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D3.3 Report on infrastructural and industrial production requirements

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Summary of key findings

- There is an urgent need to decarbonise the global energy system with increased renewable energy. This is compounded by ongoing war in Ukraine and the need to reduce imported gas.
- Ocean energy (wave and tidal stream) can offer multiple potential benefits, including:
  - An alternative source of domestic renewable energy to contribute towards meeting decarbonisation and net-zero targets.
  - More predictable and often available at different times to wind and solar power.
  - A significant opportunity for jobs and GVA to the European economy.
  - Contributing to the just transition, offering skilled jobs and clean energy in and around coastal communities.
- If ocean energy follows a similar deployment trajectory to wind, there will be significant infrastructure requirements over the coming decades, planning for this should start now.
  - The cumulative European (EU27+UK) space requirement for offshore wind ports by 2030 might be 2800 ha or more.
  - This study estimates ocean energy may only need 1% of the port space needed for offshore wind in the early 2030s. By the end of the decade this could grow to around 13%, or 240 ha.
  - Continued growth in deployment of ocean energy, as seen in wind, would lead to considerably higher requirements by the 2040s, albeit with greater uncertainty.
- Planning and delivering strategic national investments in projects such as ports have long lead times. Port upgrades, being planned now or in future, to support more widespread deployment of offshore wind should consider implications of ocean energy deployments.
- There are huge infrastructure synergies between offshore wind and ocean energy, however with some divergent needs which can be complementary. A range of smaller or more constrained ports may be suitable for ocean energy that cannot support offshore wind projects.
  - Offshore wind projects of ~1GW/year may require 10–100 ha of space, quaysides 600 m or more in length, with unlimited clearance for vessels and turbines.
  - Ocean energy projects of 10–50 MW annually may only require 0.7–6 ha, 50–200 m quayside, and clearance of 10–50 m, depending on the device and project.
- Planners can harness these opportunities by comprehensively integrating ocean energy into their infrastructure planning for ocean energy. In practice this means:
  - Ensuring offshore wind ports can handle peak requirements in the 2030s and 2040s for offshore wind and ocean energy deployments combined.
  - Ensure specific offshore wind ports are sufficiently future-proofed so they can be reoriented towards ocean energy's peak in the 2040s.
  - Systematically exploring whether existing and/or new port space which is unsuitable for wind can be harnessed to facilitate ocean energy.
  - Systematically examining existing smaller ports as potential suppliers for wave and/or tidal energy projects — and provide these ports with the necessary infrastructure to effectively take the strain off larger ports.
- Support is also required at a regional, national, and European level to effectively develop suitable infrastructure for offshore renewable energy.

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Abbreviations and acronyms

AHTS	Anchor Handling Tug Supply (vessel)
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CTV	Crew Transfer Vessel
EU27	Current 27 members of the European Union, excluding the UK following Brexit.
ha	Hectare, 10 000 m^2
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
JRC	European Commission Joint Research Centre
kt	Kilo tonne (1000 tonnes, 1 000 000 kg)
LCA	LifeCycle Assessment
MSP	Marine Spatial Plans
Mt	Mega tonne (1 000 000 tonnes)
nmi	Nautical mile (1 nmi ≡ 1852 m)
O&M	Operations and Maintenance
OE	Ocean energy
OPEX	Operational Expenditure
PSV	Platform Supply Vessel
PTO	Power Take-Off
OW	Offshore wind
RIB	Rigid Inflatable Boat
Solar PV	Solar Photo-Voltaic panels
SOV	Service Operation Vessel
WEC	Wave Energy Converter
WES	Wave Energy Scotland

1 Introduction

1.1 Background and need

There is an ongoing need to decarbonise the global energy system, to meet net-zero targets and limit the impact of climate change. As part of this, there is the need for more renewable energy generation, with targets and plans already in place to drive this.

Ocean energy (wave and tidal stream) can contribute towards this urgently required increase in renewable generation. It can also offer additional systems benefits in terms of being more predictable and often available at different times to wind and solar power [1]. This study also shows that ocean energy projects may be able to use ports that are not suitable for large offshore wind projects.

To date, the ocean energy sector has focused on developing and demonstrating the technology at single device and small array scale. No devices have been volume manufactured, although some developers are now actively considering and planning this. There is therefore considerable uncertainty in forecasting the industrial production requirements and required port infrastructure for ocean energy arrays.

Regardless, major infrastructure projects can have very long lead times to develop and deliver. It is therefore important to start planning for the widespread deployment of ocean energy, particularly when considering upgrades to key infrastructure such as ports and harbours.

Significant upgrades are already being planned and developed for infrastructure to support the deployment of offshore wind in European waters, both fixed and floating. There is a need to consider ocean energy alongside wind, even if the requirements are uncertain at this time.

The objective of this study is therefore to quantify the potential scale of infrastructure required for ocean energy arrays in Europe over the coming decades, on the premise it follows a similar deployment trajectory to the rapid expansion of wind power.

1.2 Overall methodology

This study was conducted as part of the SEETIP Ocean project. It included a review of relevant literature, both in the public domain and available to project partners. This considered four key themes:

1. Available ocean energy resource and the distribution around Europe,
2. Renewable energy deployment targets and trajectories,
3. Plans for future arrays of offshore renewables, both wind and ocean energy, and
4. Port/facility requirements to construct and maintain these arrays.

To complement the literature review, discussions were held with a range of technology developers. These had two purposes: to understand their plans and requirements, and evaluate the preliminary requirements derived for ocean energy.

By investigating historical deployment of various renewable energy technologies, plus targets and projections for these, potential annual deployments of ocean energy devices in the 2030s and beyond were derived. This allows an estimate of the requirements for infrastructure to support the deployment of ocean energy in European waters to be calculated.

The infrastructure requirements for ocean energy have been derived from a synthesis of what has happened historically in ocean energy, is happening currently in offshore wind, combined with projections of what may happen in future. Reasonable assumptions have been made to develop scenarios to illustrate what infrastructure at ports and harbours may be required to support future ocean energy projects. It is not a prediction of what ocean energy deployment will happen in Europe.

1.3 Study scope and boundaries

The study focuses on the physical infrastructure at ports/harbours to fabricate, assemble, install, operate, and maintain ocean energy arrays. The geographical scope is European waters at a regional level, not looking at specific projects or facilities. The temporal scope considers deployments over the next three decades to meet 2050 targets; but the focus is on the infrastructure needs for the 2030s.

Within this study, ocean energy is used to refer to technologies harvesting energy from waves and tidal streams, in coastal waters and focused on grid-scale production of electricity. It will not assess individual devices or arrays, only considering each technology in aggregate. Schemes exploiting tidal range (impoundment via barrages or lagoons), salinity gradients, or ocean thermal energy conversion (OTEC) are considered out of scope.

Alternative markets such as remote island communities, use in offshore industries, desalination, etc. will not be assessed, as these have been studied elsewhere, e.g. [2], [3]. Additionally, these projects are likely to be of smaller scale and thus their infrastructure needs may be met by existing facilities (potentially adapted to suit as required). Alternatively, some projects for remote locations may be designed to be installed and operated with limited local infrastructure, such as in small island developing states (SIDS) or in disaster-relief situations.

The opportunity of co-locating wave energy within offshores wind farms has been widely proposed and studied, e.g. [4], although to date there are no firm proposals. There may be synergies in the infrastructure requirements to build and operate these, in addition to the potential cost savings from shared electrical connections and increased spatial energy density. The increased uncertainty of this type of deployment means that it is not considered within this study. Similarly, adding energy storage to ocean energy projects — whether batteries, hydrogen production, or some other method — also increases uncertainty in the project requirements. It is therefore also excluded from the scope of the present study. The additional balance of plant for energy storage may increase the requirements, but conversely synergies from integrating multiple technologies may offer savings. The additional uncertainty from this may be within the limits considered in this study. These may both need to be considered in an update to this work once more certainty and information is available.

The electricity grid to transmit power across countries is a key requirement for the development of ocean energy. Many areas of high resource potential can be in remote locations, distant from the main centres of demand. This may have a significant influence on the economic viability of locations for projects due to grid constraints. Assessment of grid constraints and any upgrades require to facilitate the roll out of renewable energy generation is a complex task, and not within the scope of this study.

1.4 Outline of report

The methodology and interim results are expanded in the following three sections, followed by findings on the requirements for ocean energy.

- Section 2 covers historical and future deployment of offshore renewable energy, including a high-level overview of the geographical spread across European waters.
- Section 3 summarise the infrastructure requirements for offshore wind projects based on a review of published literature.
- Section 0 investigates the likely requirements for ocean energy, firstly reviewing literature on ocean energy arrays and infrastructure required, then considering requirements for other technologies, and listing technology assumptions for ocean energy.
- Section 5 presents the main findings on the infrastructure requirements for ocean energy, firstly discussing synergies and differences with offshore wind. Quantitative requirements with European totals are then given, followed by other more qualitative considerations and requirements, plus indicative requirements for components and balance of plant.
- Section 6 offers some conclusions and recommendations from this study.

2 Deployment trends and projections for offshore renewables

This section first summarises the historical European deployment trends of various renewable energy technologies. These are combined with 2050 targets for ocean energy to forecast potential annual deployment rates through the 2030s. The geographical spread of these deployments is then considered, based on a high-level assessment of wave and tidal stream resource.

2.1 Historical deployment trends and near-term forecasts

The growth of renewable generation technologies is shown in Figure 2.1, for onshore and offshore wind, solar PV, tidal stream, and wave energy. Trend lines of compound annual growth rate (CAGR) are shown, with details in Table 2.1. Details of the data sources used are in Table 2.2, which cover the present EU27 countries plus the UK, to give consistency with historic data.

Growth rates of 30–40% per year have been seen in the cumulative installed capacity of wind turbines across Europe, although these growth rates are slowing as the installed capacity increases. Both onshore and offshore wind deployment increased from 10 MW to 10 GW in around 2 decades. The growth rate for onshore wind was relatively consistent in the early years (from 1980 onwards), as this represented the cumulative installation of many small (multi-kW scale) turbines. Conversely, for offshore wind, the early installations (1990–2002) are more sporadic, as these were from a smaller number of larger (multi-MW) projects, typically with only one project commissioned per year.

For tidal stream, taking historical deployments that are still operating combined with future plans to 2027, we see a CAGR of around 33%, with a similar sporadic pattern as seen in offshore wind. The future deployments include those funded under the UK Contracts for Difference (CfD) Allocation Round 4 (AR4), plus planned deployments in France, as set out in [5].

There is insufficient data to draw any meaningful trends for wave energy deployment at this point. At present this technology is at the stage of device demonstration, however pre-commercial arrays are expected in the next few years, followed by larger commercial projects.

For solar PV, an extremely rapid increase was seen in Europe between 2000–2011, with a CAGR of over 70%, which reduced to ~10% thereafter. Due to the modular nature of solar PV, with billions of individual panels installed per year, this may not be a good surrogate for ocean energy.

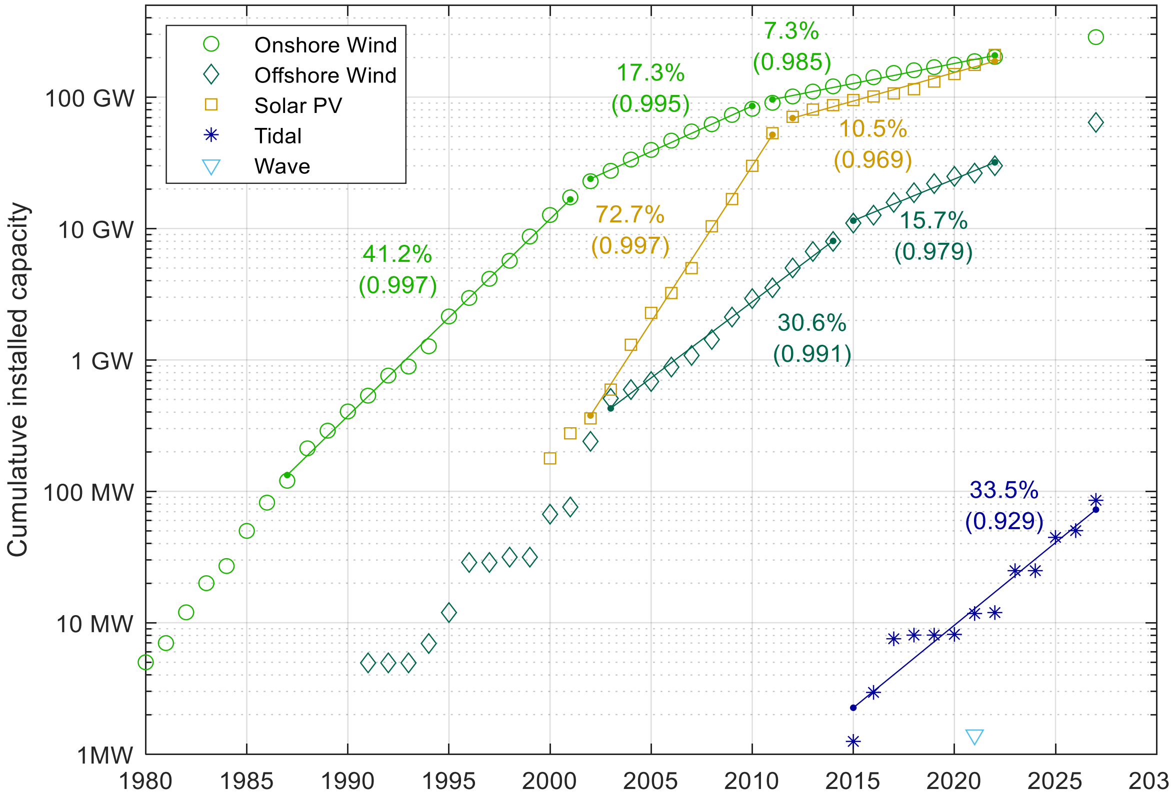

Figure 2.1. Historical trends and future estimates of European deployment of renewable technologies (EU27+UK). Trend lines show compound annual growth rates for selected periods, see Table 2.1 for details, and Table 2.2 for data sources used.

Table 2.1. Trends of compound annual growth for renewable technologies shown in Figure 2.1.

Technology	Period	CAGR	R² fit
Onshore wind	1987–2001	41.2%	0.997
	2002–2010	17.3%	0.995
	2011–2022	7.3%	0.985
Offshore wind	2003–2014	30.6%	0.991
	2015–2022	15.7%	0.979
Solar PV	2002–2011	73.2%	0.996
	2012–2022	10.5%	0.969
Tidal stream	2015–2027	33.5%	0.929

Table 2.2. Data sources for historical and projected deployment of renewable technologies.

Technology	Period	Data Source & Notes
Onshore wind	1980–1989	Earth Policy Institute (2015) [6], [7]
	1990–1999	Bilgili et al (2011) [8]
	2000-2022	IRENA (2023) [9]
	2027	WindEurope (2023) [10] (Central scenario 2023-2027)
Offshore wind	1990–1999	Bilgili et al (2011) [8]
	2000-2022	IRENA (2023) [9]
	2027	WindEurope (2023) [10] (Central scenario 2023-2027)
Solar PV	2000-2022	IRENA (2023) [9]
Tidal stream	2015–2025	ORE Catapult (2022) [5] (includes UK CfD AR4 & proposed French arrays)
Wave	2021	OEE (2022) [11] (wave technology in the water at end 2021)

2.2 Future deployment targets and scenarios

The 2020 EU strategy on offshore renewable energy [12] sets out targets for both offshore wind and ocean energy deployments for the EU27 member states. More ambitious, but non-binding, targets for offshore wind were proposed in 2023 as part of the REPowerEU initiative, building on the Regulation on trans-European energy networks [13]. The UK Government updated its Energy Security Strategy in 2022, to increase the target for offshore wind to 'up to 50 GW' by 2030 [14]. These are shown in Table 2.3.

Table 2.3. Selected European targets for renewable deployments

Source	Technology	Date	Target
EU Strategy on Offshore Renewable Energy [12]	Ocean energy	2030, 2050	1 GW, 40 GW
	Offshore wind	2030, 2050	60 GW, 300 GW
Regulation on Trans-European Energy Networks [13]	Offshore wind	2030, 2040, 2050	109–112 GW, 215–248 GW, 281–354 GW
British Energy Security Strategy [14]	Offshore wind	2030	Up to 50 GW

Deployment of offshore wind

Scenarios for offshore wind deployment in Europe have been considered, based on the targets in Table 2.3 and two projections from WindEurope [10] reproduced in Table 2.4. WindEurope's market outlook central scenario is their "*best estimate for installed capacity in Europe over the next five years*". Assuming installation rates for 2028–2030 are at a similar level to 2027 this would give around 60 GW of offshore wind capacity installed in the EU27 by 2030, although this is not stated in the scenario. The REPowerEU scenario is "*a theoretical installation rate which rises each year*" and would lead to around 112 GW by 2030. It has "*a maximum increase between 2026 and 2027. This represents the need for the supply chain to develop capacity to increase production over the next few years*". To meet the UK ambition of 50 GW by 2030, would require an average deployment of almost 5 GW per year, in addition to the 11.3 GW already installed. Again, the supply-chain build up means this could be skewed towards the latter years.

The annual rate of deployment of offshore wind is likely to reduce after 2030, although total deployed capacity will continue to increase, just more slowly. To meet the 2040 and 2050 European targets would require an average of 13 GW/year to be deployed through the 2030s, reducing to an average of 8–10 GW/year through the 2040s.

Table 2.4. Projected annual deployment (GW/year) of offshore wind turbines in Europe [10]

Year	WindEurope central scenario (GW/year)			WindEurope REPowerEU scenario (GW/year)
	EU27	UK	Total	
2023	3.5	1.4	4.9	1.8
2024	2.7	1.7	4.4	3.8
2025	2.8	1.9	4.7	5.7
2026	4.5	3.9	8.4	9.8
2027	7.7	3.8	11.5	15.1
2028	—	—	—	17.5
2029	—	—	—	20.1
2030	—	—	—	22.4

Scenarios for deployment of ocean energy

Three scenarios for ocean energy deployment were considered in the 2021 ETIP Ocean GVA Study [15]. These reach 2050 European (EU27+UK) deployment of ocean energy of between 60 GW and 100 GW and are based on IEA/JRC modelling.

Scenario 1. *Achievement of the SET-Plan*, with 192 GW ocean energy globally and 61 GW in Europe, reaching net-zero in Europe by 2050 and globally by 2070.
Scenario 2. *Europe follows the global market*, again achieving the SET-Plan LCOE targets but reaching net-zero globally by 2050, with 293 GW globally and 60 GW in Europe.
Scenario 3. *Europe leads the global market*, as with Scenario 2 but with a more ambitious 100 GW of deployment in Europe.

These three scenarios for 2050 ocean energy deployment together with the EU offshore strategy target are detailed in Table 2.5. Note that the split between wave and tidal energy varies over time; presently there are more tidal deployments than wave, but this is expected to change over the coming decades as wave energy is commercialised.

Table 2.5. Scenarios for 2050 ocean energy deployment

Scenario	2050 global deployment (GW)	2050 European deployment (GW)			2050 split Wave/Tidal
		Total	Wave	Tidal	
EU offshore strategy	—	40	20	20	50/50 assumed
ETIP Scenario 1	192	61	31	30	JRC modelling
ETIP Scenario 2	293	60	36	24	60/40
ETIP Scenario 3	293	100	60	40	

The future deployment of ocean energy is uncertain; therefore a series of European deployment scenarios were developed, consistent with the 2050 targets in Table 2.5. Constant exponential growth is often used to model deployment; however this implies most of the deployment occurs in the final years. As discussed in section 2.1, this is not what has been observed in renewable energy deployments to date. Therefore, different models were developed for tidal and wave energy given their differing resource and technology status.

Tidal energy deployment was modelled using a logistic function, which is an exponential model with a resource limit. Peak growth in deployment is assumed to occur in the mid-2040s, after which deployment continues but at a reducing rate per year rather than continuing to increase year-on-year. The projections are broadly consistent with the European tidal deployment from now to 2035 assumed in the TIGER project [5]. The predicted annual deployment of tidal stream technology in the 2030s is 50–100 MW/year at start of the decade, 250–350 MW/year by 2035, and 0.6–1.2GW/year by end of the 2030s. In this model, annual deployment peaks around 2–4 GW/year in the mid-2040s, reaching a total of 20–40 GW in Europe by 2050.

Wave energy deployment has a larger uncertainty. The technology is further from deploying full commercial arrays at present. However, the available resource is potentially much larger and more geographically diverse, as discussed further in section 2.3. The deployment has therefore been modelled as exponential with a variable growth rate. This assumes peak growth in the 2030s, then the growth rate reduces as seen in onshore wind. This avoids extremely large annual deployments by the late 2050s. The predicted annual deployment of wave energy in the 2030s is 15–30 MW/year at start of the decade, 100–150 MW/year by 2035, and 300–750 MW/year by end of the 2030s. Annual deployment rates could reach 2–10 GW/year by 2050, giving a total European deployment of 20–60 GW.

As seen in other sectors, the growth is unlikely to be a constant rate over the whole period. The initial years may be less consistent, due to the greater impact of individual projects. Later years may experience slower growth, potentially with a limit on annual deployments. This is likely to be especially true if/when approaching the limits of the resource, when the best sites may already have been developed.

The deployment scenarios used for this work are summarised in Table 2.6. These are deliberately wide-ranging, as there is considerable uncertainty in both the quantity and timing of ocean energy arrays. There is also uncertainty in the scale of continued deployment of offshore wind over the coming decades. Regardless of this uncertainty, these scenarios provide a basis to estimate a range of values to help plan for the infrastructure required if we are to build considerable deployments of ocean energy.

Table 2.6. Annual European deployments assumed for ocean energy and offshore wind over coming decades

Timeframe	Assumed annual deployment (MW/year)			
	Tidal	**Wave**	**Total**	**Offshore wind**
Early 2030s	50–100	15–30	65–130	12000–25000
Mid 2030s	250–350	100–150	350–500	11000–20000
Late 2030s	600–1200	300–750	900–1950	10000–17500
Mid 2040s	1750–4100	1550–6200	3300–10300	9000–15000

2.3 Geographical spread of resource and deployments

Existing offshore renewable energy deployments, plus historical and future proposals are presented in this section. An estimate of the geographical spread of the ocean energy resource is also shown, as this will influence the locations for future deployments.

A review of literature on the wave and tidal stream resource in European waters was conducted, with the results summarised in this section. These studies consider differing geographical scope and are not necessarily directly comparable as differing methodologies and models are used. It is also not yet known how much of the theoretical energy resource in the waves and tidal currents can be technically and economically harvested within acceptable environmental limits.

The indicative geographical spread of tidal stream and wave energy resource in European waters is shown in Figure 2.2 and Figure 2.3 respectively. These also show grid-connected deployments, test centres, and selected project lease areas (not all are actively being developed).

Following the 2014 Directive, most European countries have implemented, or are in the process of implementing, Marine Spatial Plans (MSP). These are a tool to manage the use of the seas and oceans coherently and to ensure that human activities take place in an efficient, safe, and sustainable way. A key objective is to reduce conflicts and create synergies between competing uses for maritime space including fishing, aquaculture, shipping, renewable energy, and nature conservation. [16]

Offshore wind farms at various stages in development are shown in Figure 2.4 along with areas allocated in marine spatial plans for renewable energy development. Note that this is illustrative only, some projects are only shown by a point, others by the site boundary, and this may omit some projects or have an outdated status.

Indicative European tidal stream resource and grid connected projects/proposals

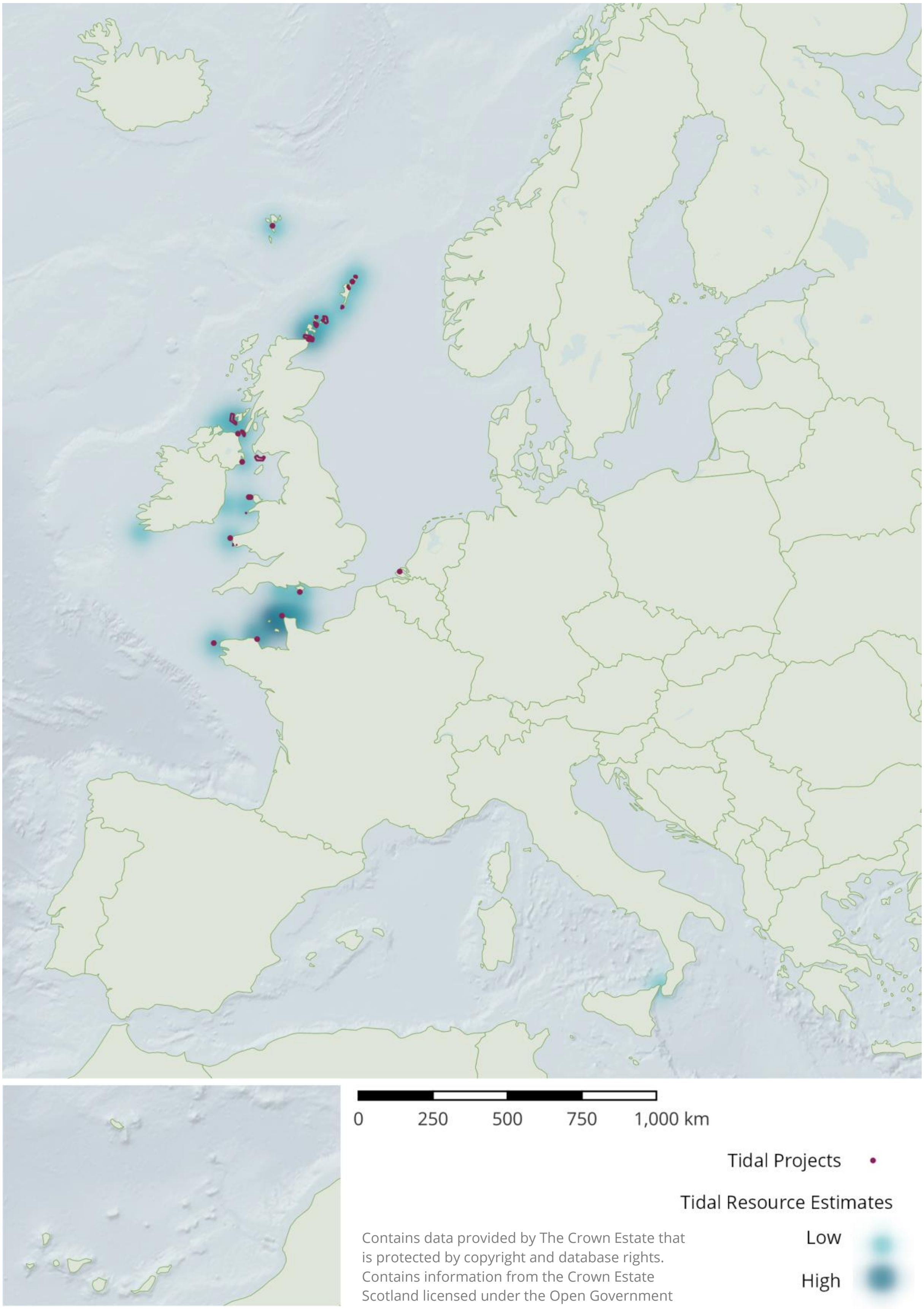

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Figure 2.2. Indicative European tidal stream resource and grid connected projects/proposals. Note: low tidal resource may be suitable in other areas not shown. Data sources [17]–[27]

Indicative European coastal wave energy resource and grid connected projects/proposals

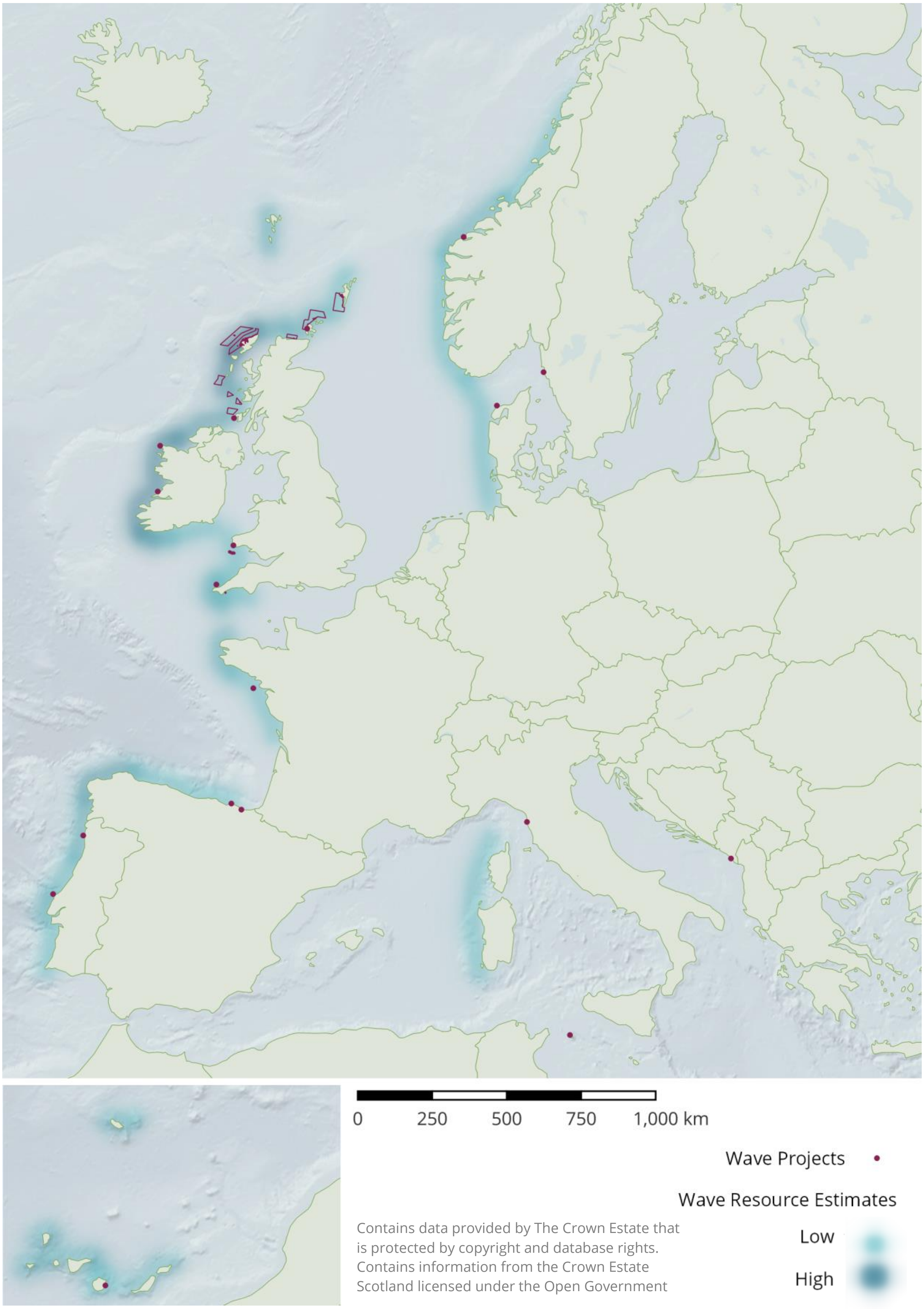

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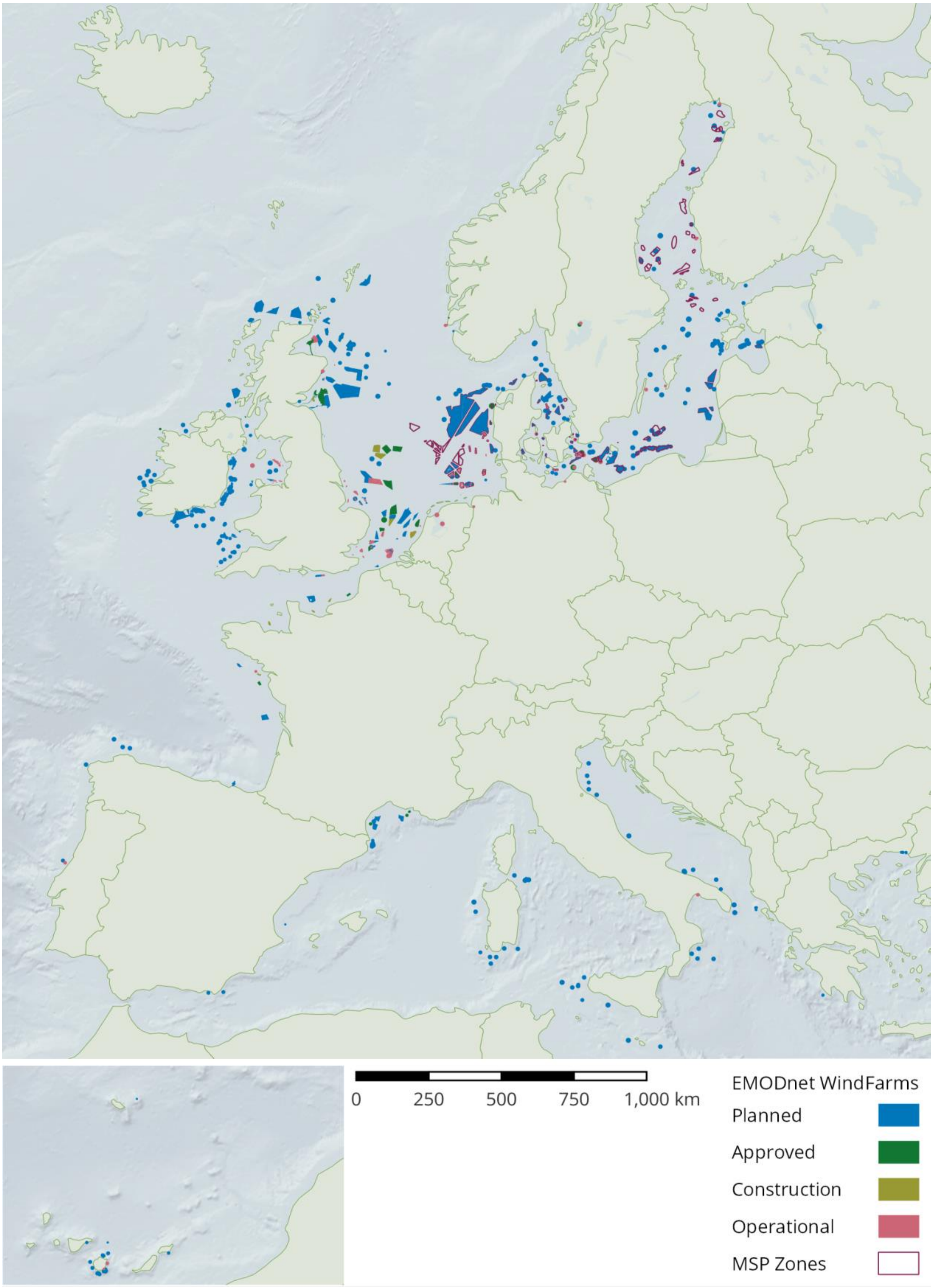
Figure 2.3. Indicative European coastal wave energy resource and grid connected projects/proposals. Note: low wave resource may be suitable in other areas not shown. Data sources [17], [18], [23], [28]–[33]



European offshore wind farm locations and renewable energy Marine Spatial Plan zones

Figure 2.4. European offshore wind farm locations, both currently operation and plans.
Offshore windfarms shown for Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Spain, Sweden, and United Kingdom. Marine Spatial Plans (MSP) included for Belgium, Denmark, Finland, Germany, Latvia, Poland, and Sweden. Data sources [17], [18], [34], [35].

2.4 Summary of deployment trends and projections for offshore wind and ocean energy

There has been an exponential growth in the construction of wind turbines across Europe, with compound growth rates of 30–40% increase per year for sustained periods. Both onshore and offshore wind deployment increased from 10 MW to 10 GW in around two decades. Beyond this growth rates are slowing as the installed capacity increases. The ambitious targets for offshore wind would see 10–25 GW of new capacity added per year through the late 2020s and 2030s.

The pipeline of tidal stream projects in Europe appears to be following a similar trend, although there is insufficient data on future wave energy arrays as this technology is several years behind in commercialisation. Assuming ocean energy does follow a similar path to wind, scenarios of annual deployments have been developed to assess the infrastructure requirements in the 2030s and beyond. These show tens to hundreds of MW per year of ocean energy deployments in the early-2030s, rising to 0.9–2 GW/year by the late-2030s, and potentially 3–10 GW/year by the mid-2040s.

The geographical spread of projects and resource gives some indication of the potential deployment sites, noting these will be subject to environmental, economic, and other considerations. The tidal stream resource in Europe is concentrated in hotspots predominantly located around the north and west of Scotland, west of Wales, the English Channel/la Manche including the coasts of Normandie and Bretagne. The wave resource is more widely distributed, but strongest along the northwestern Atlantic coasts of Europe. There are areas of lower energy resource elsewhere that may also be exploited.

3 Synthesis of literature on infrastructure requirements for offshore wind projects

This section presents a summary of the infrastructure requirements for offshore wind projects, both fixed and floating, based on a review and synthesis of recent literature, primarily [36]–[44].

Construction timelines

A recent Floating Wind Offshore Wind Taskforce report highlights the long timescales for major infrastructure development projects such as ports [36]. Noting, this may impact on deployment ambitions. Assuming feasibility studies start in the latter half of 2023, the facilities might be ready by 2030, as shown in Figure 2.1. This is based on the "*combined development time of ports from commencement to construction (up to 4–5 years), and an assumed operationalisation of 18 months*". This example is for the UK but is likely to be broadly representative of most European countries.

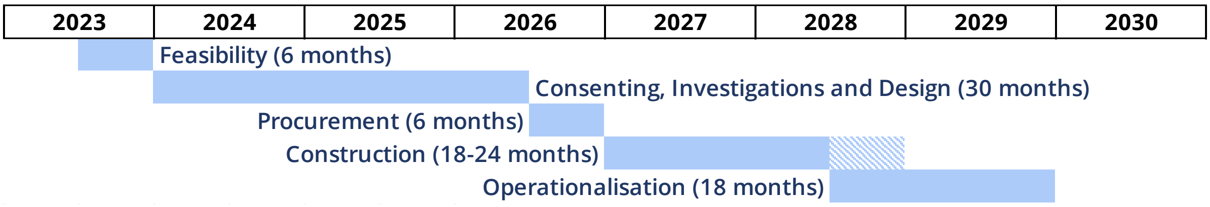


Figure 3.1. Indicative port development timeline. Adapted from [36].

3.1 Technology assumptions

Most offshore wind infrastructure studies consider the requirements for projects of several hundred MW to around 1GW installed per year, with individual turbines of between 10MW and 20MW. The largest wind turbines installed at present are around 10MW, with rotor diameters of 150–200m. The average for new offshore wind turbines installed in 2022 was 8MW, with the largest at 10.9MW [10]. Even larger models are in development, with rotor diameters of around 250m or more.

For offshore wind, the design of turbines has largely converged on three-bladed horizonal axis turbines, with the nacelle mounted above a tubular tower. The nacelle contains either a direct-drive generator, or a gearbox and generator. The tower contains a transformer to step up the voltage and provides access to the nacelle, it is then connected to the supporting structure by a transition piece located above the water level.

The design of the supporting structure varies however, largely depending on water depth and seabed conditions, with either:

- Fixed foundations, most often a steel monopile, but jackets or gravity bases also used.
- Floating foundation, typically semi-submersible, barge, spar buoy, or tension leg platform.

Some floating platform concepts have multiple rotors per floating platform. All floating offshore wind turbines require a length of dynamic cable to connect to the seabed, which is designed with additional reinforcement to withstand the motion experienced by the platform.

The spacing of offshore wind turbines is typically 6–10 rotor diameters. The turbines are connected in arrays with medium voltage intra-array cables (typically 11kV to 66kV) to a substation platform. This is then connected to shore via one or more HVAC or HVDC cables depending on the farm size and distance to shore.

Typical dimensions and masses for turbines and selected foundations are given in Table 3.1 and Table 3.2. These are just intended to give a scale of these machines and are not intended to be comprehensive or exhaustive.

Table 3.1. Dimensions and masses of typical wind turbines currently being used and typical forecast

Turbine	Rated Power (MW)	Rotor diameter (m)	Blade length (m)	Nacelle L×W×H (m)	Tower height (m)	Blade, nacelle, tower mass (t)
MHI Vestas Offshore V164-8.3 MW [45]	8.3	164	80	20 × 8 × 8	105–140	35, 390, –
Siemens Gamesa SG 11.0-200 DD [46]	11	200	97	15 × 8 × 8†	—	—
15 MW turbine [37]	15	240	115	20 × 10 × 10	120+	65, 650, 1000
17 MW turbine [36]	17	270†	130	25 × 13 ×13	144‡	68, 860, 1200‡
20 MW turbine [36]	20	300†	147	26 × 14 ×14	160‡	80, 1020, 1400‡

† Estimated, ‡ Tower formed of 4 sections

Table 3.2. Dimensions and masses of typical 15MW wind turbine foundations [40]

Foundation	Water depth (m)	Dimensions (m)	Mass (t)
Monopile	40	85 × 10 ⌀	1350–1850
Jacket	60	34 × 34 footprint	1250–1700
Jacket	80	38 × 38 footprint	1450–2000

Table 3.3. Dimensions and masses of typical floating offshore wind turbine semi-submersible substructures [36]

Turbine rating (MW)	Dimensions L×W×H (m)	Substructure draft (m)			Mass (t)	
		Excluding turbine	Turbine installed	Operational	With steel construction	With concrete construction
17	90 × 90 × 27.5	11.5	13.5	22.5	3 500	17 500
20	100 × 100 × 30	13.0	15.0	25.0	4 000	20 000

3.2 Key metrics used to quantify infrastructure requirements

To quantify the infrastructure requirement for offshore wind projects, key metrics such as those in Table 3.4 are commonly used. Some studies use slightly different names/terminology to refer to the same or similar concepts.

For these metrics, the magnitude obviously depends on the type and size of the turbine and foundation used, as well as the assumptions made in the study. Some studies present a range of requirements for different design options, or for minimum and ideal requirements. The scope of what is covered also varies, with some studies focusing on foundations for floating, e.g. [38], whereas others included manufacturing of subassemblies, e.g. [44].

Table 3.4 Key metrics used to quantify infrastructure requirements for offshore wind projects

Metric	Units	Description
Manufacturing/ fabrication space	ha (m^2)	Typically for foundations, but some studies also cover other subassemblies such as blades, nacelle, and towers. These may be at separate locations per subassembly or combined into one larger facility which may offer economies of scale.
Laydown area	ha (m^2)	Space contiguous with quayside to store components/ subassemblies before being assembled/transported to site. Used to minimise risk/downtime for expensive vessels used in the construction.
Quayside berth size (length/width/draft)	m	Quayside berth dimensions to fit both the vessel(s) used, and floating turbine foundations where required.
Laydown/quayside bearing capacity	t/m^2	Required load bearing capacity of the quayside and laydown space, often to facilitate cranage or modular transporters.
Access channel size (width/draft/clearance)	m	Minimum dimensions for any access channel between the port and open sea to accommodate the size of vessels used, and the size of floating foundations/turbines where applicable. The vertical clearance above the water is often called the 'air gap'.
Nearshore wet-storage area	ha	An area of sheltered water near to the quayside where floating foundations can be anchored and stored as required
Office/welfare facilities	m^2	Onshore office space and welfare facilities for workers. Particularly relevant for O&M operations.
Distance to site	km (nmi)	The distance of the port to the project site is an important consideration as this affects the transit time. Some activities/ operations are more sensitive, particularly ongoing O&M.

3.3 Port infrastructure and indicative sizes

The port infrastructure to support offshore wind projects can be grouped into three broad types:

1. **Manufacturing/fabrication ports,** where the main subsystems are constructed. The components used in offshore are now so large that they are normally manufactured at or close to a port and transported by sea.
2. **Marshalling/assembly ports**, where the main components are stored/staged at a location closer to the windfarm ready for installation. Floating turbines may be assembled onto foundations as this type of facility, then towed to site.
3. **Operations & maintenance ports**, where the vessels and crew for routine ongoing O&M of the array are based. Larger maintenance operations, such as blade replacement, would require use of facilities such as used for construction.

In some cases, different geographical locations may be used for the manufacture of components such as towers and nacelles, and/or one port may perform more than one of roles above. This might be a trade-off between increased facility size required and the more efficient use of infrastructure.

In addition, smaller ports will be needed for survey vessels etc. during the development and consenting of the projects. As noted in [39], ports and vessels already exist for survey purposes, and may be suitable for future development, or are not a significant challenge to expand.

For all ports, round-the-clock direct access to the open sea (without lock gates, tidal time windows, opening bridges, etc.) is a strong requirement. This is particularly the case for CTV-based O&M ports, but possibly a lower priority for component manufacturing facilities.

The construction activities can also be split by location relative to the coast, considering:

1. **Onshore** facilities for component manufacture (substructure components, tower, nacelle, blades, moorings, etc.). These are typically located close to ports but are not necessarily directly at the quayside.
2. **Quayside** for operations such as substructure construction and assembly, wind turbine component marshalling and potentially assembly
3. **Nearshore** sheltered waters can be used for wet storage of floating substructures and potentially also the assembly of the tower/turbine on top
4. **Project site** for the installation of substructures, wind turbines, moorings, cables, etc.

Detail on operations at the project site are not within the scope of this report. Similarly, the supply chain upstream of the onshore component manufacturing is not included, as this could be geographically diverse and not limited to ports.

Subsystem/component manufacturing facility ports

As noted above, the manufacturing facilities for the key components and subsystems are typically located at or close to a port, so that these can be moved by sea. The transport requirements for subsystems and components are not as great as for fully assembled turbines, but they are such that road or rail transport is not practical.

There may be synergies through co-location of the infrastructure to manufacture and assemble components, however this requires larger individual facilities. Similarly, multiple components and/or subassemblies may be manufactured together or at nearby locations.

Most studies assume that the electrical cables to deliver power to shore are delivered directly to the project site from the manufacturing facility, without being stored at an assembly site. Similarly, this may be the case for mooring systems including chains and anchors. If not, then additional laydown space may be required for these items.

Marshalling/assembly ports

Most large offshore windfarm construction in Europe relies on a port located relatively close to the project site to marshal/collate and possibly assemble the turbines and foundations. These may also be referred to as staging ports. The Crown Estate Scotland study [40] notes "*They are a key feature of the logistical methodologies, approach to risk management, and contractual arrangements of these projects and as such their use can be inferred to have been a contributing factor to increasing project scale and lower project costs.*"

Significant areas of land adjacent to the quayside are required to lay down the turbine components such as blades, nacelles, towers, and foundations. These need to have sufficient bearing capacity for cranes and modular transporters to move these as required, with values of 6–20 t/m² suggested in the literature. The size requirements are discussed further below.

Unlike other ports for offshore wind, marshalling facilities may not necessarily be developed from existing facilities, given their challenging requirements that may limit suitable options [39].

Maintenance ports

To facilitate maintenance of offshore wind turbines, two main types of vessels are typically used:

- Smaller, shorter range Crew Transfer Vessel (CTV)
- Larger, longer-range, Service Operation Vessel (SOV)

The Crown Estate Scotland study [40] also notes "*Typically, northern European projects to date have adopted a CTV based O&M strategy, whereby the vessels and technicians only stay at sea for a single shift. Due to their relatively small size, CTVs are well suited to utilising historic ports and harbours that may have experienced declines in their traditional industries.*" As offshore wind projects are installed further offshore or in more remote locations, it may be necessary to use SOV based O&M, where staff live onboard the vessel whilst working at sea.

Onshore facilities, ideally located close to the berth, are require for office and welfare facilities. There may also be a need for storage space for small spares, and/or operations monitoring offices.

Ports used for maintenance may also be suitable base for vessels used for the pre-construction surveys required during design and consenting.

3.3.1 Indicative facility size requirements

The literature on space requirements at facilities for offshore wind projects is summarised in Table 3.5. These studies consider various locations, with a range of assumptions on turbine and project size, annual throughput, and technologies (be it generic offshore wind, bottom fixed, or floating with various foundation types). They were conducted over the past decade as the industry developed and sometimes reference values from earlier studies. Some studies specify a value or range of space required for turbines and/or foundations, while others combine these. Many of the studies exclude turbine manufacturing, presumably on the assumption they would be brought in from existing turbine manufacturing facilities.

There is not so much literature on the requirements for ports used for the ongoing operations and maintenance, possibly as these are less onerous and there are a wider range of locations that can be used. For O&M ports, [40] suggests an onshore area of 0.75–1.5 ha for new build facilities, and 1–2 ha of sheltered water with heavy-duty pontoons for berthing CTVs.

Table 3.5 Summary of key literature on space requirements at offshore wind manufacturing and assembly ports

Study	**Year**	**Location**	**Tech.**	**Turbine size (MW)**	**Project size (MW)**	**Throughput (units/year)**	**Manufacture/fabrication (ha)**			**Laydown/assembly (ha)**			**Wet storage (ha)**
							Turbine	**Found.**	**Combined**	**Turbine**	**Found.**	**Combined**	
Floating Wind Offshore Wind Taskforce [36]	2023	UK	Floating	17.5–20	850–1000	25[a]	—	—	—	—	—	20–25[b]	—[c]
						50[a]	—	30–40	—	—	—	—	—
Wind Energy Ireland [37]	2022	Ireland	Fixed	15	750–1000[d]	50-67[e]	—	—	—	10–13	5–7	—	—
			Floating	15	750–1000[d]	50-67[e]	—	16–20	—	12–18	6–12	—	30–280[f]
Floating Offshore Wind Centre of Excellence [38]	2022	UK	Floating	17.5–20	437–500[e]	25+	—	20	—	—	10	—	5–10
Parkison & Kempton [39]	2022	USA	Offshore	12–14	1000	83	—	—	25	—	—	40–80	—[g]
Arup/Crown Estate Scotland [40]	2020	Scotland	Fixed	8–20	1000	50–125[e]	4–12+[h,i]	4–12+[i]	—	4–20[j]	4–20[j]	—	—
BVGA/Offshore Wind Industry Council [41]	2016	UK	Offshore	8	800[e]	~100	8–10[k]	8–10[k]	—	—	—	12–20	—
US Bureau of Ocean Energy Management [42]	2016	USA	Floating	6–10	180–300[e]	30+	25–49	124	—	—	—	25–247[l]	—

Notes:

a. 25 turbines/year at assembly site, with construction over 2 years, but 50 foundations/year at a manufacturing facility
b. Storage of blades, towers, nacelles, and assembly of turbines
c. No value given but required unless just-in-time delivery is viable. Noted wet storage may de-risk the supply chain.
d. Requirements for bigger projects are expected to be similar but take longer.
e. Assumed from other parameters, Throughput = Project size/Turbine size.
f. 30–70 ha for 10 substructures only, or 80–280 ha for 10 substructures with turbines.
g. No value given, noted this may be required.
h. Manufacturing of a single component, e.g. towers
i. May include relevant indoor/covered facilities.
j. Storage & marshalling of either turbines or foundations: 4–8 ha minimum, 10–20 ha ideally.
k. Port space to manufacture one subassembly (turbine nacelles, blades, towers, foundations, or offshore substation topsides or foundations).
l. Area of 10–15 acres (24–37 ha) minimum, 50-100 acres (124–247 ha) ideal.

3.3.2 Vessel, quayside, and channel sizes

Increasingly large vessels are being used for the transport of offshore wind turbines and components as these also increase in size and power. This necessitates the use of correspondingly large ports and quays. Fully assembled floating wind turbines on their foundation substructures have even more onerous requirements.

Differing values are quoted in the literature, but vessels of 120–240 m long and up to 50–60 m beam are now often used for offshore wind projects, requiring a depth of 6–12 m. In some cases, it may be advantageous to have multiple vessels berthed at the same time, requiring a main quayside of 200–600 m or possibly longer. Ports alongside manufacturing facilities may have slightly lower requirements, as they are only transhipping components not complete turbines.

The quayside bearing capacity should be 10–20 t/m², facilitating the movement of turbines and components by cranes and modular transporters. For some floating foundations, bearing capacities of up to 50 t/m² may be preferable.

The access channel from the port to open sea needs to be sufficiently large to permit passage of the largest vessels, potentially with overhanging loads. Minimum channel width of 100–200 m is typically quoted, with a depth of 5–15 m, and unlimited air clearance given the large height of wind turbines.

For floating turbine foundations, the draft may be up to 15m for semi-submersibles and possibly 80m for spar buoys, further limiting the ports for these types of foundations.

3.4 Other requirements and criteria

There are many other requirements and considerations for infrastructure to support offshore wind projects. Key points are summarised here, building on [37].

Location and connectivity

The location should ideally be close to both the project site and the supply chain to minimise transport distances and thus costs. It is noted that a local supply chain may become established around the port facilities as this industry develops further. Good road/rail access, and proximity to airport connections are important. This applies for both the supply chain and workforce.

Skilled workforce nearby

Ideally, there would be a large skilled workforce within the commuting distance hinterland of the port, or at least suitable accommodation and facilities for them.

Cranage capacity

The large size and weight of offshore wind turbine components necessitates the need for high capacity cranage. Mobile and crawler cranes, plus self-propelled modular transporters (SPMT) are often used. Less common, although still useful, are overhead gantry cranes. Cherry pickers may be used for personnel access.

Drydock availability and size

Especially for floating foundations, large drydocks may be advantageous, however there are limited sites with the available capacity and size.

Ro-Ro capability

To speed up future loading and unloading of vessels, roll-on roll-off (Ro-Ro) linkspans may be used at ports, and as such may be a desirable facility for future offshore wind ports.

3.5 Summary of infrastructure requirements for offshore wind

Current offshore wind turbines are around 8 MW with 160 m diameter rotors. This is expected to increase up to 20 MW and around 300 m diameter. Nacelles are around 20 m long, 8–14 m in width and height, weighing 300–1000 tonnes. Fixed foundations mass around 1000–2000 tonnes, while floating substructures may be up to 20 000 tonnes. Given the scale of these components, the only option is transport by sea on specialised vessels.

In the literature, ports for offshore wind projects are often grouped into three categories: 1) manufacturing/fabrication, 2) marshalling/assembly, and 3) operations & maintenance, although these activities ay be split amongst one of more locations. Ports for O&M tend to have less onerous requirements as they are not handling large subsystems, although this may change for floating wind.

Port requirements for offshore wind are typically quoted for projects installing about 0.5–1 GW per year. These require around 5–50 ha of fabrication space, another 5–50 ha for laydown, and potentially 10–100 ha of wet-storage for floating wind projects. To accommodate the large vessels, these manufacturing and assembly ports may need quaysides 200–600 m or more in length, with the adjacent berth 40–80 m wide and 8–15 m deep. The access channel out to sea should be at least 100–200 m wide, 5–15 m deep, with unlimited clearance.

4 Investigating requirements for ocean energy

This section considers the available information on infrastructure requirements for ocean energy arrays. It summarises the discussions held as part of this work. Then the requirements for ocean energy are investigated, firstly reviewing published studies on ocean energy arrays and their supporting infrastructure, then considering other similar manufacturing and assembly facilities. It concludes with the technology assumptions on future ocean energy arrays. The resulting requirements for infrastructure to support ocean energy are then detailed in section 5.

Discussions were held with a range of ocean energy device developers and other stakeholders over the course of the task to inform and refine the study. Details were requested regarding plans for future devices, and arrays where appropriate, plus the possible/expected infrastructure required to support these where known. These plans reflected near-medium term arrays, and a varying level of information was provided by developers depending on the maturity of their technology and planning for future arrays. It may be that as the sector develops and expands, more efficient use can be made of infrastructure to fabricate and install devices.

Preliminary results from this work were presented at the All-Energy conference in Glasgow, UK in May 2023, which prompted some discussion and input from attendees. Preliminary estimates of the infrastructure requirements for ocean energy were also circulated to the device developers for comment. More in-depth discussions were then held with selected developers to refine the assumptions of the study. The findings from these discussions and developers' plans were used in aggregate to guide the study.

4.1 Literature on ocean energy arrays and supporting infrastructure required

A literature review was conducted of technical reports and academic papers outlining plans and requirements for future arrays of ocean energy devices, and the infrastructure required to construct them. Given the nascent state of the sector, this is quite limited and has significant uncertainties. It is also noted that the historic plans may not be representative of future technology development.

4.1.1 Infrastructure requirements for ocean energy devices

Only one study was found that specifically discussed infrastructure requirements for ocean energy. This was a 2006 study for the US Bureau of Ocean Energy Management [42], which considered floating offshore wind and marine hydrokinetic technologies, with the latter focusing on wave energy. The vessel and port access requirements in this study were considered similar for wind turbines and WECs. As noted in section 3.3.1, the port area requirements suggested in this study were an order of magnitude larger than the other studies for offshore wind. The other requirements, such as road/rail access, nearby workforce, etc. were consistent with other studies.

In addition to present developers, the plans and scale of the DCNS/OpenHydro construction facility in Cherbourg, France were reviewed. Although this technology is no longer being developed, the aim was for volume manufacture of 25–50 devices per year in this facility, opened in 2018, although closed shortly thereafter [47], [48].

4.1.2 Pentland Firth and Orkney water projects

A study into how the Pentland Firth and Orkney waters Round 1 Development Sites could be built was commissioned by The Crown Estate in 2011 [49]. While over two decades old, some of the points may still be relevant today. It considered the development of 1.6GW of capacity, comprising 1GW tidal stream and 0.6GW wave, to be rolled out over a period of about seven years. The lack of an established supply chain to support this was noted as a significant issue, however.

This study suggested several device manufacturers rolling out batch-production of 20-50 devices per year. Indicative quantities were given for some key components, summarised below, although these would obviously depend on the designs used in the final projects:

- 600–750 t/MW of steel used in device manufacture, >1 Mt total.
- Up to 100 foundations per project, using 500 t of steel each
- 15 km of steel cables used in moorings
- Almost 1000 km of intra-array electrical cables, and 80 km of export cables

Regarding ports, the study highlighted that projects would prefer to use facilities local to the project site to minimise the logistics of transporting devices long distance. As much of the commissioning should be done at the port, to minimise offshore operations. Key requirements for a construction port suitable for a range of devices were listed as:

- A heavy lift capacity of up to 1000 tonnes
- Large lay-down and storage areas of several hectares to enable assembly of components and rapid deployment of devices for larger scale developments
- Suitable space for final assembly adjacent to the quayside
- Dry and potentially wet commissioning of electrical parts with the need for a sufficient quay length for in-water activities that could exceed 200 m
- Supply of support vessels and personnel. During installation of an individual project phase up to six vessels and several person years of support are required on site, and
- Sufficient draft and beam to facilitate movement of vessels and devices at a range of tides.

In terms of ongoing O&M, both in-situ repairs and disconnect/return to shore for repair methods were foreseen. Minimising response time by having the O&M port local to the project site was highlighted, as was the potential to develop the supporting supply chain by clustering port facilities between projects. With routine maintenance expected every 5-years, potentially 400–500 devices a year might be refurbished, and a similar number returned for unplanned repairs. Once the projects were in operation, around 2–3 ha of quayside space, 1–2 ha of storage, and about 1 ha of workshop space was forecast to support the 1.6GW of deployment.

Supporting the development of these projects, the various other roles were highlighted:

- Professional services, such as technical, legal, financial, communications, recruitment, logistics, and management support.
- Training and skills development, some via on-the-job learning, but supported by courses, access to training facilities and other activities.
- Academic research and university-level education were seen as key to developing these projects, given their novelty.
- National and local public bodies and trade associations could help raise awareness of challenges, facilitate cooperation, supply-chain development, and attracting investment.

Finally, the role of public bodies in championing the need for investment in ports and other infrastructure was highlighted.

4.1.3 WES project CREATE

One of the projects for Wave Energy Scotland's Structural Materials and Manufacturing Processes call was 'CREATE – Concrete as a Technology Enabler', led by engineering consultancy Arup. This investigated the use of concrete for the design of WECs, using case studies of the Carnegie Clean Energy 'CETO 6' and the AWS Ocean Energy 'Archimedes WaveSwing' devices to a pre-FEED (pre-Front End Engineering Design) stage [50]–[52].

The study found that concrete WECs are likely to be heavier than comparable steel designs, but this may replace ballast and is unlikely to affect performance if this additional mass is not within the prime mover. The lifetime and inspection interval proposed for concrete structures was longer, at 50 years and every 15 years respectively, compared with 25-year lifetime inspected every 5 years for steel; this could slightly reduce the number of vessel movements required. The three installation options considered all assumed the WEC was launched into the water at the fabrication port, then towed to site and installed.

Several assumptions were made as part of this study that may be more widely applicable. Mobile cranes of varying capacity would be used for the construction processes and lift of the completed WECs into the sea. Construction was assumed at completing 1 unit per week over two years, with installation of 2 units per week over the summer period. Year-round installation would reduce the laydown storage space requirements, but with additional weather downtime risk. Wet storage of the devices would reduce the onshore space required, potentially increasing the suitable construction sites, but with increased costs and risks of wet storage. Provision of covered manufacturing space with gantry cranes would reduce the susceptibility to weather and may increase efficiency, but the costs would need assessed.

4.1.4 Other studies and plans for ocean energy arrays

Academic literature on ocean energy arrays predominantly focuses on energy capture and device interaction. There are only a few studies that consider the expected requirements in terms of materials and operations for arrays of around 5 MW or more. In addition, relevant project licence application documentation for past and future ocean energy arrays were reviewed. Details of these studies and projects are given below.

Table 4.1. Literature on ocean energy arrays considered for this study

Project/study	Date	Array Size
Simply Blue Energy, CorPower CorPack wave cluster at Billia Croo (EMEC), Orkney, UK. Marine Licence Application [53].	2023	14 × 350 kW ≈ 5 MW
Simply Blue Energy, Saoirse Wave Energy – CorPower WEC array County Clare, Ireland. Project website [54].	2022	15 × 350 kW ≈ 5 MW
MeyGen Tidal Energy Project Phase 1a, Pentland Firth Inner Sound, Caithness, UK. [55]–[57].	2012+	4 × 1.5 MW = 6 MW
Environmental scoping opinion documentation for proposed Pelamis P2 arrays in Scotland: Farr Point, West Orkney South & Marwick Head. [58]–[60]	2011 2012 2012	20 × 750 kW ≈ 15 MW 13 × 750 kW ≈ 10 MW 66 × 750 kW ≈ 50 MW
Minesto Holyhead Deep array proposals from PowerKite project [61], [62], Anglesey, North Wales, UK	2018	24 × 500 kW = 12 MW 156 × 500 kW = 78 MW
Life cycle assessment of a point-absorber wave energy array, CorPower C4, Aguçadora, Portugal [63]	2022	28 × 350 kW ≈ 10 MW

Project/study	Date	Array Size
Overall tidal farm optimal design–Application to the Alderney Race and the Fromveur Strait, France [64]	2021	45 × 1.5 MW = 67.5 MW 36 × 1.5 MW = 54 MW 42 × 1.5 MW = 63 MW 36 × 1.5 MW = 54 MW
Tidal energy machines: A comparative life cycle assessment study (hypothetical site) [65]	2013	10 × 1 MW = 10 MW 5 × 2 MW = 10 MW

4.2 Infrastructure requirements for other technologies

Manufacturing and assembly of diesel and electric multiple-unit (DMU/EMU) trains was considered as another potentially relevant example for facility size requirements. This was not used directly to estimate requirements for ocean energy; the requirements were instead used as a sense check and for wider context. While very different technology in many respects, this does share some similarities with ocean energy device production and assembly:

- Volume manufacturer of 100s of units per year, but not an automated mass-production line such as used in the automotive industry
- Production of relatively standardised equipment, enabling more accurate quantification of the requirements per unit
- Size of assembled trains/carriages is relatively similar to current and proposed ocean energy devices, albeit a more linear format.

Two UK facilities were investigated, considering the facility size and production throughput,

1. CAF (*Construcciones y Auxiliar de Ferrocarriles*), Newport, South Wales, UK [66], [67], and
2. Hitachi Rail Europe, Newton Aycliffe, County Durham, UK [68]–[70].

Details of these facilities are given in Table 4.2.

Table 4.2. Details of railway manufacturing/assembly facilities investigated

Parameters Facility:	CAF, Newport	Hitachi, Newton Aycliffe
Vehicles produced	2/3 car, Class 195/197	5/9 car, Class 800/801
Approx. dimensions (per car)	24 × 2.7 × 3.9 m, 44 t	25 × 2.7 × 3.9 m, 50 t
Approx. power output (per car)	380 kW	~400 kW[†]
Indoor fabrication/assembly space	15 000 m^2	44 000 m^2
Outdoor storage	50 000 m^2 (5 ha)	210 000 m^2 (21 ha)
Approx. throughput (cars/year)	100	420

[†] Trains have 3 or 5 power units per 5 or 9 car train rated at 700 kW each.

4.3 Ocean energy technology assumptions

As with offshore wind, some assumptions need to be made regarding the future devices used and project configurations when estimating the future infrastructure requirements.

Tidal stream is at a relatively advanced status towards commercialisation. The first pre-commercial arrays have been operating since 2016, and several more and larger arrays planned to be deployed in the next few years [5]. There are a few technology variants, either horizontal or vertical axis turbines, typically with two or three blades, plus tidal kites are also being developed. Both bottom fixed (gravity base or piled) foundation and floating devices are used. Some concepts are considering multiple (typically two or four) rotors and power take-offs (PTOs) per device. Power output is typically in the range 100 kW–2 MW, although slightly larger devices up to 2.5–3 MW are being planned.

Wave energy, however, is still at the single device demonstration level. Some of these devices have been tested at part scale and generating only several kW, whereas other devises are planned for 2–3MW scale. There are a wide range of concepts, with little standardisation or design convergence across the industry. EMEC list eight main types of WECs: attenuator (including hinged rafts), point absorber, oscillating wave surge converter, oscillating water column, overtopping/terminator device, submerged pressure differential, bulge wave, rotating mass, plus other novel/unique concepts [71]. There can also be considerable variation of design concepts within these typologies, depending on the number and configuration of buoyant section(s), how the device reacts against moorings or device sections, method, and number of power take-off, and more. Some wave energy concepts also have multiple WEC units mounted on a single platform, including floating-wind-turbine-scale bases. Most WEC concepts generate electricity directly, however some are designed to pump water to shore where it drives a hydropower turbine.

It is unlikely the size and design of tidal stream or wave energy devices will converge completely. There are a range of applications being considered, and the resource energy level can vary considerably between sites thus favouring different designs.

Some projects may be located at the shoreline, for example wave energy incorporated within a breakwater[1] or tidal turbines mounted to existing barrage structures[2]. These are likely to be installed from land and thus do not contribute to the port infrastructure requirements. However, such projects are not expected to form a significant proportion of ocean energy, and thus have been excluded from this study.

4.3.1 Assumptions at different array lifecycle stages

Manufacturing and assembly

Over the coming decades, the scale of individual ocean energy devices is expected to be significantly smaller than wind turbines, ≤3 MW compared to 10–20 MW. Therefore subsystems such as the nacelle/power take-off may be more easily transported by standard road/rail freight facilities. Similarly, individual blades for tidal turbines are unlikely to exceed these limits. This means that direct port access may not be required at all the component manufacturing facilities, thus widening the potential supply chain opportunities for ocean energy.

The final assembly and related manufacturing of most devices will still require a quayside location, however, as grid-scale devices are expected to be too large to be transported easily overland.

Array installation

The installation of different components in the array can be considered separately, although the specific steps, order, and vessels used will vary depending on the technology and project location.

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[1] e.g. Mutriku Wave Power Plant, Spain, https://tethys.pnnl.gov/project-sites/mutriku-wave-power-plant

[2] e.g. Oosterschelde Tidal Power project, Netherlands https://tethys.pnnl.gov/project-sites/oosterschelde-tidal-power-project

Cables can be installed either via a dedicated cable-laying vessel, or for smaller projects may be installed via a cable-spooler mounted on another vessel. The design of the electrical network to connect the array including subsea hubs and/or substations is unclear at this stage; however, this is not expected to significantly impact on the infrastructure required to build future arrays. Onshore electrical works, including the cable landfall, are not considered in this study.

Foundations, including anchors and moorings, are typically pre-installed before the device. It is assumed these will be transported on the deck of the installation vessel, therefore the vessel size and number of foundations installed per trip are linked. Gravity based foundations will typically be more massive, while piled foundations may be more complex and time consuming to install.

Devices can be transported to site either on the deck of a vessel or barge or towed through the water. Floating tidal turbines and most WECs are expected to be towed, however if they are to be transported long distances, on-deck transport might be preferable due to towing speed restrictions and the corresponding weather windows required. Bottom fixed tidal turbines have typically been installed from the deck of a ship, and this is expected in future. Most projects have used standard vessels, however purpose-built installation vessels have been considered.

For tidal projects, installation and device recovery is assumed to occur around slack water on neap tides. This puts an additional (albeit predictable) constraint on the timing and rate of installation.

Operation and maintenance

Ongoing operation and maintenance activities will be prescribed by the technology design. For devices floating at the surface, routine access via small vessels is likely to be possible. Significant operations may require the device be returned to shore. Submerged devices will need to be recovered to the surface, and possibly to shore, for inspection and maintenance. Swapping of devices/subsystems is also being considered for maintenance; this reduces the number of vessel trips required and increases uptime, albeit with expense and storage requirements for an additional device in the array. O&M activities and the port requirements are discussed further in section 5

The frequency and scheduling of routine maintenance for ocean energy devices is still uncertain and will depend on the device type. In some cases it may be possible to possible to operate devices for multiple years without intervention. Conversely, some literature assumes multiple planed minor servicing operations per year. There may also be major servicing, overhaul, or replacement of key components one or more times over the lifetime of the device or array. In addition to planned operations, it may be necessary to react to any unplanned issues arising over the lifetime of the project.

Decommissioning/repowering

The activities and vessels required for decommissioning and/or repowering a project site may be similar to those used for installation, however some items such as piles, foundations, or ballast may be left in-situ, subject to environmental considerations. Decommissioning has not been considered in detail in this study, due to the uncertainty and longer timescales.

4.3.2 Indicative device types and sizes

As noted above, there are a wide variety of ocean energy device types and sizes being developed, especially for wave energy. Selected concepts tested to date and public plans are summarised in Table 4.3, which is far from exhaustive. Their dimensions can be summarised as length typically 20–75 m, width 10–60 m, and towing draft 2–10 m.

Table 4.3. Indicative sizes and installation for selected ocean energy devices (derived from published details)

Device	Type†	Rated Power (MW)	Overall dimensions (m)‡	Device mass (t)	Installation method & vessel(s) used
Tidal Devices					
Andritz AR1500	Fixed HATT	1.5	10L × 18W × 23H, 18⌀	110	On deck
Minesto Dragon 4	Tidal Kite	0.1	4L × 4.9W × 2.8H, 1.3⌀	3	Towed
Minesto Dragon 12 concept	Tidal Kite	1.2	Approx. 10L × 12W × 7H		
Nova M100	Fixed HATT	0.1	13.5L × 12W × 13.5H, 9⌀	13.5	On deck, multicat
OpenHydro	Fixed HATT	0.5	22L × 22w × 20H, 16⌀	230	Catamaran lift barge
Orbital Marine Power O2	Floating HATT	2.0	74L × 59W × 3.8H, 2.1D, 20⌀	590	Towed, multicat
Sabella D10	Fixed HATT	0.5–1	20L × 20W × 17H, 10⌀	450	On deck, general cargo/ offshore support vessel
Wave Devices					
Carnegie CETO	SPD WEC	1.5	20⌀ × 6H		Towed
CorPower Ocean C4	PA WEC	0.35	50L × 10⌀	130	Towed, multicat/tug
Mocean Blue Star (M100P)	HR WEC	0.01	19.2L × 4.2W × 6.4H	40	Towed, multicat
Mocean Blue Horizon concept	HR WEC	0.25	Approx. 48L × 11W	~400	On deck, multi-purpose heavy lift
Ocean Energy OE35	OWC WEC	0.5–1.2	38L × 18W × 15H, 9.4D	826	Towed, tug
Wavepiston	Attenuator WEC	0.2	200L× 8W × 8H		Towed, multicat
Wello Penguin 1	RM WEC	0.5	30L × 15W × 9H, 7D	1600	Towed, multicat

† HATT: Horizontal Axis Tidal Turbine, SPD: Submerged Pressure Differential, PA: Point Absorber, HR: Hinged Raft, OWC: Oscillating Water Column, RM: Rotating Mass.

‡ In transport configuration including foundation/substructure where appropriate, L: length, W: width, H: height, ⌀: hull/rotor diameter, D: towing draft

4.3.3 Vessels used for ocean energy installation

As noted in Table 4.3, a range of vessel types have been used, or are being considered, for the installation of ocean energy devices. Approximate typical dimensions of these are summarised in Table 4.4

Table 4.4. Vessel dimensions used/proposed for ocean energy device installation

Vessel type	Length (m)	Beam (m)	Draft (m)
Multicat	26–28	10–12	~3
Tug	26–35	8–14	3–6
AHTS/PSV/SOV*	100–160	22–27	6–9
Cargo/heavy lift	115–160	20–24	6–9

* Various terms are used depending on capability: Anchor Handling Tug Supply (AHTS), Platform Supply Vessel (PSV), Service Operation Vessel (SOV), Offshore Subsea Construction Vessel, Multi-Purpose Offshore Vessel, etc.

A wider analysis of vessels for all types of offshore renewable energy projects was conducted as part of the DTOceanPlus project, using a database of nearly 15 000 vessels from GRS Offshore [72], [73]. The range of dimensions for the different vessel types are given in Table 4.5. Given the smaller scale of ocean energy devices compared with offshore wind, it may be that the largest of these vessels are unlikely to be used for ocean energy projects.

Table 4.5. Vessel dimensions from analysis of vessels for offshore renewable energy projects [72], [73]

Vessel Type	Length (m)	Beam (m)	Draft (m)
Anchor Handling Tug Supply (AHTS)	41–92	11–22	4–8
Cable Laying Vessel	97–178	21–46	5–10
Crew Transfer Vessel (CTV)	15–30	5–10	1–2
Dredging Vessel	45–225	9–37	3–15
Dive Support Vessel	38–143	9–27	2–8
Jack-up Vessel	43–148	30–48	3–6
Multicat	19–54	8–14	2–4
Non-propelled crane vessel	51–129	22–58	3–6
Propelled crane vessel	41–319	17–97	2–18
Platform Supply Vessel	51–93	12–20	3–7
Rigid Inflatable Boat (RIB)	7–15	2–4	1
Service Operation Vessel	38–150	8–52	2–18
Survey Vessel	27–95	7–20	2–7
Transport Barge	12–137	3–37	2–7
Tug	23–75	8–18	3–7

4.4 Summary of investigations into infrastructure requirements for ocean energy projects

To gain an understanding of the potential future infrastructure requirements for ocean energy projects, a review was conducted of studies and other literature on ocean energy arrays. Given the nascent state of the sector, this was somewhat limited. Discussions were therefore held with a range of ocean energy device developers and other stakeholders to inform and refine the study. This included requesting plans for future devices and arrays, and how these might be constructed and operated. The indicative requirements identified were also discussed and refined. The quantitative and qualitative requirements are presented in the following section.

5 Ocean energy infrastructure requirements

This section collates the expected infrastructure requirements for ocean energy deployments, focusing on grid-connected arrays of around 10–50 MW built in the 2030s, noting that these may take the form of annual capacity additions to larger projects. It first sets out some key synergies and difference with offshore wind projects. In section 5.2, quantitative requirements for infrastructure are proposed, followed by cumulative European requirements. Other more qualitative considerations and requirements are discussed in section 5.3. Finally, in section 5.4, indicative quantities for components and balance of plant are derived to illustrate the supply chain requirements and the potential quantities of materials to be handled at assembly ports.

5.1 Key synergies and differences with offshore wind

While all are harvesting energy from the seas around our coasts, offshore wind, tidal stream, and wave energy are three quite different technologies. Most obviously, they are harvesting three separate types of energy, namely the movement of air in surface winds, movement of seawater in tidal currents, and the movement of the sea surface as waves pass. Moreover, they are currently at differing levels of commercialisation and installed capacity.

Some areas of similarity and key differences between offshore wind and ocean energy are discussed below, covering:

- device and component/subsystem sizes,
- location of resource, and thus potential projects,
- ports used for final assembly of both technologies,
- operations and maintenance aspects, and that
- smaller ports may be used for ocean energy than for offshore wind projects.

Device and component size

The biggest difference between offshore wind turbines and ocean energy devices is likely to be the device size. As noted in section 3.1, wind turbines of around 10 MW with rotor diameters of 160–200 m are currently being installed, with even larger machines of 20 MW and 240 m diameter envisaged in the coming years. Conversely, ocean energy devices are typically 0.1–2 MW at present, with devices of perhaps 0.3–3 MW installed in the 2030s for grid-scale power. Given the constraints of the resource, it is unlikely that individual ocean devices will become significantly larger. Note that smaller ocean energy devices have and are being tested, but these are mostly small-scale prototypes or for alternative (non-grid) markets and applications.

Due to the large size of offshore wind turbine, arrays are often located some distance from the coast to mitigate the visual impact. The wind resource is also greater and more uniform further from the coasts. Conversely, wave and tidal energy devices are either low to the water or completely submerged, so the visual impact is more limited than wind turbines.

As noted previously, the enormous scale of offshore wind turbine components such as blades and tower sections dictate that they must be transported by sea. Conversely, subsystems for ocean energy device may be transportable overland. For example, even the largest blades currently being envisaged for horizontal-axis tidal turbines would be transportable by road. This may facilitate a more geographically diverse supply chain across Europe, and this may not all be located at or close to the coast.

Resource and project location

Offshore wind projects have historically been built in shallower waters to minimise foundation depth. The relatively shallow depth of much of the North Sea basin has led to widespread deployments and proposals far from land, as shown in Figure 2.4. Floating foundations are now being used or proposed to access areas of high wind resource in deeper waters. As noted above, locating offshore windfarms further from the coast minimises visual impact, and the wind resource is typically greater where it is less influenced by land.

Energetic tidal streams are mostly located where water is forced though narrow channels and around headlands. They are therefore typically close to the coast in relatively shallow waters (≲100 m). The European tidal resource is predominantly located around the British Isles and northwest France, as shown in Figure 2.2. These geographically constrained areas of high resource are where significant development of tidal stream projects will be located. Tidal kites and other options are being developed to harness more widespread, but less energetic currents.

Due to shoaling effect of waves transitioning into shallow water, the wave resource and thus wave energy devices are sensitive to water depth. Many devices are designed to work in water depths of around 10–100 m, albeit with a more specific requirement for a given device depending on the design. It is expected that arrays will be located as close to the coast as possible, within the depth constraints, to minimise costs.

Overall, ocean energy projects installed in the next decades are less likely to be located large distances (≳10 km) from land, as is being seen for offshore wind projects, particularly floating offshore wind. This may reduce the transit to site times, provided suitable ports are located nearby. Consequently, this may increase availability to access the site as a shorter weather window is required. It will also reduce the requirements for export cables to deliver power to shore; primarily in terms of distance or length of cable required, but also the physical size and voltage level required to maintain acceptable losses.

Ports for final assembly

As with offshore wind, it is expected that most ocean energy projects will need port facilities for the final assembly of devices before they are transported by sea to the project site. Regardless of technology, ideally these assembly port facilities are located as close as possible to the project site, however there are other considerations such as the supply chain, connectivity, and workforce as discussed in section 5.3. The size of these assembly facilities is likely to be smaller for ocean energy than offshore wind, as discussed below.

Operations and maintenance

For fixed offshore wind, routine O&M is undertaken at sea, with engineers either commuting via crew transfer vessels, or living on-board larger service operation vessels. Significant repairs to main components (gearbox, generator, blades) are likely to need construction-scale jack-up and/or heavy left vessels with cranes. Floating offshore wind turbines offer novel challenges in this respect, but some types may be towed back to port for repair, depending on floating foundation draft and port clearance. [74]

Seabed mounted ocean energy devices will need to be raised to the surface for O&M. For smaller routine operations, this may be undertaken on the deck of a ship or barge. Similarly, some O&M for floating ocean energy projects may be possible from small vessels, such as RIBs and other workboats. A return to port strategy would be expected for more significant maintenance and/or for some devices. A variant on this return-to-port strategy is to have one (or more) spare devices, which are switched with the device requiring servicing, which has higher CAPEX but potentially lower OPEX and increased availability. This may also be the case for major subsystems (where the device design allows these to be swapped), such as blades, drivetrains, PTOs, and electrical systems.

Where small vessels are used for O&M, it may offer the opportunity to utilise facilities at much smaller harbours, especially if there are suitable sites close to the array. The same facilities may be used for O&M as for final assembly, especially for floating devices where specialised equipment is required to get the device in and out of the water. This may not always be the case however, as it may be preferable in some instances to keep construction and maintenance separate to avoid potential conflicts.

Smaller ports for ocean energy than offshore wind

As noted above, individual ocean energy devices are likely to be significantly smaller than offshore wind, with devices of around 100 kW to 3 MW compared with 10–20 MW for modern offshore wind turbines. As shown in section 5.2 below, this results in lower requirements for the size of ports to build ocean energy arrays, particularly in terms of quayside length and access channel requirements. Therefore, it is expected that smaller and/or more constrained ports will be suitable for ocean energy than are required for offshore wind.

In some countries, there may be existing ports that are not sufficiently large for offshore wind, but these may be suitable for ocean energy. These may have previously been utilised for other industries that are now in decline, such as transport of coal or the oil & gas sector, and ocean energy may offer an alternative role or use for these. Some ports may be located upstream of a major bridge or other barrier that prevents them being used for offshore wind, but this might not hinder their use for ocean energy projects where clearance requirements are less restrictive.

Where new-build ports are being constructed to support offshore wind projects, it may be appropriate to consider some additional space in these plans to accommodate the future development of ocean energy.

While not always ideal, ocean energy projects may also be able to make use of more constrained sections of larger ports that might not be suitable for wind projects. For example, using shorter quays or where the adjacent berth is not sufficiently large/deep to accommodate the large vessels used for offshore windfarms. It is important to note that not all ports are uniform, they come in different shapes and sizes that reflect the local physical conditions and historical development pathway.

Depending on the design of ocean energy device, the cranage or quayside bearing capacity requirements may not be as stringent as for offshore wind. This might allow the use of other ports, or possibly sections of ports, otherwise not suitable for offshore wind.

As the port requirements for ocean energy projects are expected to be less onerous than for offshore wind this will allow a wider range of facilities to be used. The deployment trajectory also lags behind offshore wind, potentially some facilities could then be used for installing ocean energy projects, as the installation rate of wind drops in future.

These points could all lead to more optimal use being made of Europe’s ports and harbours over the next few decades, with job spread over a more diverse range of coastal communities.

5.2 Quantitative infrastructure requirements

This section presents quantitative estimates for the infrastructure required to construct and maintain ocean energy arrays. Firstly, as unit rates (per MW) illustrated by a nominal 25 MW project, then the cumulative European requirements for different timescales are presented in section 5.2.2.

5.2.1 Requirements at a unit or project level

The infrastructure requirements for ocean energy investigated in section 0 are presented here as unit rates (per MW). They are illustrated with requirements for a nominal project of 25 MW. The requirements may differ between wave and tidal stream, they will also differ depending on specific device(s); therefore only an aggregate requirement is given for ocean energy. As projects get bigger, there are likely to be some economies of scale, however this is included within the uncertainty ranges of the analysis.

The quantitative infrastructure requirements for ocean energy are presented in three parts, based on the synthesis of literature review and discussions with device developers.

1. Fabrication space to build devices and major components
2. Laydown space for storage
3. Quayside and access channel sizes

The spatial requirements are expressed in terms of m^2/MW (or ha/GW)[3]; however, this implicitly assumes an annual throughput. The space required at a specific site or port (in m^2 or ha) would allow for a corresponding throughput (in MW/year) assuming it continues to be used. These metrics can be combined to give a requirement in m^2/MW/year, which has been used in the calculations, but the requirements are presented separately for clarity.

The requirement for fabrication space depends very much on how far up the associated supply chain is considered. Each step back towards the raw material increases the requirements. As this study is focussed on port infrastructure, a nominal cut-off of components requiring sea-based transport can be used. This fabrication is likely to require a mix of indoor and outdoor space. It may not all be directly located at the port, but it will need good connectivity to a port. Any indoor facilities will require suitably large doors to facilitate movement of large components and potentially fully assembled devices; this will obviously be a device-specific requirement.

Some requirement is expected for laydown and storage space for components and devices at or near the quayside for final assembly and load out. In some cases, this might include wet-storage in sheltered waters. The type and size of laydown space for storage will again obviously depend on the type and size of devices. It will also depend on the number of devices to be installed in an array and the installation schedule.

This study postulates the following requirement for future ocean energy projects:

- around 200–1000 m^2/MW of fabrication space4, and
- a slightly wider range of 100–1200 m^2/MW of laydown space.

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[3] 1 ha/GW = 10m^2/MW.

[4] Early device and array demonstration projects may have significantly greater requirements per MW, lacking the economies of scale of larger arrays. Additional requirements for the supply chain are not included.

For a typical project (or cluster of projects) with about 25 MW installed per year, this equates to sites requiring around 0.5–2.5 ha for fabrication and 0.25–3 ha for storage, although obviously technology and project specific.

The quayside berth and port access channel requirements will depend on the vessels used, plus the device size and draft where towed. As most ocean energy device concepts are relatively low to the water, the vessel may set the clearance required at bridges, but this is expected to be much less of a constraint than for offshore wind ports.

- It is expected that quaysides of 50–200 m length will be suitable for most ocean energy projects, although up to 350 m may be required in some instances, depending on the device dimensions.
- A quayside berth width of 10–80 m and water depth of 3–10 m should suffice for most ocean energy projects.
- The minimum size of any access channel between the quay and the port is expected to be 20–100 m wide, 5–10 m deep, with 10–50 m of clearance above water level, although this very much depends on the size of the device and vessels used.

These key quantitative requirements for ocean energy ports are listed in Table 5.1 and illustrated diagrammatically in Figure 5.1.

Table 5.1. Indicative requirements for ocean energy ports

Metric	**Assumed Requirement**	**25 MW project**
Fabrication space (at port) †	200–1000 m²/MW	0.5–2.5 ha
Laydown/storage space	100–1200 m²/MW	0.25–3 ha
Quayside (length/width/depth)	50–200‡ m / 10–80 m / 3–10 m	
Access channel (width/depth/clearance)	20–100 m / 5–10 m / 10–50 m	

† Does not include full supply chain.

‡ May be up to 350 m for some devices.

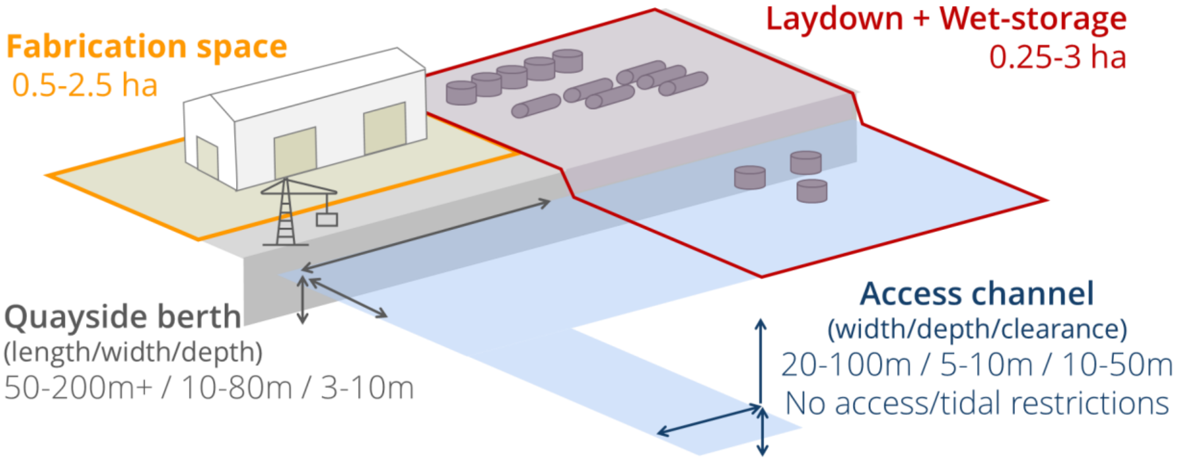

Figure 5.1. Illustration of indicative infrastructure requirements ocean energy ports, to support 10–50 MW/year in the 2030s. These requirements are project and technology specific, and they may be located at one or more ports.

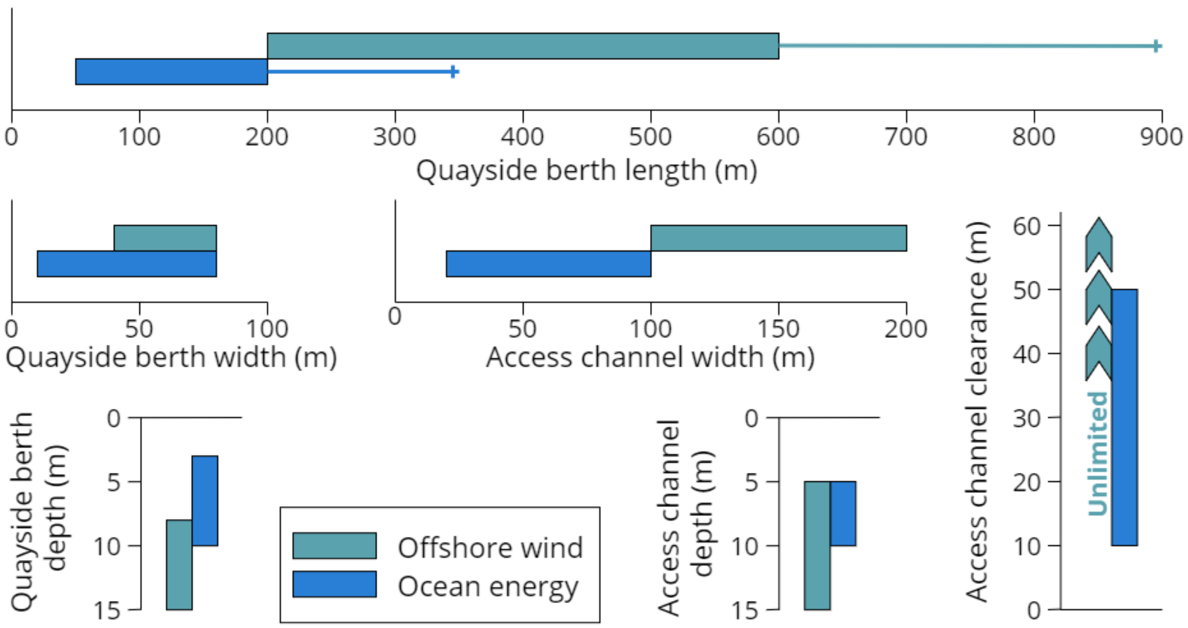

Figure 5.2. Indicative range of quayside size requirements for offshore wind and ocean energy projects. Bar ranges account for uncertainty in device size and type, plus installation vessels used.

5.2.2 Total European requirements for port space

Using the infrastructure requirements per MW discussed above and the scenarios of annual deployment presented in section 2.2, an estimate can be made of the total European port space requirement for ocean energy in the 2030s, and with greater uncertainty into the 2040s.

To put this into context, total European port space requirements for offshore wind have been estimated using the same methodology, using the range of quantitative requirements from the literature review in section 3.3 and projected deployments also in section 2.2. It is unclear at this stage what the requirement for infrastructure to support the decommissioning and repowering of offshores wind farms at the end of their operation lifespan. WindEurope note that the current situation with high power prices supports lifetime extension of turbines and projects [10]. They also project that around 300 turbines totalling 700 MW may be decommissioned by 2030 [43]

There is considerable uncertainty in the total space requirements. This is a combination of an unknown deployment rate compounded by a wide range in potential technology and project requirements. The variation in port space requirements over time can be illustrated using scenarios that separate these two main uncertainties, and consider:

1. Low/mid/high deployment rates, for offshore wind and ocean energy separately.
2. Low/mid/high space utilisation, which is a function of the type of device (including foundations), vessels, operations, etc. and is assumed to be similar for offshore wind and ocean energy projects.

The technological assumptions on how much space may be required for a given deployment has greater uncertainty[5]. It is also proportional to the annual deployment rate.

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[5] Illustrated by the median with an error encompassing P25–P75 assuming a uniform distribution

Although there is around an order of magnitude difference between the lower and upper estimates presented, a few key points are apparent in the port space estimates presented in Figure 5.3 and Table 5.2:

1. The requirements for offshore wind are considerably greater than for ocean energy, due to the larger turbine sizes and more advanced state of the wind sector with significantly higher deployment. This is particularly apparent in the early 2030s, when ocean energy is expected to require only around 1% of the space needed for offshore wind ports.
2. Annual deployment of new offshore wind farms is expected to peak around 2030, thus port space required to construct them may drop over the following years. Some of this space could therefore be used to support future construction of ocean energy arrays.
3. If the deployment of ocean energy follows the trajectory proposed in section 2.2, the port space requirements will increase by an order of magnitude over the 2030s, requiring around 12% of the space for offshore wind by the end of the decade.
4. Albeit with greater uncertainty, by the mid-2040s ocean energy could require between 40% and 80% of the space required for offshore wind, although this is only 30–50% of the peak offshore wind requirements of the early 2030s. Indeed the cumulative requirement for offshore wind and ocean energy in the 2040s might not exceed the peak for offshore wind in the early 2030s.

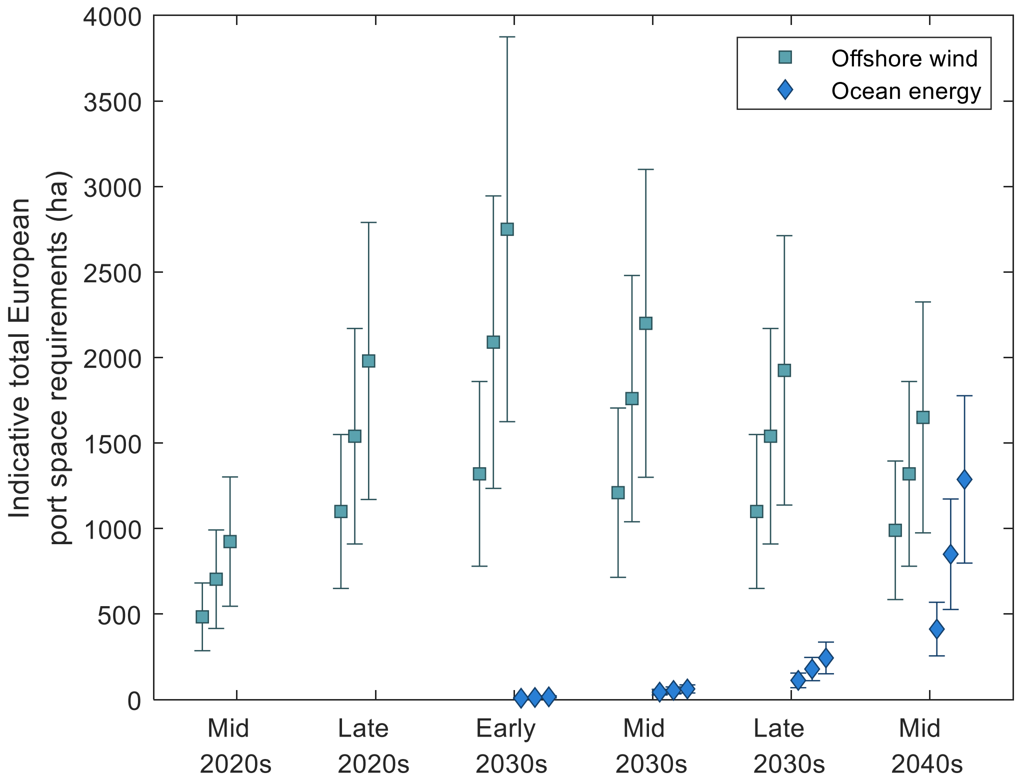

Figure 5.3. European port space requirements for offshore wind farm and ocean energy array construction. Markers show low/medium/high deployment rates with error bars for uncertainty in port space required.

Table 5.2. Total European port space requirements for offshore wind farm and ocean energy array construction in the 2030s and 2040s. Ranges account for uncertainty in both deployment rates and space required per project.

Tech-nology	Timescale	Annual deployment (GW)	Fabrication space (ha)	Laydown & storage (ha)	Total area (ha)	Fraction of wind
Offshore wind	mid 2020s	4.4–8.4	72–330	210–980	290–1300	—
	late 2020s	10–18	160–700	490–2100	650–2800	
	early 2030s	12–25	200–970	590–2900	780–3900	
	mid 2030s	11–20	180–780	540–2300	720–3100	
	late 2030s	10–17.5	160–680	490–2000	650–2700	
	mid 2040s[†]	9–15	150–580	440–1700	590–2300	
Ocean energy	early 2030s	0.065–0.13	2.6–10	2.4–12	5–22	~1%
	mid 2030s	0.35–0.5	14–40	13–46	27–86	~3%
	late 2030s	0.9–1.95	36–160	34–180	70–340	~13%
	mid 2040s[†]	3.3–10.3	130–820	120–950	260–1800	40–80%[‡]

[†] Note significantly greater uncertainty for 2040s

[‡] 30–50% of 2030 peak

Considering the low deployment scenario for both ocean energy and offshore wind, together with the midpoint space requirements, would require 110 ha of port space for ocean energy by the late 2030s, approximately 10% of the 1100 ha requirement for offshore wind. The high deployment scenario would require 240 ha, or 13% of the 1900 ha needed for wind, noting that up to 3900 ha might be needed for the peak offshore wind deployment around 2030.

For both offshore wind and ocean energy, the ongoing operations and maintenance will be an increasing requirement as more technology is deployed. A recent WindEurope study suggest that by 2030 there could be over 200 offshore windfarms, totalling 12 000 turbines, that will require ongoing O&M [43]. As noted in section 5.1, some O&M might be carried out using smaller vessels, and as such will not contribute significantly to the port space requirements. More significant maintenance, as well as decommissioning and repowering projects may however use the same or similar facilities to construction.

5.3 Qualitative considerations and requirements for ocean energy port facilities

This section summarises some more qualitative requirements and other points to consider for ocean energy port facilities, namely:

- Location and connectivity requirements,
- Transhipment of devices and subsystems at assembly ports, and
- Summary of other potential considerations.

Location and connectivity

As noted in section 5.1, ocean energy projects are expected to be located relatively close to the coast, not far offshore, especially for early deployments through the 2030s. The location and order of project sites being developed will also depend on the availability of suitable infrastructure within a reasonable distance. Thus the infrastructure at and around ports, along with the associated supply chain, will likely develop in parallel with the roll-out of projects.

Reducing transport distance can often reduce costs, so the port location relative to the supply chain may be an important consideration. As noted elsewhere, the transit distance to site is particularly critical for O&M operations that are carried out repeatedly over the lifetime of the project. Some operations may be less sensitive to distance, however.

Good transport links are important, both for moving components around the supply chain and for the project workforce. Road, rail, and airport connectivity should therefore be considered in addition to coastal access when considering and developing ports for ocean energy projects, as is the case for offshore wind. The smaller size of ocean energy devices means that, unlike wind, it may be possible to transport some subsystems overland.

There are many socioeconomic benefits associated with the situating of ocean energy projects within or adjacent to remote coastal or island communities, for example within the north of Scotland. Given the expected reduction in oil and gas output across most of the UK, an emerging ocean energy sector will provide a potential employment safety net and provide an opportunity for existing skilled workers form the oil and gas sector to re-train and become a critical part of the net-zero transition. This in turn may help to prevent negative knock-on effects including unemployment, depopulation, and degeneration of local services. A thriving ocean energy sector will also help to develop and sustain a range of ancillary sectors, including O&M, the service industry and spur on associated regional socio-economic development. Finally, the requirement for a skilled workforce, coupled with the presence of satellite campuses for higher learning institutes could actively draw both workers and families to the region, further enhancing socio-economic growth, provided suitable accommodation and services are available.

Given the suitability of coastal and island communities to host ocean energy deployments, there is also reason to believe that they might be amongst the first to benefit from energy generation and storage schemes that can help to tackle the prevalence of fuel poverty within these communities. These locations also provide an opportunity to trial potential future energy configurations that may help to harness the unique generation profile of ocean energy technologies.

More remote sites may be more difficult to deliver materials to, and/or may not have sufficient local labour resource. While both have the potential to increase costs, the placement of ocean energy devices could help to make the case for increased development of regional infrastructure on a state level. An example of this is the combination of onshore community wind farm projects and the European Marine Energy Centre test site in Orkney necessitating the eventual upgrade of the islands grid interconnection.

Transhipment of devices and subsystems at assembly ports

At the final assembly facility, suitable methods of moving large subsystems, device components, and completed devices will be required. Various cranes and self-propelled modular transporters (SPMT) will typically be used for this purpose. Mobile cranes may be used, particularly for smaller or earlier projects; however, local availability and suitable access for these will also therefore be a consideration. It may be that some device developers design bespoke systems to facilitate movement of the device around the port for assembly and load out. Additionally, cherry pickers may be required to provide suitable access for some operations.

For devices that are towed to site, a means of transhipping the device into the water will be required. The large size and mass of ocean energy devices makes this non-trivial. This may require one or more heavy-lift cranes, a slipway, ship-lift, dry-dock, submersible barge, or other solutions. This may also apply to O&M where the device is returned to port, in which case the O&M may be based at the same facility as final assembly given the similarities in requirements.

Devices transported on deck will likely require one or more cranes for loading and deployment, although these may be vessel mounted, thus not a requirement for the port.

Even where some other method is used for the device, there may still be a requirement for suitable quayside and cranage to deliver large subsystems by boat, for example drivetrains or hull sections.

All these requirements will be technology specific and could vary significantly for the wide variety of ocean energy device concepts developed to date. It may also be that different options are used in different locations, depending on local conditions and constraints. Transhipment of the device and major components could be a critical requirement for assembly (and O&M) ports for ocean energy.

Other considerations

Several other qualitative considerations were raised in the discussions or found in the literature, which are summarised below.

- Sufficiently large indoor fabrication facilities are required for assembling hull sections, plus coating/painting and associated preparatory works. Buildings used for the construction/ maintenance of ocean energy devices will obviously need sufficiently large doors/openings to accommodate the device. In some cases, final assembly may take place outdoors on the quayside for space/access constraints.
- There will be multiple trade-offs and considerations towards building bespoke facilities, potentially at a new port, versus adapting existing infrastructure to suit. This includes costs, timing, location, environmental impacts, etc.
- Multiple smaller facilities may be considered for the manufacturing and assembly of devices, so that these facilities are located closer to deployment sites and/or supply chain and workforce. There will be a balance between the amount of storage space required with more devices and the number of devices that can be produced efficiently.
- Ports should ideally have minimal access restrictions for vessels. Opening bridges, locks or gates, or other tidal access constraints can all add delays and reduce the attractiveness of the site, particularly where routine access is required.
- It may be advantageous in some instances to have access to sheltered water nearby for testing or commissioning of devices, before being exposed to larger waves or currents at the deployment site.
- Especially for first-of-a-kind fabrication and assembly, the design team should ideally be based nearby in case issues arise. Suitable office space would be required at, or close to, the facility for this.
- Where small vessels are used for O&M activities, welfare and office facilities should be provided close to the port/berth.
- The planning of port infrastructure, particularly in remote areas, should involve local communities and include just transition considerations. Ocean energy offers many benefits to these communities but should not be forced upon them.
- Previous experience at the port with other offshore renewable energy projects is advantageous to minimise the learning curve.

5.4 Indicative component and balance of plant requirements

Together with the infrastructure to deploy and maintain arrays of ocean energy devices, a supply chain will be needed to produce the subsystems, components, and other balance of plant required for these arrays. Much of this will be processed and assembled at the ports discussed in section 5.2. Unlike final fabrication and assembly, the supply chain need not be located on the coast at a port. It thus provides an opportunity for all of Europe, not just near locations with the best wave and tidal resource.

It is not possible at this stage to state what the supply chain requirements for ocean energy arrays will be. However, some estimates of the requirements for various component/subsystems have been derived from the literature, supported by information provided by developers, with assumptions noted below. These can be combined with the deployment trajectories in section 2.2 to give future requirements, in exactly the same manner as the total port space requirements were calculated in section 5.2.2.

Electrical cables will be required, both to connect between devices in the array and to export power to shore. These are likely to be smaller cables and/or at lower voltages than used in offshore wind projects, given the relative size of individual devices. Estimates in the literature vary, but between 200–2000 m/MW of cable may be required for ocean energy projects.

Ocean energy devices to supply grid power will require electrical generators, power electronics and control systems. Some devices may have multiple PTOs, with a lower unit rating but a corresponding increase in number required. The unit rating for ocean energy PTOs may be around 0.1–1.2 MW in early 2030s and 0.2–1.5 MW by the late 2030s.

Most wave energy devices and all floating tidal turbines will require moorings and anchors to hold them in position. This will comprise perhaps 2/3 of all ocean energy devices. Typically 2, 3 or 4 lines are used per device, although shared mooring solutions are sometimes considered for arrays. The specific mooring solution will vary between devices, with a range of catenary or taught moorings, synthetic ropes and/or chains, plus embedment anchors, gravity mass anchors, and piles used, amongst others, depending on the device and seabed conditions.

Most devices to date have been constructed primarily of steel, although composite materials have also been used for some device parts. Concrete device construction has been considered in several studies; it is also used for some gravity foundations.

To estimate the scale of potential material requirements for future ocean energy arrays, input data from a lifecycle assessment (LCA) of different types of ocean energy devices by the European Commission Joint Research Centre (JRC) has been used [75]. This builds on their database of 83 tidal and 103 wave energy concepts [76], which is presented in aggregate for 15 device types, with four subsystems and seven materials. Moorings and foundations are the most significant portion of the total mass, 57%, followed by device structural components, 31%, PTO components, 8%, and the electrical connection, 5%. In terms of materials breakdown, steel is the most prevalent, 56%, other metals, 5%, electronics 1%, plastics (including composites), 9%, concrete, 20%, sand, 2%, and water, 7%. Combining these material requirements with the deployment trajectories gives an estimate of total mass required (stated in kilo tonnes, kt).

The JRC database represents historical devices, compiled in 2016, with many of these still at the developmental stage. It may not be completely representative of future devices. Nevertheless, it has been used as a starting point to develop 'what-if?' scenarios to illustrate the potential scale of material requirements for ocean energy arrays in the 2030s.

These component, subsystem, and material requirement scenarios are summarised in Table 5.3 below, together with the corresponding annual requirement for the early 2030s and late 2030s timescales. For reference, the upper bound estimate of steel of 3600 kt/year is approximately 2.5% of EU27+UK steel production in 2022, or <0.2% of global production [77].

Table 5.3. Assumed unit requirements for various ocean energy components, with derived total European requirements for early and late 2030s timescales. See text above for more details.

Component/subsystem/material	Requirement	Early 2030s	Late 2030s
Electrical cables (array + export)	200–2000 m/MW	10–200 km/year	200–3000 km/year
Generators & power electronics	rated 0.1–1.5 MW	60–500 units/year	400–6000 units/year
Mooring lines and chains	100–1000 m/MW	2–30 km/year	30–500 km/year
Structural components mass†	160–1800 t/MW	9–180 kt/year	120–2600 kt/year
PTO components mass†	30–360 t/MW	2–37 kt/year	24–540 kt/year
Mooring and foundations mass†	280–2000 t/MW	19–210 kt/year	260–3000 kt/year
Electrical connection mass†	28–110 t/MW	2–430 kt/year	29–170 kt/year
Mass of steel†	56% total mass	18–240 kt/year	240–3600 kt/year
Mass of other metals†	5% total mass	2–23 kt/year	23–340 kt/year
Mass of plastics (inc. composites)†	9% total mass	3–38 kt/year	38–560 kt/year
Mass of concrete†	20% total mass	6–85 kt/year	84–1200 kt/year

†Derived from JRC LCA study

5.5 Summary of infrastructure requirements identified for ocean energy projects

While there are expected to be similarities and synergies between offshore wind and ocean energy, there will also be differences. Most notably, ocean energy devices are expected to be smaller individually, perhaps 0.3–3 MW devices. It is therefore likely that smaller ports, or sections of ports, can be used to support the construction of ocean energy projects that may not be suitable for large offshore wind projects. Wave and tidal arrays may be located closer to the shore than future offshore wind farms, given both the location of the resource and the more limited visual impact.

The quantitative requirements for ocean energy ports developed in this study are:

- around 200–1000 m²/MW of fabrication space, and
- a slightly wider range of 100–1200 m²/MW of laydown space.

This can be illustrated by a typical project, installing about 25 MW per year, as around 0.5–2.5 ha of fabrication space, and 0.25–3 ha for laydown which may include some wet-storage. Smaller vessels are expected to be used for ocean energy, therefore quaysides 50–200 m long, with an adjacent berth 10–80 m wide and 3–10 m deep. The access channel out to sea should be at least 20–100 m wide, 5–10 m deep, with 10–50 m clearance. These requirements will depend on the specific ocean energy devices being used.

Combined with the assumed deployment trajectory, total Europe requirements for ocean energy port space can be estimated. In the early 2030s, about 2–22 ha may be required, around 1% of that expected for offshore wind projects. This may increase to 28–330 ha by the end of the decade, or 12% of offshore wind. With greater uncertainty, by the mid-2040s, ocean energy may require up to 1600 ha. By this time, offshore wind deployments may have peaked, and so will no longer be using all the port space required previously. As the ocean energy sector matures, it may be that more efficient use can be made of the infrastructure required to fabricate, install, operate, and maintain arrays of devices.

As with offshore wind, there are a range of other qualitative considerations and requirements for ocean energy port infrastructure. A balance needs to be struck between the location of the port, supply chain and workforce, and the deployment site. Good connectivity is required, both for materials and people. Cranage and transporters will be required to move components and fully assembled devices. For devices towed to site, getting the device in the water will be a key consideration.

A strong supply chain will be required to support the deployment of ocean energy across Europe and elsewhere. This will require hundreds of km per year of electrical cables to connect the arrays, plus a similar length of mooring lines and chains to secure floating devices. The devices will need thousands of generators, rated around 0.1–1.5 MW each, together with associated power electronics. Significant quantities of materials will be required to construct devices and foundations, although this will be very dependent on the mix of technologies deployed.

6 Conclusions and recommendations

There is an ongoing need to decarbonise the global energy system, to meet net-zero targets and limit the impact of climate change. Renewable energy targets have been increased following the Russian invasion of Ukraine, to help reduce the need for imported gas. Alongside continued deployment of fixed offshore wind, floating offshore wind array projects are being developed, allowing wider deployment in deeper waters. This continues the rapid expansion of renewable energy in Europe, with both onshore and offshore wind capacity increasing from 10 MW to 10 GW in around 20 years.

Ocean energy (wave and tidal stream) can also contribute towards the required rapid roll-out of renewable energy generation over the coming decades. More tidal arrays are expected to be built over the next few years, together with wave array demonstration projects. The growth of ocean energy has the potential to unlock multiple benefits:

- Firstly, increased energy security from new sources of renewable domestic generation, contributing to REPowerEU and other national initiatives. Tidal stream and wave energy are additional sources of renewable energy that can help towards meeting decarbonisation and net-zero targets.
- Ocean energy is more predictable and often available at different times to wind and solar power, thus offering additional system benefits [1].
- Developing the more nascent ocean energy sector offers significant opportunity for jobs and gross value added (GVA) to the European economy. Previous research in the ETIP Ocean project quantified this as 59–140 €bn in GVA by 2050, corresponding to 205 000–500 000 jobs in the ocean energy sector [15], [78].
- Additionally, ocean energy can contribute to the just transition, offering skilled jobs and clean energy in and around coastal communities, potentially in more remote areas.

This study aimed to quantify the European requirements for infrastructure at ports and harbours to support the commercialisation of ocean energy, through the 2030s and beyond. These requirements were developed from literature on offshore wind and ocean energy project requirements, supported and validated through discussions with key wave and tidal device developers and other agencies. There is considerable uncertainty in both the quantitative requirements and future deployment trajectories for offshore wind, and especially so for the more nascent ocean energy technologies. There also remain unknowns for how future commercial wave and tidal arrays will be rolled out, and exactly what infrastructure will be required to support this. Therefore, it would be beneficial to revisit the results of this study periodically, and update with new findings as appropriate.

Irrespective of the uncertainty, this study shows that if ocean energy follows a similar deployment trajectory to wind, there will be significant infrastructure requirements over the coming decades, and planning for this should start now.

- The cumulative European (EU27+UK) space requirement for offshore wind ports by 2030 might be 2800 ha or more.
- This study estimates ocean energy may only need 1% of the port space needed for wind in the early 2030s, but by the end of the decade this could grow to around 13%, or 240 ha.

- Continued growth in deployment of ocean energy, as seen in both onshore and offshore wind, would lead to considerably higher requirements by the 2040s, albeit with greater uncertainty. However, the cumulative offshore wind and ocean energy requirements might not exceed the peak offshore wind port space requirements from the early 2030s.

While there are expected to be similarities in the requirements for port infrastructure to support offshore wind and ocean energy projects, there will also be differences. Most notably in the size of facility required, given the disparity in both device size and, at least initially, deployment rates. Currently, ports to support offshore wind projects, deploying up to 1 GW annually may require around 10–100 ha of space, quaysides 600 m or more in length, with unlimited clearance for vessels and turbines. Conversely, ocean energy projects deploying 10–50 MW annually in the 2030s may only require 0.7–6 ha, 50–200 m quayside, and clearance of 10–50 m, depending on the device and project.

Port facilities for ocean energy may be located alongside those for offshore wind, thus requiring marginally larger facilities. However, there are significant opportunities for ocean energy to utilise a much wider range of either smaller ports or sections of ports, that are not suitable for offshore wind. The exact port requirements will be project and technology specific, and given the diversity of device concepts being developed, these requirements may vary quite considerably. This also points to the opportunity for a wider range of ports to be involved with ocean energy projects, even if they are not suitable for large offshore wind projects.

Current deployment targets and projections for offshore wind see annual deployment rates across Europe peak around 2030. Cumulative capacity is still projected to grow, just more slowly. Depending on the requirements to support decommissioning and repowering of offshore windfarms, this may free up space at some ports, allowing them to support the growth of ocean energy projected in the 2040s.

Over the next decade, with some development and upgrades, existing facilities may be suitable in most countries for early ocean energy arrays. However, plans need to be put in place within this period to facilitate the future expansion of ocean energy. Especially as there are long lead times for planning and delivering strategic national investments in projects such as ports. Any upgrades to these facilities, being planned now or in future, to support more widespread deployment of offshore wind should also consider implications of ocean energy deployments.

Support is required at a regional, national, and European level to develop suitable infrastructure for offshore renewable energy. To maximise the potential benefits and limit the need for rework or updates, infrastructure plans need to also consider potential future needs to support ocean energy projects.

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