

In 2020, fuel conversion capacities are almost non-existent, with only 1 GW of SMR. By 2030, total capacity increases notably. Electrolysers dominate with around 360 GW, while SMR+CC reaches 31 GW. Fischer-Tropsch and methanol synthesis each rise to over 100 GW and 49 GW, respectively. Ammonia synthesis remains limited to 14 GW.

By 2040, total capacities are more than doubled, driven primarily by a sharp increase in electrolyser deployment, reaching between 1077 and 1150 GW in most scenarios. Other technologies also scale up, methanol synthesis increases to about 170–174 GW, and Fischer-Tropsch rises to about 160 GW. Methanation and ammonia synthesis also modestly grow. The BPS_highOE scenarios again reflect lower electrolyser capacity compared to others, consistent with the more stable generation profiles of ORE technologies.

In 2050, capacity expansion continues across all technologies. Electrolyser capacity reaches between 1299 GW and 1517 GW, with the highest values found in scenarios with low electrification. Methanol synthesis climbs further to over 220 GW and Fischer-Tropsch nears 180–195 GW. SMR+CC also expands to about 59 GW. While electrolyser remains the dominant technology, its deployment is visibly lower in the BPS_highOE scenarios, reinforcing the trend of reduced reliance on hydrogen-based fuels when electrification is prioritised. Generally, the data reflect a strong reliance on electrolysers for e-fuel production, except in scenarios where direct electrification limits their necessity. Other fuel synthesis technologies follow a

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steady and balanced growth, with methanol and Fischer-Tropsch playing significant complementary roles by 2050. Figure 23 also indicates the corresponding fuel conversion energy output in different scenarios for 2020 to 2050. Regional fuels and chemicals supply in 2020 and 2050 across Europe based on different scenarios are shown in Figure 24 as well.

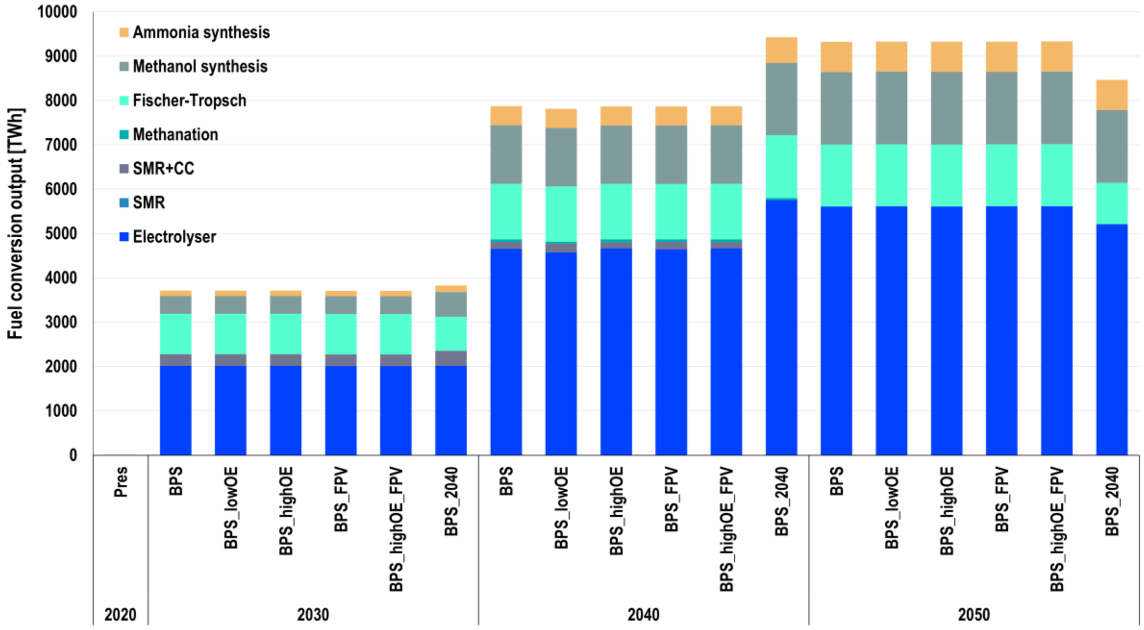
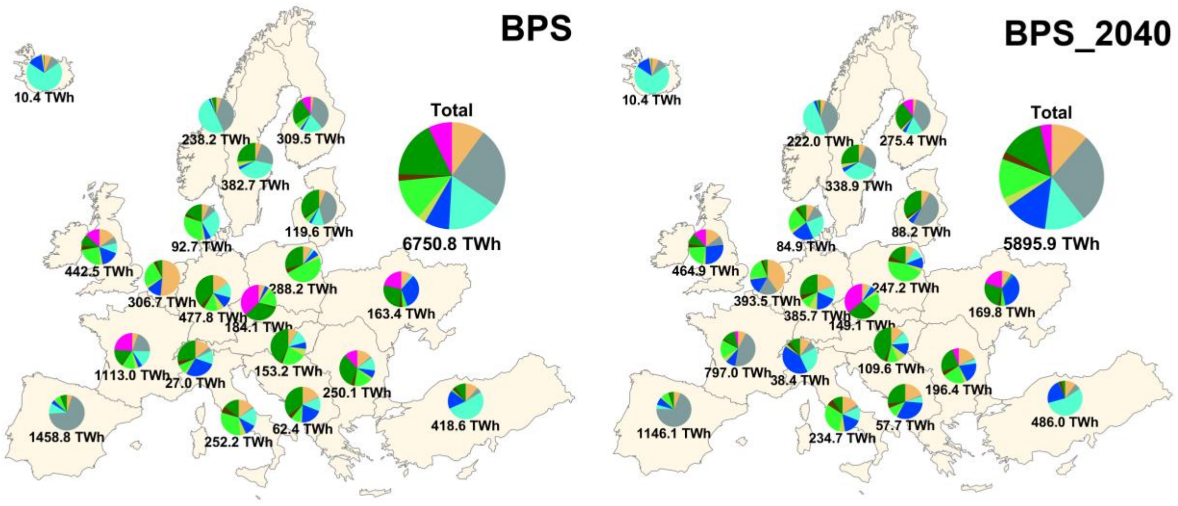


Figure 23. Fuel conversion energy output from 2020 to 2050 among all energy transition scenarios.



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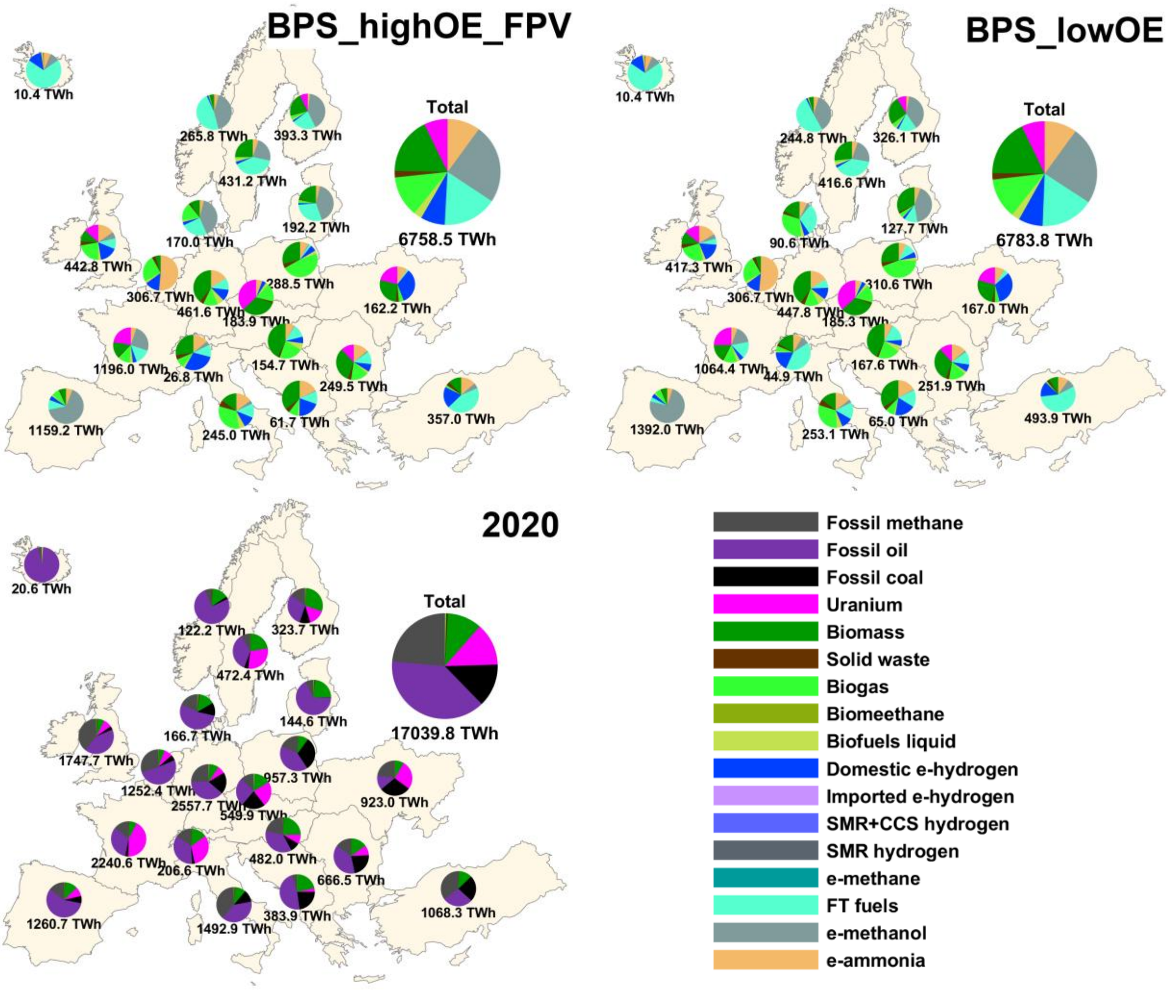

Figure 24. Regional fuels and chemicals supply in different scenarios in 2020 and 2050 across Europe.

4.6. Energy cost in the system

In Figure 25, the annualised system costs across all scenarios show a similar trend over time, with a peak around 2030 followed by a gradual decline towards 2050. In 2020, all scenarios begin at approximately 768 b€, showing no variation at the starting point. By 2025, costs increase to around 915 b€ across all cases, then peak in 2030, ranging from 952 b€ in the BPS_2040 to 997 b€ in high electrification and BPS variations.

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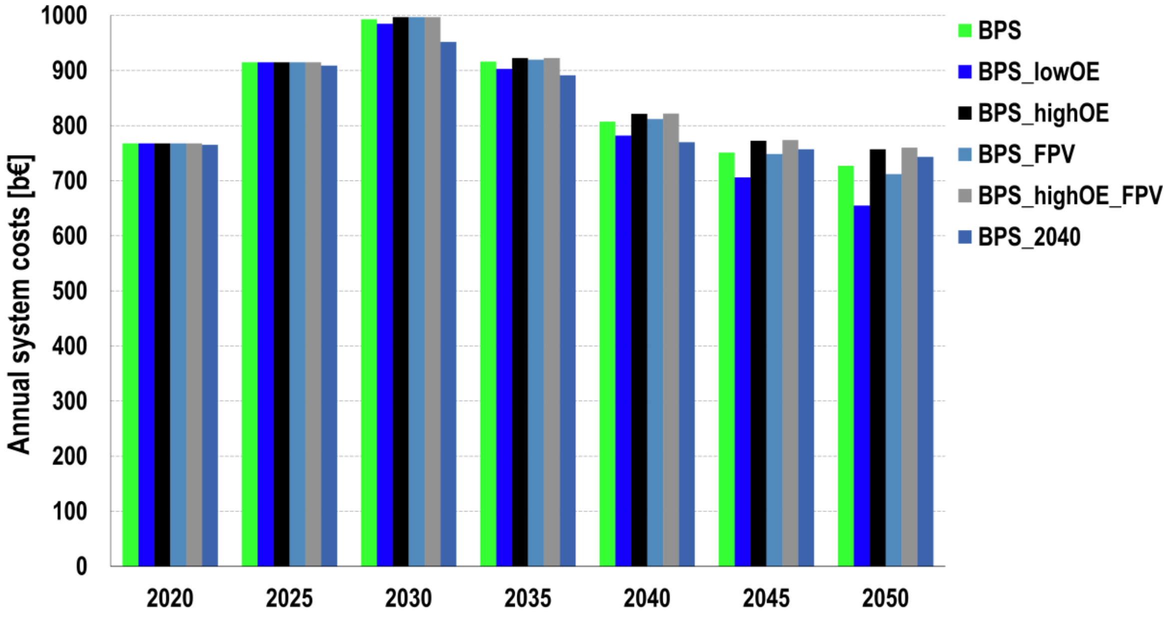

Figure 25. Annual system costs from 2020 to 2050 among all energy transition scenarios.

From 2035 onward, the annualised costs steadily decrease. By 2040, the BPS costs fall to 807 b€, while the BPS_highOE_FPV reaches 822 b€. The lowest value by 2040 is seen in the BPS_lowOE at 782 b€. By 2050, all scenarios converge closer, ranging between 655 b€ (BPS_lowOE) and 760 b€ (BPS_highOE_FPV). This shows that BPS_highOE scenarios tend to have higher long-term system costs, while BPS_lowOE scenarios result in lower costs, though they may imply higher emissions or a slower transition.

Notably, the BPS_2040 maintains a more consistent and slightly lower projection than the other variants, ending at 743 b€ in 2050. Despite some variations, the differences among scenarios remain relatively small, indicating that different defossilisation pathways lead to comparable overall system costs, with trade-offs between capital expenditures, technology deployment, and operational efficiency.

Examining the cost structure in Figure 26, there is a clear shift to capital expenditures. In 2020, fuel costs were the largest component at 264 b€, and CO_2 costs were also high at over 156 b€. In the BPS_highOE_FPV by 2050, both of these components almost disappear, with CO_2 costs reduced to zero and fuel costs down to just 5.5 b€ largely covering bioenergy. Capex steadily increases from 237 b€ in 2020 to 537 b€ by 2050, constituting it the largest component of system cost. Operational expenditures (opex) also rise, with fixed opex increasing from 78 b€ to 185 b€. This transition highlights the growing importance of upfront investments in infrastructure and technology over ongoing fuel use and emissions penalties.

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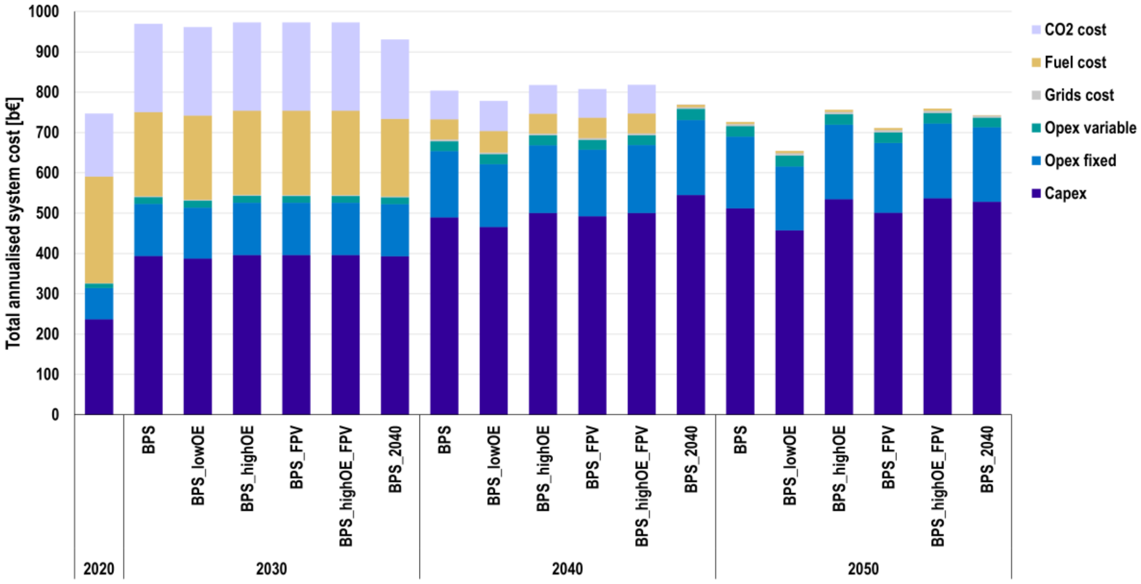

Figure 26. Annualised system costs from 2020 to 2050 among all energy transition scenarios.

The decline in fuel and CO_2 costs indicates a successful shift towards clean energy sources and efficiency improvements. Grid costs for interconnecting the 20 modelled regions grow to 5.5 b€ by 2050. The steady rise in opex fixed and capex, coupled with declining power sector costs, reflects the long-term benefits of early investments in RE and electrified infrastructure. Altogether, the data point to a profound structural shift in the energy system, away from fossil fuel-driven costs toward capex-driven, low-emission technologies across all energy sectors.

A similar trend is observed for the costs of individual energy carriers. Levelised cost of electricity (LCOE) (Figure 27) reduces from 91 €/MWh in 2020, to around 58–60 €/MWh by 2030, primarily due to a drop in fuel and CO_2 costs, and by 2050 to 32-41 €/MWh in RE-based systems. Starting from 2040, capex and opex fixed remain the largest contributors since most of the electricity is supplied by RE technologies with negligible variable opex and the share of fossil fuels in power generation already reach values close to zero.

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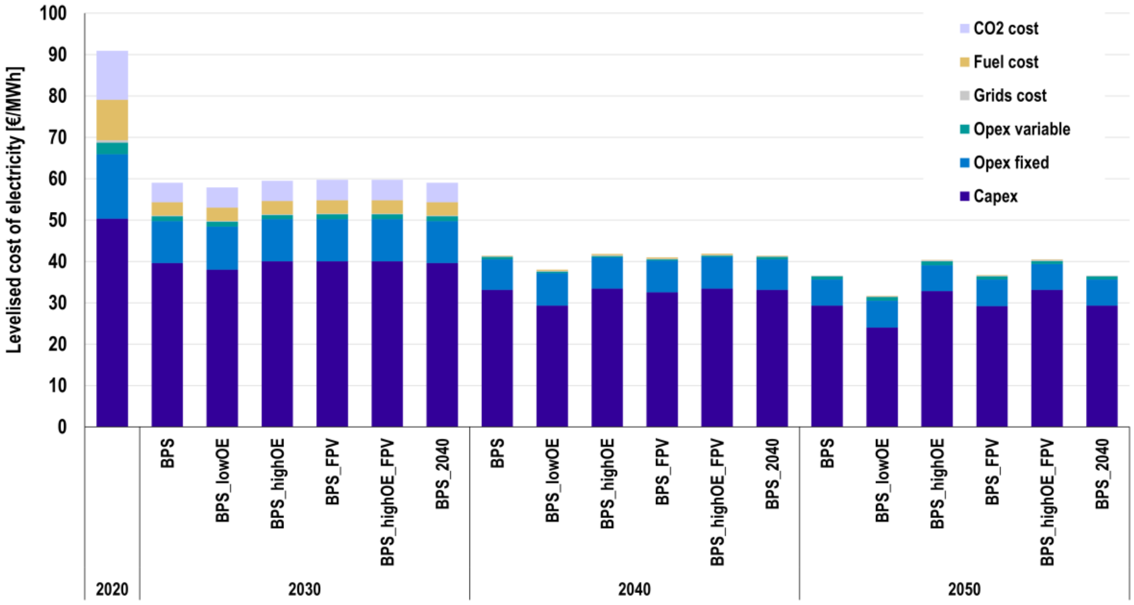

Figure 27. Levelised cost of electricity by cost components from 2020 to 2050 among all energy transition scenarios.

The lowest electricity costs appear in the BPS_lowOE in 2050 at 32 €/MWh, while BPS_highOE and BPS_highOE_FPV have slightly more expensive costs due to infrastructure requirements. Nonetheless, all scenarios maintain consistent trends, confirming the affordability of clean electricity with upfront investments.

The levelised cost of heat (LCOH) in Figure 28 shows a more stable and smoother transition. Starting at 31.6 €/MWh in 2020, costs slightly increase to 34 €/MWh by 2030 under all scenarios. The structure includes moderate capex contribution (20 €/MWh), low fuel costs (3 €/MWh), and GHG emissions costs (3 €/MWh), with small contributions from opex. A significant drop in fuel and GHG emissions costs occurs after 2030. By 2040, total costs decline to around 24–25 €/MWh, with the capex share contributing most of the cost. This trend continues through 2050, where heat costs range between 21–23 €/MWh. The minimal variation across scenarios highlights that heat decarbonisation is more cost-stable and less sensitive to pathway differences compared to electricity.

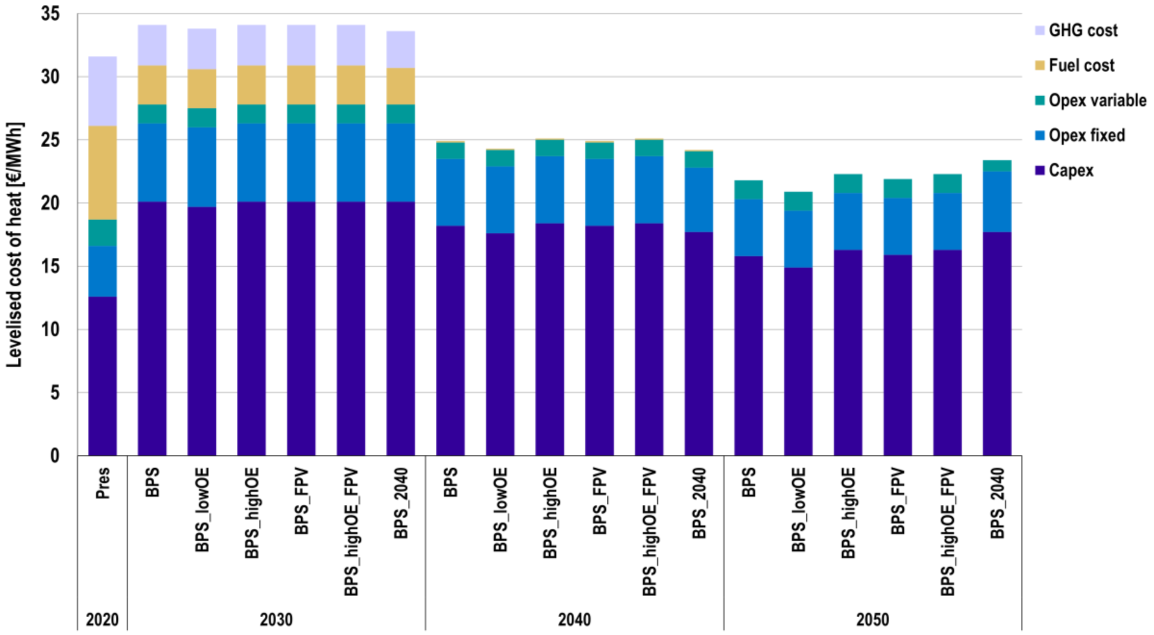

Figure 28. Levelised cost of heat by cost components from 2020 to 2050 among all energy transition scenarios.

In general, the results show a major shift from fuel- and emission-related costs to investment-driven costs over time. By 2050, all energy cost categories, total annualised system costs, LCOE, and LCOH, are largely composed of capex and fixed opex, reflecting the dominance of capital-intensive clean technologies. The BPS_highOE pathways result in slightly higher costs due to greater infrastructure demands, yet all scenarios converge toward a low-cost, low-carbon energy system. The consistent decline in CO_2 and fuel costs is a strong signal of successful defossilisation across sectors.

4.7 Greenhouse gas emissions

As Figure 29 illustrates, the total CO_2 emissions across all four scenarios of the BPS, BPS_highOE_FPV, BPS_lowOE, and BPS_2040, show a consistent projection of a steep decline from 2020 to 2050. Emissions significantly fall across the power, heat, transport, and industry sectors, indicating a high defossilisation path in line with climate targets. While the BPS, BPS_highOE_FPV, and BPS_lowOE show nearly identical patterns in terms of emission reduction, the BPS_2040 scenario stands out as a clear outlier and reaches net-zero emissions in 2040.

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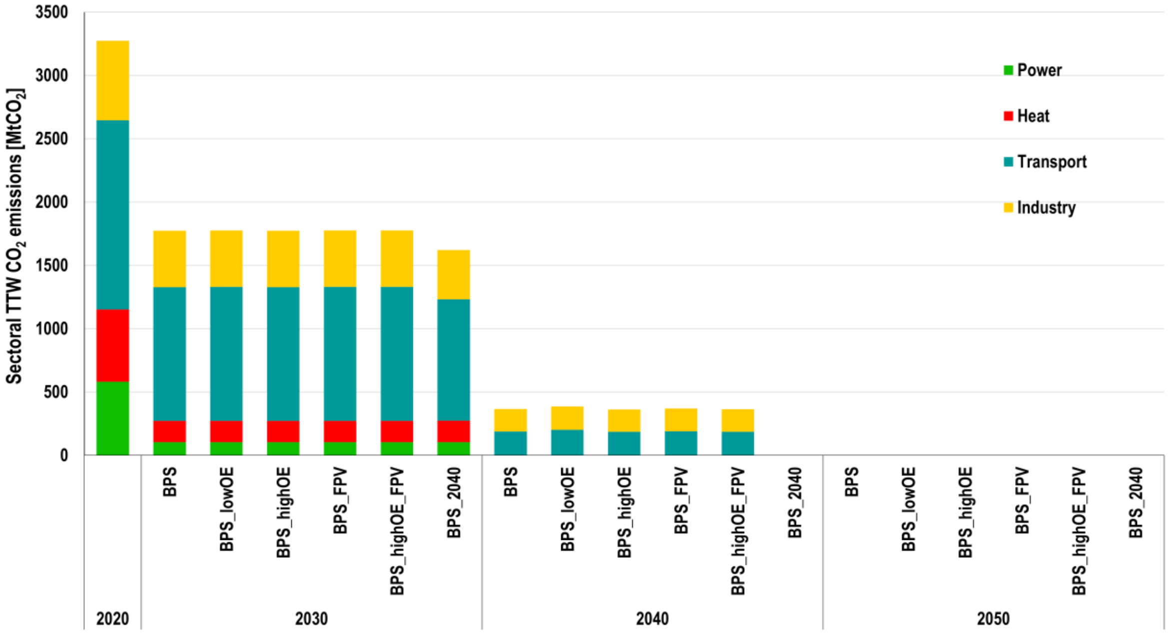

Figure 29. Total CO_2 emissions by sector from 2020 to 2050 among all energy transition scenarios. Abbreviation: TTW, tank-to-wheel, indicating emissions accounted from plant and vehicle level.

In 2020, emissions across all scenarios begin at approximately 3270 $MtCO_2$/a, dominated by the transport sector at 1494 $MtCO_2$/a, followed by industry (628 $MtCO_2$/a), heat (571 $MtCO_2$/a), and power (581 $MtCO_2$/a). By 2025, emissions modestly decline, reaching 2835 $MtCO_2$/a in most scenarios, with reductions occurring relatively evenly across sectors.

By 2030, the BPS_2040 shows 1621 $MtCO_2$/a, mostly due to earlier power and transport sector decarbonisation in that scenario whereas the other scenarios converge around 1775 $MtCO_2$/a. In 2035, the BPS, BPS_highOE_FPV, and BPS_lowOE have emissions in the range of 877–894 $MtCO_2$/a, while the BPS_2040 records a much steeper decline to almost 600 $MtCO_2$/a. This indicates that the BPS_2040 accelerates reductions in 2030, especially in the transport and industry sectors. For instance, transport sector emissions in 2035 are 509–516 $MtCO_2$/a in the other scenarios, and in the BPS_2040 they drop more significantly to 302 $MtCO_2$/a. Similarly, industry sector emissions fall to 302–307 $MtCO_2$/a in the BPS, BPS_highOE_FPV, and BPS_lowOE, compared to 226 $MtCO_2$/a in the BPS_2040.

However, by 2040, while the BPS, BPS_highOE_FPV, and BPS_lowOE achieve nearly full defossilisation with total emissions falling to 364–386 $MtCO_2$/a, the BPS_2040 reaches a negligible amount, indicating it achieves defossilisation a full decade earlier. In contrast, the other scenarios still have considerable emissions in 2040, particularly in the transport sector (187–198 $MtCO_2$/a) and industry sector (177–185 $MtCO_2$/a), whereas in the BPS_2040, both sectors are already at zero.

By 2045, the remaining emissions in the BPS, BPS_highOE_FPV, and BPS_lowOE fall further to 103–142 $MtCO_2$/a, primarily from transport and industry sectors. By 2050, all scenarios converge to zero GHG emissions, reaching full defossilisation across all sectors.

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In general, the BPS, BPS_highOE_FPV, and BPS_lowOE are nearly identical in their CO_2 emission projections, showing steady and parallel declines. Their differences in technology choice, particularly between offshore and onshore RE, do not significantly impact direct CO_2 emissions. This is because ORE technologies do not compete with fossil fuels, but rather with onshore RE. As a result, energy-related emissions are not considerably lower when ORE options are used. The life-cycle impacts are the only possible distinctions. Offshore wind power may benefit from higher full load hours (FLH), improving efficiency, but the heavier foundation structures may offset this by increasing material-related emissions. Therefore, the CO_2 footprint per kWh from ORE technologies are likely similar or slightly higher than that of onshore RE, but such effects are outside the scope of CO_2 emissions traced in this analysis that consider emissions at the plant and vehicle levels. Detailed life cycle emissions considerations of ORE were calculated and discussed in [42].

Figures 30 and 31 present cumulative CO_2 emissions across the entire energy-industry system, i.e. power, heat, transport, and industry sectors, and then individually for each sector under different scenarios. Overall, emissions across all sectors rise steadily before levelling off. In the BPS, total emissions reach approximately 39.66 $GtCO_2$, after which the increase significantly slows. Other scenarios, such as the BPS_lowOE and BPS_highOE, slightly diverge from this trajectory but still converge toward similar end values, around 39.98 and 39.56 $GtCO_2$ respectively. The OSPV scenarios show marginally lower total emissions compared to the non-OSPV scenarios, suggesting that OSPV implementation can moderately contribute to the mitigation of emissions. The most notable divergence appears in the BPS_2040, which departs significantly from the other trends, flattening much earlier and stopping at approximately 34.95 $GtCO_2$. This indicates a scenario with the most aggressive defossilisation strategy among the modelled scenarios.

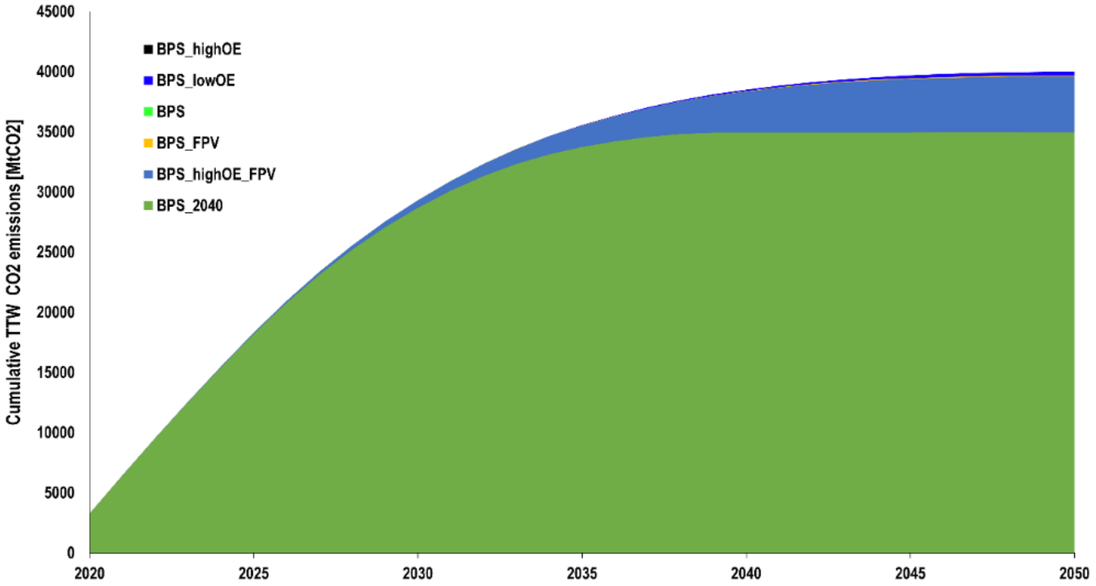

Figure 30. Total cumulative CO_2 emissions from 2020 to 2050 among all energy transition scenarios. Abbreviation: TTW, tank-to-wheel, indicating emissions accounted from plant and

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vehicle level. Various scenarios have quite close values so that they are not visualised, thus, please also refer to Figure 29.

In Figure 31, the power sector emissions increase stops earlier than in other sectors. In the BPS, emissions cap at about 4283 MtCO$_2$, and nearly all other scenarios reach a similar level. This early stabilisation suggests that decarbonising electricity generation is prioritised across all strategic pathways. Interestingly, the BPS_2040 mirrors this early plateau, indicating that power sector decarbonisation is likely a shared milestone, regardless of the broader economic and technological context.

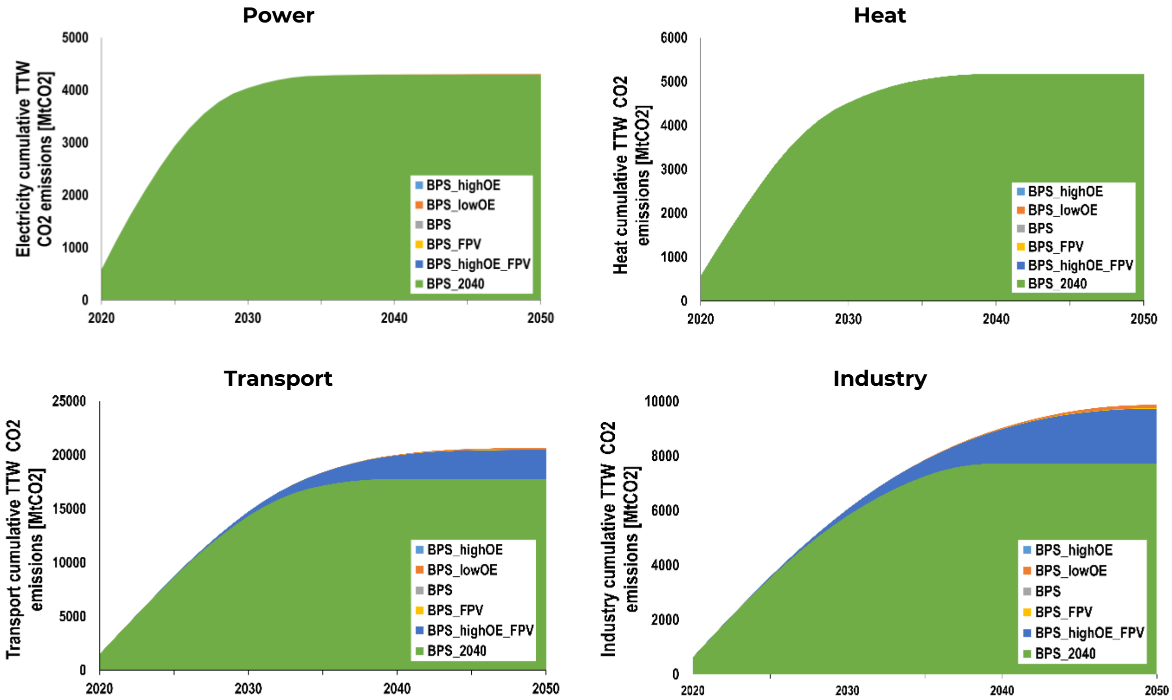

Figure 31. Cumulative CO$_2$ emissions by sector from 2020 to 2050 among all energy transition scenarios. Abbreviation: TTW, tank-to-wheel, indicating emissions accounted from plant and vehicle level. Various scenarios have quite close values so that they are not visualised, thus, please also refer to Figure 29.

The heat sector exhibits a similar trend to the power sector but reaches a slightly higher cumulative emission total. The BPS reaches about 5134 MtCO$_2$ before levelling off. Other scenarios follow the same trend with minor variations, although the BPS_lowOE shows slight increases near the end of the timeline.

The transport sector presents a different behaviour, displaying the highest cumulative emissions among the sectors. In the BPS, it peaks at almost 20.5 GtCO$_2$. Unlike power and heat, transport sector emissions consistently rise over time without flattening until the very end. This continued growth suggests a slower or more complex defossilisation processes, mostly due to factors such as the longer lifespan of vehicles, infrastructure inertia, and the complexity of defossilisation in marine and aviation transport segments. The BPS_2040 once again stands apart, flattening early and stopping at about 17.76 GtCO$_2$, which is significantly lower than the other pathways.

The industry sector cumulative emissions stabilise only closer to 2050 due to similar reasons as in the transport sector. High temperature processes require use of fuels

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making direct electrification impossible and these processes demand more costly indirect electrification with e-fuels. Even in the 2040s some fossil fuels are used as energy source and feedstock in the industry sector. The BPS results in about 9748 $MtCO_2$, and the other scenarios show only slight deviations from this figure. Scenarios with OSPV or high ORE led to nearly identical trends. However, the BPS_2040 again achieves a distinctly lower endpoint of around 7726 $MtCO_2$.

Emissions in the power and heat sectors stabilise earlier than in the transport and industry sectors, reflecting the relative ease or earlier focus of decarbonising electricity and heat supply. OSPV systems contribute to a modest but steady reduction of cumulative emissions and confirm their role as a supportive technology. The BPS_2040 consistently demonstrates the most substantial reductions across all sectors, with earlier plateaus and significantly lower final values. This indicates a comprehensive, cross-sectoral approach to emissions reductions, mostly incorporating ambitious policy, accelerated technological deployment, and changes in consumption or behaviour patterns. Considering all scenarios makes it clear that while moderate mitigation pathways lead to gradual improvements, achieving sharp and early emissions reductions require a deeper and broader commitment across all sectors.

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5. Complementary impacts

The discussed CO_2 emissions values only reflect the CO_2 emissions from the combustion of fossil fuels, the use of fossil fuels as a feedstock, and the limestone-related CO_2 emission in the cement industry. The e-fuels and biofuels are carbon neutral, and thus their combustion will not result in net CO_2 emissions as the amount of emitted CO_2 will be equal to the amount captured during e-fuel synthesis. However, possible leakages of e-fuels may have a substantial impact as hydrogen and methane have a high global warming potential and contribute to CO_2 emissions. Nevertheless, methane as a fuel is almost phased out in the investigated scenarios and hydrogen is largely limited to large-scale applications that show the lowest leakage risk. Distributed small-scale hydrogen applications are almost fully avoided in the investigated scenarios. Though the volume of e-fuels used is similar across the scenarios, scenarios with lower ORE share tend to rely on hydrogen storage to balance the seasonal supply and demand variations; however, such central hydrogen storage facilities have a rather low leakage risk.

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6. Summary and key messages

This report explores the projections of Europe's energy system from 2020 to 2050 across multiple scenarios, highlighting the impacts of offshore renewable energy deployment and sectoral defossilisation strategies on CO_2 emissions. One of the core findings is the consistent and significant reduction in final energy demand, which drops by 20% in 2050 compared to 2020 in most scenarios despite increasing activity in transport and industry sectors. This reduction is primarily driven by enhanced energy efficiency and widespread electrification. The BPS_2040 achieves even greater savings through more ambitious policies and technological uptake, leading to earlier and deeper declines in energy use.

A drop in final energy demand in combination with a switch to renewable energy supply results in a substantial reduction of primary energy demand. In 2020, fossil fuels dominate the supply mix, but by 2050, renewable electricity becomes the main energy source across all scenarios. This transition drives primary energy demand down from 20,634 TWh to as low as 16,700 TWh in the most ambitious scenario, with the integration of offshore renewable energy technologies contributing to this efficiency.

Electrification of the energy system requires the fast growth of electricity generation capacities. Electricity generation capacity expands dramatically over the period, growing from about 3000 GW in 2020 to nearly 7000 GW by 2050. Solar photovoltaics and wind power emerge as the leading technologies, with solar photovoltaics exceeding 5000 GW of installed capacity and up to 9000 TWh of generation in some scenarios. Offshore wind power also becomes increasingly important, particularly in BPS_highOE cases, reaching 450 GW in capacity and up to 1861 TWh in electricity generation. Fossil fuel-based generation is entirely phased out by mid-century, and nuclear power significantly declines, reaching only 75 TWh in the BPS_2040. Emerging technologies including wave power and geothermal grow steadily but remain secondary contributors.

Electricity storage systems rapidly scale up to accommodate the variability of renewable energy. By 2050, prosumer batteries and vehicle-to-grid systems each exceed 1000 TWh of output, playing critical roles in system flexibility. While the BPS_lowOE achieves the highest total storage deployment through utility-scale batteries, the BPS_2040 relies more on prosumer batteries and pumped hydro energy storage, decentralised solutions, reflecting its early transition towards renewable energy. Other flexibility sources such as smart changing of electric vehicles and heat storage options also contribute to the system stability.

The heat sector also undergoes a major transition, nearly eliminating fossil fuel use by 2050. Heat pumps become the dominant technology, reaching 470 GW of capacity and generating 2900 TWh annually. Electric heating, particularly strong in the BPS_2040, and a steady contribution from bioenergy help support the transition. Hydrogen buffer storage serving as seasonal balancing is similarly important in all scenarios and particularly in scenarios with high solar photovoltaics contribution, reaching up to 1920 TWh of throughput in the BPS_lowOE. Offshore

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wind power-rich scenarios, conversely, require less storage due to more stable generation profiles.

The industry sector shows moderate energy demand growth overall, with chemicals and other industry sectors expanding, while steel and cement decline due to material efficiency and substitution. In the transport sector, road transport energy demand drops significantly with the uptake of electric vehicles. By 2050, aviation becomes the largest single transport energy consumer due to limited electrification options. To supply sustainable fuels for marine, aviation, and industry, fuel conversion capacities, especially electrolysers, expand from nearly zero to over 1500 GW, alongside steady growth in methanol and Fischer-Tropsch synthesis.

Economically, energy system costs slightly rise to a peak around 2030 before declining through 2050, converging between 655 and 760 b€. The BPS_2040 maintains a consistently lower cost trajectory, reflecting its early transition and high efficiency. The structure of system costs shifts substantially: fuel and CO_2 costs, which are significant in 2020, fall to near zero by 2050, while capital expenditures double, becoming the dominant component. Levelised cost of electricity and levelised cost of heat drop considerably, confirming the long-term affordability and stability of renewable energy.

All scenarios project a sharp decline in CO_2 emissions. From around 3270 $MtCO_2$/a in 2020, emissions fall to zero by 2050 in all cases, with the BPS_2040 achieving net-zero as early as 2040. This scenario leads in defossilising transport and industry sectors, bringing 2035 emissions down to 600 $MtCO_2$/a compared to nearly 900 $MtCO_2$/a in other scenarios. Cumulative CO_2 emissions reach 39.66 $GtCO_2$ in the BPS but are significantly lower at 34.95 $GtCO_2$ in the BPS_2040. Sectoral patterns show that emissions from power and heat sectors plateau early, while the transport sector accumulates the highest emissions due to its slower defossilisation. The BPS_2040 notably brings the transport sector cumulative emissions down from 20.5 $GtCO_2$ in the BPS to 17.76 $GtCO_2$.

Results show that accelerated or limited scaling of offshore renewable energy and also offshore floating solar photovoltaics has modest impact on energy-related CO_2 emissions, indicating that cross-sectoral policies play a far greater role in determining the defossilisation speed. CO_2 emissions are strongly affected by decarbonisation rates in the first decade of the transition, where the onshore renewable energy technologies are the main contributors. Scaling of offshore renewable energy does not reduce fossil fuels use but rather reduces onshore renewable energy technologies capacity.

However, the introduction of offshore renewable energy technologies, such as offshore wind power, wave power, and floating offshore solar photovoltaics, reduces system reliance on long-term e-fuel storage and can reduce the risks of hydrogen and methane leakage to the atmosphere. Nevertheless, methane volumes reach very low levels across the investigated scenarios and the large-scale hydrogen applications have a rather low hydrogen leakage risk.

In conclusion, the findings underscore that while multiple technology pathways can deliver net-zero energy-industry system configurations by 2050, early action, strong electrification, and a diversified renewable energy mix offer a most effective, feasible, and reliable path to achieving net-zero targets across Europe's energy system.

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