European Scalable Offshore Renewable Energy Source (EU-SCORES)

D6.10 Report on the energy system transition relevance of offshore energy for Iberia

14.10.2025

Delivery Date	14th october 2025
Dissemination Level	Public
Status	Final Version
Version	1.0
Keywords	Offshore energy systems; wave energy; transition

Disclaimer

Document information

Grant Agreement Number	101036457
Project Acronym	EU-SCORES
Work Package	6
Related Task(s)	6.5
Deliverable	6.10
Title	Report on the energy system transition relevance of offshore energy for Iberia
Author(s)	Aleksandr Borzunov, Dmitrii Bogdanov, Christian Breyer
File name	D6.10 Report on the energy system transition relevance of offshore energy for Iberia

Revision history

Revision	Date	Description	Reviewer
1	19/09/2025	Task partners revision	Aleksandr Borzunov, Dmitrii Bogdanov, Christian Breyer
2	08/10/2025	Consortium revision	EU-SCORES consortium
3	10/10/2025	Final revision for submission	Christian Breyer, Sarah Kluge

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

Contents

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

Abbreviations

BNL	Benelux region
BPS	Best Policy Scenario
BPS_favourVPV	Best Policy Scenario with floating OSPV
BPS_favourOE	Best Policy Scenario with high ORE
BPS_lowPV	Best Policy Scenario with low share of PV
BPS_noBPV	Best Policy Scenario with no bifacial PV
BPS-2040	Best Policies Scenario with carbon neutrality reached by 2040
BFOW	Bottom-fixed offshore wind
Capex	Capital Expenditures
CO_2	Carbon Dioxide
EC	European Commission
EU	European Union
FED	Final Energy Demand
FTL fuels	Fisher-Tropsch Liquids fuels
GHG	Greenhouse Gas
HDV	Heavy Duty Vehicle
IEA	International Energy Agency
LCOC	Levelised Cost of Curtailment
LCOE	Levelised Cost of Electricity
LCOFE	Levelised Cost of Final Energy and Non-energy Use
LCOH	Levelised Cost of Heat
LCOS	Levelised Cost of Storage

LDV	Light Duty Vehicle
LUT-ESTM	LUT Energy System Transition Model
MDV	Medium Duty Vehicle
NOAA	National Oceanic and Atmospheric Administration
Opex	Operational Expenditures
ORE	Offshore Renewable Energy
OSPV	Offshore Solar Photovoltaics
O&M	Operation and Maintenance
PED	Primary Energy Demand
PV	Photovoltaics
RE	Renewable Energy
SDGs	Sustainable Developments Goals
TES	Thermal Energy Storage
TPED	Total Primary Energy Demand
UN	United Nations
WMO	World Meteorological Organization
WACC	Weighted Average Cost of Capital

0. Executive summary

Offshore renewable energy (ORE) plays a pivotal role in the transition to a carbon-neutral energy system in the European Union (EU). Accurately capturing the contribution of offshore wind power, wave power, and floating offshore solar photovoltaic (OSPV) in the development of Europe's future energy systems is becoming increasingly important to better define energy transition scenarios and unlock the full potential of renewable energy.

The purpose of this report is to assess the importance of ORE in the Iberian energy system transition through high-resolution modelling of the regional energy system. The study aims to support the EU's energy transition by offering a clear vision of how different ORE technologies may impact the energy transition in Spain and Portugal. By applying a multi-node approach and high-resolution spatial and operational data in modelling, the report aims to analyse how offshore wind power, or OSPV interact with onshore electricity supply, influence system costs and grid demands, and contribute to defossilisation pathways in Iberia in the wider European context up to 2050.

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

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

Energy transition scenarios for the Iberian energy system were modelled using LUT-ESTM, a linear optimisation tool designed to create cost-optimised scenarios for the full energy-industry system. It features hourly resolution over a full year, a geographical multi-node structure, and methodologies for dispatch and investment optimisation. The energy transition across Iberian peninsula is explored through six scenarios: the reference Best Policy Scenario (BPS), aligned with the European Green Deal and the European Commission's ORE growth targets, scenario examining the effects of expanded ORE technologies including OSPV, scenario with lower share of fixed tilted PV systems, increased share of vertical bifacial PV systems, scenario with restricted bifacial PV systems, and accelerated pathway to carbon neutrality by 2040.

The key findings of this report are that the scenario with favoured offshore wind power and OSPV slightly increases system costs compared to the baseline scenarios. However, this favoured ocean energy (OE) is not the most expensive in

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

terms of annualised system cost and levelised cost of electricity. The favoured OE scenario significantly improves the stability of the energy system by reducing the need for electricity storage and hydrogen-based balancing, while grid reinforcement increases the role of transmission capacity and allows landlocked regions to benefit from OE technologies introduction. Technological diversity in PV, especially the use of OSPV, facilitates land use optimisation and improves system integration in the context of spatial constraints and is the optimal cost-effective solution for the isolated island regions, i.e., the Canary Islands, Azores, and Madeira. The scenario with a lower share of PV technologies increases the total annualised cost of the energy system by 1.5%, emphasising the importance of PV technologies in terms of optimal cost-effective solutions.

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

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

1. Introduction

The impacts of climate change are leading to an increase in global average surface temperatures. The global average surface temperature according to the National Oceanic and Atmospheric Administration (NOAA) annual report [1] reached 1.29°C above the 20th century average and 1.46 °C above the pre-industrial average. According to the World Meteorological Organization (WMO) [2] the global average temperature was 1.55°C in 2024 above the 1850-1900 average. The average air temperature in Europe during the same period increased even faster to 2.88-3.01°C [3] indicating that Europe is warming twice as fast as the global average [4]. This unfavourable change in global and European temperatures indicates a significant increase in extreme weather events and leads to climate hazards [2]. Climate change, and in particular the average increase in air temperature is primarily caused by anthropogenic emissions of greenhouse gases (GHG), especially carbon dioxide (CO_2) emissions, the main source of which is the use of fossil fuels in the energy system. A transition from fossil fuels to low-carbon energy sources such as renewable energy (RE) is a necessary climate change mitigation strategy to prevent the worst impacts of the climate change [5].

The long-term vision presented by the European Commission in the European Green Deal [6] provides possible scenarios for Europe's transition to a climate-neutral economy by 2050, in line with the goals of the Paris Agreement [7]. Among the key strategic objectives of the European Union (EU) are the reduction of GHG emissions by at least 55% by 2030 and the achievement of carbon neutrality by mid-century [8]. In March 2023, the EU stepped up its efforts to accelerate the deployment of RE sources, setting a target of bringing their share in total energy consumption to 42.5% by 2030, with an additional target of 45% [9]. To achieve these objectives, the EU and its member states play a leading role in the deployment of RE technologies, including offshore renewable energy (ORE). In particular, technologies such as floating offshore solar photovoltaics (OSPV) are seen as a promising element of future energy systems in European countries [10], especially in regions with high ORE potential, such as the Iberian Peninsula and its associated islands. The growing share of ORE contributes to the resilience, security and flexibility of the European energy system.

The adoption of a more sustainable energy system based on clean technologies are key indicators of a sustainable energy future. The transition towards a low-carbon energy system is already progressing in numerous countries. According to studies [11-14], this process not only contributes significantly to climate change mitigation, it also generates considerable economic advantages. Many countries are already making progress towards low-carbon energy, and the EU, particularly the Iberian region with its favourable conditions for RE [15], [16], is well placed to lead the way, becoming the first region in the world to achieve net-zero GHG emissions and setting the benchmark for global climate neutrality by 2050.

Solar PV, one of the main and the fastest-growing RE technologies in the world [17], [18] will play a significant role for achieving the EU's climate-neutral goal by 2050. It is the most cost-effective electricity source, with the capability to meet all final energy demand (FED) through sector coupling and power-to-X (PtX) technologies [19], [20].Together with onshore wind power, solar PV has the potential to become the main energy source across Europe in near future [21], [22]. However, to support flexibility and reliability of the system, and to supply energy where and when solar PV and wind power are limited, ORE becomes an important part of the future energy mix [23], [24]. ORE in general delivers a more stable electricity generation profile and has relatively high capacity factors [25], [26]. Moreover, in a region such as Iberia, wave power, offshore wind power, and OSPV could provide power to the coastline agglomerations, where energy demand is high and available land area is limited. In addition, due to relatively stable electricity generation profiles, ORE could potentially reduce the need for energy storage in future energy systems and stand on par with onshore RE technologies [27].

Europe holds a leading position in the offshore wind power industry [28]. The existing offshore wind power capacity in Europe can cover the region's electricity needs, with demand projected to rise steadily in the years ahead. By 2024, Europe had around 37 GW of installed offshore wind power capacity connected to the grid [29]. Thereof, 2.6 GW was added in 2024, marking a 28% decrease compared to the 3.6 GW installed in 2023 [29], [30]. However, meeting the EU's climate targets will require a significant acceleration in the pace of installation and, as a result, an increase in investment in offshore wind power projects. According to targets set by the EC [6], to reach climate neutrality by 2050, offshore wind power capacity is expected to reach 160 GW by 2030 and 450 GW in 2050 thereof 212 GW in the North Sea, 85 GW in the Atlantic Ocean (including the Irish Sea), 83 GW in the Baltic Sea, and 70 GW in the Mediterranean and other Southern European waters [31]. The installed capacity figures for 2030 and 2050 provide the foundation for constructing offshore wind power scenarios applied in the energy transition modelling for Iberia in this report.

Thanks to favourable conditions for the development of solar PV and wind power, the Iberian region has solid preconditions to transition to 100% RE. In 2024, RE sources provided 87.5% of electricity generation in Portugal and around 56.8% in Spain, with wind power and solar PV accounting for almost 46.4% of total electricity generation for both countries together [32], [33]. Portugal, which closed its last coal-fired power plant in 2021 [34], met 90% of its electricity needs in 2024 from local RE sources and imports from Spain [35].

To reach Iberia's as well as all of Europe's full net zero emission target, ORE must be considered, developed, and evolved in the energy system [36]. The European Institute of Innovation and Technology (EIT) [37] estimates that Iberia in the most ambitious scenario could have 3 GW of floating offshore wind power installed capacity by 2030 and 22 GW by 2050. According to Rusu [38], in the north-western part of the Iberian Peninsula (coastal area of Galicia), the energy of waves has significant values that can reach up to 30 kW/m. In the work Majidi et al. [39], it is noted that Portugal represents one of the largest wave energy resources in continental Europe, as evidenced by its high annual yield potential (more than 4 GWh/year). Additionally, according to the International Renewable Energy Agency (IRENA) renewables statistics 2025 report [40], Spain accounted for approximately 5 MW capacity of marine energy. With these figures, ORE can complement solar PV and wind power and provide the energy system with additional flexibility needed to ensure reliable energy supply.

Besides ORE, the excellent solar resource potential has put both countries at the forefront of PV development. Spain and Portugal together have some of the highest solar irradiation values in Europe, especially in regions such as Seville and Almeria, which have global horizontal irradiation of 1700-1800 kWh/m² per year [41], significantly higher than the European average of around 1000 kWh/m² [42], [43]. As of 2024, Spain's total solar PV capacity exceeded 30 GWp [44], highlighting its proactive energy policy. Portugal, on the other hand, had an installed solar PV capacity of 1.8 GWp by the end of 2020 and increased this figure to 5.53 GW by the end of 2024 [45], [46].

The updated National Energy and Climate Plan (NECP) [47] of Spain envisages a reduction in GHG emissions by 55% by 2030 compared to 2005 levels. By this time, the country plans to achieve a 42% share of RE in final energy consumption and 74% in electricity generation. In addition, the plan sets the target for the gradual phase-out of fossil fuels, including the staged closure of nuclear power plants from 2027 to 2035. Portugal, in turn, also updated its NECP [48], setting a goal of achieving carbon neutrality by 2045, five years earlier than the EU target.

In recent years, the consolidation of offshore wind power technology, advancements in OSPV and wave power technology have made combining these technologies a viable alternative [25]. The combinations of wind power and wave power, and wind power and OSPV in multi-source energy parks are based on two main principles: (i) increasing the sustainability of RE technologies through more efficient use of resources, and (ii) reducing costs by sharing significant expenses of ORE projects.

Technological diversity in PV and ORE is leading to increased flexibility and sustainability of future RE systems while making them more efficient than current ones [49]. In regions such as Iberia, where solar resources are abundant [43], [50], deploying a combination of advanced PV technologies such as bifacial PV, single-axis tracking PV, and OSPV offers distinct advantages. Bifacial PV modules, which can capture sunlight from both sides, significantly increase electricity generation, especially in Iberia's high albedo conditions [51]. Additionally, research [49], [52] shows that using single-axis tracking can increase energy yield by 15–20% compared to fixed tilted solar PV installations, while bifacial modules offer a more modest gain, generally up to 10% in most regions. In some specific conditions, however, higher bifacial gains may occasionally be achieved. This technology allows for more efficient land use, higher generation density, and economical benefits, which is especially valuable in areas with limited space or high energy demand [53].

On the other hand, for Iberia, OSPV is particularly relevant along densely populated coastal areas where land availability is limited but grid access is favorable [54], [55]. Combined with offshore wind power and wave power, where OSPV is most often installed, it contributes to a more balanced and stable RE mix, complementing solar irradiation patterns and reducing seasonal variability [56]. This technological diversification supports greater system reliability, reduces the need for storage and curtailment, and helps Iberia benefit from its full RE potential both onshore and offshore.

Combining PV technological diversity with the ORE including floating OSPV leads to a more resilient, regionally optimised and efficient system architecture [24]. The results of this combination support a strategic shift towards greater technological diversity in ORE and onshore PV diversity as a key driver for a sustainable energy transition in Iberia and entire Europe.

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

The report also examines techno-economical results of alternative energy transition pathways of the Iberia with a focus on the comparative advantages of ORE technologies (OSPV, offshore wind power, and wave power) deployment compared to a best policy scenario (BPS) set as baseline with a favouring standard PV expansion.

Since PV emerges to the dominating source of energy supply in Iberia it is also considered how diversification in PV technologies can contribute to increasing the share of RE, reducing system costs and reducing land use pressure, but also how this may interact with ORE technologies, thereby contributing to a more sustainable and reliable energy transition strategy.

2. Methodological approach

2.1. Methods energy system modelling

The energy transition scenarios of the European energy-industry system were performed with the LUT Energy System Transition Model (LUT-ESTM) [11, 19, 57], a linear optimisation tool. For the given financial and technical assumptions and scenarios 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 different energy transition pathways to be explored. With its wide range of over 150 energy technologies across various sectors and uses, including transitional technologies, LUT-ESTM is ranked amongst the most sophisticated tools for the analyses of long-term energy transition pathways [58] and it is currently one of the most widely used tools for research on the transition to 100% RE systems [59]. In the case of fuels, the model simulates the production of electricity-based e-fuels (gaseous and liquid) based both on green e-hydrogen and CO_2 from point source capture of sustainable CO_2 sources and direct air capture units, which are part of the PtX concept as an integral element of the arising Power-to-X Economy [60]. 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. [11] and updated in Satymov et al. [57]. The output of the model is a transition path optimised for a given scenario definition, considering factors such as CO_2 emission targets, shares of conventional and RE sources, technology costs in different transition years, implementation costs, and GHG emissions. Figure 1 shows the basic architecture of LUT-ESTM. The simplified scheme of a sector-coupled energy system as modelled with LUT-ESTM is shown in Figure 2 [19].

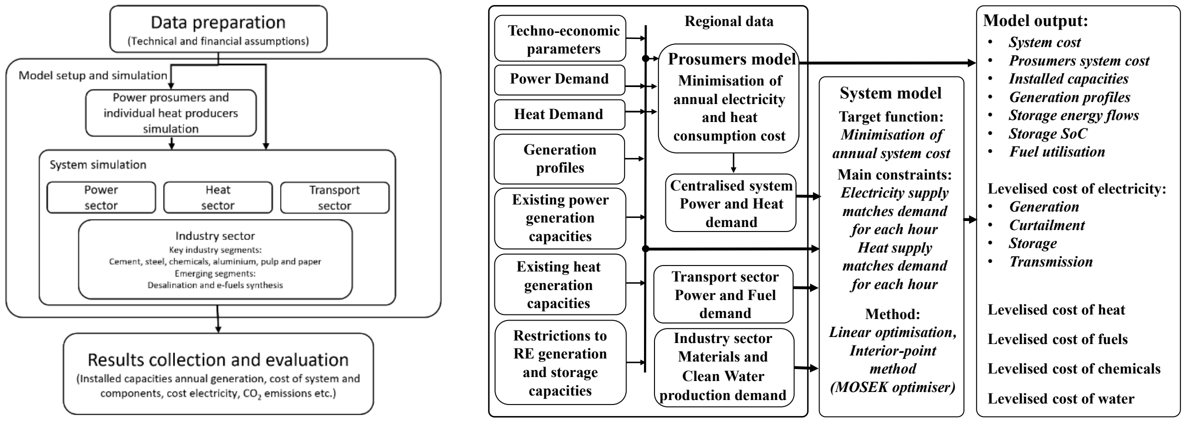

Figure 1 - Schematic representation of LUT-ESTM (left) and the model flowchart (right).

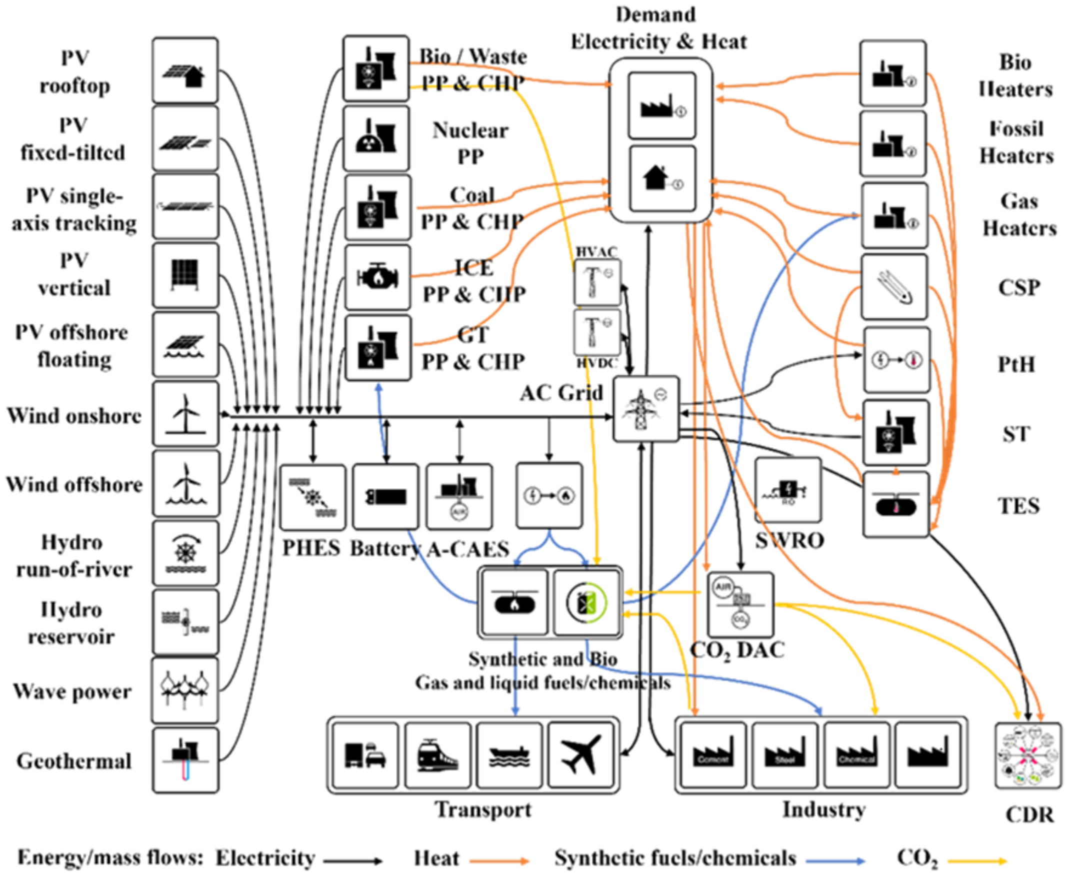

Figure 2 - LUT-ESTM integrated energy system structure scheme.

LUT-ESTM covers ORE technology, including offshore wind (bottom-fixed BFOW and floating), OSPV, and wave power based on the respective energy potential, e.g. for wave power [25], and considers the electricity generation across the different technologies based on the installed capacities, and the respective energy yield following the applied scenarios. A diverse portfolio of generation and storage technologies, coupled with hourly resolution, facilitates the exploration of key insights into the optimal structure of future energy systems and the potential synergies among different generation and storage technologies. Moreover, the ability to model at an hourly resolution for an entire year allows for the uncovering of crucial insights on RE technologies operation. Grid connection capital expenditures (capex) are included in all power generation technologies, also for ORE. CO_2 emissions are priced at the point of emissions, such as for fossil fuel plants, industrial emitters, or transport vehicles.

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

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

The model guarantees that the energy demand for all sectors will be satisfied for all energy carriers and for each hour of a year. The inputs define electricity demand for general application, heat consumption for space heating, domestic hot water, and industrial process heat demand, transportation services demand, and demand for key industrial products. The model considers both energy and feedstock requirements for industries including cement, steel, chemicals, pulp and paper, aluminium, and others [19]. A crucial part of the transition is to divert from use of fossil fuels as feedstock and source of energy enabling the industry sector to rely entirely on renewable energy and feedstock. Transportation demand is derived across various modes, including road, rail, 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 (LDV), two- and three-wheelers (2W/3W), buses for passenger transport, and medium and heavy-duty vehicles (MDV and HDV) 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. [61].

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. [62]. These are based on the detailed description of the model applied to the global power sector in Bogdanov et al. [63] and all energy sectors in Bogdanov et al. [11], [19].

2.2. Regional structure of Iberia for energy system modelling

In order to achieve robust energy system analyses for Iberia in LUT-ESTM, Iberia is comprised of ten regions with the power systems of the nodes being interconnected according to existing power grids. The region nodes follow the borders of autonomous communities: Galicia, Pais Vasco, Madrid, Castile and Leon, Catalunya, Andalusia, and an additional three nodes to represent the Canary Islands, Azores, and Madeira (see Table 1 and Figure 3). The study covers territories connected to the power grid of Spain and Portugal of as January 2015 and isolated grids.

Table 1. Description of the regional structure

Node name	Autonomous community/ Region	Center of consumption	Area (km²)
ES1	Galicia, Asturias, Cantabria	Galicia	45,498
ES2	Basque, Navarre, Aragon, Rioja	Pais Vasco	70,387
ES3	Community of Madrid	Madrid	8031
ES4	Castile and Leon, Extemadura, Castilla La Mancha	Castile and Leon	215,317
ES5	Catalonia, Valencia, Balearic Islands	Cataluna	60,355
ES6	Andalusia, Murcia	Andalucia	98,948

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

Node name	Autonomous community/ Region	Center of consumption	Area (km²)
ES7	Canary Islands	Canarias	7447
PT1	North, Central, Alentejo, Lisbon, Algarve	Norte	89,103
PT2	Azores	Azores	2322
PT3	Madeira	Madeira	802

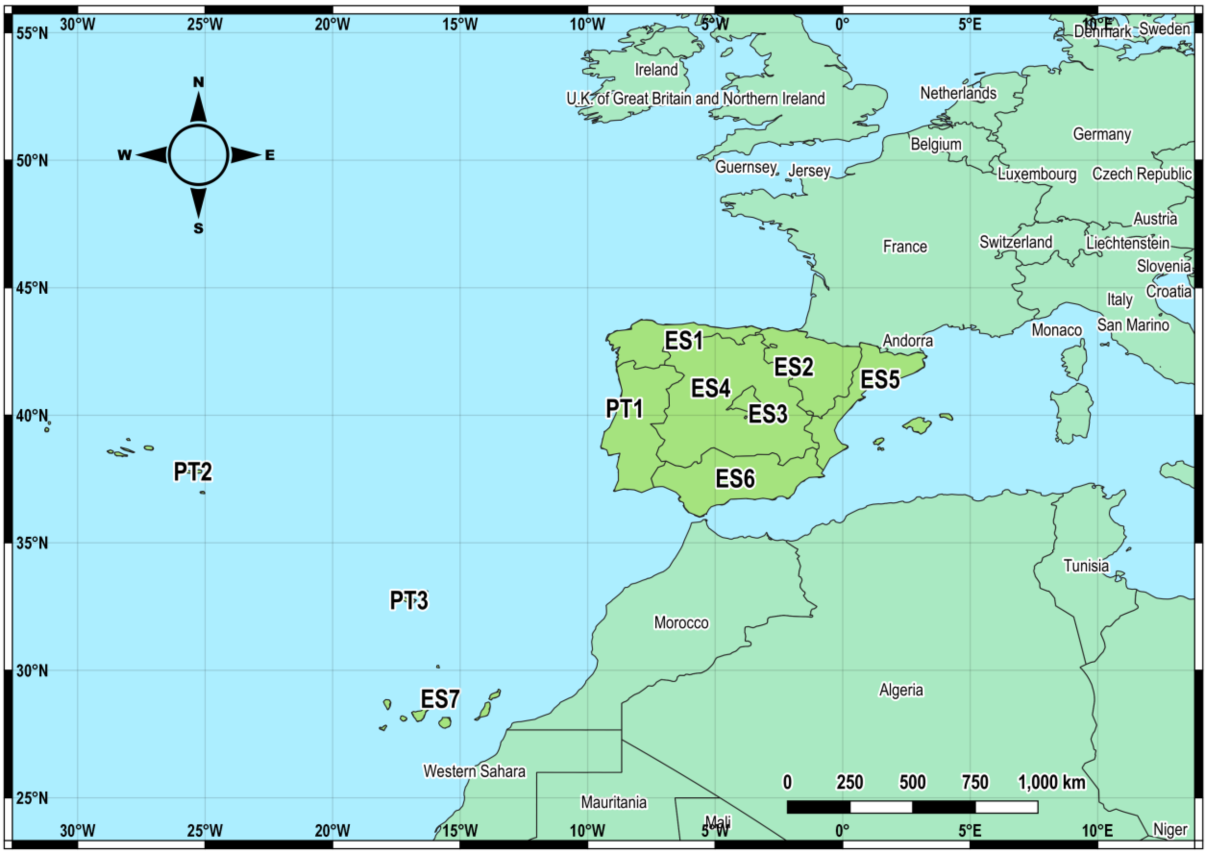

Figure 3 – Regional structure the Iberian Peninsula.

2.3. Scenarios for energy system modelling

The energy transition across the Iberian Peninsula is explored in six distinct scenarios with the following boundary parameters and conditions: The reference BPS sets the net-zero emissions target for 2050 according to the European Green Deal and follows the plans of the EC on ORE growth. Other scenarios test the impact of higher ambitions of offshore wind power, wave power growth and the impact of OSPV introduction (favourOE). Additionally, two scenarios were designed to test the impact of PV technology diversity (low PV, noBPV and favourVPV) and the sixth scenario tests the impact of an accelerated transition with carbon neutrality reached by 2040.

Best Policy Scenario (BPS): In this scenario, the Iberian energy system is set on a current ambition pathway. The climate neutrality vision for Spain and Portugal [47], [48] by 2050 is achieved, as GHG emissions will be net-zero by 2050 and reduced by at least 55% in 2030 below 1990 levels. No wave power is considered as a favoured capacity, but build-out as part of a least-cost solution is allowed.

Best Policy Scenario with favoured ORE (BPS_favourOE): Follows the BPS targets, but with more ORE technologies installed. The targets for offshore wind power, wave power, and OSPV introduction are increased. The offshore wind power capacity is set to reach 600 MW across Spain and Portugal shores by 2030, 6.4 GW by 2040, and 12 GW by 2050. Similarly, the wave power capacity for the continental part of Iberia is set to 150 MW by 2030, 3.2 GW by 2040, and 6 GW by 2050. OSPV capacity for the continental part are set to 123 MW in 2030, 3 GW by 2040, and 6 GW by 2050, following insights of upgrading offshore wind power with OSPV.

Best Policy Scenario with vertical bifacial PV (BPS_favourVPV): follows the BPS targets, the offshore wind power and wave power capacity are on the same level as in the BPS, however, additional vertical bifacial PV capacities are introduced to trace which changes follow high VPV share in the energy system. The VPV capacities for each 5-year interval are set to be 10% of the PV utility-scale capacity built in BPS2050. VPV capacity for the continental part are set to 28 GW in 2030, 53 GW by 2040, and 62 GW by 2050.

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

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

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

3. Results

Significant changes will be required for the following energy transition from the current state of the Iberian electricity, heat, transport, and industry sectors to a sustainable and efficient integrated energy system. The transition will allow the demand for energy and raw materials in the Iberian Peninsula to be met by locally available sustainable energy resources. This study evaluates the evolution of the Iberian energy system for several transition pathways, with particular attention to the BPS_favourOE, which emphasises the role of offshore wind power, wave power, and floating offshore solar PV (OFPV) in achieving system stability and cost efficiency. This section presents trends in primary and final energy demand, installed electricity and heat capacity, electricity and heat supply mix, and examines the transition in the transport and industry sectors and the comparative role of offshore renewable energy in these transitions. The last sub-sections of this section compare energy costs and CO_2 emissions in all presented scenarios, highlighting regional differences. The results are presented for all the Iberian regions mentioned in section 2, with a comparative analysis, and regional specificities for key elements of the energy system are further discussed.

3.1. Final energy demand

The same energy and service demand assumptions, apart from the accelerated scenario, are used in all scenarios. Despite the expected growth in the transport services sector and demand for industrial products, electrification and overall energy efficiency improvements lead to a significant reduction in FED over time in the baseline scenario. From 2020 to 2050, a clear and consistent downward trend in overall energy consumption is demonstrated. The other scenarios, except for BPS-2040, follow identical FED reduction pathways. The BPS_favourOE contributes further to this reduction by enabling a more stable and geographically distributed renewable electricity generation from offshore RE sources, supporting the electrification of coastal industries and maritime transport hubs. BPS-2040 is the most ambitious scenario, assuming advanced policies across all sectors, including accelerated building retrofits, modal shifts in transport, and accelerated electrification in transport and industry. Implementation of the appropriate policies is expected to lead to an even faster reduction in FED.

The FED in 2020 is just over 1450 TWh. As shown in Figure 4, the transport sector has the maximum share of 44% with 640 TWh. The second place is taken by the industry sector with a share of 22% at 327 TWh. By the end of the transition in all scenarios, due to the improvement in the efficiency of the power system, the FED decreases in all sectors, from a total of 1125 TWh in the BPS and its variations to 1090 TWh in BPS-2040. The main change is the decrease in FED in the transport sector by 42% for the BPS from 640 TWh in 2020 to 368 TWh in 2050. In the BPS_favourOE, offshore wind and wave power support the defossilisation of coastal industrial clusters and port transport operations, contributing to the overall FED reduction while improving energy supply reliability along the Iberian coastline.

In the different scenarios such as the BPS, BPS_favourOE, BPS_noBPV, and BPS_lowPV, the FED shows the same slight downward trend compared to 2020,

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

with transport sector demand declining to 368 TWh in 2040 despite growth in the aviation segment, and industry sector demand declining to 304 TWh. This is due to the high share of electric vehicles in transport, which leads to efficiency gains, as well as a shift towards greater use of electrified rail. Notably, in the accelerated transition scenario, total demand stabilises at a lower level than in the other scenarios, around 1159 TWh from 2040. Heat energy demand remains stable in all scenarios, and there is a slight increase from 243 TWh to 156 TWh. The industry sector dominates in 2050, while other sectors are more evenly balanced.

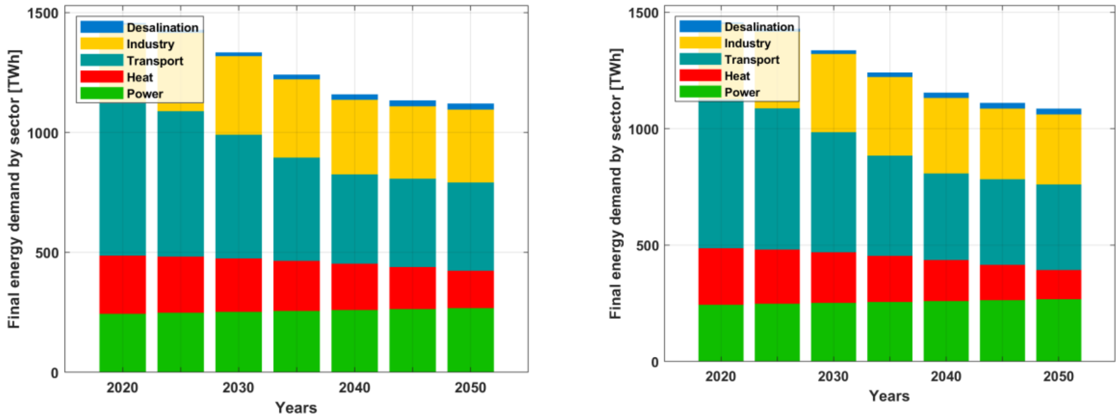

Figure 4 - Final energy demand by sector across the BPS (left) and BPS_2040 (right) scenarios during the transition in Iberia.

3.2. Primary energy demand

Electrification and the growth of renewable energy supplies in all sectors that is occurring during the energy transition lead to significant changes in primary energy demand (PED) in the Iberian region. The heat, transport, and industry sectors become increasingly dependent on electricity as demand for electricity increases. The pace of this growth is most evident in the transport and industry sectors. Renewable electricity from low-cost solar PV and wind power makes process electrification even more attractive and further increases the demand for new generation capacity. As a result, renewable electricity phases out fossil fuels and feedstock in the energy mix at an accelerated pace.

At the beginning of the transition, the Iberian energy system is dominated by fossil fuels with a small share of RE. The TPED for Iberia (including primary energy consumption and non-energy use) in 2020 was around 1782 TWh, including fossil fuels 1310 TWh (74%) and feedstock 74 TWh (4%), nuclear energy 178 TWh (10%), and renewable electricity contributing with 166 TWh (9%) (see Figure 5). By 2050, in the BPS, the TPED stabilises at around 1721 TWh. Renewable electricity becomes the main source of energy in all scenarios with 1501 TWh (87%) in the BPS, 1596 TWh (90%) in the BPS_2040 and 1494 TWh (87%) in the BPS_favourOE. The remainder of the demand is covered by bioenergy and solar thermal energy at 217 TWh (13%) in the BPS, 171 TWh (10%) in the BPS_2040, and 216 TWh (13%) in BPS_favourOE.

This project has received funding from the Europeans Union’s Horizon 2020 research & innovation programme under grant agreement number 101036457.

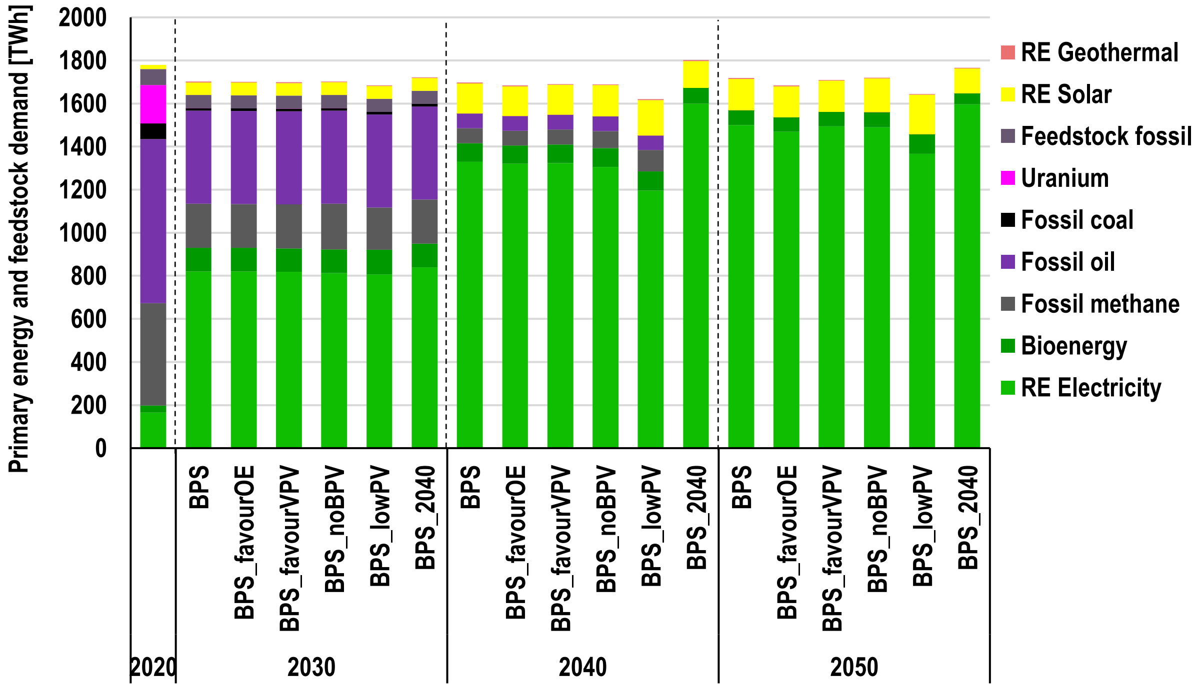

Figure 5 - Primary energy and feedstock demand in Iberia from 2020 to 2050 between all scenarios during the transition.

The shift towards RE becomes obvious as early as 2030, although fossil fuels continue to play a major role in the system. Scenarios show relatively the same TPED values around 1705 TWh. The maximum TPED values for 2030 are observed for the BPS_noBPV at around 1706 TWh and for 2040 in the BPS and BPS_favourOE at 1701 TWh. By 2040, the BPS_2040 shows complete defossilisation, whereas the BPS_favourOE displays a smoother RE expansion profile supported by offshore electricity generation that alleviates the need for extensive energy storage and grid reinforcement. In contrast, in scenarios with limited PV deployment (e.g., BPS_lowPV), the system compensates through increased onshore wind power and storage utilisation, which raises the TPED to 1648 TWh due to higher conversion and storage losses.

By 2050, the impact of ORE on the TPED becomes noticeable. Scenarios with higher installed capacity of offshore wind and wave power technologies tend to have lower TPED compared to the BPS. Among the BPS variations, the second lowest TPED of 1713 TWh is achieved in the favoured OE scenario. This reduction is primarily due to the ORE resource profiles, which complement onshore solar PV and wind power, making the power system more efficient by reducing the demand for daily and seasonal energy storage and avoiding the corresponding energy losses. In scenarios with a low PV share, TPED increases slightly due to a greater reliance on other variable RE in the electricity mix and hence higher use of storage to balance the daily and seasonal variability of supply. At the same time, VPV reduces grid losses in limited areas on islands. The highest demand is observed in the BPS_2040 with 1770 TWh. Although different energy transition paths are possible, the future of Iberia is characterised by a transition from fossil fuels to a predominantly RE system.

The speed of this transition depends on the level of RE phase-in, the build-up of ORE, and particularly OSPV integration on the island regions. However, all scenarios show that a fully renewable and defossilised energy system is achievable by 2050, and in the case of the BPS_2040 even by 2040, in line with European climate targets and national decarbonisation plans.

3.3. Electricity supply

The share of RE in gross electricity consumption in Spain and Portugal continues to grow, indicating a positive trend in the energy transition to 100% RE. In 2024, RE accounted for 57% and 72% of gross electricity consumption in Spain and Portugal, respectively [64], [65]. This fast growth trend is maintained in all scenarios with different levels of renewable electricity generation, as shown in Figure 6. Electrification in all sectors leads to a required increase in electricity generation by almost 5 times by 2050 in all scenarios.

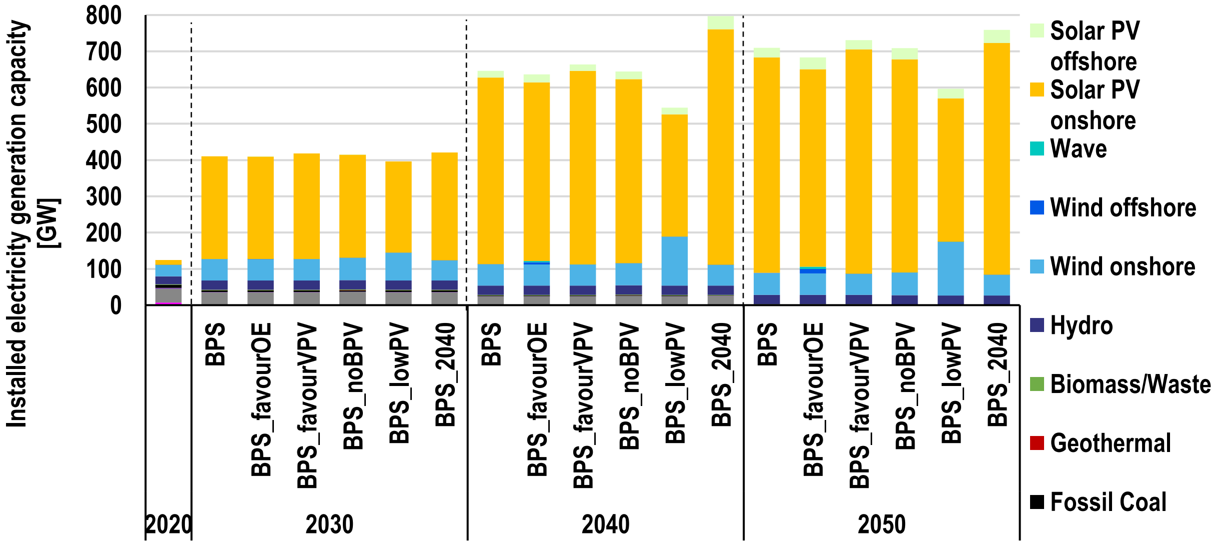

Figure 6 - Installed electricity generation capacities for all scenarios during the transition.

Fast electrification and scaling of RE sources leads to a rapid increase in electricity generation capacity. In 2030, electricity generation capacity amounts to around 400 GW in all scenarios and increases to 600 GW by 2040. From 2040 onwards, the differences between the scenarios become more significant. Scenarios with supported ORE deployment show lower installed capacity of solar PV and the total system, mainly due to the higher full load hours of offshore wind and wave power technologies compared to solar PV. In contrast, scenarios with a limited share of PV show the lowest total installed capacity around 545 GW by 2040. This capacity equals about 0.67% of the land area of Iberia, assuming about 27% PV module efficiency in average of the transition and about 50% ground cover ratio of ground-mounted PV systems. The BPS-2040 scenario requires the highest renewable electricity capacity in 2040 to completely replace fossil fuel use and achieve the carbon neutrality target.

By 2050, the power generation further increases and the impact of scenarios on the power generation capacities remains similar. Most ORE capacities are installed in the BPS_favourOE scenario: the installed capacity of offshore wind power reaches 12 GW. Conversely, no offshore wind power capacities are installed in the baseline BPS. Wave power increases to 6 GW, and OSPV increases from zero to 33 GW. As a result, the total capacity of ORE increases by 51 GW, significantly reducing the share of onshore RE, e.g., onshore PV decreases from 595 GW in the BPS to 544 GW in the BPS_favourOE (see Figure 6 and Figure 7). This substitution highlights the systemic value of ORE, which complements the variability of onshore PV and wind power, thereby lowering the overall capacity requirements and curtailment while increasing system efficiency.

Fossil fuel-based power generation is phased out in all scenarios by 2050, except for the accelerated scenario where it ceases to operate by 2040. Nuclear power plants continue to operate until the end of their technical lifetime till 2030. However, nuclear power is recognised in all scenarios as being uncompetitive compared to low-cost renewable electricity and poses significant environmental and social risks, which are well documented in Europe and worldwide [66] and thus new investments have been blocked in scenarios for overall societal reasons [67], [68]. Consequently, the model does not find new nuclear power capacities as part of a cost optimal solution in any scenario, whereas its high cost would not have led to investments in new capacities.

In a regional outlook, RE sources are evenly distributed across the countries, influencing the energy balance of different countries and regions. Electricity generation capacities are installed in Iberia, covering energy demand from the power, heat, transport, and industry sectors until 2050. Solar PV capacities are the largest source of electricity generation in all regions, while onshore and offshore wind power also represent a significant share (25%), especially in the lowPV scenario and northern coastal regions (see Figure 7). Additionally, the BPS_lowPV result is a substantial generation capacity drop in PV-rich regions, implying higher reliance on energy imports from neighbouring regions.

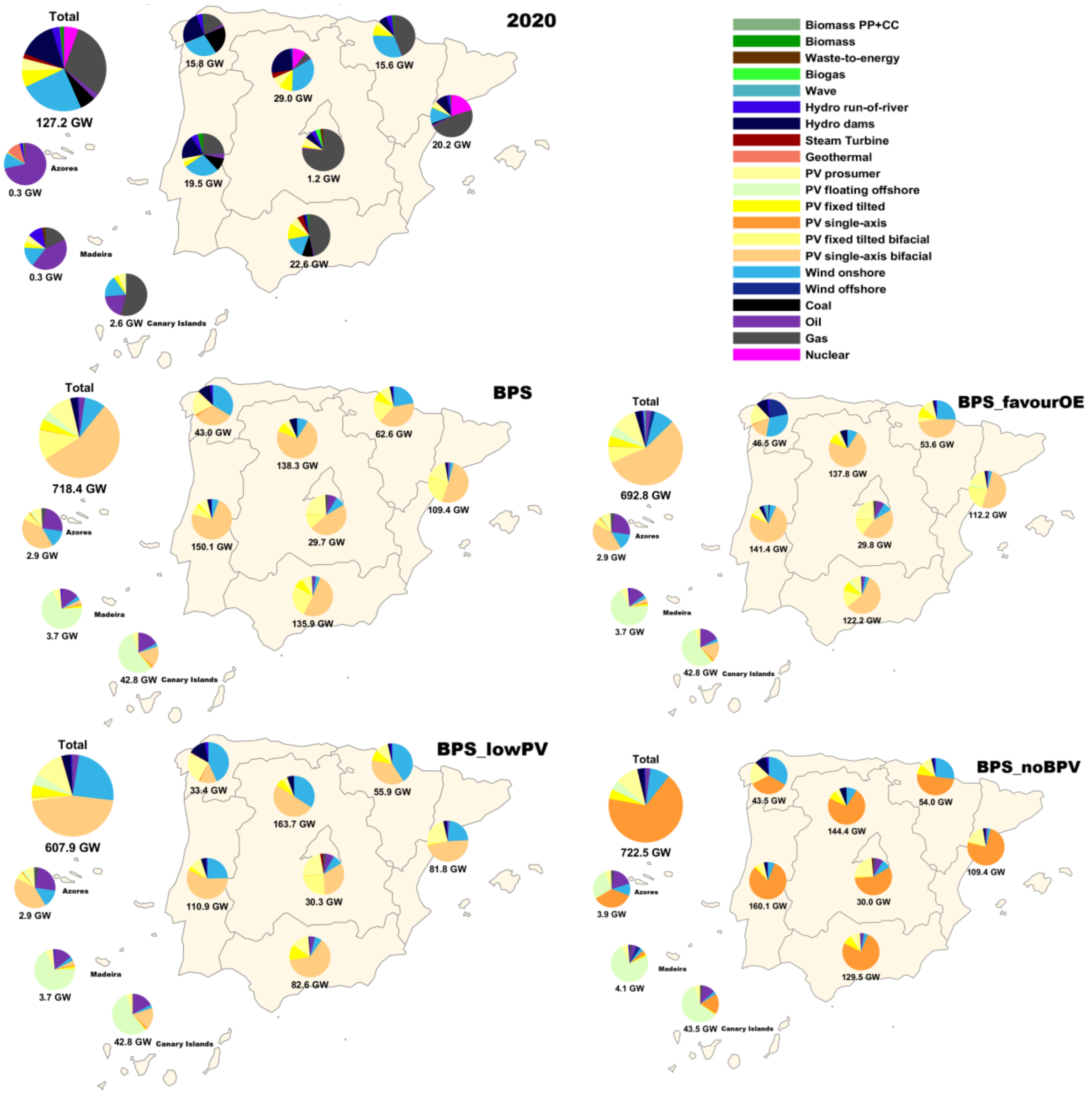

Figure 7 - Regional electricity generation capacities in different scenarios in 2020 and 2050.

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

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

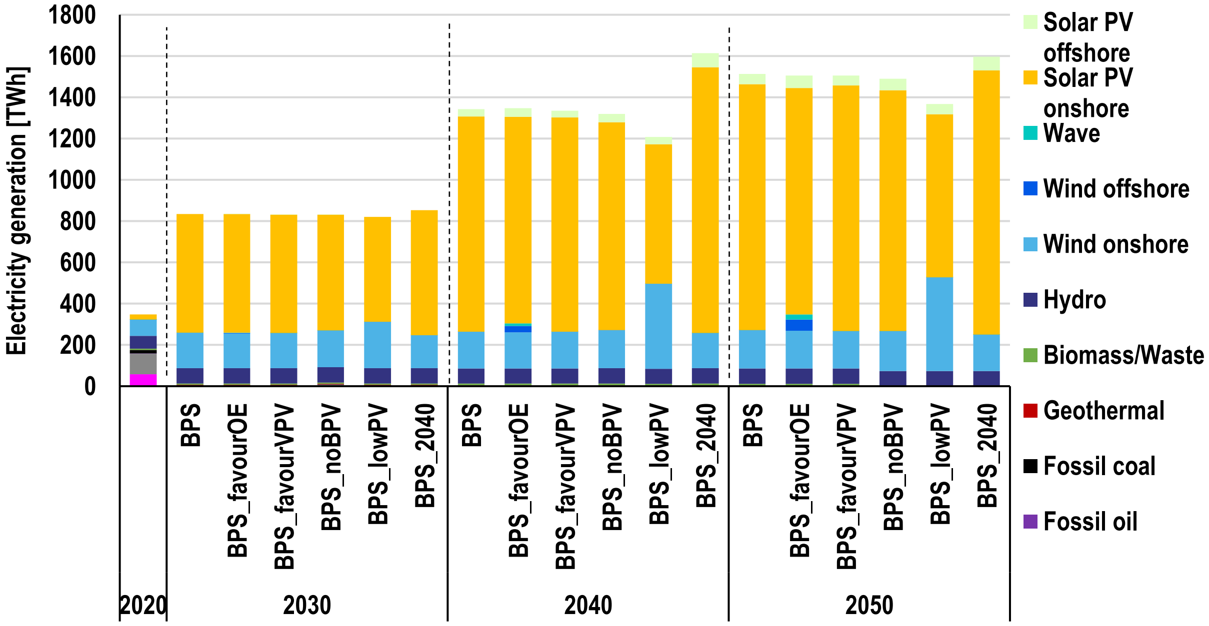

Figure 8 – Electricity generation for all scenarios during the transition.

By the end of the transition, electricity generation from offshore wind power ranges from 1 TWh in the BPS_noBPV to 54 TWh in the BPS_favourOE, keeping the position of the largest source of electricity generation among ORE. In the same scenario, wave power adds 25.6 TWh and OSPV generates 60 TWh, which, together with offshore wind power, gives 140 TWh of generation from ORE technologies, approximately 10% of the total electricity generation in the favoured OE scenario.

Similar to the electricity generation capacity, a higher share of wind electricity generation is observed in the Northern and Western parts of the Iberian Peninsula (see Figure 9), while a higher share of solar PV generation is concentrated in the southern regions. A more efficient power system is also reflected in the total electricity generation in the BPS_lowPV, which is the lowest among all scenarios. Solar PV prosumers make a significant contribution in Iberia and complement utility-scale solar PV generation. Solar PV provides more than 80% of electricity across Iberia, while the share of wind power averages 30% in the BPS_lowPV. Total electricity generation in 2050 is projected to be 1607 TWh in the BPS_2040, 1512 TWh in the BPS, 1505 TWh in the BPS_favourOE, and 1378 TWh in the in BPS_lowPV.

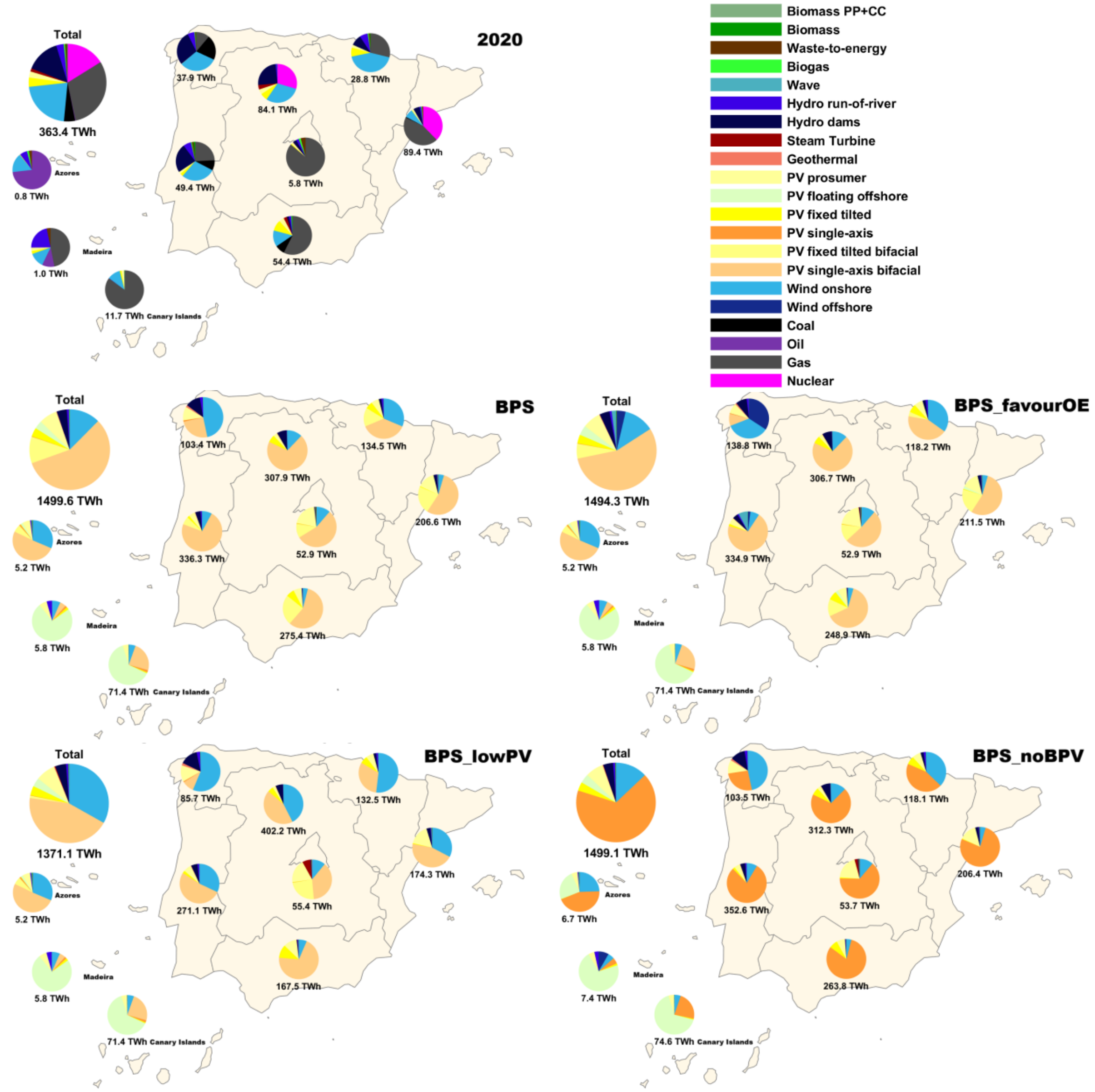

Figure 9 – Electricity generation by technologies during the transition in 2020 and 2050 in different scenarios.

In the BPS_favourOE, compared to the BPS, the installed electricity storage capacity decreases from 622 GWh$_{cap}$ (BPS) to 587 GWh$_{cap}$ (BPS_favourOE) see Figure 10, and the storage throughput decreases from 129 TWh to 107 TWh, respectively, (Figure 12). This reflects lower reliance on onshore solar PV, and lower daily and seasonal variability of electricity supply. This effect is achieved through more stable generation from ORE, namely, offshore wind power, wave power, and OSPV, which together provide a stable supply of electricity and reduce the demand for storage capacity.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

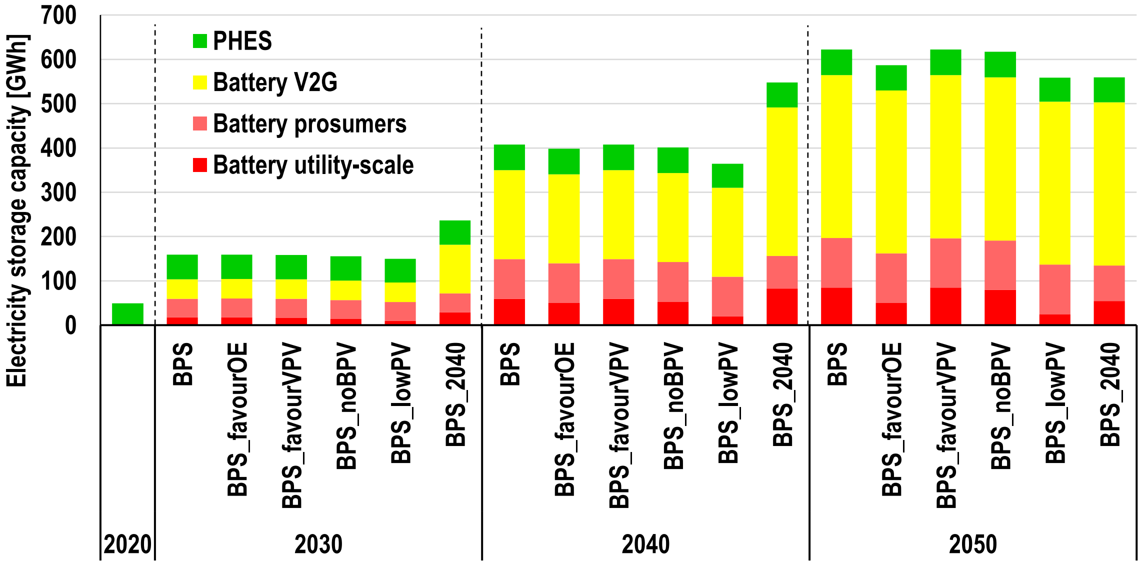

Figure 10 – Electricity storage capacity for all scenarios during the transition.

In 2050, the BPS_lowPV has a lower storage capacity (558 GWh_{cap}) compared to the BPS, while the BPS_favourVPV shows the highest reliance on electricity storage (622 GWh_{cap}). Consequently, the BPS_favourOE throughput is about 5% lower, 587 TWh versus 622 TWh in the BPS (see Figure 12). This indicates a lower intensity of storage use in the BPS_favourOE, due to a lower share of green hydrogen production. Figure 11 presents the regional distribution of electricity storage capacities, highlighting the impact of ORE technologies on storage capacity in coastal regions.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

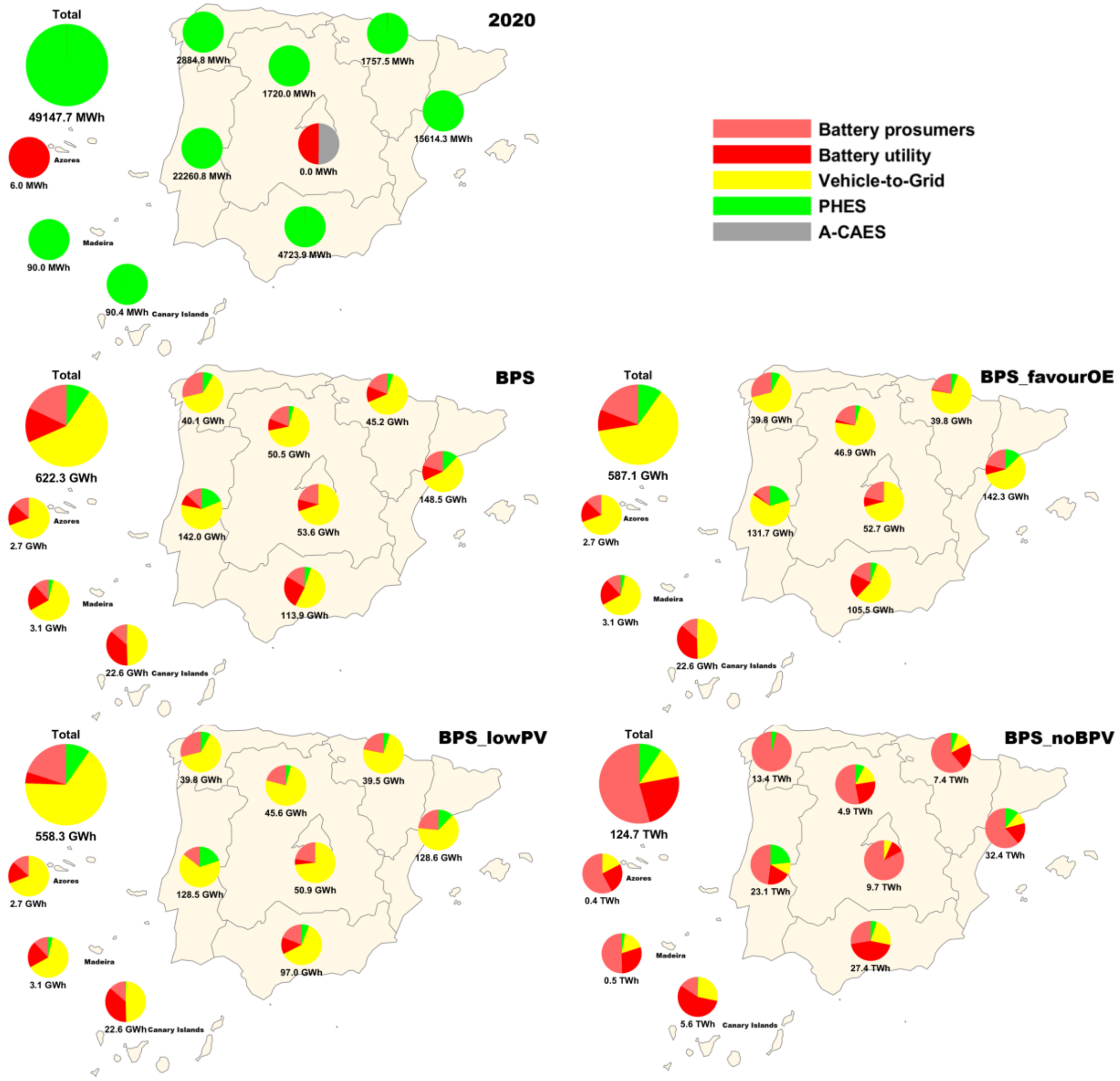

Figure 11 – Regional electricity storage capacities across different scenarios in 2050.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

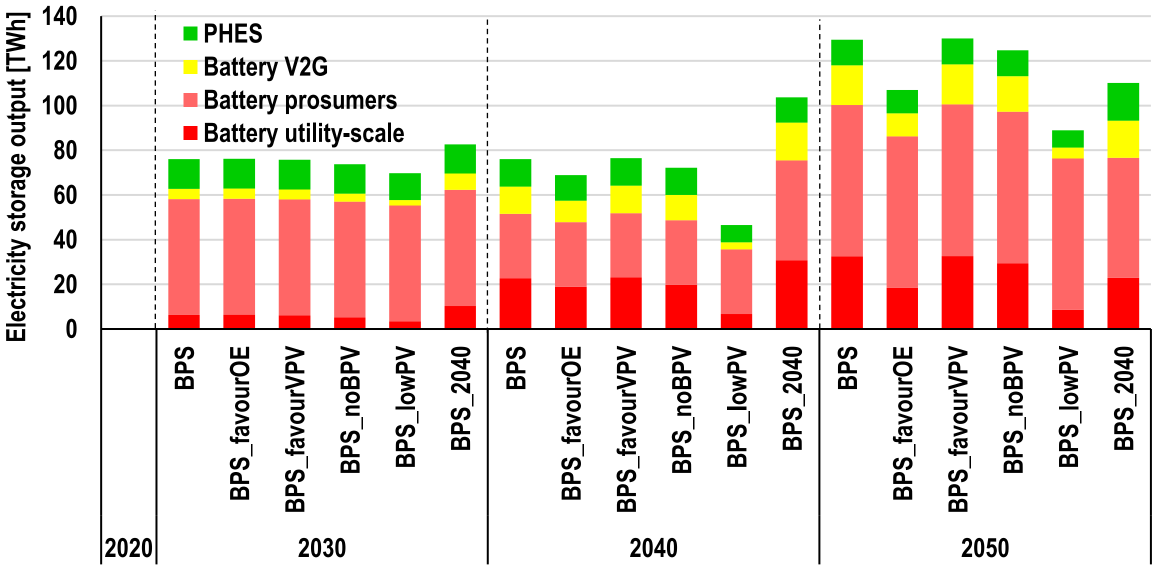

Figure 12 – Electricity storage output for all scenarios during the transition.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

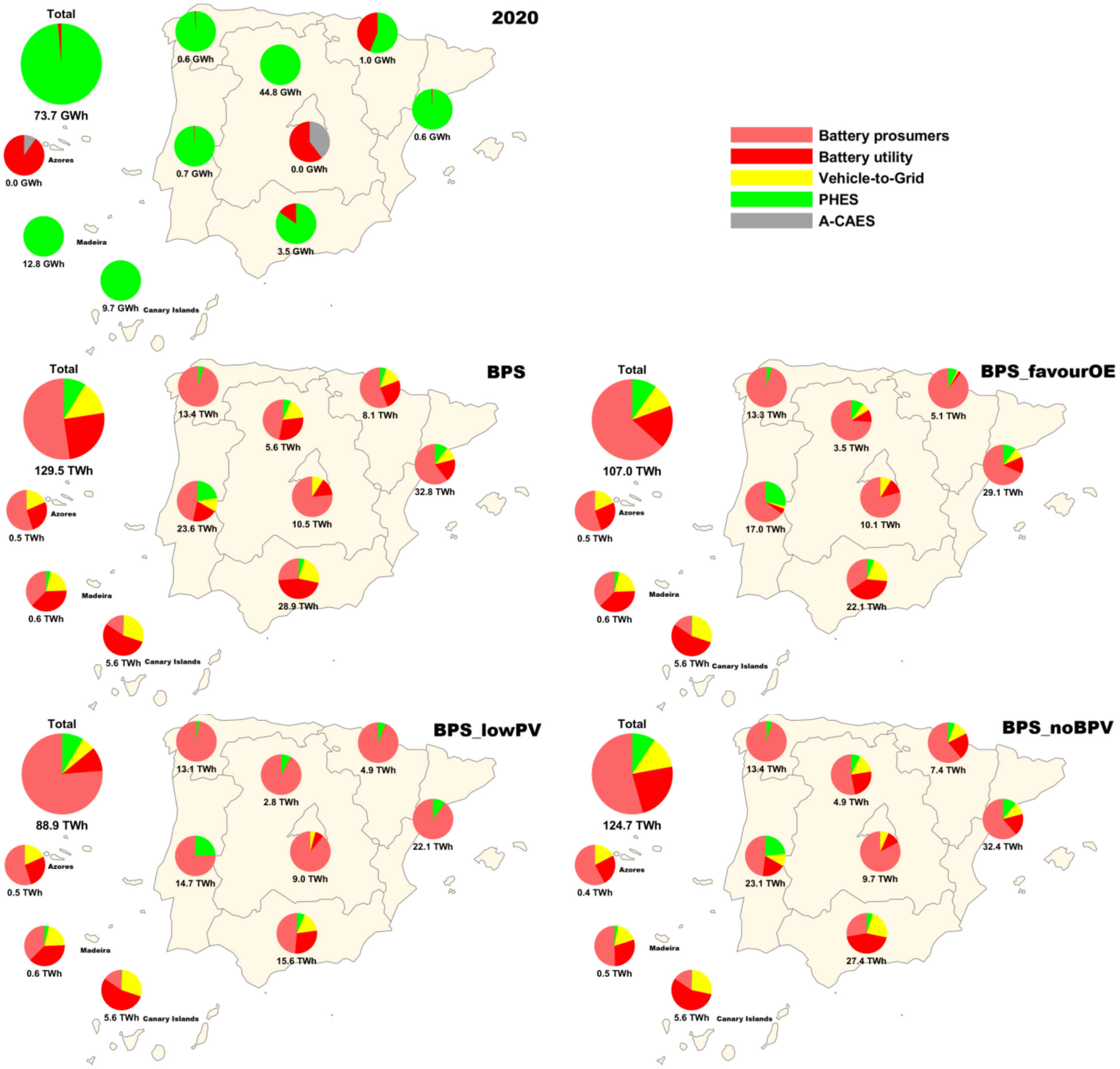

Figure 13 – Regional electricity storage output capacities across different scenarios in 2020 and 2050.

The BPS_favourOE achieves a more stable and balanced supply with reduced storage needs and grid congestion, underscoring the role of ORE technologies as stability enablers in Iberia's fully renewable power system.

3.4. Heat supply

Despite the relatively mild climate compared to northern European countries, heat is one of the key energy carriers in the Iberian Peninsula. Heat demand is mainly met by space heating, domestic hot water, and industrial thermal processes. In 2020, fossil gas was the dominant heat source in both countries, especially in urban areas and the industry sector, while heat pumps and electric heating played a significant role, especially in rural and residential areas, providing around 25-30%

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

of the heat supply (see Figure 14). Decreasing technology costs and increasing energy efficiency lead to an increasing share of heat pumps and electric heating. The electrification trend is also evident in the heat sector, both in new installations and in the gradual replacement of gas boilers, especially in the major cities of Portugal and Spain. Electrification of the heat sector certainly allows for a gradual reduction in dependence and eventually a complete replacement of imported fossil fuels.

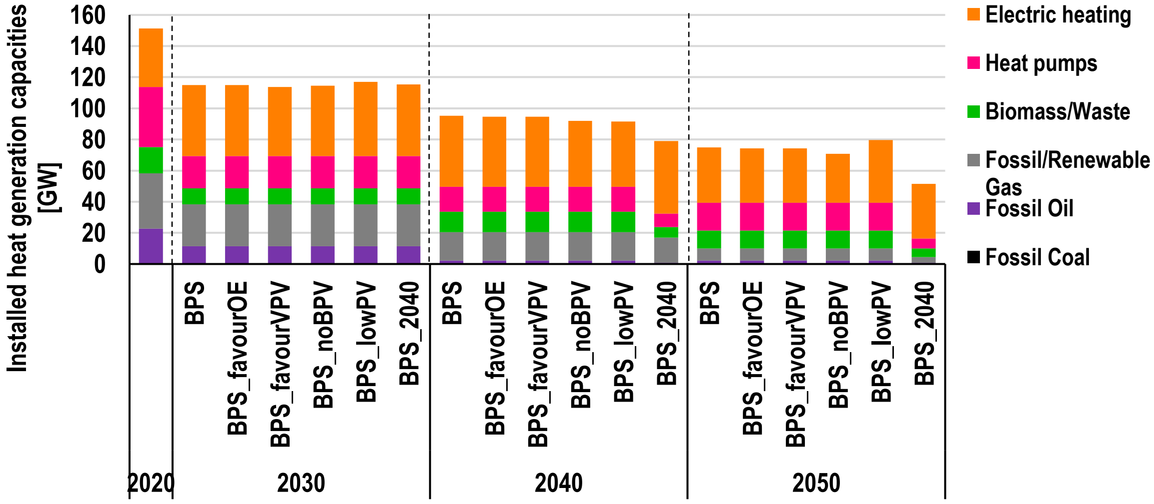

Figure 14 – Installed heat generation capacities in all scenarios during the transition.

In 2050, in Iberia, in the BPS_lowPV the installed heat capacity is about 80 GW, which is about 5 GW more than in the BPS of 80 GW. In scenarios with ORE, the installed capacity decreases between the scenarios by 1 GW and 6 GW, respectively (see Figure 15). This decrease in installed capacity reflects assumed efficiency improvements in heating systems and in case of developed district heating networks, the possibility to use waste heat from PtX processes.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

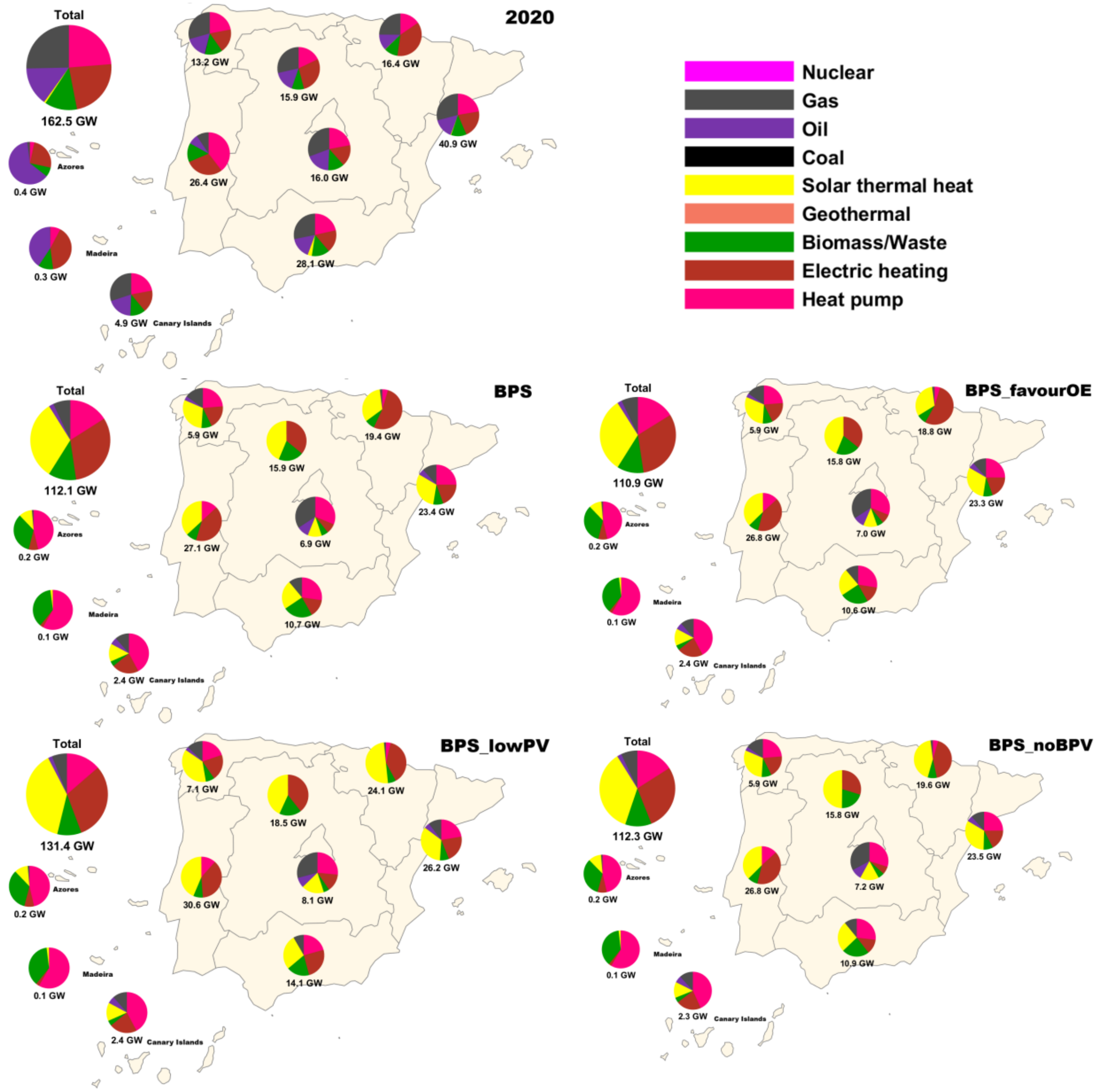

Figure 15 – Regional heat capacities across different scenarios in 2020 and 2050.

From 2030 onwards, the share of fossil gas in heat generation capacity is reduced by more than half in all scenarios, while heat pump capacity steadily decreases from 39 GW in 2020 to 18 GW for all scenarios. In 2050, all scenarios show a large-scale reduction of heat generation from the total 346 TWh to 176 TWh in the BPS in 2050, with electric heating take the lead with a generation of around 78 TWh (see Figure 16) and heat pumps decrease to 64 TWh. The installed capacity of heat pumps varies from 6 GW in the accelerated BPS_2040 to 18 GW in the BPS and BPS_favourOE. Installed heat capacity for the BPS_favourOE in 2050 is about 74 GW, with 46% in electric heating (35 GW), and 24% with heat pumps (18 GW). Heat generation in scenarios with favoured OE is 177 TWh on the same level as the favoured VPV scenario.

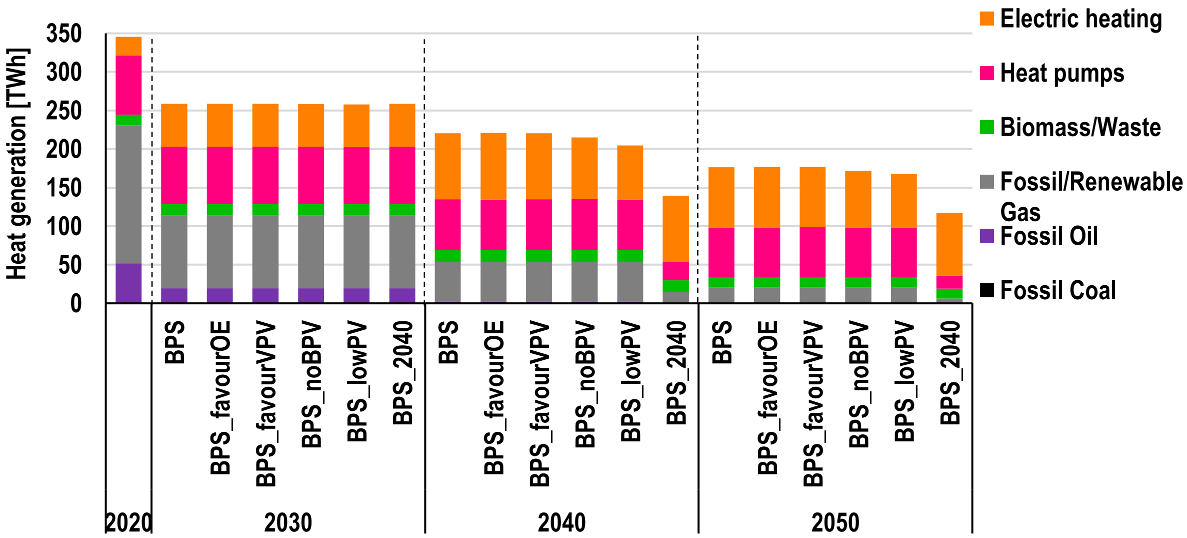

Figure 16 – Heat generation mix in all scenarios during the transition.

The high ORE scenario (BPS_favourOE) in 2050 shows moderate use of hydrogen and gas storage (Figure 17), ranging within 3000–6000 GWh$_{cap}$. Hydrogen storage reaches 3127 GWh$_{cap}$ and methane storage reaches 6282 GWh$_{cap}$. On the other hand, in the BPS, the gaseous storage facilities have the highest installed capacity among all scenarios: hydrogen up to 2918 GWh$_{cap}$, methane up to 6808 GWh$_{cap}$, and TES up to 250 GWh$_{cap}$. Total storage capacity reaches up to 9990 GWh for the BPS_favourOE. Thus, ORE helps reduce the load on the TES system, increasing resilience and reducing the need for large-scale seasonal storage facilities.

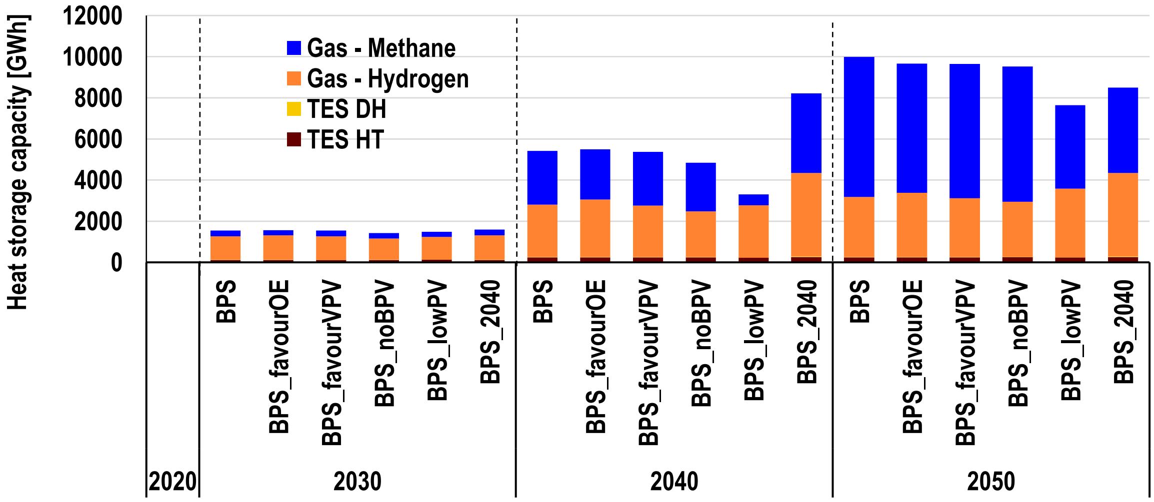

Figure 17 – Heat storage capacity in all scenarios during the transition.

At the regional scale, the heat storage capacities in the BPS_lowPV and BPS_favourOE in 2050 differ significantly. In the former case, they are in total 7640 GWh$_{cap}$, while in the latter they are 9667 GWh$_{cap}$, i.e., almost 20% higher in the scenario with a limited share of PV (see Figure 18). The main type of storage in both

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

scenarios is gas methane storage, which reflects the value of storage in seasonal balancing of electricity demand and more constant hydrogen supply for transport, industry, and e-fuels and e-chemicals synthesis. Madrid stands out in the overall Iberian picture, where the dominant storage type is methane storage rather than hydrogen.

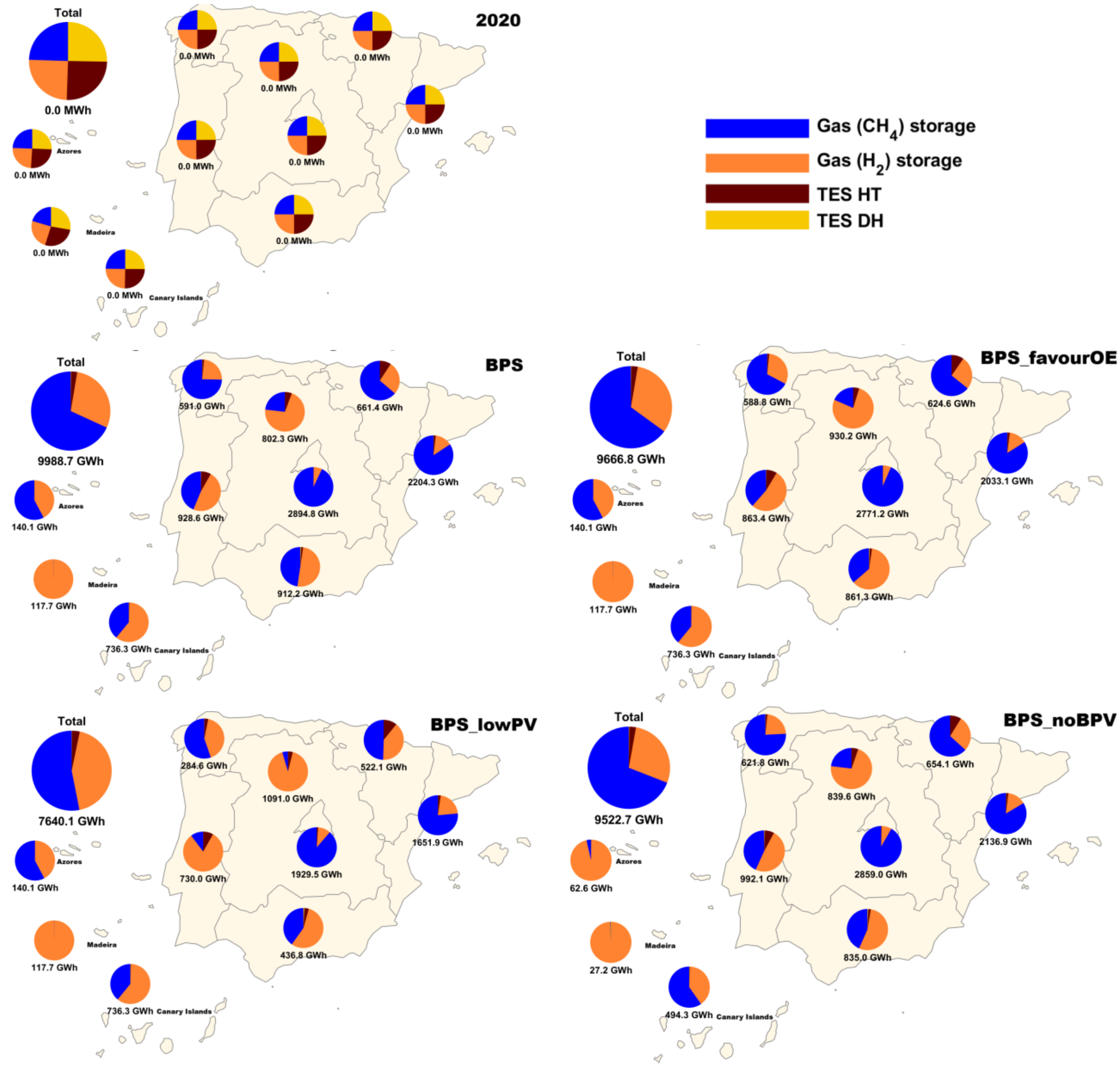

Figure 18 – Regional heat storage across different scenarios in 2020 and 2050.

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

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

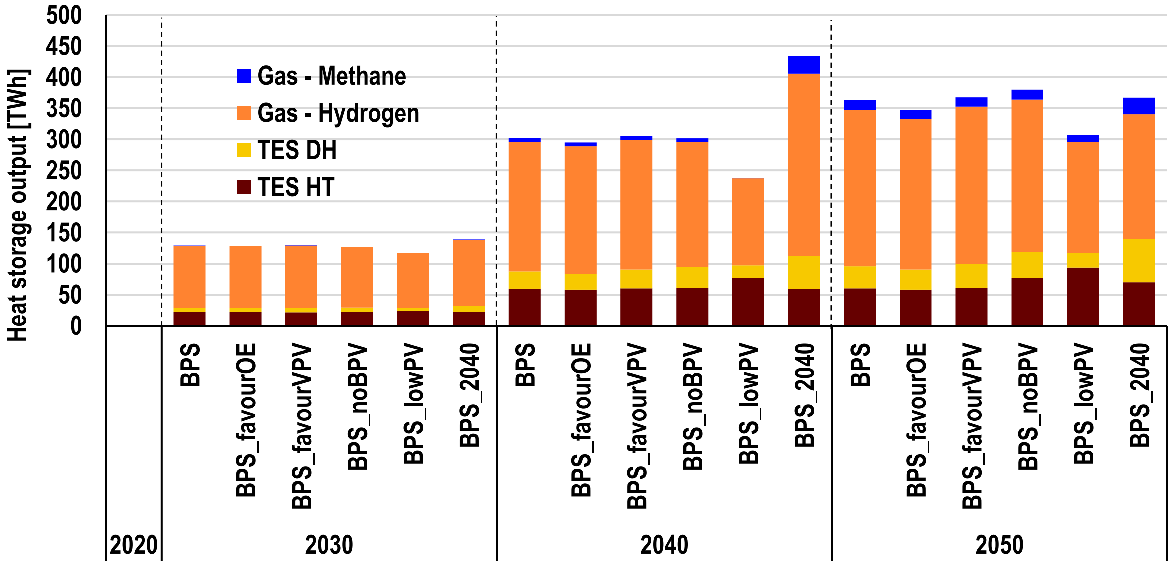

Figure 19 – Heat storage output in all scenarios during the transition.

3.5. Transport, industry, and e-fuels

The transport sector plays a significant role in the energy transition of Iberia and is undergoing significant changes. Electrification and the sharing economy are rapidly changing the FED picture. Figure 20 shows the FED in the different segments of the transport sector, divided into road passenger and freight transport, rail passenger and freight transport, marine passenger and freight transport, and aviation passenger and freight transport. The road segment has the highest level of electrification. In all scenarios, the FED for road passenger and freight transport decreases by more than five times (from 242 TWh to 44 TWh). Aviation freight transport is the most energy intensive and continues to consume the largest share of energy in all scenarios. Aviation transport, mainly passenger, has a growing FED in all scenarios from 103 TWh in 2020 to 130 TWh by 2050, as the additional expected demand for transport services cannot be offset by efficiency gains. At the same time, the transport FED shifts from a fossil fuel-dominated mix to a more balanced energy mix, with electricity accounting for over 40% and the remaining share distributed between various e-fuels and sustainable biofuels, although the biofuel share does not exceed 5% due to limited feedstock. In the BPS_favourOE, the additional offshore wind and wave power generation supports a larger share of renewable e-hydrogen and e-fuel production, further reducing reliance on fossil-based fuels. This highlights the systemic contribution of ORE in enabling a fully renewable transport sector through the provision of renewable electricity and feedstocks for e-fuels.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

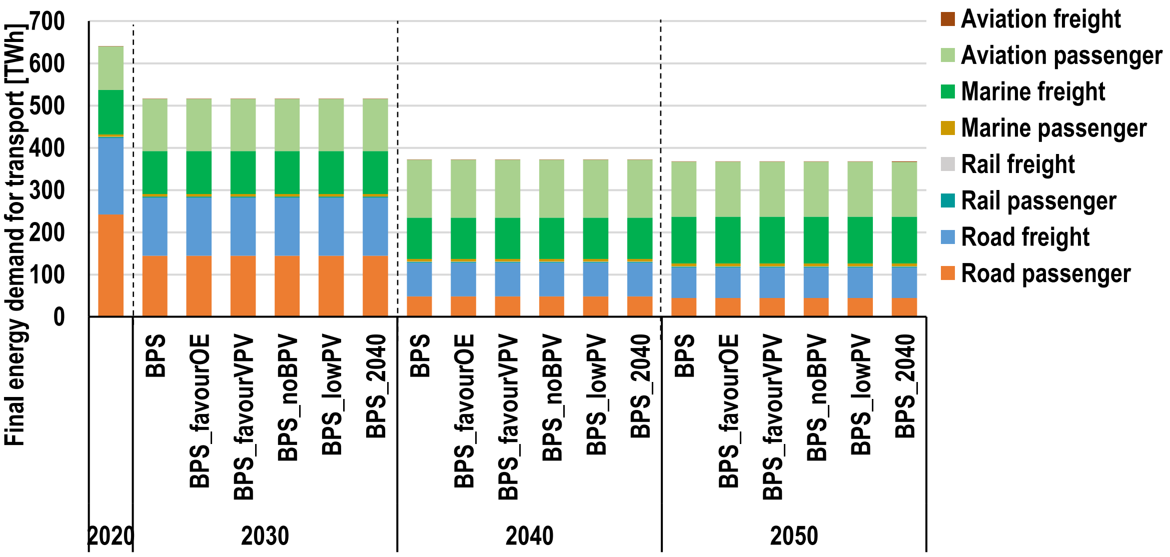

Figure 20 – Final energy demand for the transport sector across all scenarios from 2020 to 2050.

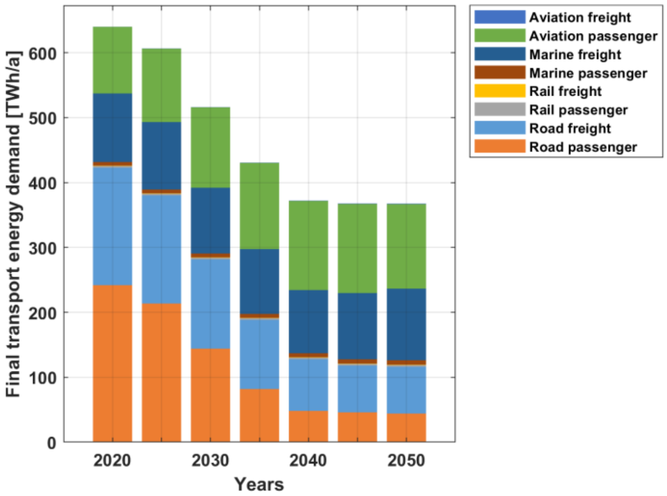

Figure 21 – Final energy demand for the transport sector by fuel during the transition for the scenarios.

Iberian regions have a well-developed energy-intensive industry, such a cement production, which significantly contributes to CO_2 emissions, primarily because fossil fuels are their main source of energy as well as raw material related process emissions. However, the transition is accompanied by an increase in energy demand in the chemical industry, as shown in Figure 22, due to the growing demand for hydrogen-based chemicals. By 2030, the energy and feedstock demand in the chemical industry reaches 112 TWh. The share of the chemical industry in total energy demand in 2030 is around 32% in the BPS. By 2050, the share of electrolysers in the industry sector significantly increases. The chemical industry will require significant energy inputs, especially to produce e-ammonia and e-methanol based on e-hydrogen as the non-energy use feedstock, which will enable the transition to sustainable chemicals production. The most significant reduction in energy demand is expected in the steel and cement industry, where processes will become increasingly electrified also driven by growing shares of secondary steel and blended cement. In all scenarios, energy demand in the steel industry is projected to decline by almost 2 times, from 24 TWh to 12 TWh. Meanwhile, energy demand in the cement, aluminium, and other industries is expected to remain stable throughout the transition period in all scenarios.

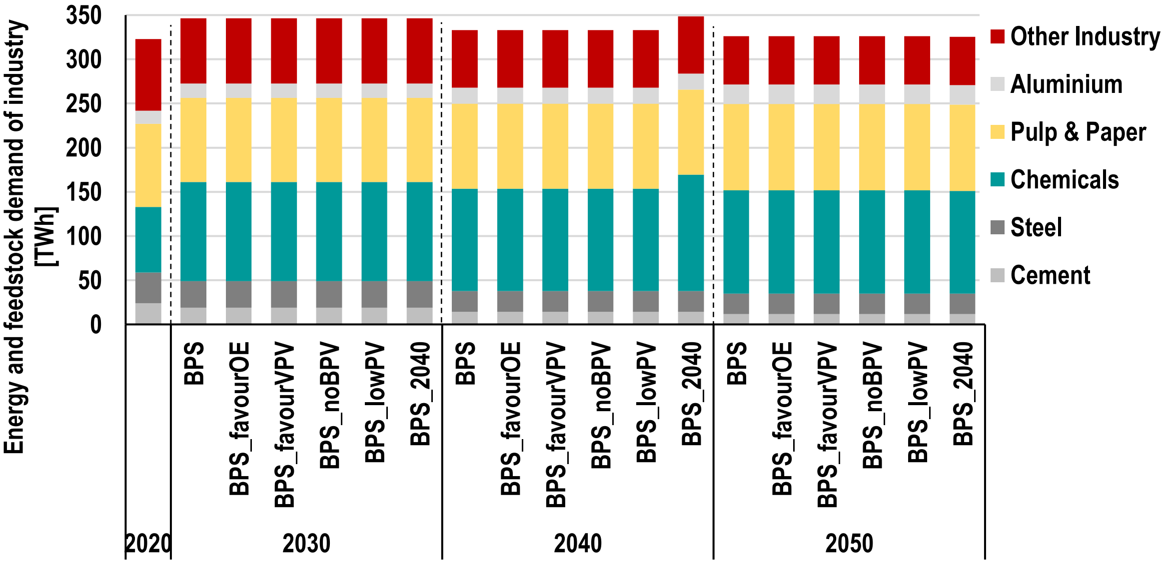

Figure 22 – Energy and feedstock supply for energy-intensive industries across the scenarios from 2020 to 2050.

Industrial-scale production of sustainable e-fuels and e-chemicals is required to displace fossil fuels from the transport and industry sectors. By mid-century, e-hydrogen becomes the primary feedstock for industry and the synthesis of other e-fuels, and the main fuel for aviation and marine transport. By 2030, most hydrogen is produced by water electrolysers. In the BPS, electrolyser capacity exceeds 169 GW_{el} by 2050, which is higher than in the BPS_lowPV (141 GW_{el}) and BPS_favourOE (164 GW_{el}), see Figure 23. This indicates that more stable and predictable generation from offshore wind power, wave power, and OSPV reduces the need for large-scale hydrogen production ramp-up to maintain grid stability. ORE reduces peaks in e-hydrogen production, reducing the reliance on further storage, as discussed in the thermal storage section.

This highlights the systemic role of ORE in enhancing the flexibility and efficiency of Iberia's future energy system. Instead of relying on large-scale hydrogen production and storage for balancing.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

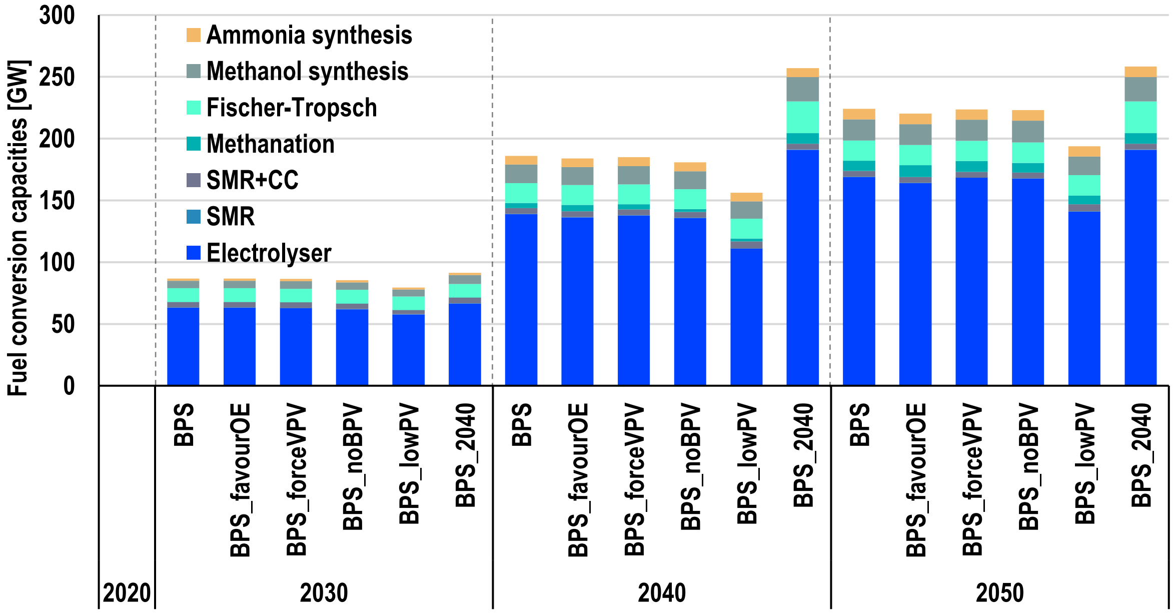

Figure 23 – Fuel conversion capacities across the scenarios from 2020 to 2050.

3.6. Sector coupling and flexibility in the energy system

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

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

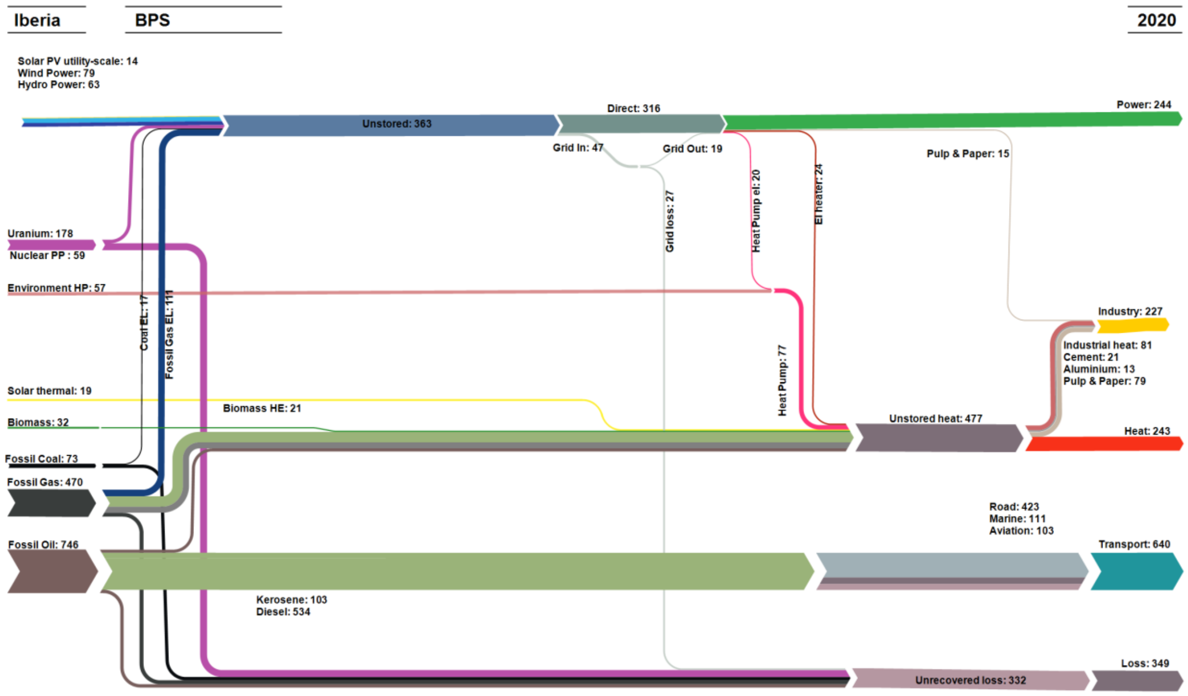

Figure 24 – Energy flows of the Iberian energy system in 2020.

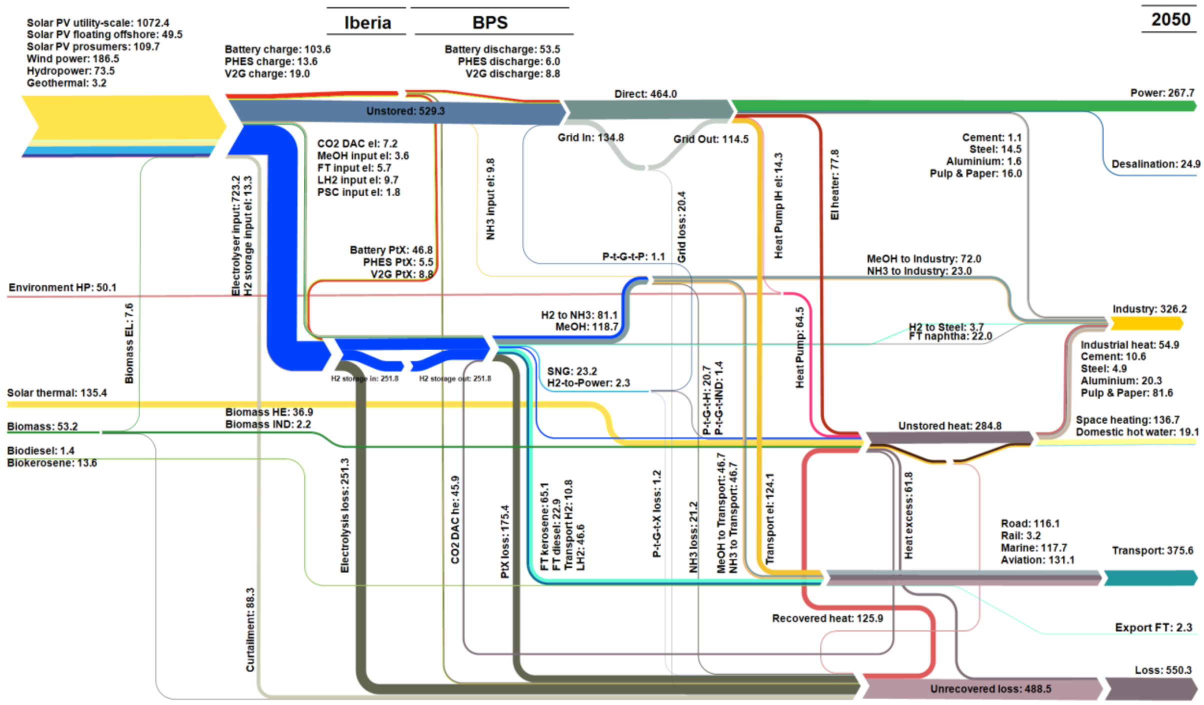

Figure 25 – Energy flows of the Iberian energy system in 2050 for the BPS.

The energy transition in the BPS and other scenarios results in a more interdependent and integrated energy system by 2050 (see Figure 25). The main characteristic of this system is the high share of diversification of the power, heat, transport, industry, and desalination sectors. The energy system is dominated by

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

utility-scale solar PV and wind power, contributing 1072 TWh (thereof 49 TWh of OSPV) and 187 TWh, respectively. Solar PV prosumers add 110 TWh, further emphasising their important role in the energy mix. The energy system gains considerable flexibility due to the large capacities of the electrolysers: flexible electricity consumption for electrolysis reaches 723 TWh, which includes 13 TWh of hydrogen converted back into electricity (1.8% of hydrogen production), mainly for seasonal balancing.

Thanks to high flexibility, electrolysers can effectively adapt to variability in electricity generation from different sources such as solar PV and wind and wave power. The combination with vehicle-to-grid technology significantly reduces the need for energy storage. Direct electrification plays a decisive role in increasing the overall energy efficiency of the power system. However, by 2050, the main sources of energy losses are the e-fuel synthesis processes and indirect electrification used to replace traditional hydrocarbons. Although some of the thermal energy released during synthesis can be reused, e.g., to capture CO_2 or heat buildings, it is the losses associated with the production of e-fuels that constitute the largest share of the total losses in the energy system.

3.7. Energy system cost and emissions

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

Initially, the annualised energy system costs increase in all presented scenarios up to 2030 and then decrease until 2050. In 2030, in all scenarios, costs increase to almost 91 b€. The BPS_lowPV presents higher annualised system costs, which increase to 84 b€ by 2035 (see Figure 26) and then decrease to 63 b€ by 2050. Costs start to decrease steadily from 2035 as the system transitions to 100% RE by 2050. By 2050, the total annualised energy system costs in the BPS_favourOE scenario are lower than in 2020 (74 b€ vs 64 b€) underscoring the long-term cost benefits of large-scale RE integration. This is especially noticeable in the BPS_2040, BPS, and BPS_noBPV which becomes the cheapest by 2050 (61 b€). This suggests that the transition to 100% RE across Iberia provides significant long-term cost benefits compared to the costs of the present energy system.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

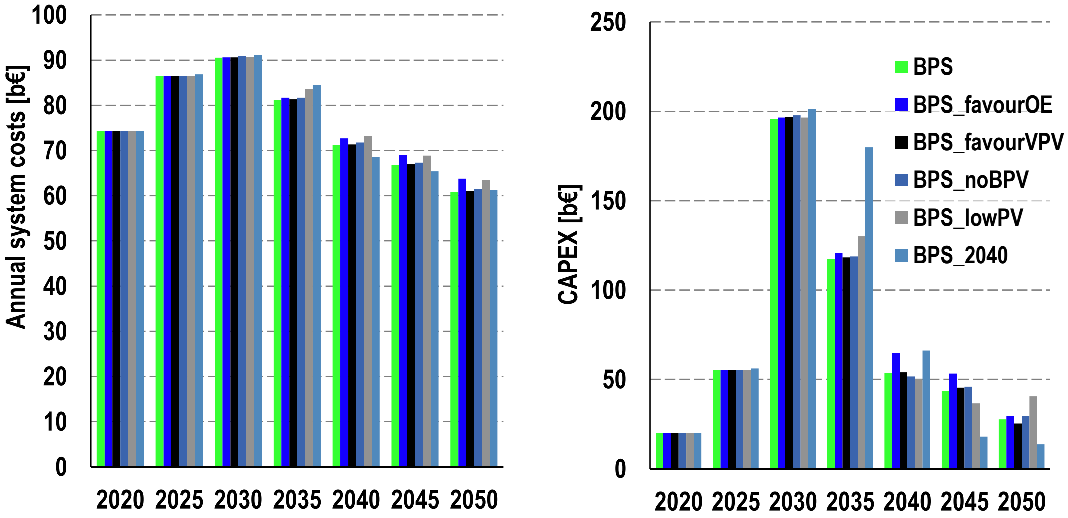

Figure 26 – Annualised energy system cost and capex across the scenarios from 2020 to 2050.

Figure 26 (right) illustrates the differences in investments from 2020 to 2050 across the scenarios. In the BPS variations, investments in RE technologies and infrastructure reach their highest levels, peaking at around 198 b€ in 2025-2030 for the BPS_noBPV and 201 b€ in the BPS_2040. However, annual capex significantly decrease in later stages of the transition, in 2045-2050 falling to 29 b€ and 14 b€, respectively. In the BPS_favourOE, investments also peak during a similar period but at a lower level of approximately 196 b€ and falling to 30 b€ in 2045-2050. The BPS_favourVPV and BPS_noBPV show the same trend in capex over all years and in 2045-2050 amount to 25 b€ and 29 b€, respectively. Meanwhile, the BPS_favourOE in 2045-2050 is expected to result in capex of only 30 b€. Although initial investments in the energy system are substantial, especially from the late 2020s to the early 2040s, the long-term benefits outweigh the costs, as clearly documented by the considerably declining total energy system cost for the 2040s compared to the present. The scenario with favoured VPV shows the lowest capex of 25 b€ in 2045-2050. The BPS_lowPV is expected to result in capex of approximately 41 b€ in 2045-2050 (see Figure 26), since most of least cost PV resources are already used and the system has to invest in higher cost energy sources.

When comparing cumulative investments over the transition period (2025–2050), the baseline BPS and BPS_favourVPV emerge as the lowest-cost pathways, requiring about 515 b€ in new investments. The BPS_noBPV scenario is slightly more expensive at 519 b€, while the BPS_lowPV pathway raises investment needs further to 529 b€ due to the additional reliance on alternative technologies when PV deployment is constrained. The BPS_favourOE scenario reaches 540 b€, reflecting higher upfront costs of offshore technologies, but remains lower than the accelerated BPS_2040, which demands the highest cumulative investments of about 555 b€.

Importantly, when moving from cumulative investments to overall system expenditures, the baseline BPS confirms its position as the least-cost scenario. By

This project has received funding from the Europeans Union’s Horizon 2020 research & innovation programme under grant agreement number 101036457.

2050, it reaches around 2412 b€ in cumulative annual energy system cost, compared with higher values in all other scenarios (e.g., 2437 b€ in the BPS_favourOE, 2449 b€ in BPS_lowPV). These differences, while modest, indicate that integrating ORE slightly increases total expenditures due to higher capital costs, yet contributes to greater grid stability and reduced storage dependency, enhancing overall system robustness.

As seen in Figure 27, the levelised cost of electricity (LCOE) significantly decreases throughout the transition period. The increasing proportion of renewable power, improved efficiency via sector coupling, and a decline in fossil fuels costs and the CO_2 emission costs that go along with them are the main causes of this decline in LCOE. The overall costs of the system are projected to decrease significantly, supported by technological advancements and the declining capex of solar PV and wind power.

In all scenarios, the LCOE decreases by more than 50% by 2050 compared to 2020 levels. In the BPS, the LCOE drops from 70 €/MWh to 25 €/MWh. This highlights that renewable electricity is expected to become the least cost energy carrier. As the transition progresses, fuel and CO_2 costs steadily decline, and from 2040 onwards, capex becomes the primary driver of energy system costs, with fuel costs becoming nearly negligible. After 2050, the LCOE is projected to fall by an additional 10%, largely due to major reinvestments occurring beyond 2050, which benefit from further cost decline of RE and storage technologies and consequent lower capex. This suggests that long-term investments in RE will continue to drive down electricity costs well into the future. In addition, the BPS andBPS_favourVPV by 2050 take a lead among other scenarios for the lowest LCOE of about 25 €/MWh. However, for all other scenarios including the BPS_favourOE the LCOE remains below 30 €/MWh.

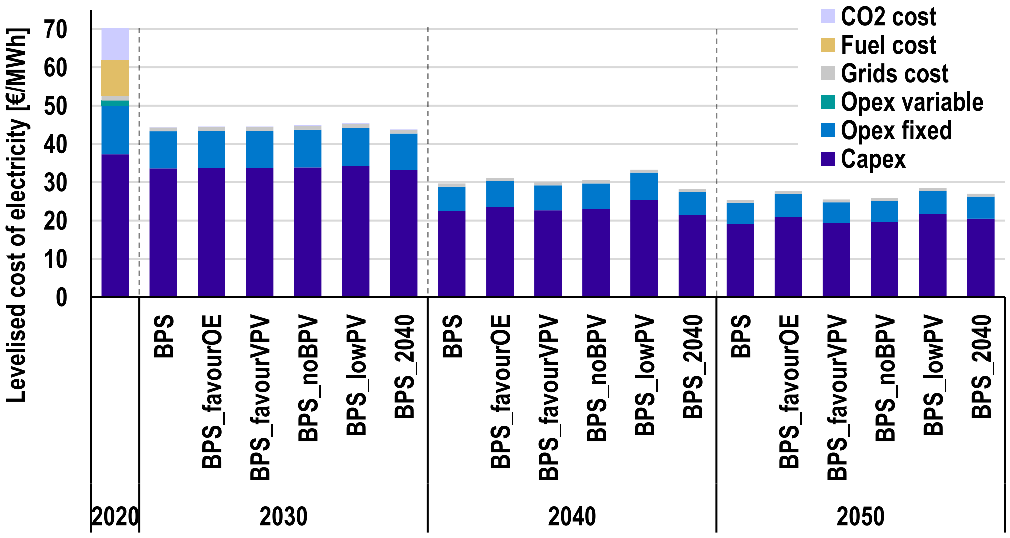

Figure 27 – Levelised cost of electricity during the transition.

The levelised cost of heat (LCOH) and levelised cost of final energy and non-energy use (LCOFE) follow a similar pattern to the total annualised system cost across the

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

different scenarios (as shown in Figure 28 and Figure 29). In 2020, the LCOFE stood almost at 50 €/MWh, primarily driven by CO_2 emissions expenses and fuel expenses.

By 2050, the BPS achieves the lowest system-wide LCOFE, around 54 €/MWh, while the scenario with favoured ORE technologies shows a slightly higher LCOFE of approximately 56.8 €/MWh. The accelerated transition scenario reaches 59 €/MWh by 2040. Other scenarios, which incorporate varying shares of solar PV or wind power technologies, maintain a similar LCOFE around 54 €/MWh. This indicates that an accelerated shift towards 100% RE is appealing from an energy security standpoint, while the LCOFE remains comparable to 2020 levels. Over the long term, the LCOFE becomes increasingly dominated by capex as fuel costs diminish in significance during the transition, suggesting enhanced energy security across Europe by 2050. Additionally, the LCOFE accounts for all aspects of the energy system, with electricity and heat being the primary energy sources. A smaller decline of LCOFE compared to LCOE and LCOH reflects cost increase of fuels and chemical feedstock, as e-fuels and e-chemicals are unavoidably more expensive than electricity or heat and exceed the price of fossil fuels observed today. This limited cost reduction potential brings another argument for support of direct electrification across all sectors.

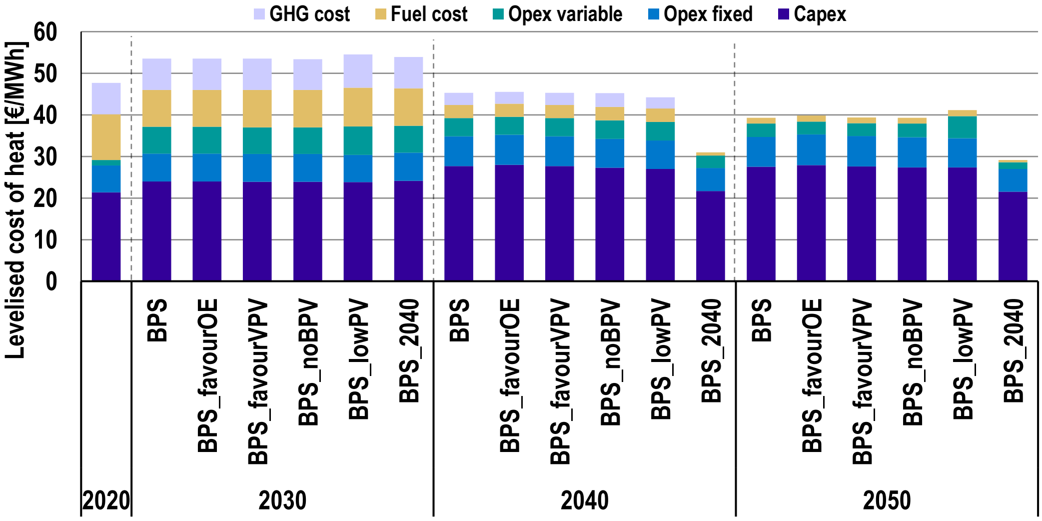

Figure 28 – Levelised cost of heat during the transition.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

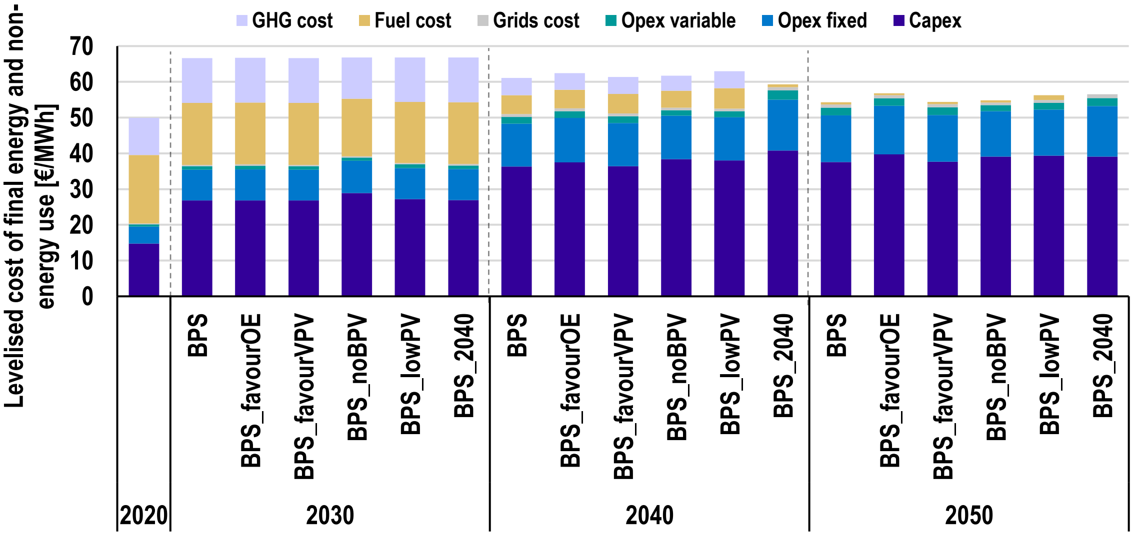

Figure 29 – Levelised cost of final energy and non-energy use during the transition.

The results of the energy transition demonstrate a sharp decline in CO_2 emissions across the power, heat, transport, and industry sectors in all three scenarios by 2050, as shown in Figure 30. In 2020, CO_2 emissions from the power sector were over 46 $MtCO_2$, however, they experience a rapid decrease to zero by 2040 in the BPS_2040 and by 2050 in other scenarios. In 2030, the lowest emissions occur in the accelerated scenario. The transport sector, which accounts for the highest emissions in 2020 of around 173 $MtCO_2$, achieves zero emissions by 2040. In other scenarios, emissions from the transport and industry sectors persist but remain minimal. Overall, emissions across all sectors experience an accelerated reduction to zero by 2040 in the relevant scenario, and a steady decline to zero by 2050 in other scenarios.

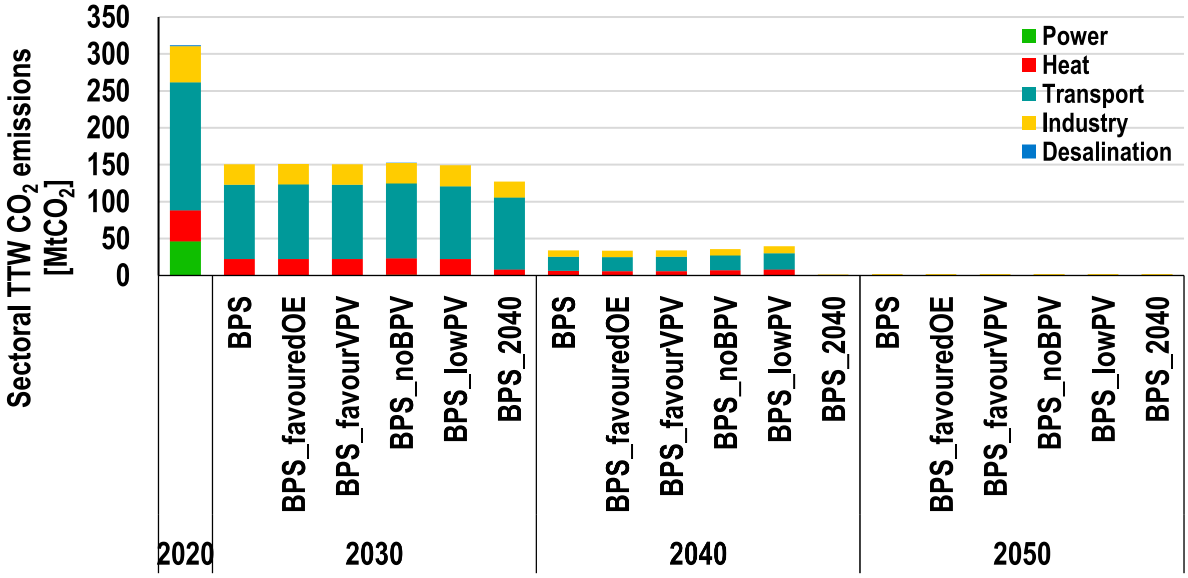

Figure 30 – Sectoral annual CO_2 emissions in all scenarios during the transition.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

4. Complementary impacts

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

Part of the importance of integrating ORE in the energy system is determined by the limited land surface both in major urban centres at the coast of the Iberian Peninsula and directly in the Azores, Madeira, and Canary Islands. Due to the limited land resources in the island regions, ORE technologies can make a significant contribution to energy system defossilisation [24]. When onshore land availability is restricted, OSPV can supply a significant portion of total solar PV generation with only marginal additional costs [53].

In the BPS_favourOE, the use of ORE technologies was supported; unlike the rest of the system, the installed capacities of offshore wind power, wave power, and OSPV were not defined by the cost-optimisation. In other BPS variations, the system was free to define a cost optimal ORE capacity, which makes the role of ORE in these results especially interesting. The model results of the BPS demonstrate the important role of OSPV can play in area-constrained regions, especially on the Azores, Madeira, and Canary Islands. In the cost-optimised scenario, OSPV capacities are present without any support, solely due to the scarcity of onshore area. This highlights the competitiveness of ORE solutions under area constraints.

The BPS results analysis shows that the cost-optimised energy-industry system has a wide distribution of OSPV, and the favoured OE development scenario does not increase the overall cost of the system by more than 2% by 2050, making it more sustainable and responsive. Besides the economic performance, wave power can provide additional value via the diversification of energy supply, as discussed for several RE sources by Aghahosseini et al. [69]. Thus, ORE sources make a significant contribution to smoothing and balancing the temporal variability inherent in solar PV generation, especially during the winter months when solar irradiation is lower and demand is high. This results in a more stable energy system, with a notable decrease in electricity storage and hydrogen balancing requirements. As described in Kies et al. [70], Satymov et al. [36], in the regional case of Seychelles [71], and in the case of Hawaii [24], and confirmed in the current results, wave power complements solar PV generation due to its seasonally output power profile, contributing to a more balanced energy supply throughout the year and reducing the requirements for energy storage in the power sector or hydrogen-based balancing. Moreover, such a complementarity and impact on storage demand was shown by Keiner et al. [27] for the case of Maldives, a region with solar PV becoming the dominant source of electricity in the near future, where wave power is uniquely suited to compliment solar PV in times of lower solar resource availability.

The integration of diverse ORE sources, including offshore wind power, wave power, and OSPV, enhances the resilience and reliability of the Iberian energy system. Each technology provides a distinct temporal generation profile: offshore wind power contributes strongly during winter months, wave power offers stable output throughout the year, and OSPV supports daytime and summer demand.

Their combined deployment reduces reliance on large-scale energy storage and grid reinforcement by smoothing temporal and spatial variability in electricity generation. This technological diversity enables a more balanced and efficient operation of the energy system, particularly in coastal and island regions where land availability is limited, positioning Iberia as a potential leader in the integration of complementary ORE technologies within a fully RE framework.

4.2. The role of solar photovoltaics systems diversity in achieving Iberia's energy targets

The comparison between the BPS, BPS_favourOE, and other scenarios that impose restrictions or changes to solar PV deployment highlight the important role of PV technologies in Iberia's transition. The BPS_lowPV, which limits the expansion of solar PV systems, results in higher system costs of 1.5% than the BPS by 2050 as it uses more expensive renewable electricity generation sources. This scenario also sees a reduction in electricity storage capacity. The BPS_favourVPV, which achieves a more balanced intraday generation profile and thus reduces grid usage by lowering curtailment and peak transmission loads, has little impact on reducing overall system costs, as in contrast, increasing the overall share of VPV leads to higher system costs of less than 1% compared to the BPS. Meanwhile, the BPS_noBPV, a scenario that excludes bifacial PV systems, results in slightly lower full load hours for PV installations. These results show that while PV technology diversity alone does not lead to drastic cost reductions, it contributes to greater system flexibility [72], eases land-use pressure, and reduces curtailment by improving the match between generation and demand profiles. For example, in the BPS_noBPV, the loss of generation diversity led to an increase in annual electricity generation by 12 TWh, compared to the BPS, which highlights how limited PV diversity can result in underused capacity and inefficient system expansion.

OSPV, although currently more expensive than land-based PV systems, is becoming increasingly viable in scenarios and will become a key power generation technology in future in regions where land availability is limited [71], [73]. In the BPS_lowPV scenario, the reduction in ground-mounted PV deployment led to a compensating increase in installed wind power capacity, while in the no bifacial PV scenario to a higher reliance on batteries and hydrogen storage. This outcome led to higher system costs and curtailment, highlighting the system value of combined benefits of PV diversity and spatial deployment which help to smooth the generation profile and reduce the need for additional balancing capacity. The lack of such flexibility in these scenarios resulted in higher system costs, e.g., plus 37 b€/a in the BPS_lowPV compared to BPS, demonstrating the critical role of diverse PV technologies in an optimised and cost-effective energy transition. VPV systems have a minor impact on the total solar PV capacity [74]. However, in the BPS_favourVPV, the presence and high share of vertical PV in island energy systems plays a significant role in reducing land-use pressure, making it a valuable solution for regions with limited available space.

5. Summary and key messages

This report explores the projections of Iberia's energy system from 2020 to 2050 across multiple scenarios, with particular attention to the high ocean energy deployment in the favoured ocean energy scenario and solar photovoltaics diversity on sectoral defossilisation strategies on greenhouse gas emissions. One of the core findings is the consistent and significant reduction in final energy demand, which drops by 20% in most scenarios despite increasing activity in the transport and industry sectors. This reduction is primarily driven by enhanced energy efficiency and widespread electrification. The BPS_2040 scenario in particular achieves even greater savings through more ambitious policies and technological uptake, leading to earlier and deeper declines in energy use.

The drop in final energy demand in combination with the switch to renewable energy supply results in a substantial reduction of primary energy demand. In 2020, fossil fuels dominate the supply mix, but by 2050, renewable electricity becomes the main energy source across all scenarios. This transition drives the primary energy demand down from 1779 TWh to as low as 1683 TWh in the most ambitious scenario, with the integration of offshore renewable energy technologies contributing to this efficiency.

Electrification of the energy system requires a fast growth of electricity generation capacities. The electricity generation capacity expands dramatically over the period, growing from about 125 GW in 2020 to 411 GW in 2030 and to nearly 710 GW by 2050. Solar photovoltaics and wind power emerge as the leading technologies, with solar photovoltaics exceeding 594 GW of installed capacity and up to 1190 TWh of electricity generation in some scenarios. Offshore wind power also becomes increasingly important, particularly in the high ocean energy scenario, reaching 12 GW in capacity and up to 54 TWh in electricity generation. Fossil fuel-based and nuclear power generation is entirely phased out by 2030.

Electricity storage systems scale up rapidly to accommodate the variability of renewable energy. By 2050, prosumer batteries and vehicle-to-grid systems each exceed 85 TWh of output, playing critical roles in system flexibility. The BPS_favourOE shows a moderate total storage deployment (587 GWh capacity and 107 TWh throughput), reflecting the stabilising impact of offshore renewable energy. Offshore wind power, wave power, and floating offshore solar photovoltaics provide a smoother electricity generation profile, reducing the need for daily and seasonal storage compared to scenarios with limited offshore renewable energy deployment, e.g., BPS_lowPV. In contrast, scenarios with restricted photovoltaics or no bifacial photovoltaics deployment rely more heavily on batteries, hydrogen, and pumped hydro energy storage to balance supply.

The industry sector shows a moderate overall energy demand growth, with chemicals and other industry sectors expanding, while steel and cement decline due to material efficiency and substitution. In the transport sector, energy use for road transportation drops significantly with the uptake of electric vehicles, while aviation becomes the largest single transport energy consumer by 2050 due to limited direct electrification options. In the BPS_favourOE, the reliable offshore

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

renewable energy supply supports electrification and e-fuels production for transport and industry, with electrolysis capacity growing to over 200 GW. Methanol and Fischer-Tropsch liquids production scales in parallel to meet the e-fuel demand.

The main results and conclusions of this study highlight that the integration of floating offshore solar photovoltaics and wave power into the Iberian energy system leads to moderately higher total system costs compared to scenarios without them, but for the benefit of a higher system diversity and lower reliance on energy storage and transmission. The scenario with low photovoltaics share is the most expensive in terms of annual system cost, emphasising the economic importance of having a considerable solar photovoltaics share in the system. In 2050, the BPS_favourOE has annualised system costs of about 61 b€. The BPS_lowPV costs 63 b€ in 2050, which is about 2 b€ higher than in the BPS. The levelised cost of electricity similarly increases in 2050 from 25 €/MWh in the BPS to 28 €/MWh in the BPS_lowPV. Offshore renewable energy contributes to the system stability, as demonstrated by a 11% reduction in electricity storage output in 2050 (from 130 TWh in the BPS to 107 TWh in the BPS_favourOE). This implies less reliance on long-term fuel storage and balance, reduced operational uncertainties, and increased security of supply in a system dominated by variable renewable energy.

The observed variation of electricity generation and levelised cost of electricity between the BPS, BPS_favourOE, and BPS_lowPV clearly demonstrates that ocean renewable energy technologies are in some regional cases such as the Iberian Islands, Azores, Madeira, and Canary Islands, part of the least cost solution. Electricity generation in islands for the BPS_favourOE from offshore solar photovoltaics reaches 50 TWh in 2050 compared to 45 TWh from same source in the same year for the BPS, highlighting the system optimisation for given constraints in the region. Offshore renewable energy resource profiles complement onshore solar photovoltaics and onshore wind power on the continent making the energy system on the Peninsula more resilient and resulting in less energy storage and more stable energy services. Including offshore renewable energy despite the relative increase in system cost remains advantageous compared to importing from other regions to regions with an energy deficit and is part of the least cost solution. Moreover, it shifts the overall architecture towards a more balanced and spatially diversified one.

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

In conclusion, although the offshore renewable energy and floating offshore solar photovoltaics favouring scenarios result in slightly higher capital expenditures and also annualised system costs, they offer a more resilient, regionally optimised and efficient system architecture. These results support a strategic shift towards greater technological diversity in offshore renewable energy as a key driver for a sustainable energy transition in Iberia.

This project has received funding from the Europeans Union’s Horizon 2020 research & innovation programme under grant agreement number 101036457.

6. References

[1] [NOAA] - National Oceanic and Atmospheric Administration, “National Centers for Environmental Information, Monthly Global Climate Report for Annual 2024,” Washington, D.C., Jul. 2025. doi: https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00672.

[2] [WMO] - World Meteorological Organisation, “State of the Global Climate 2024 (WMO-No. 1368),” Geneva, Mar. 2025. Accessed: May 30, 2025. [Online]. Available: https://wmo.int/publication-series/state-of-global-climate-2024

[3] [EEA] - European Environmental Agency, “Europe’s changing climate hazards — an index-based interactive EEA report,” Copenhagen, Feb. 2023. doi: 10.2800/458052.

[4] Copernicus Climate Change Service (C3S) and World Meteorological Organization (WMO), “European State of the Climate 2024,” Geneva, 2025. doi: doi.org/10.24381/14j9-s541.

[5] IPCC, “Renewable Energy Sources and Climate Change Mitigation — IPCC,” Geneva, 2011. Accessed: Aug. 24, 2020. [Online]. Available: https://www.ipcc.ch/report/renewable-energy-sources-and-climate-change-mitigation/

[6] [EC] - European Commission, “The European Green Deal,” Brussels, 2019. [Online]. Available: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

[7] [UNFCCC] - United Nations Framework Convention on Climate Change, “Adoption of Paris Agreement. Proposal by the President.,” Bonn, 2015. Accessed: Apr. 22, 2025. [Online]. Available: https://unfccc.int/documents/184656

[8] [EC] - European Commission, “Technology pathways in decarbonisation scenarios,” Brussels, 2018. Accessed: Apr. 17, 2025. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/599a1d8e-509a-11eb-b59f-01aa75ed71a1/language-en

[9] [EC] - European Commission, “Renewable Energy Directive ,” Brussels, Oct. 2023. Accessed: Apr. 19, 2025. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2023/2413/oj

[10] A. Y. Aznar, N. Lee, and S. S. Booth, “International Applications for Floating Solar Photovoltaics,” Golden, CO (United States), Jun. 2019. doi: 10.2172/1526906.

[11] D. Bogdanov *et al.*, “Low-cost renewable electricity as the key driver of the global energy transition towards sustainability,” *Energy*, vol. 227, p. 120467, Jul. 2021, doi: 10.1016/j.energy.2021.120467.

[12] M. Z. Jacobson *et al.*, "Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries," *One Earth*, vol. 1, no. 4, 2019, doi: 10.1016/j.oneear.2019.12.003.

[13] S. Teske *et al.*, "It Is Still Possible to Achieve the Paris Climate Agreement: Regional, Sectoral, and Land-Use Pathways," *Energies*, vol. 14, no. 8, p. 2103, Apr. 2021, doi: 10.3390/en14082103.

[14] G. Luderer *et al.*, "Impact of declining renewable energy costs on electrification in low-emission scenarios," *Nat Energy*, vol. 7, pp. 32–42, Nov. 2022, doi: 10.1038/s41560-021-00937-z.

[15] P. M. R. Bento, S. J. P. S. Mariano, J. A. N. Pombo, and M. R. A. Calado, "Large-scale penetration of renewables in the Iberian power system: Evolution, challenges and flexibility options," *Renewable and Sustainable Energy Reviews*, vol. 204, p. 114794, Oct. 2024, doi: 10.1016/j.rser.2024.114794.

[16] R. Vázquez, W. Cabos, J. C. Nieto-Borge, and C. Gutiérrez, "Complementarity of offshore energy resources on the Spanish coasts: Wind, wave, and photovoltaic energy," *Renew Energy*, vol. 224, p. 120213, Apr. 2024, doi: 10.1016/j.renene.2024.120213.

[17] C. Breyer *et al.*, "On the role of solar photovoltaics in global energy transition scenarios," *Progress in Photovoltaics: Research and Applications*, vol. 25, no. 8, pp. 727–745, 2017, doi: 10.1002/pip.2885.

[18] N. M. Haegel *et al.*, "Photovoltaics at multi-terawatt scale: Waiting is not an option," *Science (1979)*, vol. 380, no. 6640, pp. 39–42, Apr. 2023, doi: 10.1126/science.adf6957.

[19] D. Bogdanov, A. Gulagi, M. Fasihi, and C. Breyer, "Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination," *Appl Energy*, vol. 283, p. 116273, Feb. 2021, doi: 10.1016/j.apenergy.2020.116273.

[20] M. Sterner and M. Specht, "Power-to-Gas and Power-to-X—The History and Results of Developing a New Storage Concept," *Energies 2021, Vol. 14, Page 6594*, vol. 14, no. 20, p. 6594, Oct. 2021, doi: 10.3390/EN14206594.

[21] C. Breyer *et al.*, "Reflecting the energy transition from a European perspective and in the global context—Relevance of solar photovoltaics benchmarking two ambitious scenarios," *Progress in Photovoltaics: Research and Applications*, vol. 31, pp. 1369–1395, 2023, doi: 10.1002/pip.3659.

[22] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, and M. Greiner, "Early decarbonisation of the European energy system pays off," *Nat Commun*, vol. 11, p. 6223, 2020, doi: 10.1038/s41467-020-20015-4.

[23] P. Diesing, D. Bogdanov, R. Satymov, M. Child, I. Hauer, and C. Breyer, "Offshore versus onshore: The underestimated impact of onshore wind

and solar photovoltaics for the energy transition of the British Isles," *IET Renewable Power Generation*, vol. 17, no. 13, pp. 3240–3266, Oct. 2023, doi: 10.1049/rpg2.12840.

[24] G. Lopez, R. Satymov, A. Aghahosseini, D. Bogdanov, A. S. Oyewo, and C. Breyer, "Ocean energy enabling a sustainable energy-industry transition for Hawaiʻi," *Renew Energy*, vol. 237, p. 121831, Dec. 2024, doi: 10.1016/j.renene.2024.121831.

[25] R. Satymov, D. Bogdanov, M. Dadashi, G. Lavidas, and C. Breyer, "Techno-economic assessment of global and regional wave energy resource potentials and profiles in hourly resolution," *Appl Energy*, vol. 364, p. 123119, Jun. 2024, doi: 10.1016/j.apenergy.2024.123119.

[26] R. Satymov, D. Bogdanov, and C. Breyer, "Techno-economics of offshore wind power in global resolution," *Applied Energy. In press*, 2025.

[27] D. Keiner *et al.*, "Powering an island energy system by offshore floating technologies towards 100% renewables: A case for the Maldives," *Appl Energy*, vol. 308, p. 118360, Feb. 2022, doi: 10.1016/j.apenergy.2021.118360.

[28] [EC] - European Commission, "An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future," Brussels, Nov. 2020. Accessed: Apr. 10, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN&qid=1605792629666#footnoteref5

[29] Wind Europe, "Wind energy in Europe: 2024 Statistics and the outlook for 2025-2030," Brussels, Feb. 2025. Accessed: Apr. 22, 2025. [Online]. Available: https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2024-statistics-and-the-outlook-for-2025-2030/

[30] WindEurope, "Wind Europe. Offshore wind energy." Accessed: Apr. 10, 2025. [Online]. Available: https://windeurope.org/policy/topics/offshore-wind-energy/

[31] Wind Europe, "Our energy, our future How offshore wind will help Europe go carbon-neutral ," Brussels, 2019. Accessed: Apr. 10, 2025. [Online]. Available: https://proceedings.windeurope.org/biplatform/rails/active_storage/disk//WindEurope-Our-Energy-Our-Future.pdf

[32] Eurostat, "Renewable Energy Staristics," Eurostat. Accessed: Apr. 14, 2025. [Online]. Available: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250319-1#:~:text=In%202024%2C%2046.9%25%20of%20net,73.7%25%2C%20mostly%20hydro).

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.

[33] Red Eléctrica de España, “Spanish electricity system reports 2024,” Madrid, Mar. 2025. Accessed: May 30, 2025. [Online]. Available: https://www.ree.es/sites/default/files/2025-04/EN_1803_ISE_Nacional.pdf

[34] R. Moreira, “A tale of two (un)Just Transitions: the end of the coal-fired power plants in Portugal,” *Energy Policy*, vol. 204, p. 114658, Sep. 2025, doi: 10.1016/j.enpol.2025.114658.

[35] P. [REM] - Redes Energéticas Nacionais, “Record renewable energy production supplies 71% of electricity consumption in 2024.” Accessed: May 30, 2025. [Online]. Available: https://www.ren.pt/en-gb/media/news/record-renewable-energy-production-supplies-71-of-electricity-consumption-in-2024

[36] R. Satymov, D. Bogdanov, M. Dadashi, G. Lavidas, and C. Breyer, “Techno-economic assessment of global and regional wave energy resource potentials and profiles in hourly resolution,” *Appl Energy*, vol. 364, p. 123119, Jun. 2024, doi: https://doi.org/10.1016/j.apenergy.2024.123119.

[37] [EIT] - European Institute Innovation and Technology, “The Iberian region as a hub for technology development and industrial leadership in the field of floating offshore wind,” Eindhoven, 2020. Accessed: Jun. 02, 2025. [Online]. Available: https://www.eit.europa.eu/news-events/news/eit-innoenergy-study-says-offshore-wind-energy-could-stimulate-job-creation

[38] L. Rusu, “The near future expected wave power in the coastal environment of the Iberian Peninsula,” *Renew Energy*, vol. 195, pp. 657–669, Aug. 2022, doi: 10.1016/j.renene.2022.06.047.

[39] A. G. Majidi, V. Ramos, P. Rosa-Santos, L. das Neves, and F. Taveira-Pinto, “Power production assessment of wave energy converters in mainland Portugal,” *Renew Energy*, vol. 243, p. 122540, Apr. 2025, doi: 10.1016/j.renene.2025.122540.

[40] [IRENA] - International Renewable Energy Agency, “Renewable capacity statistics 2025,” Abu Dhabi, Mar. 2025. Accessed: Jun. 02, 2025. [Online]. Available: https://www.irena.org/Publications/2025/Mar/Renewable-capacity-statistics-2025

[41] “Global Solar Atlas.” Accessed: Jul. 17, 2025. [Online]. Available: https://globalsolaratlas.info/map?c=11.609193,8.4375,3

[42] “Spain’s Solar Supremacy: A Radiant Revolution in Renewable Energy - Robinsun.” Accessed: Jun. 02, 2025. [Online]. Available: https://robinsun.com/blogs/news/spains-solar-supremacy-a-radiant-revolution-in-renewable-energy

[43] N. S. Pérez and J. Alonso-Montesinos, “Economic and environmental solutions for the PV solar energy potential in Spain,” *J Clean Prod*, vol. 413, p. 137489, Aug. 2023, doi: 10.1016/j.jclepro.2023.137489.

[44] " Red Eléctrica | Installed capacity ." Accessed: Jun. 02, 2025. [Online]. Available: https://www.ree.es/en/datos/generation/installed-capacity

[45] [IEA - PVPS] - International Energy Agency Photovoltaic Power Systems Programme, "Trends In Photovoltaic Applications 2024," 2024. Accessed: May 02, 2025. [Online]. Available: https://iea-pvps.org/trends_reports/trends-in-pv-applications-2024/

[46] A. Jäger-Waldau, "Snapshot of photovoltaics − March 2025," *EPJ Photovoltaics*, vol. 16, p. 22, May 2025, doi: 10.1051/epjpv/2025012.

[47] [EC] - European Commission. Directorate-General for Communication, "Spain - Final updated NECP 2021-2030 (submitted 2024)," Sep. 2024, *EC, Brussels*. Accessed: Jun. 03, 2025. [Online]. Available: https://commission.europa.eu/publications/spain-final-updated-necp-2021-2030-submitted-2024_en

[48] [EC] - European Commission. Directorate-General for Communication, "Portugal - Final updated NECP 2021-2030 (submitted in 2024)," Dec. 10, 2024, *EC, Brussels*. Accessed: Jun. 03, 2025. [Online]. Available: https://commission.europa.eu/publications/portugal-final-updated-necp-2021-2030-submitted-2024_en

[49] D. Keiner, L. Walter, M. ElSayed, and C. Breyer, "Impact of backtracking strategies on techno-economics of horizontal single-axis tracking solar photovoltaic power plants," *Solar Energy*, vol. 267, p. 112228, Jan. 2024, doi: 10.1016/j.solener.2023.112228.

[50] M. S. Javed, J. Jurasz, M. Guezgouz, F. A. Canales, T. H. Ruggles, and T. Ma, "Impact of multi-annual renewable energy variability on the optimal sizing of off-grid systems," *Renewable and Sustainable Energy Reviews*, vol. 183, p. 113514, Sep. 2023, doi: 10.1016/j.rser.2023.113514.

[51] C. D. Rodríguez-Gallegos, M. Bieri, O. Gandhi, J. P. Singh, T. Reindl, and S. K. Panda, "Monofacial vs bifacial Si-based PV modules: Which one is more cost-effective?," *Solar Energy*, vol. 176, pp. 412–438, Dec. 2018, doi: 10.1016/j.solener.2018.10.012.

[52] D. Keiner, L. Walter, D. Bogdanov, I. M. Peters, and C. Breyer, "Assessing the impact of bifacial solar photovoltaics on future power systems based on capacity-density-optimised power plant yield modelling," *Solar Energy*, vol. 295, p. 113543, Jul. 2025, doi: 10.1016/j.solener.2025.113543.

[53] C. Breyer, A. S. Oyewo, A. Kunkar, and R. Satymov, "Role of Solar Photovoltaics for a Sustainable Energy System in Puerto Rico in the Context of the Entire Caribbean Featuring the Value of Offshore Floating Systems," *IEEE J Photovolt*, vol. 13, no. 6, pp. 842–848, Nov. 2023, doi: 10.1109/JPHOTOV.2023.3319022.

[54] S. Fan, Z. Ma, T. Liu, C. Zheng, and H. Wang, "Innovations and development trends in offshore floating photovoltaic systems: A comprehensive

review," *Energy Reports*, vol. 13, pp. 1950–1958, Jun. 2025, doi: 10.1016/j.egyr.2025.01.053.

[55] M. A. Koondhar, L. Albasha, I. Mahariq, B. B. Graba, and E. Touti, "Reviewing floating photovoltaic (FPV) technology for solar energy generation," *Energy Strategy Reviews*, vol. 54, p. 101449, Jul. 2024, doi: 10.1016/j.esr.2024.101449.

[56] [IEA] - International Energy Agency, "Managing Seasonal and Interannual Variability of Renewables," Paris, Apr. 2023. Accessed: Jun. 03, 2025. [Online]. Available: https://www.iea.org/reports/managing-seasonal-and-interannual-variability-of-renewables

[57] R. Satymov, D. Bogdanov, T. Galimova, and C. Breyer, "Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling, and power-to-X," *Energy*, vol. 319, p. 134888, 2025, doi: 10.1016/j.energy.2025.134888.

[58] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, "Classification and challenges of bottom-up energy system models - A review," 2020. doi: 10.1016/j.rser.2020.109917.

[59] S. Khalili and C. Breyer, "Review on 100% Renewable Energy System Analyses – A Bibliometric Perspective," *IEEE Access*, vol. 10, pp. 125792–125834, 2022, doi: 10.1109/ACCESS.2022.3221155.

[60] C. Breyer, G. Lopez, D. Bogdanov, and P. Laaksonen, "The role of electricity-based hydrogen in the emerging power-to-X economy," *Int J Hydrogen Energy*, vol. 49, pp. 351–359, Jan. 2024, doi: 10.1016/j.ijhydene.2023.08.170.

[61] S. Khalili, E. Rantanen, D. Bogdanov, and C. Breyer, "Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World," *Energies*, vol. 12, no. 20, p. 3870, Oct. 2019, doi: 10.3390/en12203870.

[62] D. Bogdanov *et al.*, "Costs and benefits of highly ambitious energy transition pathways for Europe," *Submitted*, 2024.

[63] D. Bogdanov *et al.*, "Radical transformation pathway towards sustainable electricity via evolutionary steps," *Nat Commun*, vol. 10, no. 1, p. 1077, Dec. 2019, doi: 10.1038/s41467-019-08855-1.

[64] Red Electrica, "Red Electrica Data Library." Accessed: Jun. 10, 2025. [Online]. Available: https://www.ree.es/en/datos/generation

[65] REN - Redes Energéticas Nacionais, "REN Data Hub." Accessed: Jun. 10, 2025. [Online]. Available: https://datahub.ren.pt/

[66] M. Ram, M. Child, A. Aghahosseini, D. Bogdanov, A. Lohrmann, and C. Breyer, "A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period

2015–2030," *J Clean Prod*, vol. 199, pp. 687–704, 2018, doi: 10.1016/j.jclepro.2018.07.159.

[67] F. Präger *et al.*, "Evaluating nuclear power's suitability for climate change mitigation: technical risks, economic implications and incompatibility with renewable energy systems," *Frontiers in Environmental Economics*, vol. 3, Apr. 2024, doi: 10.3389/frevc.2024.1242818.

[68] L. Haywood, M. Leroutier, and R. Pietzcker, "Why investing in new nuclear plants is bad for the climate," *Joule*, vol. 7, no. 8, pp. 1675–1678, Aug. 2023, doi: 10.1016/j.joule.2023.07.006.

[69] A. Aghahosseini *et al.*, "Energy system transition pathways to meet the global electricity demand for ambitious climate targets and cost competitiveness," *Appl Energy*, vol. 331, p. 120401, Feb. 2023, doi: 10.1016/J.APENERGY.2022.120401.

[70] A. Kies, B. U. Schyska, and L. von Bremen, "The optimal share of wave power in a highly renewable power system on the Iberian Peninsula," *Energy Reports*, vol. 2, pp. 221–228, Nov. 2016, doi: 10.1016/j.egyr.2016.09.002.

[71] D. Keiner *et al.*, "Future role of wave power in Seychelles: A structured sensitivity analysis empowered by a novel EnergyPLAN-based optimisation tool," *Energy*, vol. 303, p. 131905, Sep. 2024, doi: 10.1016/j.energy.2024.131905.

[72] J. Subtil Lacerda and J. C. J. M. van den Bergh, "Diversity in solar photovoltaic energy: Implications for innovation and policy," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 331–340, Feb. 2016, doi: 10.1016/j.rser.2015.10.032.

[73] J. Wang and P. D. Lund, "Review of Recent Offshore Photovoltaics Development," *Energies*, vol. 15, no. 20, p. 7462, Oct. 2022, doi: 10.3390/en15207462.

[74] D. Keiner, L. Walter, D. Bogdanov, I. M. Peters, and C. Breyer, "Assessing the impact of bifacial solar photovoltaics on future power systems based on capacity-density-optimised power plant yield modelling," *Solar Energy*, vol. 295, p. 113543, Jul. 2025, doi: 10.1016/j.solener.2025.113543.

This project has received funding from the Europeans Union's Horizon 2020 research & innovation programme under grant agreement number 101036457.