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Abbreviations

AEP	Annual Energy Production
BFOW	Bottom-Fixed Offshore Wind
BPS	Best Policy Scenario
BPS_lowOS	Best Policy Scenario with low ORE
BPS_highOS	Best Policy Scenario with high ORE
BPS_highOS_FPV	Best Policy Scenario with high ORE and OSPV
BPS_FPV	Best Policy Scenario with OSPV
BPS-2040	Best Policies Scenario - 2040
C&I	Construction and Installation
Capex	Capital Expenditure
CED	Cumulative Energy Demand
CPBT	Carbon Payback Time
CO_2	Carbon Dioxide
EC	European Commission
EF	Employment Factor
EPBT	Energy Payback Time
EU	European Union
FOW	Floating Offshore Wind
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential

HDPE	High-Density Polyethylene
IEA	International Energy Agency
ILO	International Labour Organization
ISO	International Organization for Standardization
JAS	Just Above Sea
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Energy
LUT-ESTM	LUT Energy System Transition Model
O&M	Operation and Maintenance
OECD	The Organisation for Economic Co-operation and Development
Opex	Operational Expenditure
ORE	Offshore Renewable Energy
OSPV	Offshore Solar Photovoltaics
PEF	Primary Energy Factor
PTO	Power Take-off
PV	Photovoltaic
RE	Renewable Energy
RNA	Rotor-Nacelle Assembly
SPT	Series-Parallel Topology
WEC	Wave Energy Converters

0. Executive summary

As offshore renewable energy (ORE) plays an increasingly important role in global climate efforts, understanding the life cycle impacts of co-located systems, such as wind-wave and offshore wind-solar, is essential to guide sustainable development in the sector. This study applies the life-cycle assessment (LCA) methodology to evaluate the carbon emissions and energy intensity of two case studies. Case Study 1 comprises a wave energy converter (WEC) co-located with a floating offshore wind (FOW) system in Portugal, while Case Study 2 considered a bottom-fixed offshore wind (BFOW) combined with an offshore solar photovoltaic (OSPV) array in Belgium.

The configurations and results in this study are based on preliminary layouts and discussions under the EU-SCORES project, where real data, particularly for installation and operation & maintenance (O&M), can be refined and incorporated into future analysis.

For Case Study 1, the combined WEC and FOW array showed a carbon footprint of 17.7 gCO_2eq/kWh, with 79% of emissions arising from the material-intensive FOW components. In Case Study 2, combining BFOW with OSPV solar resulted in a carbon footprint of 21.3 gCO_2eq/kWh, where manufacturing dominated due to the energy-intensive photovoltaic production process. The Carbon Payback Time (CPBT), is 1.4 years for Case 1 and 2.9 years for Case 2, while the Energy Payback Time (EPBT) is around 2 and 2.6 years, respectively. These results are both significantly shorter than the expected operational lifespans, supporting their viability in achieving net-zero objectives.

The findings emphasise the critical importance of multi-source offshore systems in shaping the future of renewable energy (RE) portfolios. By combining resources, such as shared substations and export cables, these systems improve overall efficiency, reduce carbon intensity, and support the growth of less mature technologies, such as wave power and OSPV.

Further advancements in this sector hold great potential, including optimised project designs, innovative materials, and recycling processes, all of which align with circular economy principles. Material innovations, such as low-carbon composites and reusable or recycled components, could significantly reduce the environmental impacts of offshore installations. Incorporating advanced recycling processes could lower decommissioning impacts, enabling components to re-enter production cycles and creating new value chains.

From an economic and social perspective, it offers opportunities for local jobs creation, skill development, and supply chain growth. The integration of wave, wind, and solar technologies, along with the circular economy approach, can stimulate a variety of jobs across installation, maintenance, and recycling sectors.

Shifting the energy system towards high levels of RE sources is a major strategy to reduce greenhouse gas (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. In particular, the

socioeconomic advantages, like jobs creation within the energy system, are especially significant in times of economic crisis. As energy increasingly connects with environmental, economic, and social priorities, integrating social processes alongside technical and economic analyses of energy systems is becoming essential for comprehensive planning.

Analysing the employment impact of various energy transition scenarios is crucial as it provides a socioeconomic argument for accelerating the shift to sustainable energy systems, which promotes both green growth and social equity while aligning with climate targets. The overall change in jobs resulting from the energy transition, accounting for both jobs creation in RE application and job losses in traditional fossil fuel industries is called net employment impact. This metric is key to understanding the socioeconomic benefits of the transition, as it highlights the potential for new, sustainable employment opportunities due to ramping RE technologies. The net employment impact is a key socioeconomic indicator for gauging the success of the energy transition. This report applies the employment factor (EF) approach to compare a Current Policy Scenario aiming for carbon neutrality by 2050 with the six Best Policy Scenarios for complete decarbonisation. Specifically, it assesses the jobs creation potential of the ORE industry using the metric of jobs/MW.

Energy transition scenarios for the European energy system were modelled using the LUT Energy System Transition Model (LUT-ESTM), a linear optimisation tool designed to create cost-optimised scenarios for the full energy 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 Europe is explored through six scenarios: the reference Best Policy Scenario (BPS), aligned with the European Green Deal and the European Commission's (EC) ORE growth targets, as well as scenarios examining the effects of expanded offshore wind and wave power (lowOS and highOS scenarios), offshore solar PV (FPV scenarios), and an accelerated pathway to carbon neutrality by 2040.

This report covers the economic and social impact of BFOW, OSPV, and wave power capacities in Europe is primarily assessed through jobs creation, a crucial indicator of the value of ORE technologies add to the European energy landscape. This growth aligns with the European Green Deal's objectives, fostering a sustainable energy transition across the continent. The findings suggest that shifting to a highly RE system in Europe could generate approximately 304,000 jobs by 2050, associated with an estimated 270 GW of BFOW capacity. This includes about 31,000 jobs focused on the operation and maintenance of BFOW plants throughout their operational lifespan. In more advanced scenarios emphasising technological diversity and resilience, jobs creation could rise to roughly 660,000 by 2050, supported by an anticipated 450 GW of wave power capacity. However, OSPV installations are projected only in the most ambitious scenarios, potentially creating 86,000 jobs with a capacity of 150 GW by 2050. The wave power findings show that moving towards a highly RE system could generate about 58,000 jobs for the envisioned 60 GW in 2050, thereof almost 6,000 jobs for operation and maintenance over the operational lifetime of the installed wave power plants. In progressive scenarios, the jobs may grow to about 96,000 by 2050 associated with an installed capacity of 100 GW of wave power. ORE can evolve into a substantial contributor to the European energy system, in particular along the Atlantic coastlines across Europe where the wave power resource is the best in Europe.

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1. Introduction

Global electricity demand is surging, fuelled by economic growth, heat waves, and the rise of electric technologies like electric vehicles and heat pumps. The demand for electricity is expected to grow by 4% in 2024, up from 2.5% in 2023, and this trend will continue into 2025 [1], with expectations that total world consumption could double by 2050 in a conservative projection and grow by a factor of four in progressive scenarios [2].

Renewable energy (RE) sources are also on the rise, with their share of global electricity supply increasing from 30% in 2023 to 35% by 2025 [1] and representing more than 90% of all newly installed power capacity globally [3]. As the share of energy from variable RE sources increases, ensuring a reliable energy system becomes more complex and requires substantial investments in balancing technologies such as wave energy, complementary technologies such as solar photovoltaic (PV), advanced storage systems, and additional capacity. Space constraints are also a growing concern, with prime locations for onshore installations becoming scarce or highly competitive. Moreover, while marine resources offer higher production potential due to their abundant resources, the increased complexity of systems and the further offshore expansion of offshore capacity also put pressure on local stakeholders and protected areas.

Maintaining favourable business conditions for RE involves addressing challenges such as the development of energy storage solutions, adapting legislation to support emerging technologies, and managing temporary negative pricing during peak wind periods, as long as the energy system is not yet flexible enough for demand response. Additionally, optimising locations for new projects requires improved value-sharing mechanisms with local communities, which can be facilitated through regulatory enhancements. While higher densities of offshore wind farms may reduce electricity yields due to intra-park effects, careful planning and innovation in farm layout can mitigate these impacts. Other offshore renewable energy (ORE) sources, such as wave power and offshore solar photovoltaic (OSPV), can be considered potential opportunities despite initial deployment obstacles, including technical and financial risks for early projects. As more experience has been gained among the involved stakeholders, these challenges tend to be minimised, paving the way for a more diversified energy mix.

In recent years, the consolidation of offshore wind power technology and advancements in OSPV and wave energy technology have made combining these technologies a viable alternative. The combinations of wind and wave, and wind and OSPV in multi-source energy parks are grounded 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 offshore projects.

The synergies of combined projects can include enhanced energy yield, better predictability, smoothed power output, common grid infrastructure, and shared logistics and Operation and Maintenance (O&M) resources and infrastructures. However, the enhancement of RE parks leads to increased demand for critical materials, energy for manufacturing and transportation of devices, and increased waste management.

Sustainable development of offshore wind power, wave power, and OSPV industries requires efficient planning and use to optimise their exploitation while safeguarding the natural and social environment. To achieve the goals of a competitive, net-zero-emission economy and a sustainable energy transition, decision-making must incorporate not only technical and economic considerations but also assessments of embodied carbon dioxide (CO_2) footprints and potential socioeconomic benefits.

This report also covers the topic of jobs creation and its role in the energy transition. Jobs creation is a critical aspect of the energy transition, as it supports both economic stability and social welfare. The potential for jobs creation in RE industries offers opportunities to revitalise local economies, replace jobs lost in fossil fuel sectors, and create sustainable career paths that contribute to long-term growth. Analysing jobs creation potential is essential because it provides insight into the broader socioeconomic impacts of energy policies, helping governments and businesses make informed decisions that promote both environmental sustainability and economic resilience. By understanding how different energy transition plans affect jobs, policymakers can create strategies that boost employment, making sure the shift to RE is fair and inclusive and supports economic growth while meeting climate goals. In this study, the impact of ORE and in particular multi-source energy parks on greenhouse gas (GHG) emissions is investigated as well as the jobs impact of reaching the ORE ramping targets in Europe.

2. Contextualising

The EU-SCORES project aims to demonstrate the feasibility of multi-source energy parks by promoting the large-scale deployment of the integration of wave and floating offshore wind (FOW) technology in Portugal, as well as the combination of OSPV and bottom-fixed offshore wind (BFOW) energy generation in Belgium, co-located at the same maritime space sharing common installations and facilities. However, combining offshore systems, such as wave power and OSPV with wind power, requires innovative designs and configurations. This approach may involve different material requirements, adaptation of operational characteristics, improvements in regional infrastructures and resources and modification of local socio-economic dynamics.

Building on the environmental and socio-economic pillars, two fundamental questions arise: Can multi-source energy parks be less carbon-intensive than single-source parks to support CO_2 reduction targets? What is its local jobs creation potential?

Although recent studies have addressed the life-cycle assessment (LCA) of ORE systems, there is a notable gap in research on multi-source energy parks due to their innovative characteristics. Most LCA for RE sources focus exclusively on offshore wind generators or present a wide range of results for wave energy converters (WEC), reflecting the diversity in device designs and the early stage of the technology. Additionally, while there are several studies on various OSPV panel technologies, the technology is still emerging and consequently lacks robust data for assessment.

In the context of socioeconomic impacts, commercial-scale ORE deployments bring significant benefits, such as jobs creation and supply chain development. While these impacts are mostly local, they can extend regionally and nationally through investments in grid and port development and other infrastructure projects. In addition, indirect benefits can be observed, such as the growth of specialised training programmes to support the new industry, and the induced effects of increased economic activity and increased consumer purchasing power. Consequently, this trend in economic dynamics is accompanied by an increase in employment.

Understanding these potential socioeconomic effects is crucial for local communities, businesses, and developers. Communities need to know the employment opportunities and services available, while businesses want to understand the impact on their operations. Developers seek information on the economic viability and sustainability of their projects, including workforce availability and infrastructure. Additionally, many countries are exploring ways to unlock their local content and enhance the generation of more local benefits for the communities directly affected.

Based on the significance of socioeconomic effects, several studies have examined it in detail. In their socioeconomic study of wave power in Europe, Vanegas-Cantarero et al. [4] provide insights into the levelized cost of electricity (LCOE) and job creation impacts in Scotland and Portugal. Their findings suggest that ORE can compete with fossil fuel-based energy systems while being significantly less harmful to the environment. Lavidas [5] estimated the job creation potential of wave power for the case of Greece for the manufacturing, construction, and installation. Additionally, ETIP-Ocean (European Technology & Innovation Platform for ORE) [6] evaluates the potential social benefits for Europe from developing and deploying wave power through 2050, with valuable insights on the potential to create jobs.

According to Draycott et al. [7], two comparable 5.25 MW farms of wave power devices can create 420 jobs in Orkney, Scotland, and 190 jobs in Leixoes, Portugal, across both installations and manufacturing phases. This corresponds to 80 jobs/MW in Orkney and 36.2 jobs/MW in Leixoes. The jobs/MW are expected to decrease over time due to increase in productivity based on learning and scaling effects, however, with growing volumes this leads to an growing number of jobs in absolute terms. A study on the socio-economic impact of the Belgian offshore wind power industry in 2017 [8] shows that the offshore wind power industry development in Belgium, together with the export activity based on it, supports about 15,000 jobs for the construction and then the O&M of the power plants. This highlights the job market potential inherent in offshore energy systems. Another study [9], consistent with findings from the Belgian Offshore Platform in 2021, indicates that although the halt in offshore wind power construction in Belgium beginning in 2021 led to a loss of over 6,000 jobs, the sector is projected to reach 24,000 jobs by 2030.

Conducting these analyses is crucial for better understanding critical aspects and strategically managing them to promote a more sustainable RE industry.

3. Carbon emissions and energy intensity analyses

3.1. Methodological approach

LCA is a systematic methodology used to evaluate the environmental burdens of a product or process throughout its entire lifecycle, from raw material extraction to disposal. This methodology follows the guidelines set by the International Organization for Standardization (ISO) standards 14040 [10] and 14044 [11], ensuring a structured and consistent approach.

In this study, LCA was applied to two case studies involving multi-source offshore systems to obtain a comprehensive understanding of material flows and potential GHG emissions and the energy consumption associated to the phases of their lifecycle, including manufacturing, installation, operation, decommissioning and disposal. The LCA methodology involved the following steps:

- Goal and Scope Definition: Establishing the objectives, system boundaries, and functional unit of analysis. The goal is to assess the carbon impacts of integrating FOW system and WEC array in Portugal and BFOW and OSPV technologies in Belgium within a cradle-to-grave LCA. The system boundaries include the required materials, processes and operations related to the manufacturing, transport, construction and installation, operation and maintenance, and decommissioning and disposal, as indicated in Figure 1. The functional unit (FU) is defined as 1 kWh of electricity delivered to the grid. The annual electricity production (AEP) is calculated based on the metocean data of each project location, considering availability and electrical losses.

- Life Cycle Inventory (LCI): Collecting data on all inputs such as materials and energy, and outputs such as emissions and waste, associated with each lifecycle phase. Foreground or primary data were collected mainly from the project team. All background or secondary data were derived from the Ecoinvent database (v.3.5) [12] and data sourced from the literature. Some assumptions were made due to the ongoing project's discussion and data collection for WECs and solar devices. In the absence of a defined supply chain, materials were assumed to originate from the EU when applicable and available in the database, otherwise, a global sourcing level was applied to reflect broader availability. The installation and O&M strategies also considered premises based on discussions with technology developers as well as information gathered from relevant literature. An update of this report may be necessary in the future if significant discrepancies in the assumed data are identified.

- Life Cycle Impact Assessment (LCIA): Evaluating the potential environmental impacts associated with the inventory data. This step involves categorising and quantifying the effects over a range of impacts. The analysis was conducted using the SimaPro tool [13] and the ReCiPe 2016 Midpoint method. This method aims to translate the environmental burdens of the inventory results into environmental impacts, grouping them into different impact categories, such as global warming potential (GWP).

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- Interpretation: Analysing the obtained outputs and identifying the key contributors to carbon emissions and other environmental impacts of these multi-source offshore energy systems. Due to its quantitative nature, LCA facilitates the comparison of environmental consequences arising from conventional electricity sources and single-source parks. The results are presented and discussed in Section 3.3.1.

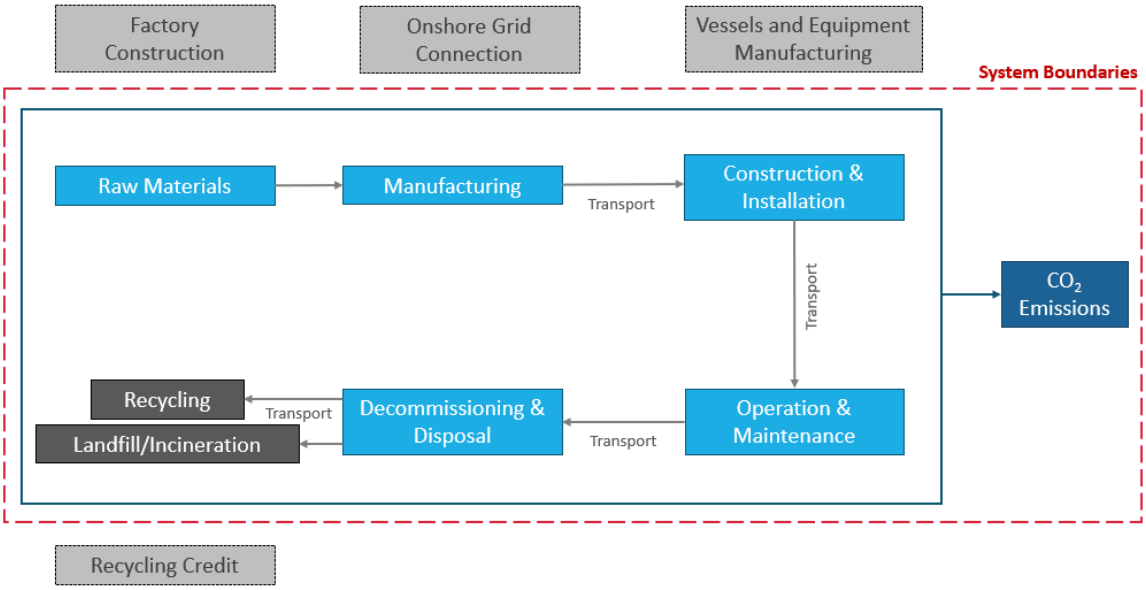

Figure 1 - System boundaries of the lifecycle analysis.

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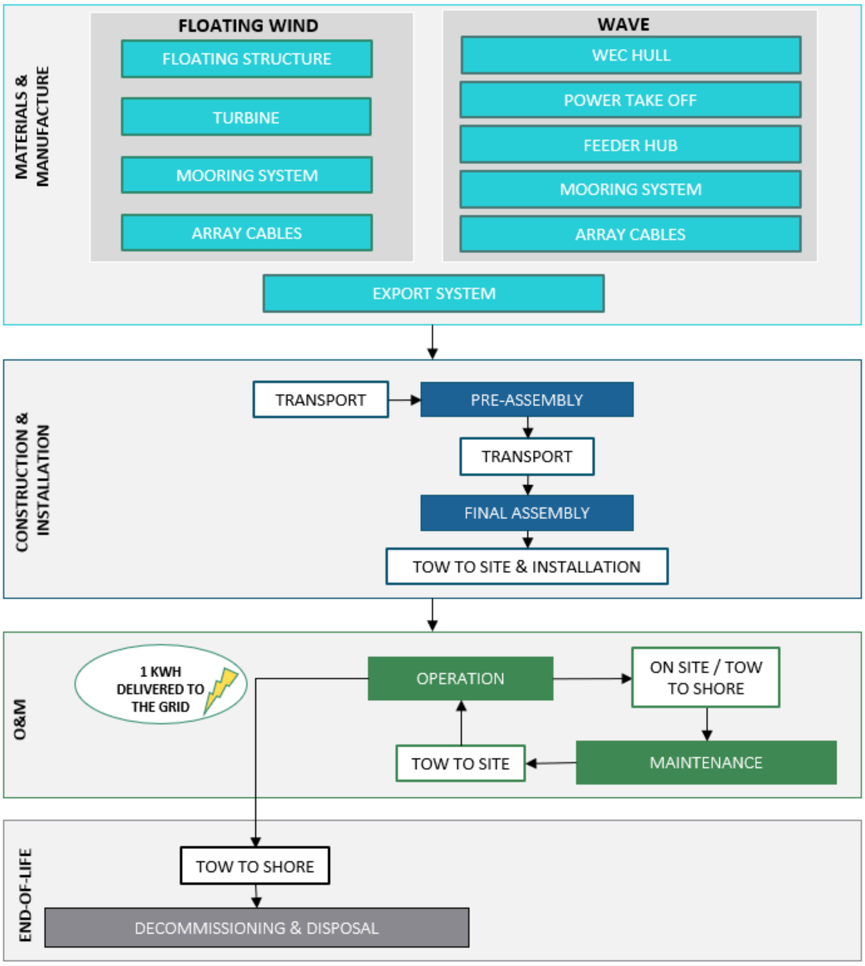

Figure 2 - Lifecycle flowchart: WEC + FOW.

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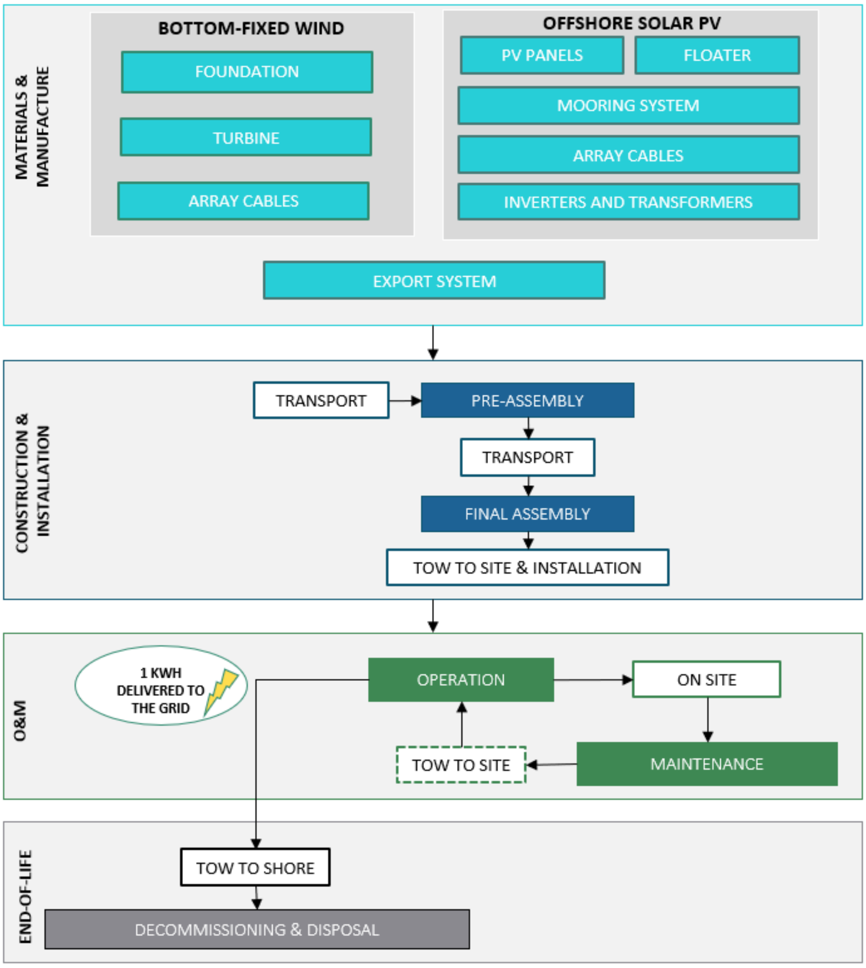

Figure 3 - Lifecycle flowchart: OSPV + BFOW.

3.2. Case Studies

Two case studies in two different regions are considered to provide a detailed regional analysis of the reference parks.

- Case Study 1: 30 MW (75 x 400 kW) wave energy array from CorPower Ocean in Portugal and next to a 300 MW floating offshore wind park composed of 20 turbines of 15 MW.

  The CorPower WEC concept features a composite buoy designed to interact with wave motion, driving a Power Take-Off (PTO). The buoy is connected to the seabed through the power conversion module and a mooring system. Standard generators and power electronics, commonly used in the wind industry, are employed. The wave device inputs were provided by CorPower and supplemented by additional data from [14].

  The FOW system consists of a semisubmersible platform moored by three catenary lines, with a wind turbine mounted on it. The wind power technology evaluated here is based on the IEA 15-240-RWT turbine [15] and the floater data inventory is drawn from [16].

The electrical architecture allows export cables and a substation to be shared between the WEC and FOW arrays for the proposed co-located offshore park.

For installation, data was gathered on the required activities and duration as well as related vessels and their specifications, including speed and fuel consumption. This information, based on literature for FOW [16] and WECs [14], was adjusted as necessary to fit the specific configurations and scenarios under consideration.

An O&M model is being developed to evaluate the most optimal strategies for the scenarios outlined in the EU-SCORES project. The model is being built on existing methodologies, utilising inputs from developers and literature [17], while addressing the actual lack of studies on co-located parks. The model assumes that preventive maintenance campaign is scheduled annually for both wind and wave technologies. The strategy assumes immediate corrective actions, with interventions initiated as soon as failures are detected. These interventions are classified as either minor or major, based on the extent of repairs needed. All corrective actions are guided by pre-assumed failure rates and modes. Tow-to-port and tow-to-site operations are only included when inspections or corrective actions at the port are deemed necessary.

At the current stage of this report, a preliminary approach is considered to guide the analysis. Given the uncertainties in the operational profile and maintenance needs of the WEC technology, preliminary assumptions were made using failure rates for key components provided by CorPower, while maintenance data of FOW were derived from the literature [18][19]. Due to the uncertainty associated with the replacement of specific components and to maintain consistency with assumptions in the literature for a more appropriate comparison, the impact of replacement parts has not been included.

The decommissioning phase is anticipated to involve activities similar to those of the installation phase. However, it is assumed that the site could potentially be repowered, allowing for the reuse of existing infrastructure such as cables and mooring systems, reducing the needs for vessel operations, as well as the demand for new raw materials in future projects.

The analysis incorporated the vessel usage time for each foreseen activity and intervention, including transit, operations, and standby, along with associated fuel consumption. Table 2 provides a summary of the total fuel consumption over the project's lifetime, categorized by the vessels required for the installation, operation and maintenance (O&M), and decommissioning phases. To estimate the impact of these marine operations in ton-kilometer (tkm) metric, the "Ferry" vessel entry from the Ecoinvent database was considered in the model and adjusted to reflect the fuel inputs in the model

Resource availability and all relevant characteristics affecting energy output for both wind and wave components were assessed to estimate the systems' potential capacity factor and energy yield.

Table 1 – Case Study 1: Wave + Floating Wind system parameters.

Parameter	**Value**
Array rating	30 MW (75 WECs x 400 kW) 300 MW (15 turbines x 15 MW)
AEP	106 GWh/year (WEC) 1116 GWh/year (Wind)
Lifetime	30 years
Location	Portugal
Distance from shore	25 km
Average water depth	80

Table 2 - Case Study 1: Wave + Floating Wind total vessel fuel consumption.

Vessel	**Fuel consumption [liters x 10^6]**		
	Installation	**O&M**	**Decommissioning**
Crew Transfer Vessel	0.23	80.25	0.23
Platform Supply Vessel	0.47		0.47
Heavy Lift Vessel	-	10.05	-
Work Vessel	-	1.32	0.47
Crane Vessel	1.24		1.24
Survey Vessel	-	0.31	-
Anchor Handler Tug Vessel	1.41	0.07	-
Cable Laying Vessel	0.16	0.13	-
Tugboat	0.93	-	0.93

Case Study 2: 300 MW of OSPV system from Oceans of Energy (670 W each panel) in Belgium and next to 300 MW bottom-fixed offshore wind park composed of 48 turbines of 6.2 MW.

The Oceans of Energy technology is designed to connect multiple floating platforms into arrays, enabling the construction of expansive solar farms at sea. The Just Above Sea (JAS) configuration was considered, with each floater supporting a set of solar PV panels mounted directly onto the platform using a specialised PV mounting system. At the time of this analysis, discussions were still underway to narrow the discussion to the final configuration to be considered for future deployments. For this study, a series-parallel topology (SPT) was adopted, where each 2.1 MW PV array is connected to central inverters and linked to 5 MVA medium-voltage transformer, ultimately feeding into a 50 MVA high-voltage transformer. Inputs for the masses and materials of OSPV components were obtained from Oceans of Energy's standardised farm system, initially based on a smaller scale. A scaling exercise was conducted to estimate requirements for larger

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arrays, representing potential future scenarios. Additional information was sourced from similar studies deemed representative. Given the challenges in accessing reliable, up-to-date data on PV module fabrication reflecting recent industrial advancements, the PV panel modelling relied on the bill of materials detailed in IEA studies [20] [21].

The BFOW system consists of a monopile foundation with a transition piece connecting to the turbine tower. The reference turbine model used in this study is the Senvion 6.2M152 Offshore [22]. Inventory data for the masses and materials of the turbine and foundation were estimated using related studies [16] [23].

For this study case, a shared export configuration, including a substation and export cables, was designed to support the combined energy outputs of both systems and take advantage of shared infrastructure.

The installation of PV floating modules, inverters, transformers, and the mooring system and cables was informed by data gathered from literature sources [24] [25] [26] [27]. For the BFOW installation, the analysis also incorporated well-established references detailing requirements and durations, as outlined in [25].

Similar to Case 1, the O&M strategy for Case 2 is based on preliminary assumptions regarding maintenance strategies. For the BFOW farm, regular inspections are primarily conducted at annual intervals, except for the array cables, which are considered to be inspected every two years. Corrective maintenance for BFOW is centred on maintenance data collected from relevant literature sources[18][19][28].

For the OSPV array, failure rates for electrical components were derived from data on onshore solar systems [29] However, due to the harsher offshore environment, it is anticipated that the failure rates for offshore systems may be higher. Given the limited experience with OSPV systems and the lack of specific data, failure rates and reliability information for moorings, floaters, and connectors were adapted from offshore wind and wave technologies. Preventive maintenance is scheduled twice per year, with operations divided into power and subsystem visits. Corrective maintenance interventions are categorised based on urgency: (i) immediate, when the intervention occurs as soon as possible in response to the component failure, (ii) deferred, when maintenance is scheduled opportunistically and combined with other preventive activities, and (iii) avoided, when corrective maintenance is not scheduled, and the failed component is neither repaired nor replaced. Nevertheless, it is important to point out that this is an initial approach and may vary as discussions with technology developers progress and more refined data becomes available. No additional material associated to component replacement was considered.

As with Case 1, this analysis adopts an equivalent approach to decommissioning, emphasising the potential for repowering. It assumes that comparable activities will be carried out for decoupling the remaining systems and transporting them to shore.

Once again, the "Ferry" vessel data from the Ecoinvent database was considered to estimate the vessels use in tkm metric. Table 4 summarises the total fuel consumption per vessel associated to the main activities assumed for installation, O&M and decommissioning phases.

Table 3 – Case Study 2: Offshore solar PV + Bottom-Fixed Wind system parameters

Parameter	**Value**
Array rating	300 MW (447,761 solar panels x 670 W) 300 MW (48 turbines x 6.2 MW)
Estimate AEP	251 GWh/year (OSPV) 1524 GWh/year (BFOW)
Lifetime	30 years
Location	Belgium
Distance from shore	50 km
Average water depth	25 m

Table 4 - Case Study 2: Offshore solar PV + Bottom-Fixed Wind total vessel fuel consumption.

Vessel	**Fuel consumption [liters x 10^6]**		
	Installation	**O&M**	**Decommissioning**
Crew Transfer Vessel	-	1726	-
Jack-up	1.3	-	1.3
Heavy Lift Vessel	0.1	8	0.1
Barge	0.02	-	0.02
Survey Vessel	-	0.01	-
Anchor Handler Tug Vessel	2.8	278	-
Cable Laying Vessel	6.2	0.1	-
Tugboat	0.1	-	0.1

Due to the sensitivity level of the design and configuration inputs, a comprehensive dataset cannot be detailed and made public.

For Case Study 1, however, from a higher level LCI the FOW system accounts for the largest portion of the mass breakdown at 86%, while the wave power devices and the common export system contribute to 8% and 6%, respectively (Figure 4). In terms of materials, steel is the most widely used, making up 89% of the system, followed by glass fibre and iron at around 3%, as shown in Figure 5. Steel is found in most structures and components, including the wind turbine tower, rotor-nacelle assembly (RNA) and floater, as well as the main WEC structure and energy conversion components like the PTO. Substation equipment, structures, and mooring systems for wind power, wave power, and export systems are also composed of significant amounts of steel.

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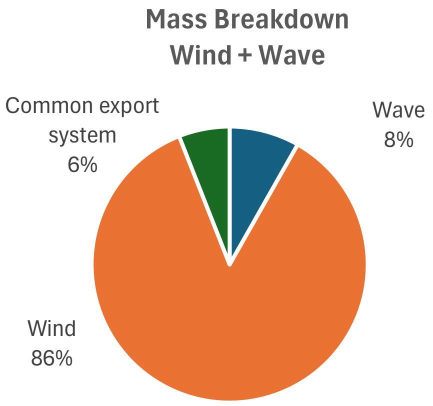

Figure 4 - WEC + FOW mass breakdown.

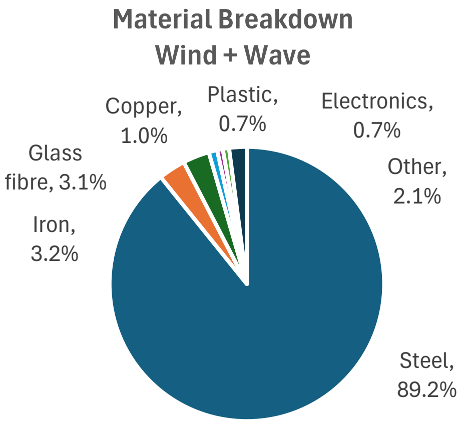

Figure 5 - WEC + FOW material breakdown.

For Case Study 2 the BFOW system accounts for 61% of the total mass, while the OSPV system represents 31% (Figure 6). In this configuration, both systems share a common offshore substation structure, along with a sufficient number of export cables to ensure efficient power transmission. This shared infrastructure represents approximately 8% of the total mass.

In terms of materials, about 60% of the total mass is attributed to steel, primarily used in BFOW foundations, towers, transformers, and substation components. Aluminium is the second most common material, accounting for around 13%, largely used in the OSPV floater structures such as PV mounting frames, and walkways, and as a component in PV modules and cables (Figure 7). While copper plays a significant role in the string cabling configuration, aluminium cables are used for the inverter input setup and submarine collection.

Plastic also plays a significant role, making up 10% of the total mass. This includes high-density polyethene (HDPE) used in OSPV floaters and other thermoplastics found in various electrical subcomponents in both systems. Additionally, glass fibre, used in the turbine blades, and solar glass, found in the PV panels, each contributes around 4% to the total mass.

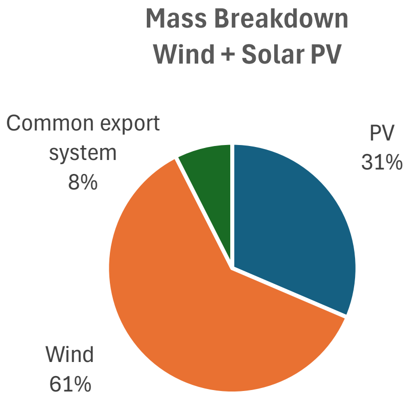

Figure 6 - OSPV + BFOW mass breakdown.

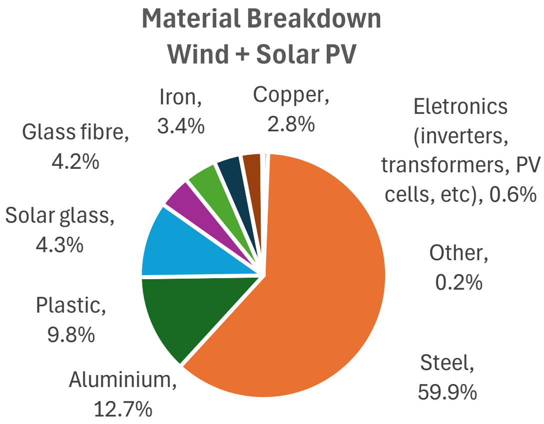

Figure 7 - OSPV + BFOW material breakdown.

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

3.3. Main findings

3.3.1. Carbon footprint

For Case Study 1, the life cycle impacts of the park composed of wind power and wave power devices indicate a GWP at 17.7 gCO_2eq/kWh. Of the total, 79% comes from the manufacturing stage, including the transportation of materials to the assembly site, 1% from devices‘ installation, 19% from O&M, and 1% from decommissioning and disposal actions, such as landfilling and incineration. While no credit is given for recycled materials, the model accounts for the avoided impacts of waste treatment, along with emissions from the recycling process itself (Figure 8).

During the manufacturing phase, the wind system is responsible for approximately 91% of the total CO_2 emissions associated with fabricating the wind farm components. This is primarily due to its larger capacity, which requires significantly more materials compared to the WEC array, as already indicated in Figure 4. Similarly, in subsequent phases, the FOW system continues to contribute a higher share of emissions than the WEC system.

The results presented in this study can be compared with LCA studies for single-source parks found in the literature. For FOW technologies, carbon intensity results range from 11.5 to 38.1 gCO_2eq/kWh, with variations attributed to local energy supply capacities, study methodologies, and minor technical differences [30]. In contrast, wave power is still an emerging technology, resulting in a wide range of carbon emissions from 23 gCO_2eq/kWh [31] to 105 gCO_2eq/kWh [32], varying according to different technological approaches. A similar concept of a wave array developed by CorPower shows a carbon footprint ranging from 25.1 to 46.0 gCO_2eq/kWh, influenced by the O&M strategies employed [14].

For comparison purposes, assessing each configuration of EU-SCORES as a single-source installation, rather than co-located, it shows carbon footprints of 15 gCO_2eq/kWh for FOW and 33.6 gCO_2eq/kWh for a WEC array. These variations from the mentioned previous studies likely stem from park size, variations in site characteristics, specific O&M strategies, and uncertainties in assumptions. However, this comparison emphasises the potential advantages of co-locating wave power with offshore wind power projects. By sharing infrastructure and increasing total energy output, the combined approach can dilute the carbon intensity of the overall project. Additionally, WEC technology could benefit from the design and operational advancements gained from experience in commercial projects, further reducing carbon impacts over time.

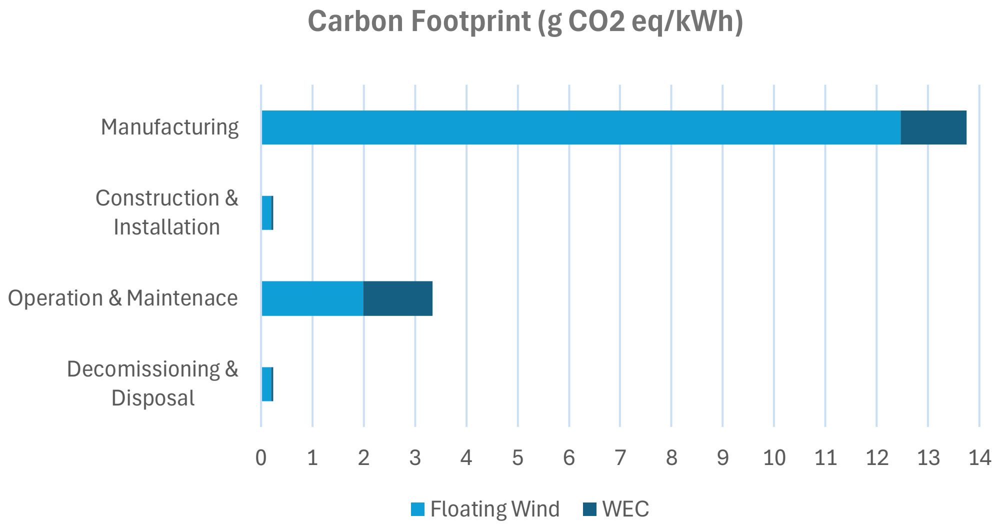

Figure 8 - Case Study 1: Carbon footprint per phase and technology.

In Case Study 2, the carbon footprint of the co-located BFOW and OSPV systems is estimated at 21 gCO2eq/kWh. Approximately 80% of these emissions are from the manufacturing phase and 12% are attributed to O&M. The impact of transportation from manufacturing to the assembly site is less significant when considering the anticipated development of local supply chain hubs (Figure 9).

Similarly, in Case Study 1, the potential for repowering the site of Case Study 2 is considered, which reduces the environmental impact of decommissioning by avoiding the need to remove the mooring system and certain electrical cables. Additionally, although no recycling credits are included in the final results, the avoided impacts from recycling materials further reduce the carbon footprint. This makes the decommissioning and disposal phase have a lower impact (3%) compared to the construction and installation (C&I) phase (5%).

As a consequence of the larger requirements for the BFOW system, as indicated in Figure 4, its manufacturing phase has a slightly higher share of the environmental impact (54% of overall manufacturing results) (

The Case 2 results reflect the system's deployment in a Belgian site, as outlined in the EU-SCORES project. While Belgium's temperate climate provides limited solar irradiation, resulting in modest power output per MWp of installed PV capacity, the potential for solar energy production is significantly higher in southern European regions such as the Mediterranean. In these areas, solar output could increase approximately 50% compared to Belgium's [34], reducing significantly the individual carbon footprint of the solar system. This underscores the strong standalone potential of solar energy, particularly in sun-rich regions.

However, in the context of multi-source parks, site selection introduces critical trade-offs. While solar resources improve significantly in southern Europe, wind resources in these regions generally tend to be reduced compared to those in the North Sea. For example, a 300 MW wind farm (50 turbines of 6 MW each) located in Greece, Croatia, and Cyprus would experience estimated annual energy

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production (AEP) reductions of approximately 23%, 54%, and 68% [35], respectively, relative to North Sea wind availability.

These findings highlight the complexity of designing co-located systems. The OSPV system alone contributes approximately 49% of the total carbon emissions in the analysed co-located project in the Belgian site. Further comprehensive analyses integrating technical, economic, and environmental factors are essential for optimizing site selection and system configurations. Such an approach could unlock the full potential of multi-source renewable energy systems, enabling sustainable and site-specific solutions that maximize benefits while addressing resource variability.

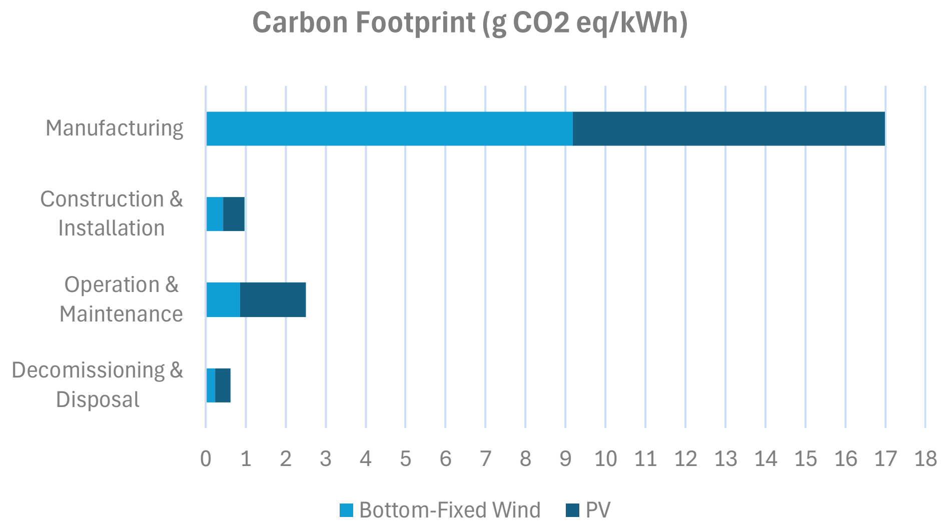

Figure 9). In contrast, the O&M phase has a greater impact on the OSPV system (66% of overall O&M results). These estimates are based on a preliminary O&M model developed under Task 5.1 in the EU-SCORES project, which evaluates maintenance strategies for multi-source energy parks at the same scale as addressed in this report. The current assumption on the O&M strategy combines preventive and corrective actions for both technologies, relying primarily on documented or estimated failure rates due to the lack of real-world data for some components. BFOW technology benefits from its maturity, with more widely documented failure rates, better-discussed maintenance strategies, and predictable repair times. On the other hand, the O&M impact for OSPV is assessed more conservatively due to the limited operational and failure data currently available in the literature. The maintenance strategy is also considered to reduce the degradation rate of the panels and maintain optimal energy production, which ultimately helps minimise the carbon emissions per unit of electricity delivered to the grid.

Using the same initial assumptions, the impact assessment of a single-source project estimates the OSPV array's carbon footprint at approximately 75 gCO_2eq/kWh. This value is notably higher than that of the multi-source configuration, highlighting the benefits of resource-sharing and increased energy production in combined BFOW and OSPV parks. While this figure is close to the 73

gCO_2eq/kWh reported in previous studies [33], the direct comparison remains challenging due to the limited number of LCA studies specific to OSPV. Furthermore, differences in system configurations, deployment locations, solar resource availability, PV technologies, and analytical assumptions can create inconsistencies. Additionally, the variation in background data sources makes it difficult to align these results directly. Despite these challenges, the breakdown of carbon footprints across life cycle stages appears consistent with the trends observed in other studies, suggesting some alignment in the broader environmental impacts of OSPV systems.

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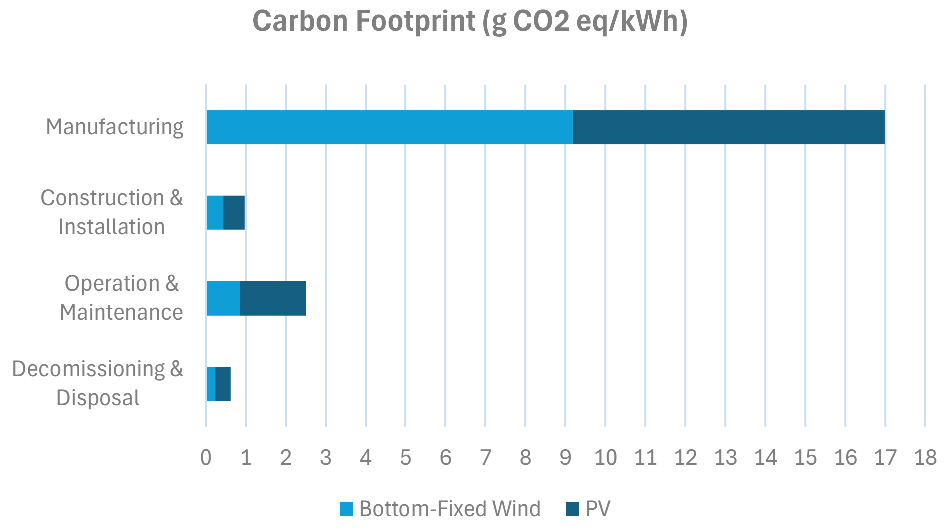

Figure 9 – Case Study 2: Carbon footprint per phase and technology.

Besides the carbon dioxide emissions per kWh produced, the carbon payback time (CPBT) is another key metric for comparing the proposed technologies with traditional energy sources. CPBT represents the time needed for a system to offset the carbon emissions generated throughout its life cycle. This is compared against the emissions from the energy grid if conventional sources were used.

In these scenarios, the CPBT for Case 1 and Case 2 are approximately 1.4 and 2.9 years, respectively. The difference between both cases relies not only on the associated carbon footprint of each project but also on the share of the energy mix for electricity generation in Portugal and Belgium. However, the current inventory does not reflect the recent increase in renewable energy within both countries' energy mixes. This suggests that the estimated avoided carbon emissions might be understated compared to what current RE contributions would indicate.

For instance, from 2019 to 2023, Portugal increased its renewable energy share in electricity generation by about 28% [36], while Belgium's share rose by 42% [37]. This shift towards renewables reduces the carbon intensity of electricity generation, potentially extending the timeframe for full project carbon offsetting. Nonetheless, the CPBT remains well below the project's expected lifespan, supporting progress toward net-zero goals.

To evaluate the benefits of multi-source energy parks, the CPBT of standalone technologies was compared under identical conditions. For the technologies in Case 1, the FOW and WEC showed CPBTs of 1.2 years and 2.9 years, respectively. In Case 2, BFOW achieved a CPBT of 2.6 years, while OSPV required 13.3 years. These findings highlight the significant advantages of multi-source parks in reducing CPBT compared to certain standalone technologies, emphasising their potential for improved environmental performance. While these comparisons provide useful context, it is important to note that the results are not directly comparable with individual LCA studies on electricity generation from renewable sources, due to differences in the scope and methods used to assess life cycle impacts in the various studies.

3.3.2 Energy footprint

From the data of inventory considered, the life cycle analysis of Case 1 shows a cumulative energy demand (CED) of 237 kJ per kWh of electricity delivered to the grid, while Case 2 requires about 310 kJ per kWh. The higher energy demand in Case 2 is largely due to the energy-intensive processes involved in manufacturing PV panels.

In addition to the type and scale of industrial processes, the energy demand is influenced by the location of component manufacturing and the energy mix of the countries where production occurs. Variations in energy mix composition, efficiency, and the availability of renewable energy sources within local energy infrastructures can significantly affect the total energy required to produce and deploy the system.

Evaluating the primary energy factor (PEF) reveals that the ratio between the primary energy required by the proposed system components and operation and the final electricity output is 0.07 and 0.09 for Case 1 and 2, respectively. It demonstrates the system's lifecycle energy efficiency, emphasising its performance relative to other energy sources, especially when compared to the EU-27 PEF for electricity, calculated as 2.1 in 2018. However, it is essential to consistently update PEF calculations at the European level to reflect the evolving energy mix for power generation in many countries.

Similar to CPBT, the energy payback time (EPBT) refers to how long it takes for the power plant to supply the same amount of energy that was used for the system deployment. For Case 1 and Case 2, these periods are about 2.0 and 2.6 years, respectively.

Looking at future perspectives, CED can be reduced mainly by lowering the energy requirements during manufacturing, installation, and other life cycle stages of a system. This can be achieved through energy-efficient manufacturing processes, such as innovations in PV manufacturing, which is known as energy learning [38]. These ongoing industrial innovations hold great potential for creating less energy-intensive technologies. While this report could not incorporate such advancements due to current limitations in data availability on industrial processes, their future integration remains a promising opportunity for enhancing sustainability.

Material optimisation is also a critical factor, involving designs that minimise material usage, reduce reliance on energy-intensive materials, or incorporate recycled or alternative materials with lower embodied energy.

Localised manufacturing is another effective strategy, as producing components closer to the installation site reduces energy use related to transportation. With these reductions in CED, the EPBT decreases as well, allowing the system to offset its initial energy investment more quickly.

With CED reductions, the EPBT tends to decrease as the system can offset the lower initial energy investment more quickly.

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4. Socio-economic impact focussing jobs

The socio-economic impact of arising ocean energy capacities including BFOW, OSPV, and wave power in Europe is focused on related jobs as a most important indicator of the value of ORE capacities added to the European energy system as part of the energy transition linked to the European Green Deal.

In the following sections, the methods are introduced for the underlying energy system transition modelling, the jobs projections based on the EF approach, the applied scenarios, and the main findings in the context of related projections.

4.1 Methodological approach

4.1.1 Methods energy system modelling

The energy transition scenarios of the European energy system were performed with the LUT Energy System Transition Model (LUT-ESTM) [2] [39], which is a linear optimisation tool to obtain cost-optimised scenarios for the entire energy system. It has a full year of hourly temporal resolution, geographical multi-node design, dispatch optimisation methodology, and single objective investment optimisation. The model has been gradually developed from the power sector to the integration of power and heat, transport, industry, and desalination sectors. In the case of fuels, the model simulates the production of electricity-based e-fuels (gaseous and liquid) based both on green e-hydrogen and CO_2 from point source capture of sustainable CO_2 sources and direct air capture units, which are part of the power-to-X concept as an integral part of the arising Power-to-X Economy [40]. LUT-ESTM with its comprehensive list of energy technologies (over 150 different energy technologies across different sectors, end uses and applications) is ranked amongst the most robust tools for the analyses of long-term energy transition pathways and it is currently one of the most widely used tools for research on the transition to 100% RE systems. The model allows for the modelling of energy transition pathways considering a technology-rich portfolio. 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. [2]. The simplified scheme of an integrated energy system as modelled with LUT-ESTM is shown in Figure 10 [39].

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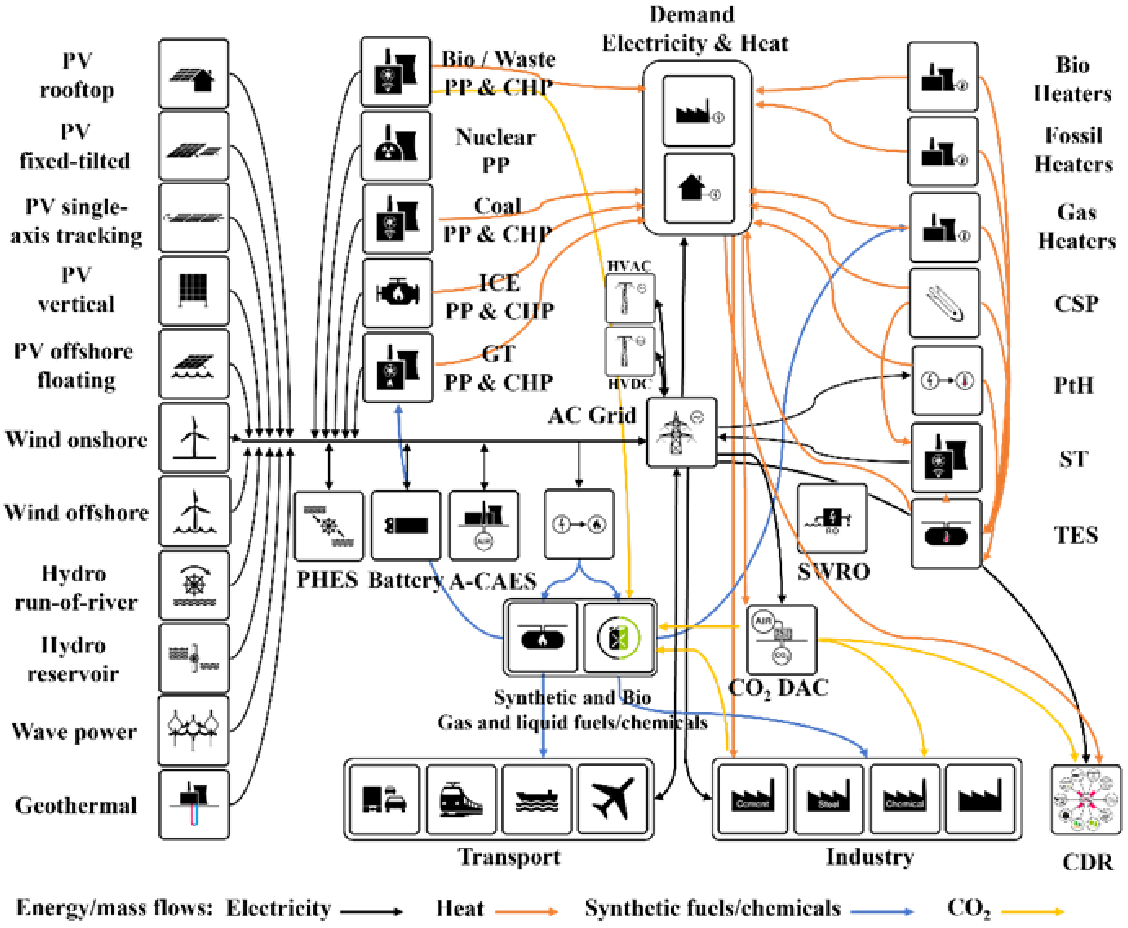

Figure 10 - LUT-ESTM integrated energy system structure scheme.

LUT-ESTM covers ORE technology, including BFOW, OSPV, and wave power based on the respective energy potential, e.g. for wave power [41], and considered the electricity generation across the different technologies based on the installed capacities, and the respective energy yield following the applied scenarios. The cost-optimised energy system transition modelling was conducted in 5-year steps with each step represented with a reference year simulated in hourly resolution to ensure that supply and demand are balanced for every hour.

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.

To guarantee the best supply and demand balance and the lowest total costs for the system, the model develops the scenarios using optimisation for the energy system. The sum of costs, such as annualised capital expenditures, operational expenditures, fuel costs, GHG emission costs, and ramping costs, are considered to optimise the total annualised cost of the entire energy system based on assumptions in techno-economics and technologies. Assumptions were made about future technological development, the use of different technologies, economic development, cost changes, and changes in consumer behaviour. ORE is considered to include the combination of offshore wind power, wave power, and OSPV. The weather data from 2005 is considered as a reference in this study, which represents a resource year around the average for a solar PV and wind power-based energy system in Europe.

4.1.2 Regional structure of Europe for energy system modelling

In order to achieve robust energy system analyses for Europe and correspondingly for the 27 European Union (EU) member states, a two-step modelling approach is adopted [42]. The first step represents the hierarchical approach to energy system optimisation. The second step enables further disaggregation of the regional results to retrieve the country-specific results for representative energy transition pathways.

STEP 1: Europe is categorised into four macro-regions, which are Nordic, West, Central and Southeast as shown in Figure 11 [43]. Energy transition pathways in six distinct scenarios are simulated for these interconnected macro-regions of Europe and the results serve as a guiding reference for the next step. The four macro-regions are further comprised of 19 regions across Europe. Iceland is not connected to the integrated European power grid and modelled as an energy island. The composition of the four macro-regions and the corresponding 19 regions of Europe plus Iceland are as follows:

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

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

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

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

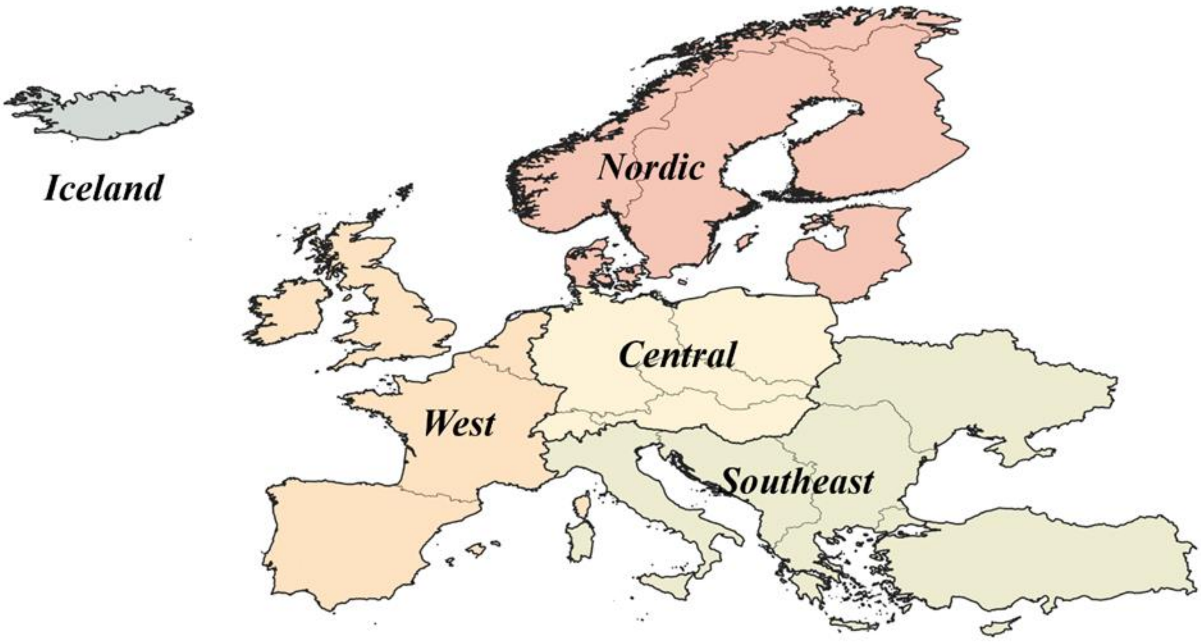

Figure 11 - Europe four macro-region division.

STEP 2: Europe is further disaggregated from four macro-regions to 19 regions across Europe, plus Iceland. Wherein some of the smaller countries have been merged with larger countries to form sizeable local regions. This reflects the highly interconnected energy infrastructure across Europe, as the energy transition is envisioned on a regional basis. The energy system transition is simulated for the whole of Europe, which is structured into 20 interconnected regions. These interconnections follow the interconnected patterns of the 5 macro-regions, as electricity is predominantly exchanged within regional electricity pools. The 20 regions are interconnected with optimised transmission networks, e-methanol and Fischer-Tropsch fuels can be exchanged between regions and, Iceland remains as an isolated region. Cost-optimised transition pathways for an integrated European energy system are modelled for three distinct scenarios.

For the socio-economic impact analyses for jobs the scenario results on the level of the macro-regions have been used.

4.1.3 Methods jobs projection

Net employment impact is one of the key socio-economic footprints to measure the efficacy of the energy transition. Jobs will be created across the different value chain steps including manufacturing, construction and installation, operation and maintenance, decommissioning, and fuel supply, while the latter is not relevant for ORE. Likewise, jobs are expected to be lost in some energy sectors, predominantly in the fossil fuels value chain. Jobs created during the global energy transition from 2020 to 2050 are estimated utilising the EF approach, which was adopted from Ram et al. [44]. One of the main advantages of the EF approach is that it can be modified for specific contexts, as well as applied over a range of energy scenarios. In fact, this is an analytical approach for estimating direct energy jobs corresponding to the value chain during the energy transition across the different regions, which is based on a dynamic approach with learning effects of technologies through the transition years and change in labour intensities across the different regions involved in the analysis. This approach was considered over others for its effectiveness in estimating direct employment associated with energy technologies through the value chain. Thus, the total direct jobs are a sum of jobs in manufacturing, construction and installation, operations and maintenance, decommissioning of energy plants at the end of their lifetimes, and transmission and distribution of electricity. Lavidas [5] analysed the jobs creation on the case of Greece and identified a breakdown of the jobs in the integrated manufacturing, construction and installation phase to electromechanical (49%), structure (27%), project management (2%), grid connection (4%), installation (13%), and mooring (5%) for 10 jobs/MW in total for these value chain elements and for year 2030 conditions.

Figure 12Figure 12 presents an overview of the methods utilised to estimate jobs created during the energy transition from 2020 to 2050 across the value chain associated with different energy technologies categorised into electricity, heat, and storage. Some of the parameters considered in the estimation of the jobs creation potential of various energy technologies are the number of jobs per unit of installed capacity, separated into manufacturing, construction and installation, operation and maintenance, and decommissioning. It also covers jobs per unit of primary energy for fuel supply and jobs per unit of transmitted and distributed electricity. Decline factors are linked to the decline in capital expenditure (Capex) and operational expenditure (Opex) of the different energy technologies, as jobs creation can be expected to reduce as technologies and production of these technologies mature. This maturing occurs because of the growing experience and volume in the energy industry, which applies mainly to renewables, storage, and e-fuels production, which are captured by the change of Capex and Opex. A detailed description of the methods is presented in Ram et al. [44].

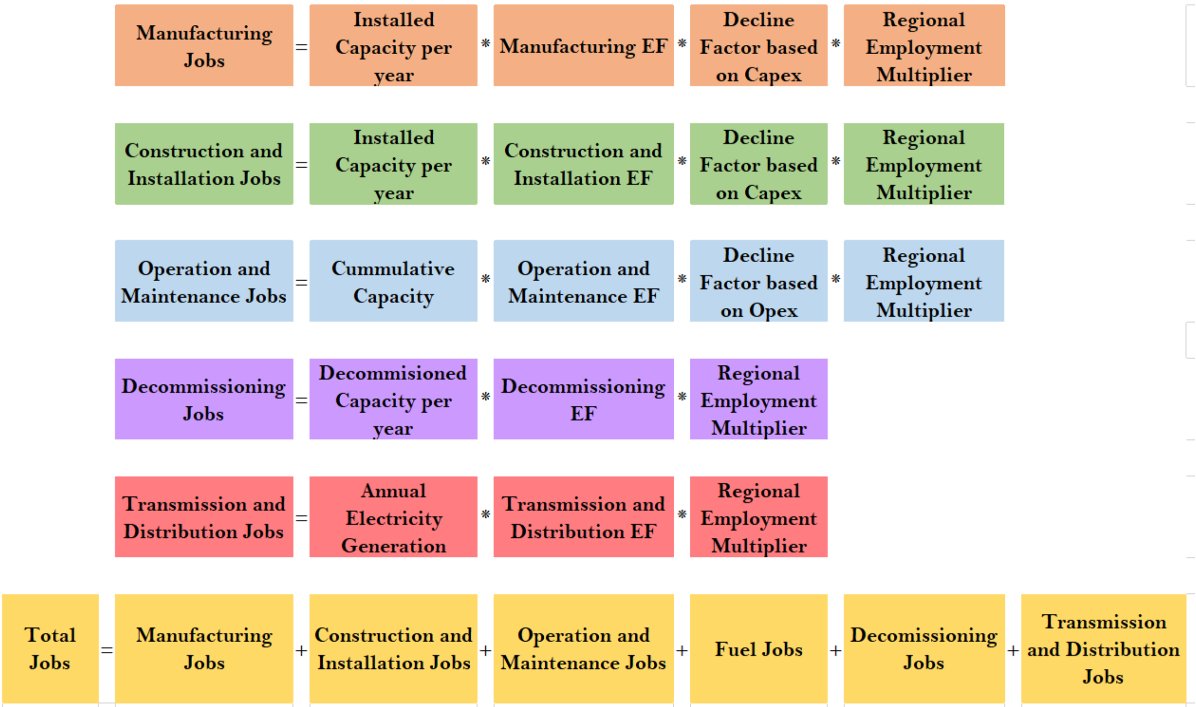

Figure 12 - Method for estimation of jobs creation during the energy transition. Abbreviations: EF, Capex, and Opex.

The EF approach can be modified for specific contexts, as well as applied over a range of energy scenarios for different regions across the world as highlighted for Jordan [45], West Africa [46], Ethiopia [47], and South Africa [48]. Moreover, the approach allows for modifications in the methods to capture the dynamic nature of jobs creation through the transition years and the inclusion of different dimensions of regional trade and labour productivity, as considered for Europe. In this report, the methods from Ram et al. [44] have been adopted for the estimation of jobs and net employment analysis across the energy system including the transmission and distribution of electricity. Moreover, the factors that influence direct energy jobs and net employment analysis, such as labour productivity, and EFs of key energy technologies have been derived for Europe.

Some of the key influencing factors that have been considered to reflect the local conditions across Europe:

- Regional Employment Multipliers: the regional employment multipliers for Europe are adopted to account for the differential labour-intensive economic activities in Europe in comparison to the different regions across the world. Since the EFs considered are normalised for the Organization for Economic Co-operation and Development (OECD) countries, the regional employment multipliers need adjustment for differing stages of economic development through the transition up to 2050. In general, the lower the cost of labour in a country, the greater the number of workers that will be employed to produce a unit of any particular output, be it manufacturing, construction or services. Average labour costs are closely associated with gross domestic product (GDP) per capita, a key indicator of economic

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development [49]. The projected change in GDP per capita derived from GDP growth with corresponding population growth is factored to adjust the regional employment multipliers for Europe over time. The method from Rutovitz et al. [50], along with labour productivity data from the International Labour Organization (ILO) [51] was used to determine the regional employment multipliers for Europe. Table 5 indicates the regional employment multipliers from 2020 to 2050 for Europe.

Table 5 – Regional employment multipliers for Europe.

	2020	2025	2030	2035	2040	2045	2050
Europe	1.08	1.10	1.13	1.17	1.19	1.20	1.22

- Local manufacturing factor: this represents the percentage of local manufacturing across the various regions of Europe. As manufacturing of mainly RE, storage and power-to-X technologies is quite unevenly distributed across the world, many regions still rely on imports, as is the case in Europe (10%). The import shares and corresponding import regions are set according to current practices, which are derived from trade flows in the energy system (predominantly renewables) and industrial activity in corresponding major regions adjusted to indicators from UNIDO [44]. Currently, the more industrialised regions of Northeast Asia, Europe, and North America along with Southeast Asia and South Asia dominate the global exports of RE technologies. This report assumes that Europe will reach 100% of local manufacturing by 2050. Table 6 presents the local manufacturing shares, gas, oil, and coal production for Europe up to 2050.

Table 6 - Manufacturing shares, gas, oil, and coal production for Europe from 2020 to 2050.

Europe	2020	2025	2030	2035	2040	2045	2050
Manufacturing	90%	90%	90%	100%	100%	100%	100%
Gas production	10%	10%	10%	10%	10%	10%	10%
Oil production	10%	10%	10%	10%	10%	10%	10%
Coal production	80%	80%	80%	80%	80%	80%	80%

- Transmission and distribution jobs: these include all the jobs associated with the transmission and distribution of electricity. In general electrification of the different energy sectors leads to greater shares of electricity in the final energy demand, which implies greater needs for transmission and distribution infrastructure across Europe. Therefore, transmission and distribution jobs are linked to the total electricity generated in the system, which are expressed as jobs per unit of electricity generated. This factor is used to extrapolate the transmission and distribution jobs in the future with local labour productivity considerations in the case of Europe. Table 7 presents the jobs in electricity transmission and distribution across Europe and subregions.

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Table 7 - Jobs in electricity transmission and distribution across Europe and subregions.

	2020	2025	2030	2035	2040	2045	2050
Europe-Nordic	53,432	79,731	281,436	362,694	388,293	400,689	412,994
Europe-West	162,032	246,878	487,844	737,038	946,120	1,066,120	1,179,050
Europe-Central	124,306	137,571	236,652	297,859	324,173	344,139	358,176
Europe-Southeast	129,861	161,019	197,416	371,812	434,463	475,573	522,549
Europe	469,631	625,199	1,203,348	1,769,403	2,093,049	2,286,522	2,472,769

- Employment factors: each phase of ORE build-out and operation, i.e. manufacturing, C&I, O&M, and decommissioning, includes specific EFs in the scenarios and calculations. Table 6 presents these EFs for the three technologies of BFOW, OSPV, and wave power. The values for BFOW power can be found in Ram et al. [44] and Rutovitz et al. [50]. The values for OSPV and wave power are aligned to offshore wind power and discussed with stakeholders for validation, whereas the EF values for wave power are in line with the existing literature [4] [5]. The values for OSPV may appear not aligned to BFOW and wave power, however, the EF values of OSPV and BFOW are aligned to 2015 values, while wave power is aligned to 2025 values for the decline factors according to Capex and Opex as detailed in Table 9 and

- Table 10 which leads to ratios in particular for OSPV and wave power that are confirmed by respective stakeholders.

Table 8 - EFs considered in the jobs calculations.

	Construction time	Manufacturing	C&I	O&M	Decommissioning
unit	[years]	[Job-years/MW]			
Offshore wind bottom fixed	4.00	15.60	8.00	0.20	3.00
Offshore solar PV	2.00	6.70	26.00	0.70	1.60
Wave power	3.00	12.50	8.00	0.40	3.00

- Capex and Opex: In the scenarios, Capex and Opex are key financial metrics. Capex represents the upfront investment costs for constructing and installing ORE infrastructure, including equipment, facilities, and installation processes. Opex covers the ongoing costs of operating and maintaining the energy systems over their lifespan. Table 9 and

- Table 10 include the Capex and Opex values for BFOW, OSPV, and wave power. The Capex and Opex values are taken from Ram et al. [44], Lopez et al. [52] and Satymov et al. [41].

Table 9 - Capex values for BFOW, OSPV, and wave power considered in the scenarios.

[€/kW]	2020	2025	2030	2035	2040	2045	2050
Offshore wind bottom fixed	2880	2700	2580	2460	2380	2320	2280
Offshore solar PV	1425	1110	765	474	414	368	332
Wave power	21,000	5200	2800	2300	2100	1900	1800

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Table 10 - Opex values for BFOW, OSPV, and wave power considered in the scenarios.

[€/(kW$_{el}$·a)]	2020	2025	2030	2035	2040	2045	2050
Offshore wind bottom fixed	92	84	77	71	67	58	52
Offshore solar PV	25.9	20.2	13.9	9.5	8.3	7.4	6.6
Wave power	1057	221	77	58	50	46	43

4.2 Scenarios for energy system modelling and jobs projection

The energy transition across Europe is explored in six distinct scenarios with the following boundary parameters and conditions: The reference BPS sets the 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 and wave power growth (lowOS and highOS scenarios variations) and the impact of OSPV introduction (FPV scenarios variations), and the sixth scenario tests the impact of an accelerated transition with carbon neutrality reached by 2040.

Best Policy Scenario (BPS): In this scenario, the European energy system is set on a current ambition pathway. The climate neutrality vision of the EC [53] by 2050 is achieved, as GHG emissions will be zero by 2050 and reduced by at least 55% in 2030 below 1990 levels. The offshore wind power capacity is set to reach 90 GW across Europe by 2030, 180 GW by 2040, and 270 GW by 2050. Similarly, the wave power capacity for Europe is set to reach 1.5 GW by 2030, 15 GW by 2040, and 60 GW by 2050. No OSPV is considered as a forced capacity, while build-out as part of a least-cost solution is allowed.

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

Best Policy Scenario with high ORE (BPS_highOS): Follows the BPS targets, the targets for offshore wind power and wave power introduction are increased. The offshore wind power capacity is set to reach 90 GW across Europe by 2030, 225 GW by 2040, and 450 GW by 2050. Similarly, the wave power capacity for Europe is set to 1.5 GW by 2030, 20 GW by 2040, and 100 GW by 2050. No offshore solar PV is considered.

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

Best Policy Scenario with OSPV (BPS_FPV): follows the BPS targets, however, additional OSPV capacities are introduced. Most of OSPV is set to be installed in

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Western Europe in the North Sea reflecting the area deficit in the region. OSPV capacity for Western Europe and all Europe are set to 1 GW and 1.5 GW in 2030 respectively, 20 GW and 30 GW by 2040, and 100 GW and 150 GW by 2050.

Best Policies Scenario - 2040 (BPS-2040): In this scenario, the European energy system is set on an accelerated energy transition pathway. Increased efforts by all member states to drive the renewable energy share in final energy demand across the EU to 56% in 2030 and 100% by 2040 is envisioned. This scenario enables energy-related CO_2 emissions reduction of at least 65% compared to 1990 levels, which is compatible with the climate target of limiting temperature rise to below 1.5°C as defined in the Paris Agreement.

The offshore wind power capacity is set to reach 90 GW across the EU and across Europe by 2030 and 270 GW by 2040. Similarly, wave power capacity for all Europe is set to 1.5 GW by 2030 and 60 GW by 2040. No OSPV is considered.

4.3 Main findings

Error! Reference source not found. presents the cumulative installed capacity of BFOW, OSPV, and wave power across Europe by region. Except for OSPV in 2050 in the two most progressive scenarios with OSPV the Southeast region shows virtually no installation in none of the technologies, while the West leads with the highest capacity among all areas for all technologies. In the BPS-lowOS scenario, there is minimal change in capacities across all four regions by 2050. For BFOW, as shown in **Error! Reference source not found.**a, the Central region is expected to see the highest growth by 2030, reaching 66 GW in all other scenarios, compared to 22 GW in the Western region. However, in the following decades, while the Central region adds only 22 GW more, the Western region is projected to experience the most significant growth, reaching 89 GW and 134 GW in the BPS and BPS_highOS scenarios, respectively. In the most progressive scenario, BPS_2040, this value rises to 176 GW. These capacities, 134 GW and 176 GW, represent the highest sustainable requirements for BFOW in the Central and Western regions. By 2050, all scenarios converge on these capacities for the respective regions, while the Nordic region sees 186 GW installed in the BPS_highOS and BPS_highOS_FPV scenarios. For OSPV, depicted in **Error! Reference source not found.**b, although the projections for 2040 are modest, a significant increase is anticipated by 2050 in the BPS_FPV and BPS_highOS_FPV scenarios, primarily concentrated in the Nordic and Western regions. Regarding wave power, as shown in **Error! Reference source not found.**c, all scenarios except BPS_lowOS project similar installations across Europe from 2020 to 2030, reaching approximately 1.5 GW. A significant increase is projected in the following decade, with the BPS_2040 scenario achieving the highest capacity at 60 GW. The BPS_highOS and BPS_highOS_FPV are projected to reach 25 GW, while the BPS and BPS_FPV follow with 15 GW each. By 2040-2050, scenarios with high ORE installations are expected to reach a total of 100 GW, distributed with 85% in the West, 10% in the Nordic region, and 5% in the Central region. In the BPS and BPS_FPV, the capacity increases by 300%, reaching 60 GW by 2050, with 51 GW of this in the West region. The BPS_2040 scenario projects no additional installations beyond this period.

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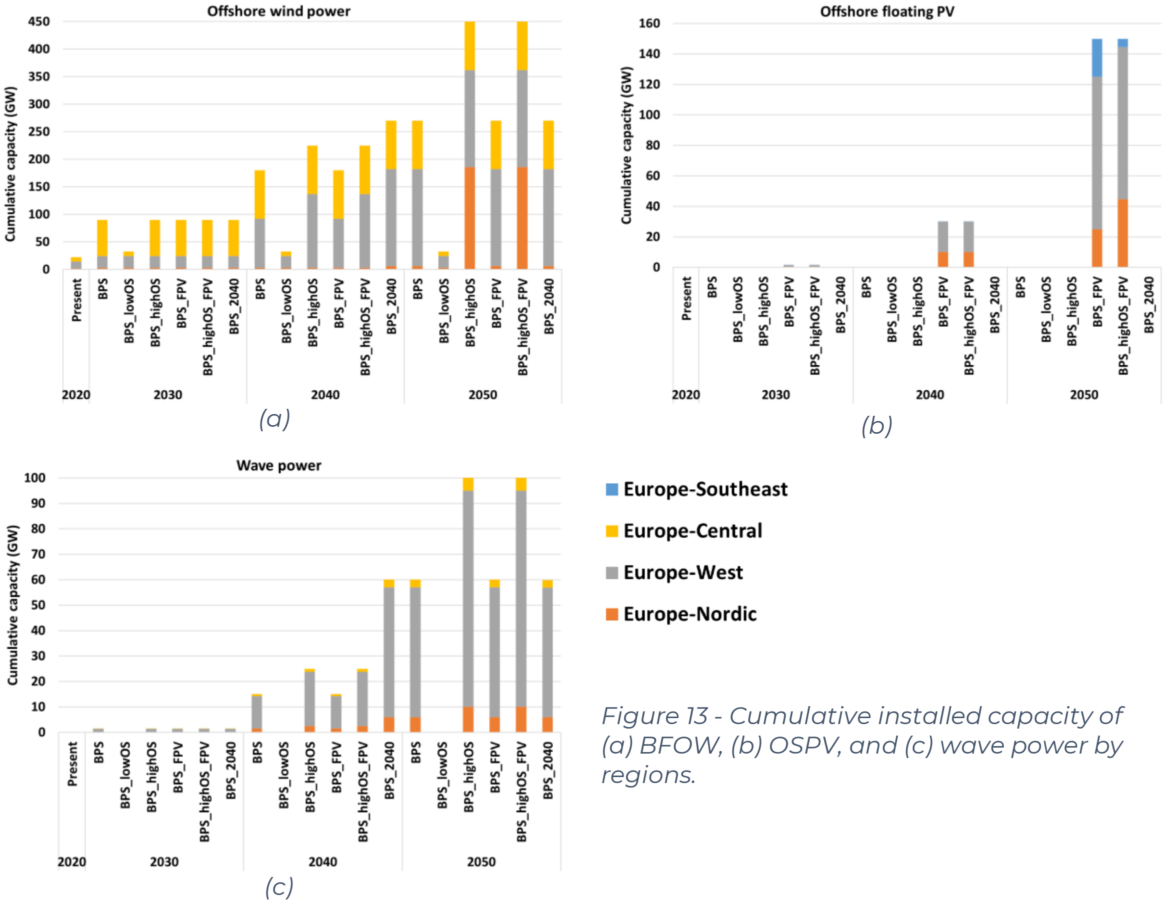
Figure 14 also shows the cumulative installed capacities for the different ocean energy technologies in different scenarios. The figure indicates despite a similar projection for 2030 there would be huge differences between installations in 2050 which will reach from 92 GW in 2030 to 550 GW and 700 GW projected by BPS_highOS and BPS_highOS_FPV respectively in 2050.



(a)

(b)

(c)

Figure 13 - Cumulative installed capacity of (a) BFOW, (b) OSPV, and (c) wave power by regions.

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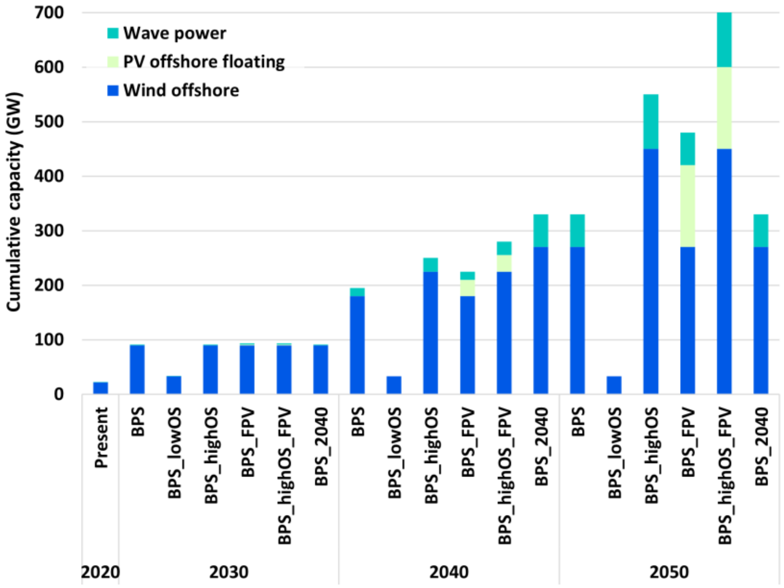
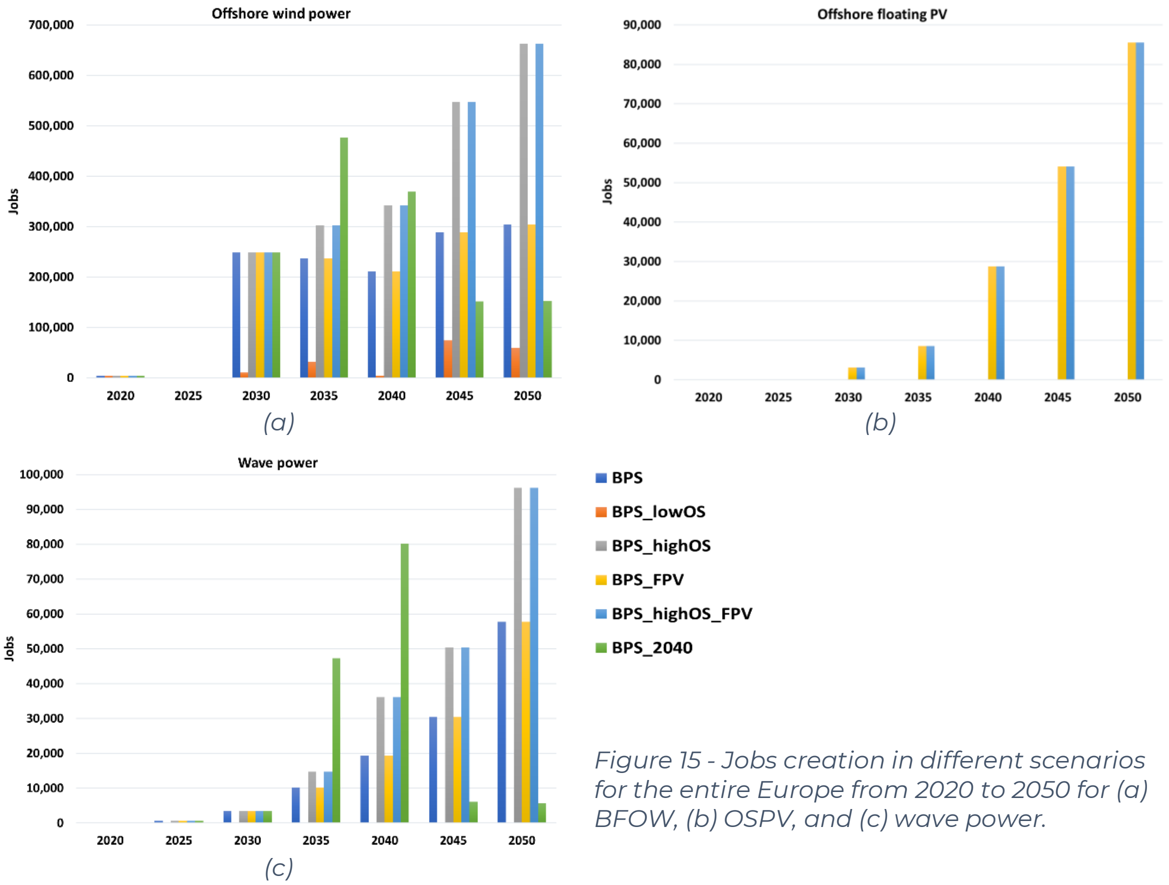


Figure 14 - Cumulative installed capacity for BFOW, OSPV, and wave power by scenarios during the transition period.

Figure 15 shows jobs creation projections across Europe from 2020 to 2050 in various scenarios. The BPS and BPS_FPV scenarios for BFOW estimate approximately 249,000 jobs by 2030, decreasing slightly to around 211,000 by 2040, before rising to 304,000 jobs by 2050. These scenarios, however, do not project any jobs creation for OSPV in the coming decades. For wave power, jobs creation begins with 650 jobs in 2025, increasing steadily to 58,000 by 2050. In the BPS_lowOS scenario, BFOW sees minimal job projections, with 32,000 jobs in 2025, 74,000 in 2045, and 59,000 by 2050. This scenario does not project jobs creation for OSPV or wave power due to the absence of installations. The BPS_highOS and BPS_highOS_FPV scenarios show steady growth in both BFOW and wave power, projecting 663,000 and 96,000 jobs, respectively, by 2050. OSPV jobs creation is only projected in the BPS_highOS_FPV scenario, matching the BPS_FPV projections, as both share the same assumptions for OSPV. In the most ambitious scenario, BPS_2040, jobs creation for BFOW peaks at 477,000 in 2035, followed by a gradual decline to approximately 153,000 by 2050. This scenario does not project any jobs for OSPV. For wave power, it anticipates that 86.7% of installations will occur between 2030 and 2040.



(a)

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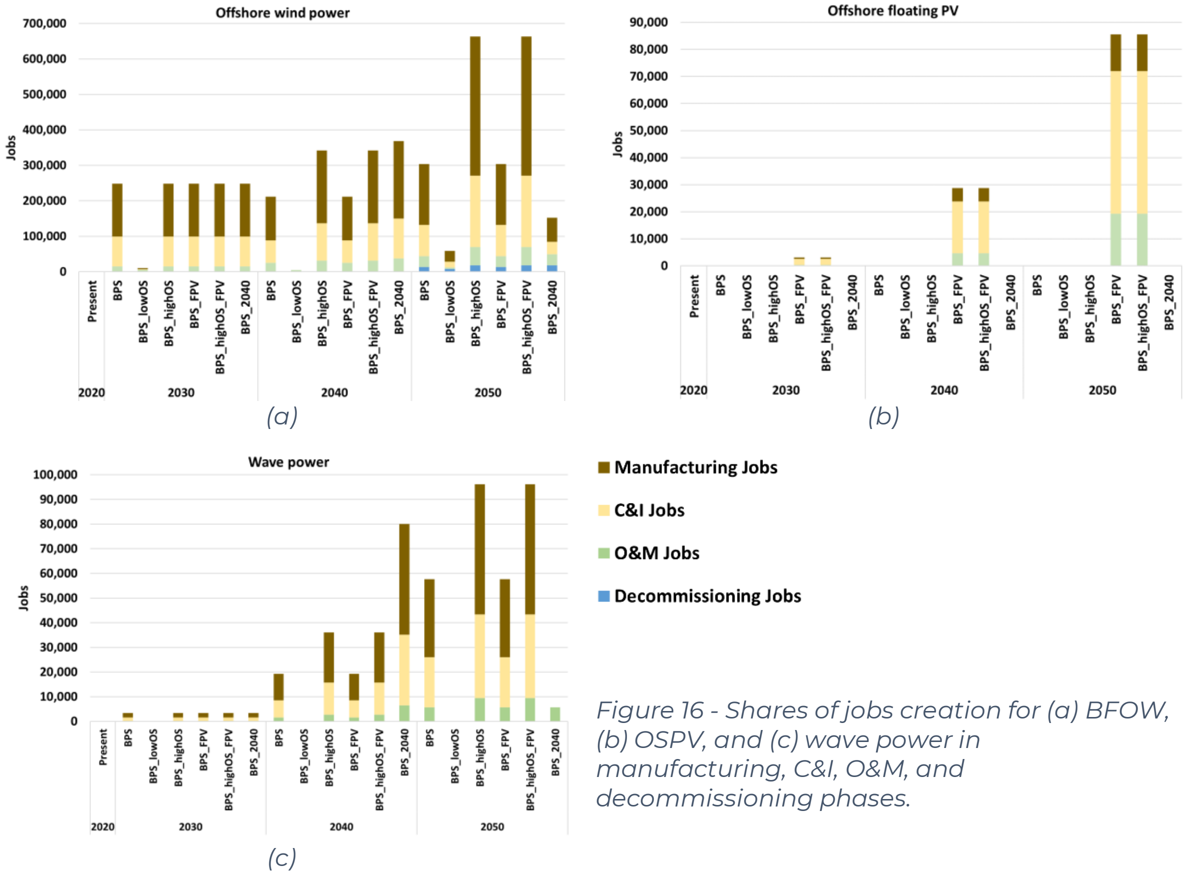
(c)

Figure 15 - Jobs creation in different scenarios for the entire Europe from 2020 to 2050 for (a) BFOW, (b) OSPV, and (c) wave power.

Figure 16**Error! Reference source not found.** illustrates the distribution of jobs linked to different ORE technologies across four sectors, manufacturing, C&I, O&M, and decommissioning, in Europe from 2020 to 2050. Due to its underlying assumptions, the BPS_lowOS scenario does not project considerable jobs creation by 2050 in ORE compared to other scenarios. For the other scenarios, all have similar projections in all phases in BFOW and wave power in 2030, however, substantial differences emerge in the following decades. For these two technologies, manufacturing jobs account for a larger share than the combined contributions of the other three buildout phases. However, for OSPV, C&I jobs dominate. In **Error! Reference source not found.**a, while the BPS and BPS_FPV scenarios show a slight decline in jobs creation by 2040, the more impactful scenarios exhibit nearly similar growth during this period. By 2050, BPS and BPS_FPV reflect an approximate 50% increase in jobs creation, whereas scenarios with high ORE shares demonstrate a 100% increase. For BFOW, the influence of the BPS_2040 scenario is limited due to its full deployment by 2030. In contrast, BPS_lowOS projects minor jobs creation by 2050, which remains significantly lower than projections from other scenarios. In **Error! Reference source not found.**b, aside from scenarios emphasising a high share of OSPV, other projections do not foresee any jobs creation in OSPV by 2050. However, the BPS_FPV and BPS_highOS_FPV both project identical jobs creation levels of 28,800 jobs by 2040 and 85,600 jobs by 2050. **Error! Reference source not found.**c illustrates that for wave power, the BPS and BPS_FPV scenarios project similar jobs creation across the different buildout phases. Similarly, the BPS_highOS and BPS_highOS_FPV scenarios align but show increases of approximately 87% and 68% compared to the BPS scenario in 2040 and 2050, respectively. The BPS_2040 scenario, the most optimistic, projects jobs creation of 45,000 in manufacturing, 29,000 in C&I, and 6500 in O&M by 2040. In the subsequent decade, the BPS and BPS_FPV scenarios are projected to generate 57,700 jobs, aligning closely with the 50,900 jobs estimated with the medium proportion global ocean deployment scenario of ETIP-Ocean [6]. The BPS_highOS and BPS_highOS_FPV scenarios project 96,200 jobs, near the 105,900 jobs projected in the high proportion deployment scenario of ETIP-Ocean [6]. The assumptions of this study and the one of ETIP-Ocean partly deviate, while the range of jobs is similar also relates to similar capacities across both studies. For 2040-2050, the BPS_2040 projects 5,700 jobs in O&M alone.

Figure 17 illustrates jobs creation across the four buildout phases for all ORE technologies. The BPS_highOS_FPV scenario, due to its significant ORE share, leads in jobs creation across all phases compared to other scenarios. For 2050, it projects 459,000 jobs in manufacturing, 288,000 in C&I, 80,000 in O&M, and 18,600 in decommissioning. In contrast, the BPS scenario for 2050 estimates 203,000 jobs in manufacturing, 108,000 in C&I, 36,400 in O&M, and 8,400 in decommissioning. Since BFOW is the dominant technology, the overall jobs creation trends are strongly influenced by the jobs creation patterns for BFOW.



(a)

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Figure 16 - Shares of jobs creation for (a) BFOW, (b) OSPV, and (c) wave power in manufacturing, C&I, O&M, and decommissioning phases.

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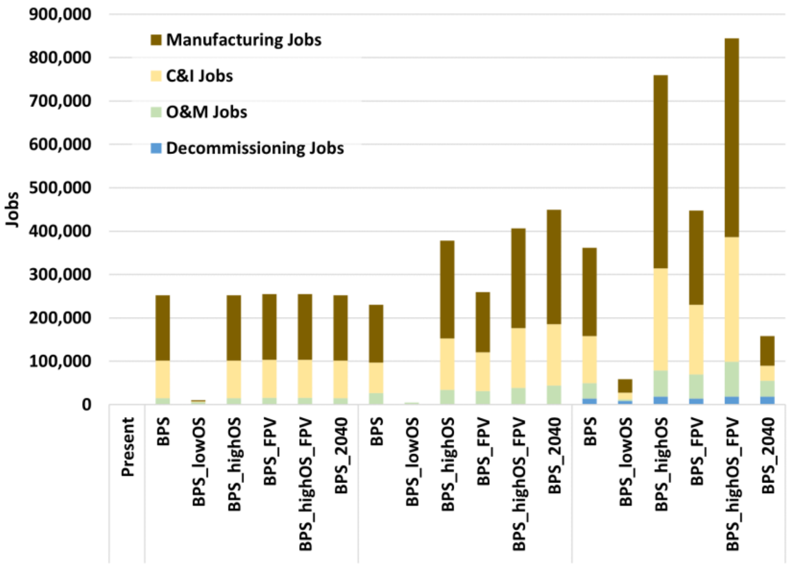
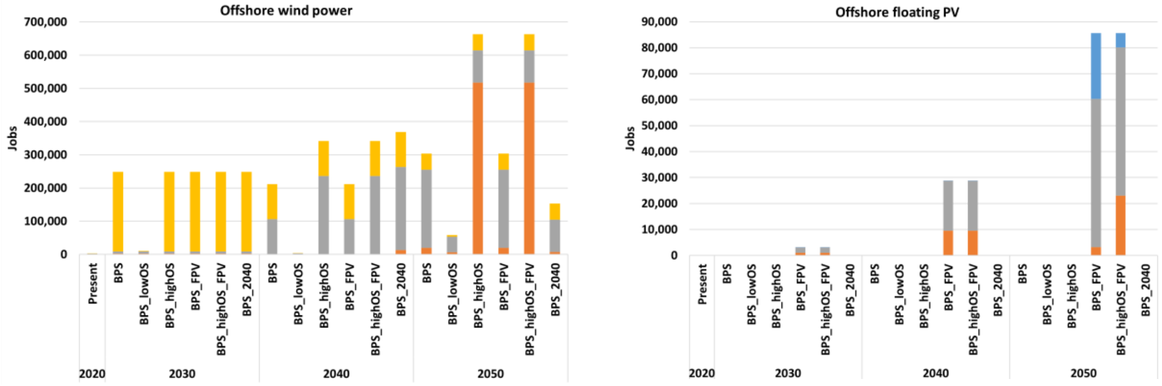


Figure 17 - The share of jobs creation for ORE technologies in manufacturing, C&I, O&M, and decommissioning phases for entire Europe.

Error! Reference source not found. presents projected jobs creation across different regions in Europe in various scenarios. In the Southeast region, no BFOW or wave power installations are projected, and consequently, no related jobs are anticipated. However, in the BPS_FPV and BPS_highOS_FPV scenarios, OSPV installations are projected for the Southeastern region by 2050. While wave power and OSPV are not expected to generate significant jobs creation across regions by 2030, the majority of jobs will be concentrated in BFOW, predominantly in the Central region. Over the following decade, the Western region shows significant growth across all three technologies, reducing the Central region's dominant role in BFOW-related jobs creation. Despite jobs creation in BFOW across all areas, the Western region leads in jobs creation for OSPV and wave power.



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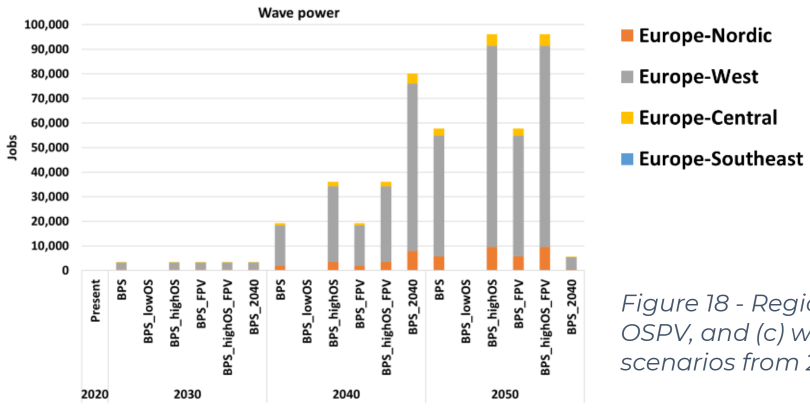

(c)

Figure 18 - Regional jobs for (a) BFOW, (b) OSPV, and (c) wave power for the different scenarios from 2020 to 2050.

Figure 19 illustrates the jobs creation by the three ORE technologies from 2030 to 2050 across Europe, as projected by different scenarios. The figure highlights the significant jobs creation driven by BFOW in all scenarios, with a surge in BFOW-related jobs expected by 2030. Wave power and OSPV are anticipated to emerge in the following decades, with wave power being more prominent than OSPV. The highest jobs creation numbers in ORE are projected for 2050, with 845,000 jobs in the BPS_highOS_OSPV scenario and 759,000 jobs in the BPS_highOS scenario. In contrast, the BPS_2040 scenario is less ambitious in ORE, projecting a more modest role by 2040. This reflects a realistic assessment of technological maturity and time constraints, limiting the scope for a dramatic increase in installations and, consequently, jobs creation.

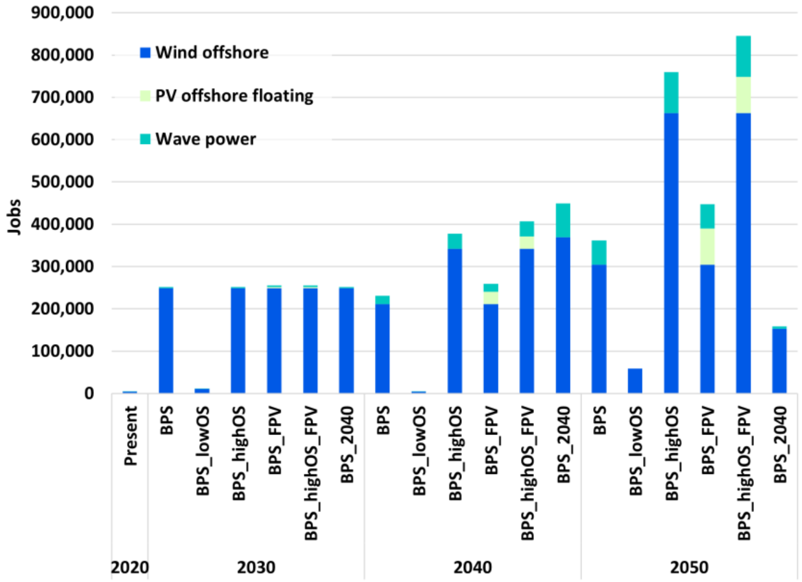

Figure 19 - Jobs creation based on the ORE technologies across the different scenarios for entire Europe from 2030 to 2050.

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Error! Reference source not found. The projections outlined above indicate a promising future for ORE and the jobs creation potential it brings. Each of the six scenarios highlights the potential for significant employment growth, though the extent of jobs creation within the ORE industry varies considerably depending on the chosen pathway. More progressive scenarios, while offering the highest potential for jobs creation, also present additional challenges and require careful planning and investment to fully realise their benefits. This underscores the importance of selecting a balanced, forward-looking approach that maximises employment opportunities while addressing the specific needs and resources required for effective implementation.

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5. Complementary impacts

The deployment of multi-source RE projects presents a valuable opportunity to enhance grid stability and reliability. These energy sources, with their complementary generation patterns, support and mitigate the intermittency challenges often associated with RE. This combination reduces the need for large-scale energy storage, ensuring a more consistent power supply. As a result, such multi-source energy parks can lead to a more reliable and resilient electricity system.

In addition to improved reliability, this diversified approach strengthens energy security by decreasing dependence on volatile fossil fuel markets and consequently external shocks, such as fuel price surges or disruptions in supply chains. The transition to RE sources often results in lower and more stable electricity prices, benefiting both households and businesses. Households can benefit from higher disposable income due to reduced energy costs, while businesses face reduced financial risks from fluctuating electricity prices, particularly those tied to fossil fuel imports. By cutting reliance on global oil and coal markets, these projects help insulate economies from geopolitical risks, making energy systems more secure and economically sound.

Moreover, the development of a strong RE sector helps restructure supply chains and promotes technological innovation. Local investment in the renewable sector may support energy efficiency and better-planned regions. This, in turn, supports national and global climate goals, as well as industrial growth. A well-established RE supply chain also creates opportunities for technological advancement, enhancing industrial competitiveness and sustainability.

Ultimately, the transition to RE yields significant public health and environmental benefits. Fossil fuel combustion is a major contributor to air pollution, which in turn exacerbates respiratory and cardiovascular diseases. By reducing reliance on fossil fuels, RE projects help mitigate these health risks, lowering healthcare costs for governments and individuals. Furthermore, the reduction in carbon emissions directly contributes to addressing the global challenge of climate change, limiting its severe economic and environmental impacts, such as rising sea levels and increased natural disasters.

6. Summary and key messages

The present study aimed to evaluate the environmental impacts in terms of carbon and energy intensity of integrating co-located RE parks through two case studies: wave power co-located with floating offshore wind (Case Study 1) in Portugal, and offshore solar PV co-located with bottom-fixed offshore wind power (Case Study 2) in Belgium. The park configurations were based on inputs from developers, and certain assumptions were made to address the early stage of project discussions.

In addition to lowering the carbon intensity of the energy mix, this innovative approach aims to evaluate the potential for job creation and economic growth. Understanding the future potential of ORE technologies across Europe is vital for evaluating the contribution to the development of local supply chains, infrastructure needs, specialised workforce training, and potential socioeconomic effects, particularly focused on jobs creation.

By analysing the described boundaries and scenarios along the document, the study provides valuable insights to promote co-located RE systems:

- The carbon intensity resulting from the proposed configurations is indicated as 17.7 and 21 gCO_2eq/kWh in Case 1 and Case 2, respectively. This impact for wind-alone systems is, in general, lower than co-located systems due to the lower maturity and additional complexity introduced by wave power and OSPV devices. However, co-location remains beneficial as it dilutes the higher carbon footprint of less mature technologies by sharing infrastructure and boosting overall electricity output. The co-location approach may not only boost overall efficiency but also support the advancement of these technologies toward a more commercial scale.
- Demonstrated systems' ability to offset their carbon emissions within their operational lifespans, with CPBT at 1.4 and 2.9 years for Case 1 and Case 2, respectively, underscoring the potential to support the net-zero goals.
- Both cases demonstrated strong lifecycle energy efficiency, with EPBTs of 2 and 2.6 years, and PEF at 0.07 and 0.09, for Case 1 and Case 2, respectively. Future improvements in manufacturing efficiency, material optimization, and local production could further reduce primary energy requirements, enhancing the systems' sustainability.
- Manufacturing is the most carbon emission-intensive phase (around 80%), both for wind-wave and wind-OSPV systems. Steel dominates the material composition in both case studies, underscoring the importance of adopting circular economy strategies.
- While shared resources with offshore wind parks provide opportunities for leveraging well-documented maintenance practices and failure rates for emerging technologies, a key limitation in modelling the O&M phase at this stage of the EU-SCORES project, is the lack of long-term real sea deployment data to validate operational assumptions. A more comprehensive O&M assessment will be performed under Task 5.1.

Nevertheless, the outcomes of this study serve as a valuable resource for understanding the carbon footprint impact of the strategies considered, offering an additional perspective to inform decision-making.

- Strengthening recycling initiatives, reducing dependence on primary raw materials, and prioritizing material efficiency can significantly lower the environmental footprint. Moreover, advancing research in recycling and industrial processes can unlock new markets, increase investment attractiveness, stimulate economic activity, and create additional job opportunities.
- Integrating complementary RE sources, combined with supportive policies that promote emissions reductions and energy efficiency, is essential for sustainable development. These efforts not only drive energy independence but also foster economic growth and environmental sustainability. By promoting jobs creation, innovation, and a more resilient energy grid, RE projects provide a crucial foundation for a future-oriented, sustainable economy.
- The socio-economic benefits of RE projects extend far beyond energy cost savings. A shift towards renewable sources fosters economic resilience by reducing the vulnerability of economies to external shocks, such as fuel price surges or disruptions in supply chains.
- ORE in general, and BFOW in particular can evolve into a competitive energy resource in the future European energy system, in particular along the Atlantic coast.
- Scenarios targeting the European goal of 270 GW of installed BFOW capacity by 2050 are expected to create approximately 304,000 jobs, with the majority in manufacturing, and construction and installation.
- Scenarios aiming for an ambitious rollout of 150 GW of installed OSPV capacity by 2050 are projected to generate approximately 86,000 jobs, primarily in manufacturing, construction and installation, and operation and maintenance. Scenarios aligning to the European target of 60 GW of installed wave power by 2050 would lead to about 57,000 jobs, most for manufacturing, and construction and installation.
- The installed capacity of 60 GW of wave power is projected to permanent jobs for operation and maintenance of almost 6000 jobs.
- Scenarios with a high emphasis on ORE and capacities up to 700 GW of installed ORE power capacity by 2050 would lead to about 845,000 jobs across the ORE industry.
- Wave power and OSPV benefit from energy technology diversity supporting a resilient and robust energy system, while it might not benefit from pressured cost optimisation whereas this may be in conflict with resiliency and diversity.

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