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D7.12 White Paper on expected Learning Rates

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Executive Summary

This deliverable D7.12 White Paper on expected Learning Rates, aims to present the work conducted to identify future cumulative deployments, corresponding levelised cost of energy (LCOE) and associated learning rates (LR) to identify likely cost reductions and technology improvements for floating offshore wind (FOW), wave and offshore solar projects as they scale across a range of timeframes. These individual deployments, LCOE and LR are then combined to briefly explores the potential for hybrid learning by combining technologies in multi-MW farms. This deliverable also briefly introduces learning rates and the link to revenue streams and LCOE reductions.

The deliverable details the methodological framework and equations used in the analysis. In as far as possible the same overall approach has been taken to explore the three individual sectors: (1) the industry projections based on publicly available information, (2) using reference technologies to project future deployments through growth and doubling models, and (3) collating available data to build a bottom-up data based on each technology and applying exponential best fit curves to project deployments, LCOE and calculate LR.

Using the three different approaches gives a well-rounded outlook on each of the sectors. Overall, where there is more information available (e.g. FOW) the results converge, whereas, where there is comparatively information scarcity (e.g. Wave and offshore solar) results vary to a much larger degree, particularly in the projected deployments.

The finding on combining learning rates in hybrid multi-MW farm shows opportunities for cost reductions when mature technologies such as fixed offshore wind are combined with wave or offshore solar until such a time that these latter industries reach maturity.

Abbreviations

BF	Bottom Fixed Offshore Wind
CAPEX	Capital Expenditure
DECEX	Decommissioning Expenditure
FOW	Floating Offshore Wind
FPV	Floating Solar PV
LCOE	Levelised cost of Energy
LR	Learning Rate
OPEX	Operational Expenditure
OW	Offshore Wind

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1. Introduction

1.1 Aim

This deliverable, D7.12 White Paper on Expected Learning Rates, detail the work conducted using learning curve models to identify likely cost reductions and technology improvements for floating offshore wind, wave and offshore solar projects as they scale, across a range of timeframes. For each of these technologies this deliverable projects future deployments and the associated levelised cost of energy, along with identifying learning rates.

These individual results are then used to conduct analysis into combined learning on hybrid systems of fixed offshore wind parks with wave or offshore solar, and hybrid systems of floating offshore wind parks with wave and offshore solar.

1.2 Content

This report is divided into seven main chapters. Chapter 2 provides a brief introduction to learning rates and how this metric links with cost reduction pathways and associated revenue scenarios. Chapter 3 details the methodological framework used for the presented analysis along with key equations. Chapter 4, 5, and 6 show the results of the analysis for floating offshore wind, wave and offshore solar respectively. Chapter 7 details the analysis on hybrid systems and combined learning rates. The final chapter 8 provides a brief summary and the key conclusions of the work within this deliverable

2. Revenue scenarios and learning rate of technologies

Wright's Law (Wright, 1936) states that for every doubling of cumulative deployment, a technology will reduce in cost at a consistent rate. This is what is known as the learning rate, which will be explored in detail in this report. In short, a learning rate can be calculated based on cost over time, whether capital expenditure (CAPEX) or operational expenditure (OPEX) or levelised cost of electricity (LCOE), or cumulative deployment and then be used to project future costs based on expected future cumulative deployment. This is a useful tool to project when in time renewable energy technologies such as floating offshore wind, wave and offshore solar may match or fall below the cost of conventional energy, also known as grid parity. Currently, the LCOE of these technologies is much higher than that of conventional energy sources, and although LCOE does not use revenue in the calculation, it does represent the average revenue per unit of electricity required to recover the cost of the project over its financial lifetime.

There are limitations associated learning rates, owing to numerous calculation methods and the inherent uncertainties that come with predicting future events based on past ones, and to consider the different stages of development usually through technology readiness levels (TRLs) (Jamasb & Kohler, 2007). One suggestion for improvement is a move to a two-factor learning model where more learnings outside just cost reductions can be included, such as innovation theory. Further uncertainties are through often ignored cost increases during early commercialisation, and the fundamental shape of a learning curve, with S-shaped curves more realistic to describe the cost-increase peak that often befalls technology. Also, the complexity in other areas not always reflected in CAPEX including installation, operation and risk, plus other more broad categories such as social, political and economic. Multi-factor models which build on just cumulative change often bring with them uncertainties from the difficulties in estimating key parameters such as research and development, plus the spill-over effect into other associated industries (Yeh & Rubin, 2012).

The Ocean Energy Forum (Ocean Energy Forum, 2016) determined that as projects move from demonstration to pre-commercial to industrial roll-out, subsidies and government funding continue to be vital for technologies to reduce the LCOE and reach maturity, as shown in Figure 1.

However, as technologies mature and become more competitive, government subsidies decrease and, in its place, the already increasingly popular power purchase agreement (PPA) becomes an integral part of renewable energy project financing. PPAs aim to create a risk-controlled agreement between the buyer (a large company requiring large amounts of energy or a reseller) and the seller (the power generator) over a specified time period, usually 10 to 20 years. LCOE, therefore, is an important indicator as it acts as a minimum of what the PPA price needs to be for the project to be financially viable.

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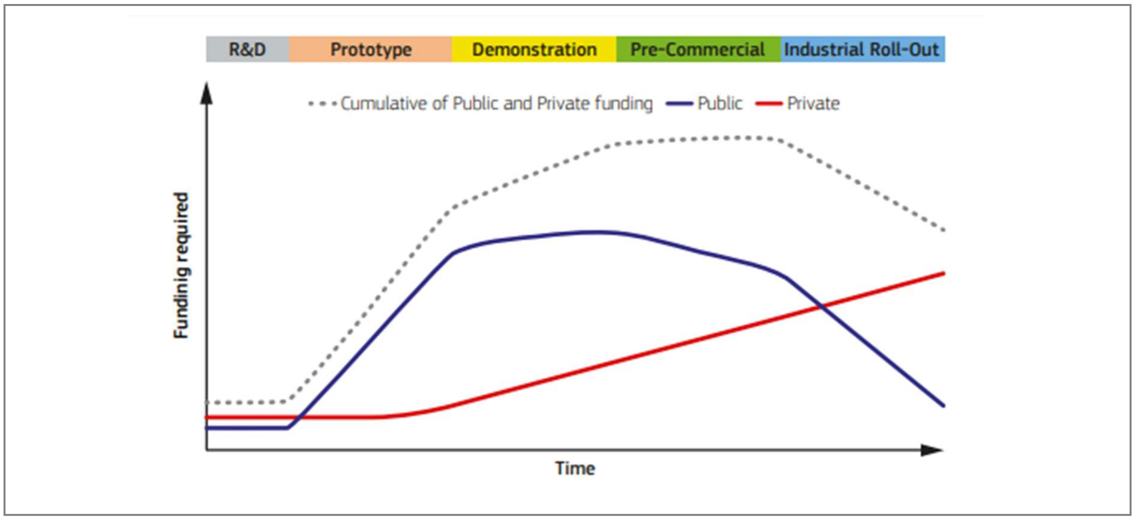

Figure 1: Indicative share of private and public funding for an ocean energy concept per development phase. Source: Ocean Energy Forum, 2016

3. Methodology

3.1 Methodological Framework

This deliverable investigates the future deployments, LCOE, and learning rates of floating offshore wind, wave and offshore solar PV. The following methodology has been used to assess each of the sectors: (1) the industry perspective based on publicly available reports and papers, (2) using reference technologies to project future deployments through growth and doubling models and (3) collating available data to build a bottom-up data based on each technology and applying polynomial best fit curves.

The industry perspective gives a (high-level) concise description of the publicly available information from reports and papers and the view of future deployments, LCOE and (in as far found) the LR on LCOE, CAPEX and OPEX. For floating offshore wind (FOW) plenty of information has been found to provide a good description of the sector out to 2050. Less information was found for the Wave sector, and even less for offshore solar in comparison to FOW.

The second approach uses reference technologies to project future deployments through growth and doubling models. Fixed offshore wind is used as the reference technology for the FOW and wave sector, whereas for offshore solar two reference technologies are used: fixed offshore wind and floating PV. DMEC has developed a market research tool (Pillet, Lehner, Stark, & van der Zant, 2023), which describes the potential growth of innovative offshore renewable energy technologies based on trends observed in comparable sectors. The key to successful analysis is creating a database for the reference technology with historical data that corresponds to at least the same time period to be projected. In combination with typical learning

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rates (e.g. found in publicly available reports), this model can also be used to project the cost of energy at different points throughout this development.

Thirdly, the bottom-up database, the information gathered includes current and future announced cumulative deployments based around deployed or planned projects for CAPEX, OPEX, and LCOE. Large sectoral projections are avoided where possible and serve only to validate or provide LCOE forecasts where none are available on a project-level. Using this information future projections are made for deployments and LCOE by applying best fit curves and the corresponding learning rates are calculated. For FOW there was enough general technological information as well as on the four main floating substructures to conduct this analysis. Although less information was available for Wave and offshore solar to conduct a platform-specific study, analysis on these sectors was conducted alongside that follows the bottom-up technological method.

3.2 Equations used

This section describes the equations used for analysis in this report: polynomial and exponential functions, LR equations, and LCOE equation.

Polynomial function from the growth model:

$$q(t) = a \cdot e^{b*t} + q_0 - a \cdot e^{b \cdot t_0} \tag*{1.}$$

where *a* and *b* are the two coefficients of the growth curve, $q(t)$ the cumulative capacity in MW, t the number of years since the year of reference, q_0 and t_0 the first values of the interval.

Exponential function from doubling model:

$$q(t) = q_0 \cdot 2^{\frac{t}{T_D}} = q_0 \cdot e^{r \cdot t} \tag*{2.}$$

where q_0 is the cumulative capacity for the first year of the interval, T_D the length of the period between two doublings, r the constant growth rate and t the time in years.

To project the developments in the offshore renewable sector, based on the third approach described in the methodology section, the growth of the reference sector(s) is(are) followed and two analyses applied. The first analysis uses a growth curve that follows the polynomial shape defined by Equation (1) of the cumulative deployments in the reference sector. The second uses a doubling model, which follows the exponential growth defined by Equation (2) based on different phases (periods) in the development. Figure 2 illustrates both analysis each one using mentioned corresponding equation.

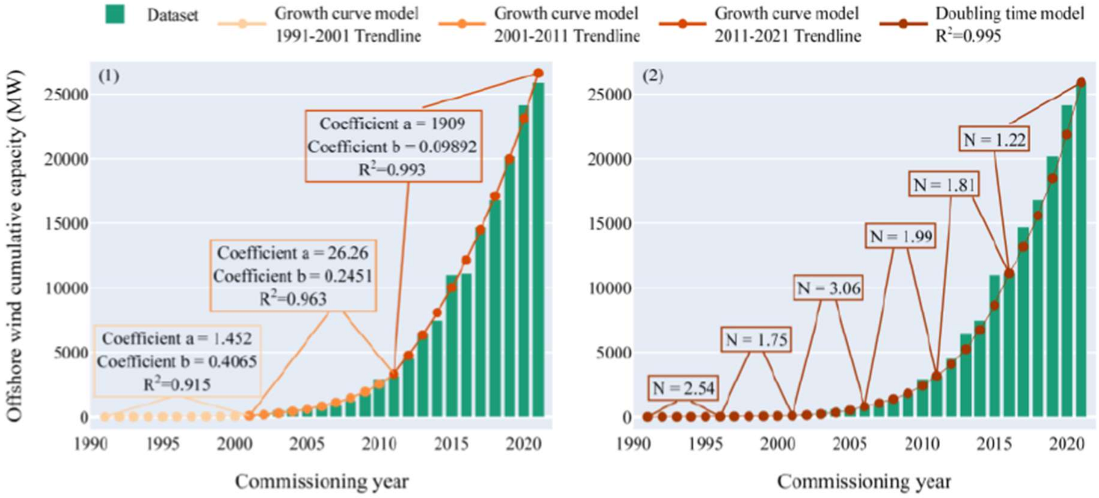

Figure 2: Growth model and Doubling time model (Pillet, Lehner, Stark, & van der Zant, 2023)

Learning rate equation:

The below equations (3-6) define how LR was calculated in this study. Equation (3) is the law described by (Wright, 1936), where Y is the average cost for each unit of x in our case megawatts of installed capacity of a technology. a is the cost of the first unit and b a constant and always ($b < 0$) for LR that see cost reductions.

$$Y = ax^b \qquad 3.$$

The LR in equation (4) can be found by plotting the log of cost ($\log Y$) against the log of cumulative capacity ($\log x$). b is the slope of the power law relationship between the two variables.

$$LR = 1 - 2^b \qquad 4.$$

Whereas Equation (3) is more concerned with the percentage decrease in cost from zero production or labour or any factor influenced by the doubling of x. Equation 5 is a continuous model that examines cost reductions $C_{(x_t)}$ with increase in capacity x_t but the start capacity can also be included x_0. This allows a range of dates or capacities to be examined, not just a calculation from the first unit to the current one.

$$C_{(x_t)} = C_{(x_0)} . (\frac{x_t}{x_0})^{-b} \qquad 5.$$

Equation (6) provides the same outcome as (5) but is tailored to the method of calculation in this study. The LR is found using a sum squared error (SSE) optimisation where the LR is adjusted until the error between the original CAPEX

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and calculated SSE is minimised across the length of calculation and shown in equation (7).

$$\boldsymbol{\hat{y}_i = C_{(x_0)}.(1-LR)^{\frac{log\frac{x_t}{x_0}}{log(2)}}} \qquad 6.$$

$$SSE = \sum_{i=1}^{n}(y_i - \hat{y}_i -)^2 \qquad 7.$$

The two following equations formulated by (Ferioli, 2009) define an approach to determining hybrid learning rates. Eq. 7 provides the formulation for a hybrid learning rate, taken from aggregated calculation of a component-based learning rate, assumed here that the components can be from separate technologies.

$$\begin{aligned} C(X_t) &= \sum_{i=1}^{n} C_{0i}\left(\frac{X_{ti}}{X_{0i}}\right)^{-b_i} \\ &= C_{01}\left(\frac{X_{t1}}{X_{01}}\right)^{-b_1} + C_{02}\left(\frac{X_{t2}}{X_{02}}\right)^{-b_2} + \cdots + C_{0n}\left(\frac{X_{tn}}{X_{0n}}\right)^{-b_n} \end{aligned} \qquad 8.$$

Where $C(X_{t)}$ is the cost relation, i the cost component (or hybrid cost component in this case), learning parameter b_i and initial cumulative production X_{0i}. A simplified model can be applied as shown below in Eq. 8 that is characterized by two parameters: Learning and consistent costs over time.

$$C(X_{t)} = \alpha C_0\left(\frac{X_t}{X_0}\right)^{-b} + (1+\alpha)C_0 \qquad 9.$$

Where α is the share of total cost initially assigned to the learning component, and $1\text{-}\alpha$ the start of the second component cost share.

The LCOE equation:

$$LCoE\left(\frac{€}{MWh}\right) = \frac{\sum_{t=0}^{n}\frac{CAPEXt + OPEXt + DECEXt}{(1+r)}}{\sum_{t=0}^{n}\frac{AEP_t}{(1+r)^t}} \qquad 10.$$

The LCOE can be classified as the sum of the discounted lifecycle costs (expenditure of capital (CAPEX), operational (OPEX), and decommissioning (DECEX)) divided by the discounted lifecycle sum of annual energy production (AEP), resulting in a cost for a single unit of energy produced. Fuel costs are normally excluded from the costs as most renewables do not require them, and usually CAPEX is not discounted over time by the discount rate r as it is usually applied in year 0, and therefore has a large impact on overall LCOE.

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4. Floating Offshore Wind

4.1 Industry projections

Floating Offshore Wind (FOW) entered the offshore wind sector in 2009 with a first demonstrator project, Hywind Demo (2.3 MW). The sector has since been growing and according to a DNV (2023) survey, 60% of the industry expects the sector will be fully commercial, e.g. subsidy free, by 2035. In 2023, there was a global cumulative deployment of 268.6 MW The latest addition has been Hywind Tampen (Equinor, 2023), off the coast of Norway, fully commissioned in summer 2023 with 11 x 8.8 MW wind turbines and using spar platforms. Figure 3 below shows the year-on-year global cumulative deployment between 2009 and 2023.

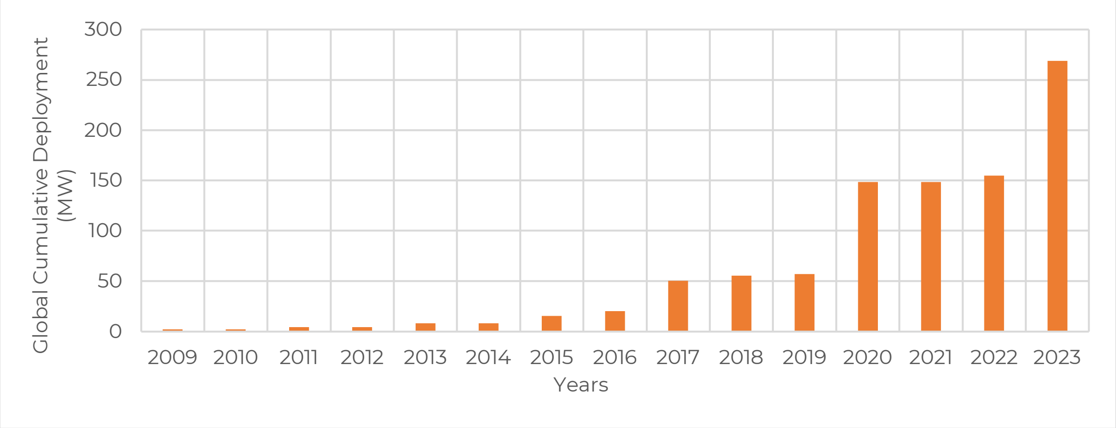

Figure 3: Global cumulative deployment of floating offshore wind. Source: (Carbon Trust, 2020), (World Forum Offshore Wind, 2023), (GWEC, 2023)

There are several voices in the sector trying to project the market growth of FOW both from deployment and LCOE reductions. Figure 4 below shows five different LCOE curves for 2020 to 2050 along with the calculated average (dotted black line). Based on these sources, the average LCOE in 2023 was 168 €/MWh, by 2030 will be 95 €/MWh, and by 2050 may be as low as 43 €/MWh. This is in line with the EU-SET plan (SET WIND, 2022) which presents the target for 2030 to be between 62 and 106 €/MWh, contingent on 6 GW installed capacity.

Each LCOE curve will have an expected deployment level in the background as an input assumption; however, for most of the curves presented here the associated deployment assumptions could not be found, except for DNV (2022) and (2023). In 2022, DNV presented an estimated 14 GW and 289 GW cumulative deployment by 2030 and 2050 respectively but revised these numbers downward in 2023 to 10 GW and 270 GW, represented by the blue (2022) and yellow (2023) bar stacks. 4C Offshore (Emanuel, 2023) estimate that 6-7 GW will be in operation in 2030 with an additional 5.4 GW under constructions.

Based on the LCOE curves and deployment levels given by DNV (2022) and (2023), LR on LCOE can be calculated to 14.1%. Due to the other sources not providing the underlying deployment assumptions, estimating the LR carries too much

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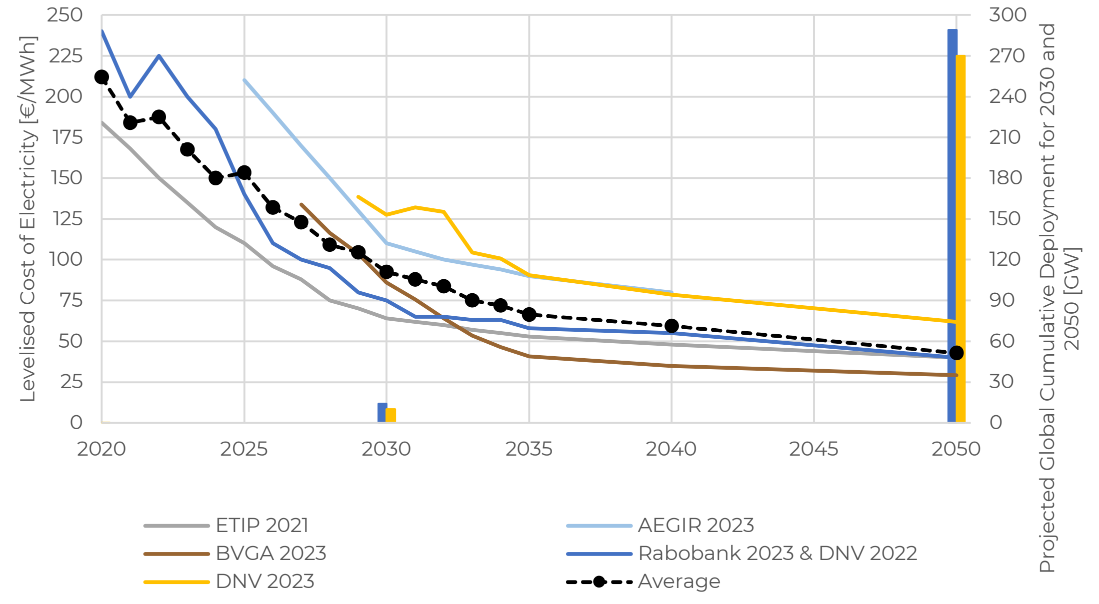
uncertainty. Other sources were found giving LR on CAPEX as summarised in Table 1.

Although there are challenges ahead, it is expected that in the next decade, FOW will see a rapid expansion and more substantial projects being deployed (GWEC, 2023).



Sources: ETIPWind, 2021. Getting Fit for 55, Set for 2050; Aegir, 2023 LCOE Development in 2 stages; BVGA, 2023. Guide to a FOW Farm; Rabobank 2023 FOW Energy reaching beyond the unreachable by FBOW & DNV 2022 Energy Transition Outlook 2022; DNV, 2023. En

Figure 4: LCOE curves from different sources to 2050, along with the projected deployment in 2030 and 2050. Sources: (ETIP, 2021), (BVGA, 2023), (Aegir, 2023), (Rabobank, 2023), (DNV, 2022) and (DNV, 2023)

Table 1: Learning rate for floating offshore wind from public sources

Learning Rate	On item	Reference
14.1% (calc.)	LCOE	Rabobank 2023 & DNV 2022. Energy Transition Outlook
14.1% (calc.)	LCOE	DNV 2023. Energy Transition Outlook
5.9% - 9.5%	CAPEX	2021, ORE Catapult. Floating Offshore Wind: Cost Reduction Pathway to Subsidy Free.
8.7% - 14.3% (avg 11.5%)	CAPEX	2022, NREL. A Systematic Framework for Projecting the Future Cost of Offshore Wind Energy
2.8% - 12.8% (avg 7.8%)	CAPEX	2022, University of Edinburgh. Deriving Current Cost Requirements from Future Targets.

4.2 Projections using fixed offshore wind as the reference technology

This section describes the analysis conducted on future deployments and LCOEs for FOW using DMEC's in house Growth Forecast Model (Pillet, Lehner, Stark, & van der Zant, 2023) and fixed offshore wind as the reference technology.

As discussed in Chapter 3, the Growth Forecast Model follows the growth that bottom-fixed offshore wind has experienced since the first farm was installed in Denmark in 1991. The extensive database of all bottom-fixed offshore wind projects has been created and used to capture the growth in the sector. Based on this, the growth and doubling models are applied to project the developments in FOW.

For a starting year, 2017 was selected, with the installation of the first multi-turbine offshore floating wind park Hywind Scotland meaning a starting value of 30 MW, to which the growth model was applied.

The results of the forecast are shown in Figure 5. Results also include LCOE values for the corresponding years when the learning rate of 14.1% from earlier mentioned Rabobank (2023) & DNV (2022) Energy Transition Outlook report is applied to the calculated installed capacities for FOW. The results suggest the total installed capacity between 450 MW and 2 GW with the LCOE of 121-170 €/MWh for 2030, 8 GW and 51 GW with the LCOE of 58-89 €/MWh for 2040 and between 116 GW and 760 GW of installed floating wind capacity with the LCOE of 32-48 €/MWh for 2050. The results are indeed quite optimistic and coming from the assumption that the learning rate is constant which in reality usually does not turn out to be the case. Projection for the period between 2040 and 2050 could be revisited once additional data is available.

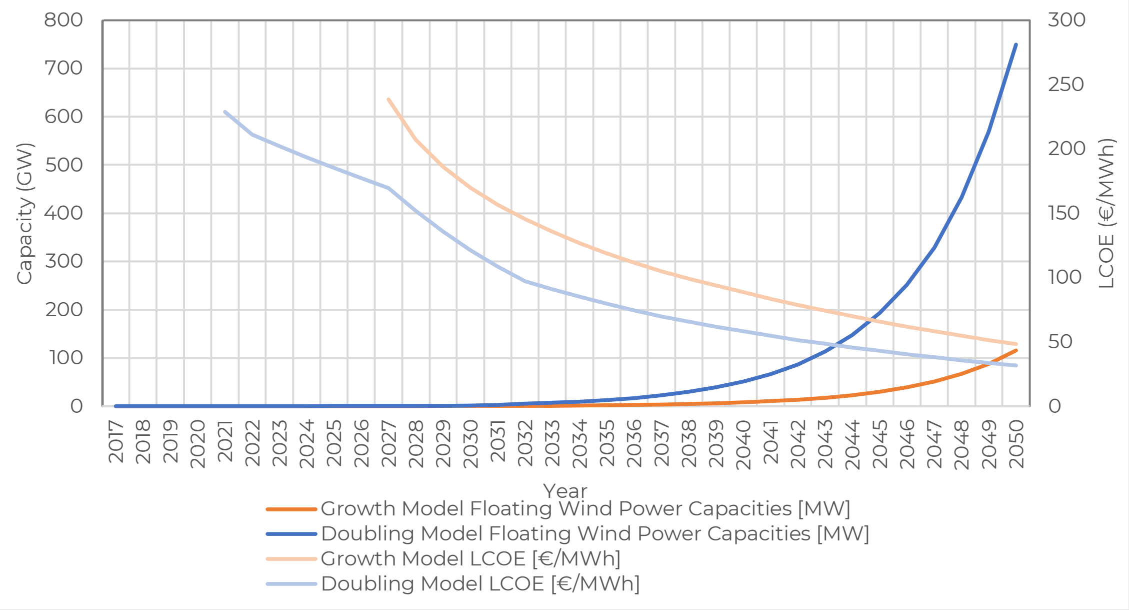


Figure 5: Projected floating offshore wind capacities and corresponding LCOE using reference technology fixed offshore wind, growth and doubling models

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4.3 Projections for FOW & floating substructures based on bottom-up database

This section describes the analysis conducted on generic FOW and FOW sub-divided into individual floating substructure types, using a bottom-up built database.

Floating offshore wind can currently be categorised into four main versions by platforms type, mainly owing to similar turbines being used across all FOW devices currently deployed. The four main categories are classified through stability method and are:

- Semi-submersible – Steel or concrete based structure with low draft that is buoyancy-stabilised.
- Spar – Long cylindrical structure made of steel or concrete with higher draft and ballast-stabilised.
- TLP – Mooring-stabilised platform with lower mass and surface area.
- Barge – Concrete and steel platform that often has an open pool to dampen wave action. Mainly buoyancy stabilised.

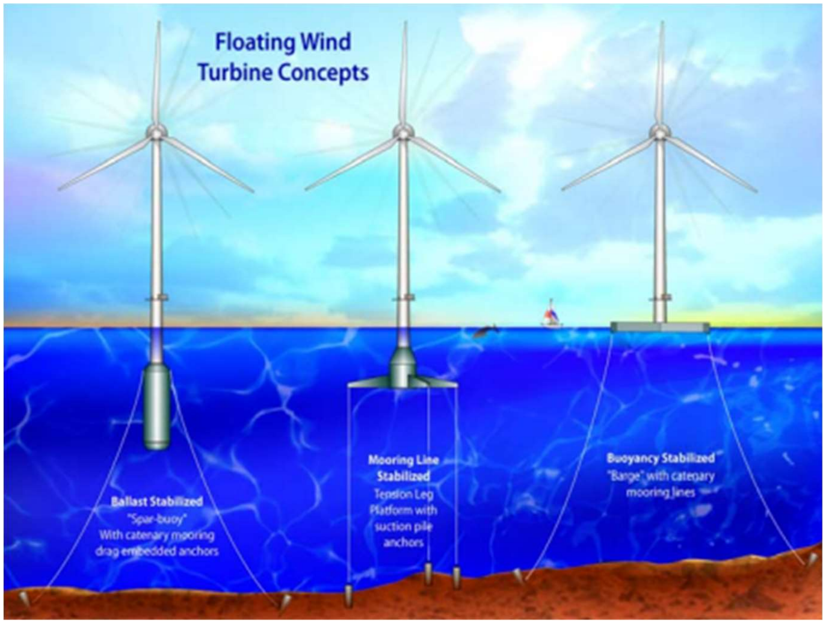

Figure 6: Three main stabilisation methods of floating wind turbines (Butterfield, Musial, & Jonkman, 2005)

This analysis investigates the future deployment of FOW to ascertain capacities up to 2050 so that learning rates can be calculated and validated against the state-of-the-art (SOTA). This period should encompass the progression to large-scale commercial maturity expected in the 2030s and a convergence on both technology and costs. For FOW, this was done collectively considering all types of platform designs in operation, but also separately into the four categories already defined above.

Annual deployment share of the four technologies can be seen in Figure 7. Capacity is dominated by semi-submersible platforms (blue) across the study range. Spar also has a significant presence but less projects have defined the spar as their main type into the 2030s. As such, based on current floating farm design expectations, it should be assumed that hybrid farms should design synergies across these four platform types, with TLP and barge also expecting some market penetration into the 2030s, but especially for the two major platforms that will expect to dominate the FOW market under current predictions.

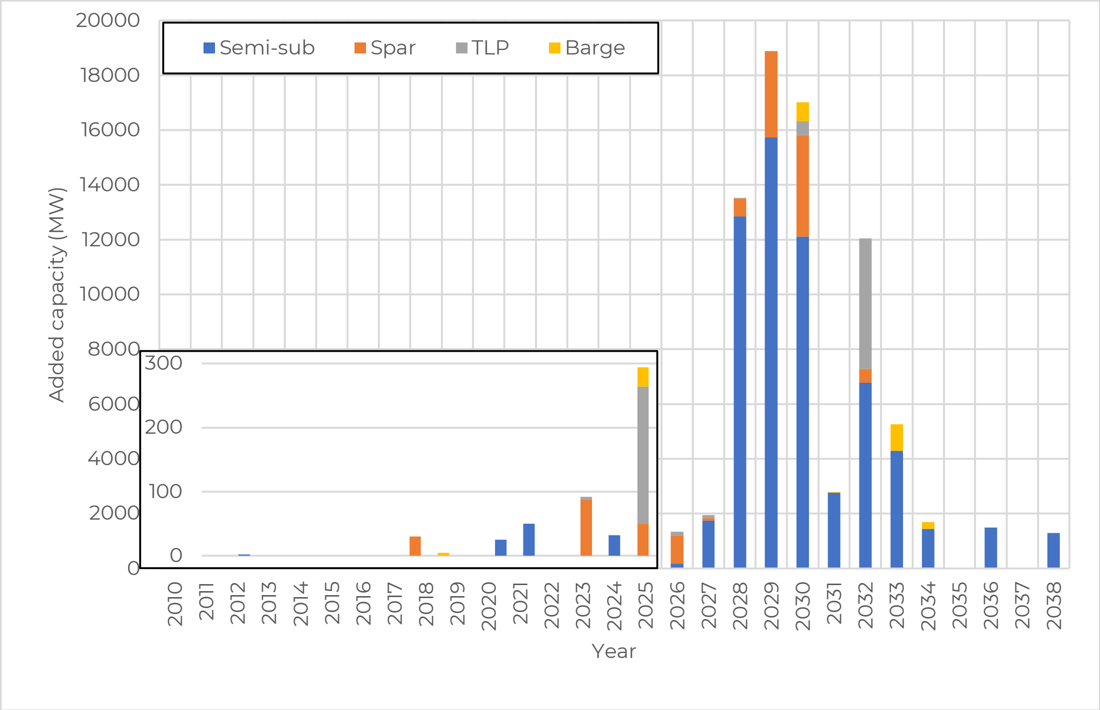

Figure 7: Annual capacity share of built and planned FOW farms across the four main platform types from 2011 to 2037 (Source: Author work adapted from (4C Offshore, 2024))

Figure 8 shows the four low order polynomial curve projections for FOW that maximise the r-squared value when fitting a trend line to the four sets of research data. All raw data across all four platform types was fitted with the same non-linear curve, namely a 2nd order polynomial curve fit. Semi-sub platform types are expected to have a large share of the market up until 2050 with 32 GW by 2030, 80 GW in 2040 and 137 GW by 2050. Spar type designs are predicted to have approximately half the installed capacity, with 6 GW in 2030, 31 GW in 2040 and 72 GW by 2050. TLPs are expected to deploy around 32 GW by 2050 and barges 11 GW. The cumulative values of the individual platform types add up to 252 GW by 2050. This is in good agreement with the total projections defined by DNV (2023), as discussed in Section 4.1 industry projections, which states an expected 270 GW collectively by 2050. It should be noted that these projections are based on current deployed capacities with few commercial-level farms stating a platform and could change as the industry progresses towards commercialisation.

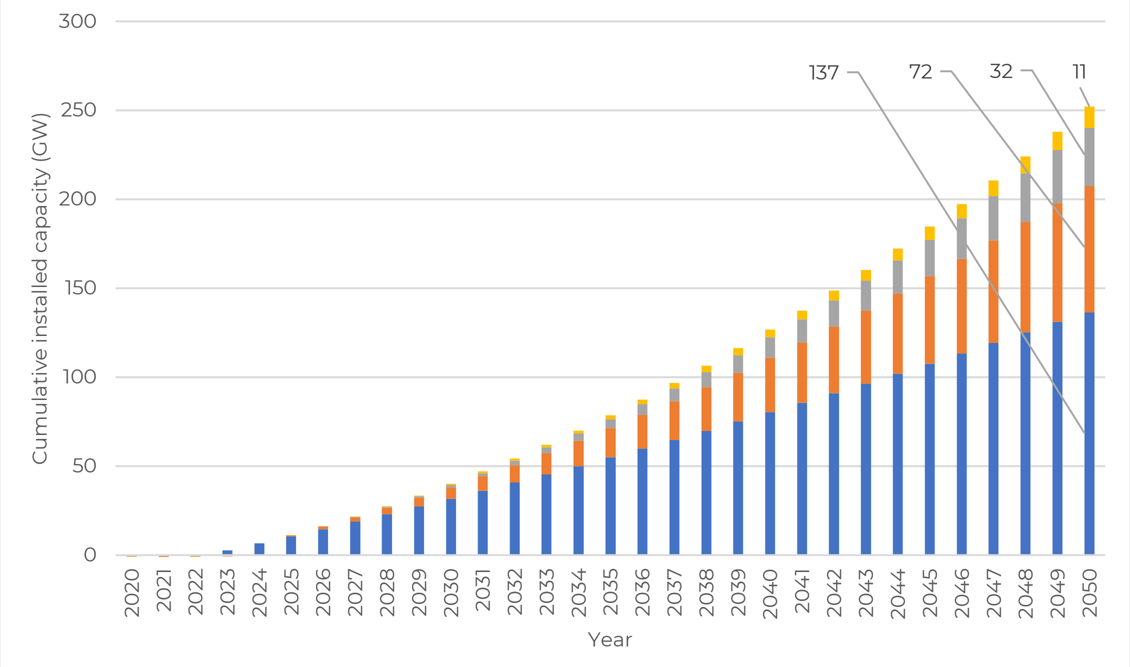

Figure 8: Capacity projections based on researched data and current installations until 2050 for four technology types. (Source: Author work adapted from (4C Offshore, 2024))

Figure 9 shows LCOE separated by platform type and calculated by built and planned projects that state one of the four main platform types with a defined or calculable LCOE value, and from a pre-commercial level of maturity. If LCOE is calculated, then key components including lifetime, OPEX, capacity factor and discount rate must be known or estimated to a high degree of accuracy. If annual generation or capacity factors are publicly defined, as is often the case for pre-commercial projects, these were preferred to calculations and were averaged across an assumed project length.

Initial LCOE is lowest for TLP due to later project commissioning and smaller platform size, although the expected final cost reductions are lower. Semi-submersible and spar types both have higher initial LCOE owing to a larger presence of expensive pilot projects but share similar cost reductions over time and both reach 61-64 €/MWh by 2050. Barge platform also starts with the high LCOE with multiple early pre-commercial demonstrators absorbing higher costs but is expected to fall rapidly due to cost reduction potential and concrete material construction.

Figure 10 shows raw LCOE data that was collected alongside planned installed capacity for generic FOW and not substructure-specific. Figure 10 shows a power law curve fitting LCOE with installation year which project around 125 €/MWh by 2030 and 55 €/MWh by 2050. Figure 10 has the same raw data but against cumulative capacity in MW. With global capacity at 130 MW, it is expected that average LCOE across all platform types should be in the range of 219 €/MWh and will reach 100 €/MWh once 14 GW is installed globally.

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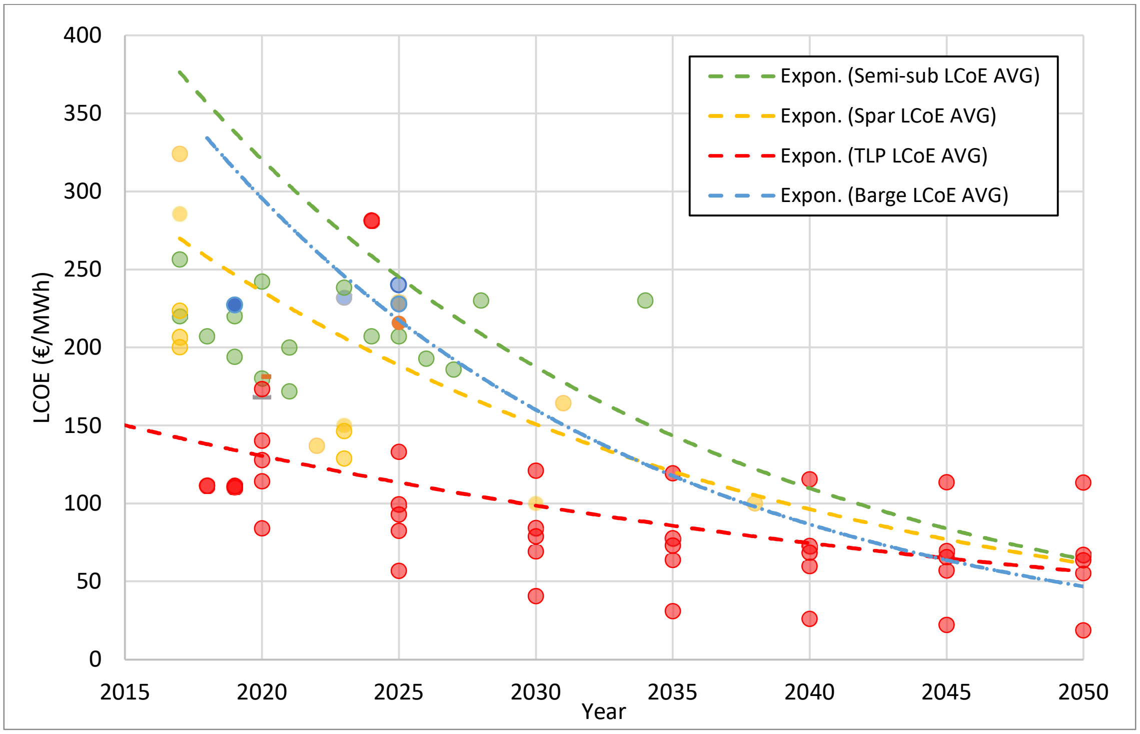

Figure 9: LCOE results for four main platform types from 2015 to 2050 (Source: Author work)

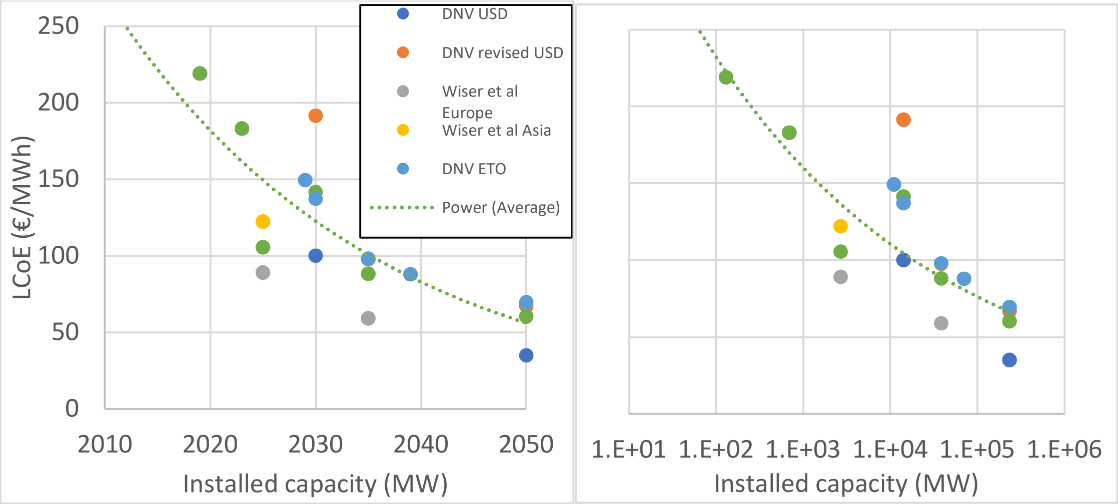

Figure 10: Average LCOE values for FOW against a) Year of installation and b) Cumulative installed capacity (Source: (DNV, 2023), (Wiser, Rand, & Seel, 2021))

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4.4 Estimated Learning Rates based on FOW bottom-up database

A study of FOW CAPEX was necessary as CAPEX values underpin the calculation of learning rates. CAPEX data was required to be consistent in regard to type of cost, assumptions and other financial factors such as inflation rate. Also, the breakdown of CAPEX into subsystems which forms a desired research outcome of this project was needed, and therefore a source needed to provide such a breakdown, with consistency and over a significant period which encompasses the development and predicted cost reductions of technology types.

Table 2: CAPEX, OPEX and other system CAPEX used to formulate FOW LR (Source: (BVGA, 2023), (NREL, 2023))

	CAPEX	OPEX	Development
Units	€/kW	€/kW/year	€/kW
2015	6273	146	266
2020	4695	119	158
2025	3702	80	96
2030	3694	75	174
2040	3436	38	
2050	2793	57	

Two sources of cost data fitted the above requirements: NREL (2023) provides yearly CAPEX data from 2015-2022, and BVG (2019) and (2023) provide up to date cost data, especially for the floating version. CAPEX and OPEX are defined for each year, and a range of subsystems including turbine, electrical system and decommissioning. All costs are exchanged in year of publication or defined year of cost and are all adjusted to Euros per kW of installed capacity. CAPEX is also defined against year of installation and by cumulative capacity in MW.

The learning rates (LR) for floating offshore wind CAPEX, OPEX, and subsystems are shown in Figure 11. LR were calculated using the method defined in section 3.2 and specifically Equation 3. They are provided for three scenarios: LR across the full range of CAPEX data (ALL), typically 2020-2050; CAPEX up to 2030 to capture early learnings (< 2030); finally using CAPEX reductions from 2030 onwards to a maximum of 2050 (> 2030). CAPEX and OPEX generally have the highest cost reduction potential, with learning rates of 6% and 7% ("all" scenario) respectively agree well with the results in Table 1. Highest LR are for under 2030, due to the nascent stage of the industry with few commercial projects, with the opposite true for LR after 2030. Construction finance costs are only available after 2030 due to a lack of cost data.

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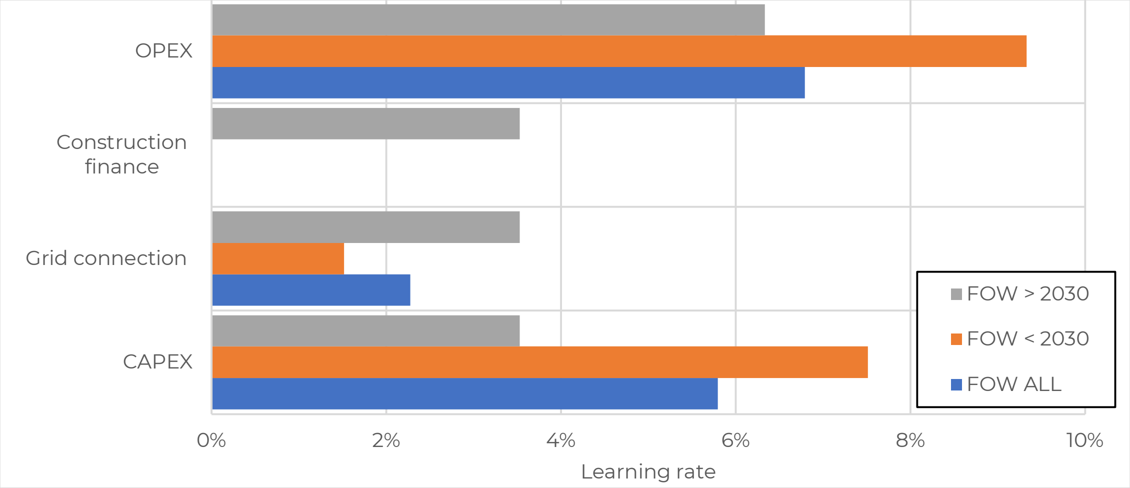

Figure 11: Learning rates for the main floating offshore wind cost areas (Source: Author work)

4.5 Key conclusions

The main takeaway from the analysis conducted on the FOW sector is that there is plenty of information available to give a concise industry perspective, enough data to build a bottom-up database to analyse both generic FOW and the four individual floating substructures, and a long enough time period of fixed offshore wind to use as reference technology for FOW analysis. The key conclusions from the individual analyses are as follows:

Deployment:

Different publicly available sources project FOW to reach between 6-14 GW by 2030, and 270 GW cumulative deployment by 2050. The analysis conducted using the bottom-up database projects 41 GW in 2030, and 252 GW in 2050, with semi-sub contributing to about half in 2050. The analysis using fixed offshore wind as the reference technology (growth and doubling models) projects FOW to reach 2 GW in 2030, 51 GW in 2040 and 116 to 750 GW in 2050.

LCOE:

Publicly available sources expect the average LCOE to drop to below 100 €/MWh by 2030, and to an average of 43 €/MWh by 2050, which corresponds well with the analysis of the bottom-up approach, which also calculates 100 €/MWh in 2030, but a slightly lower average of 35 €/MWh by 2050. The reference technology approach calculates a slightly higher LCOE of 170-121 €/MWh in 2030 but then predicts similar LCOE in 2050 of 48-32 €/MWh.

LR:

LR in publicly available sources were estimated to 14.1% on LCOE, and an average of 7.8% on CAPEX found. No LR on OPEX was found. In contrast, the bottom-up analysis calculates LR to an overall LR on CAPEX of 6% and on OPEX of 7%.

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5. Wave

5.1 Industry projections

Since 2010 the global cumulative installations for wave energy has grown to 26.4 MW, approximately half of which has been in Europe (OEE, 2024). Several of these projects have been decommissioned after successfully completing testing and far fewer projects are currently in the water. However, the next 5 years are deemed positive by the industry and expectations are that wave energy technology development will rapidly accelerate. There is currently a large project pipeline of 137 MW supported via EU programmes and national schemes, and the next 5 years may see as much new capacity added as over the past 11 years (OEE, 2024). It is expected that several full-scale wave energy devices and at least two farms could be deployed by 2028, among them CorPower Ocean.

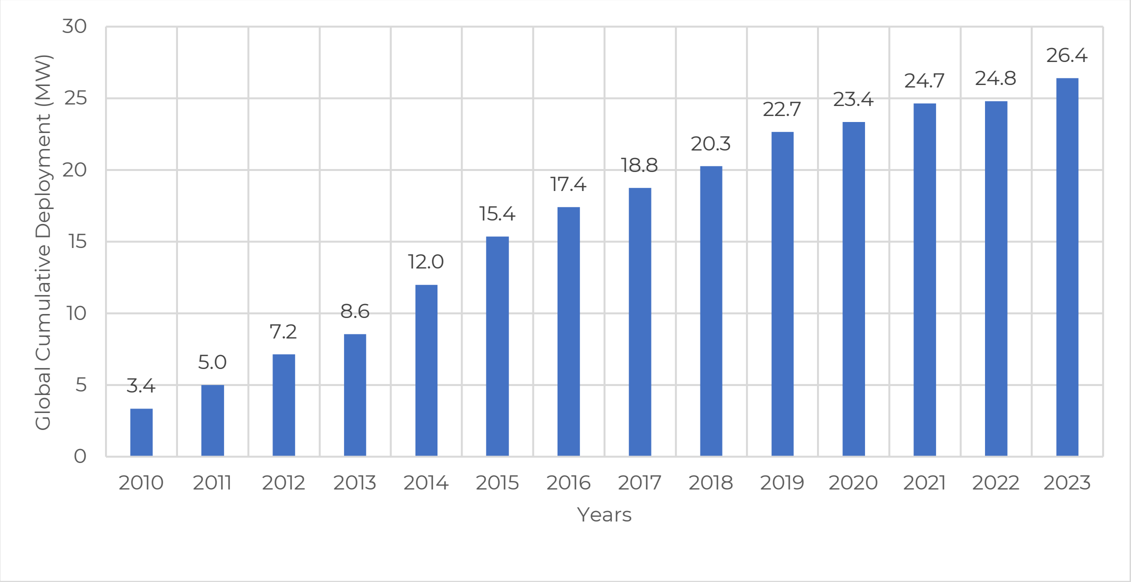

Figure 12: Global cumulative deployment of wave energy projects between 2010 and 2023. Source: (OEE, 2024)

It is difficult to find information in public reports on future deployments for wave, corresponding LCOEs, and particularly when in time these may occur. The European Commission (2020) expects for installations in the European Union 1 GW of ocean energy technologies installed by 2030, and 40 GW by 2050. These figures are only for the EU-27, excluding the UK. Ocean energy includes both wave and tidal, so it is unclear how much of these targets may be met by wave. Ocean Energy Europe (OEE, 2020) has presented low and high growth scenarios, which could see between 178 MW and 494 MW wave energy deployed by 2030. They also suggest that 100 GW of ocean energy is possible in Europe by 2050. A recent study by IEA Ocean Energy Systems (IEA-OES, 2023), suggests that globally 300 GW of ocean energy may be possible by 2050, of which 180 GW may be possible for wave under advantageous market conditions.

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In terms of corresponding LCOE, the EU SET-Plan (Working Group Ocean Energy, 2018) sets out a target of 150 €/MWh by 2030 and 100 €/MWh by 2035, although these expected cost reductions are driven by cumulative installed capacity (economies of scale) rather than passing of time. OEE's modelling (OEE, 2020) suggests that an LCOE of 150 €/MWh is achievable in the low growth scenario (178 MW) and likely reduce further to 110 €/MWh should the high growth scenario (494 MW) come to pass. They use a learning rate of 11.4% weighted average on CAPEX and 9.4% on OPEX. Based on the starting LCOE of 702 €/MWh at 1 MW deployed and the LCOE at 2,000 MW cumulative deployment of 81 €/MWh given by OEE a learning rate on LCOE of 18.7% can be estimated. IEA-OES's model (IEA-OES, 2023) on the other hand only starts in 2030 with a much more conservative estimated cumulative deployment of 42.5 MW globally and therefore a higher LCOE of 277 €/MWh on which they conduct sensitivity analysis using 10%, 12.5% and 15% learning on LCOE to 2050, achieving between 78 €/MWh and 39 €/MWh. CorPower Ocean have provided this report with up-to-date LCOE projections (august 2024), which demonstrate a realistic pathway to significant LCOE reductions with adequate commercial roll out. The average LR on LCOE over time can be estimated to 15.9%. The LCOE discussed along with an average are shown in Figure 13 and the LR discussed are summarised in Table 3.

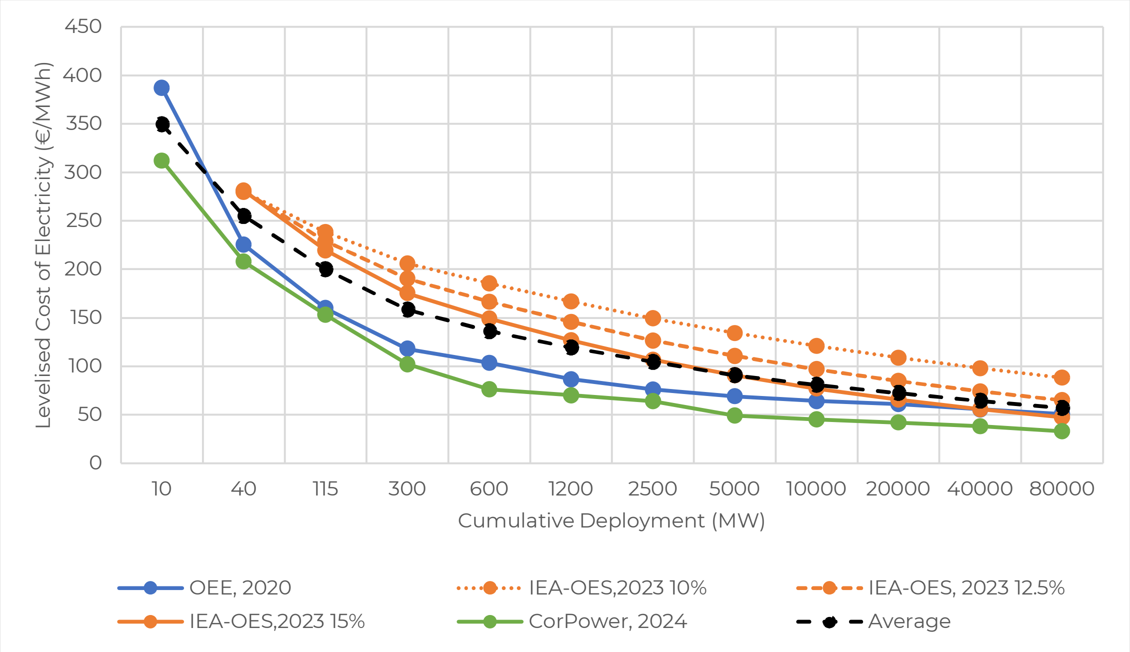

Figure 13: Global cumulative deployment for wave energy and the associated levelised cost of energy

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Table 3: Learning rates for wave energy from public sources

Learning Rate	On item	Reference
18.67% (calc. avg)	LCOE	OEE, 2020. Ocean Energy Vision for 2030
10%-15%	LCOE	OES, 2023. Ocean Energy and Net Zero, An international Roadmap to Develop 300 GW of Ocean Energy by 2050
15.9% (calc. avg)	LCOE	CorPower Ocean, 2024
4.3-14.3% (avg. 9.3%)	CAPEX	2022, University of Edinburgh. Deriving Current Cost Requirements from Future Targets.
11.4%	CAPEX	OEE, 2020. Ocean Energy Vision for 2030
9.4%	OPEX	OEE, 2020. Ocean Energy Vision for 2030

5.2 Projections using fixed offshore wind as the reference technology

Taking that the wave energy sector shares numerous similarities with the offshore wind sector in terms of installation settings, necessary supply chains, operational and maintenance practices, and electrical systems, DMEC's Growth Forecast Tool capturing the growth of cumulative capacities in the fixed offshore wind sector, was applied to the wave sector. For the wave sector, 2020 was established as the year when the sector entered a pre-commercial phase. In 2020 the constructions of the first MW scale systems started. Some prominent examples are the CorPower Ocean Wave Energy Converters array in Portugal, the Wello system in Spain and the full-scale demonstration of the Irish developer Ocean Energy in Hawaii. Others like EcoWavePower, Seabased and AW Energy demonstrated large-scale devices or arrays with PPAs and showed a large project pipeline. Altogether those companies had a cumulative capacity of 6.11 MW in 2020, which was chosen as the wave model starting value.

The results of the projections using the two described methods in Chapter 3 when the pattern of wind sector growth is applied is shown in Figure 14. The learning curves were deducted from the projection on LCOE vs cumulative installed capacity in the market recently shared by the project partner CorPower Ocean.

Each time a new device is being deployed a new learning rate has been considered. For the C6 device and therefore cumulative capacities between 10 MW and 600 MW on the graph the learning rate of 19.9% has been calculated, for the C12 device and capacity values between 600 MW and 20 GW - 12%, and for the device C17 deployed approximately after the cumulative capacities of 20 GW have been reached – 11.2% has then been found using the *curve_fit* Python function. These results were then applied to the calculated cumulative capacities of installed wave power.

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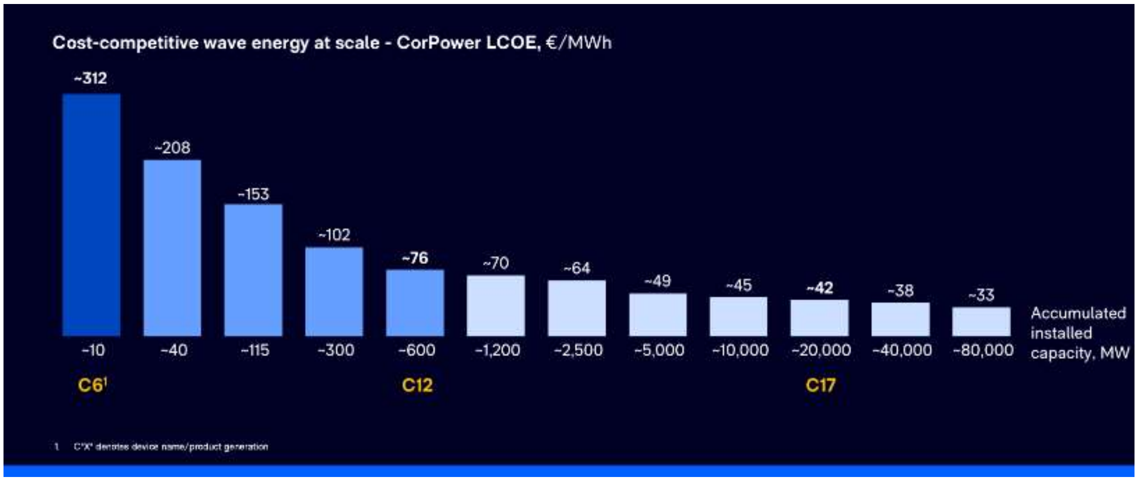

Figure 14: CorPower Ocean's current LCOE model and sales forecast: projection on LCOE vs cumulative installed capacity in the market

The results in Figure 15 show that by 2030 total cumulative wave capacity is expected to reach as high as 93 MW and 4.7 GW and 67 GW by 2040 and 2050. In these years the expected LCOEs are as low as 154.4 €/MWh, 53.4 €/MWh and 34.3 €/MWh. It can be argued that the LCOE values are on the optimistic side, but the wave energy device developers are confident that this is nevertheless feasible.

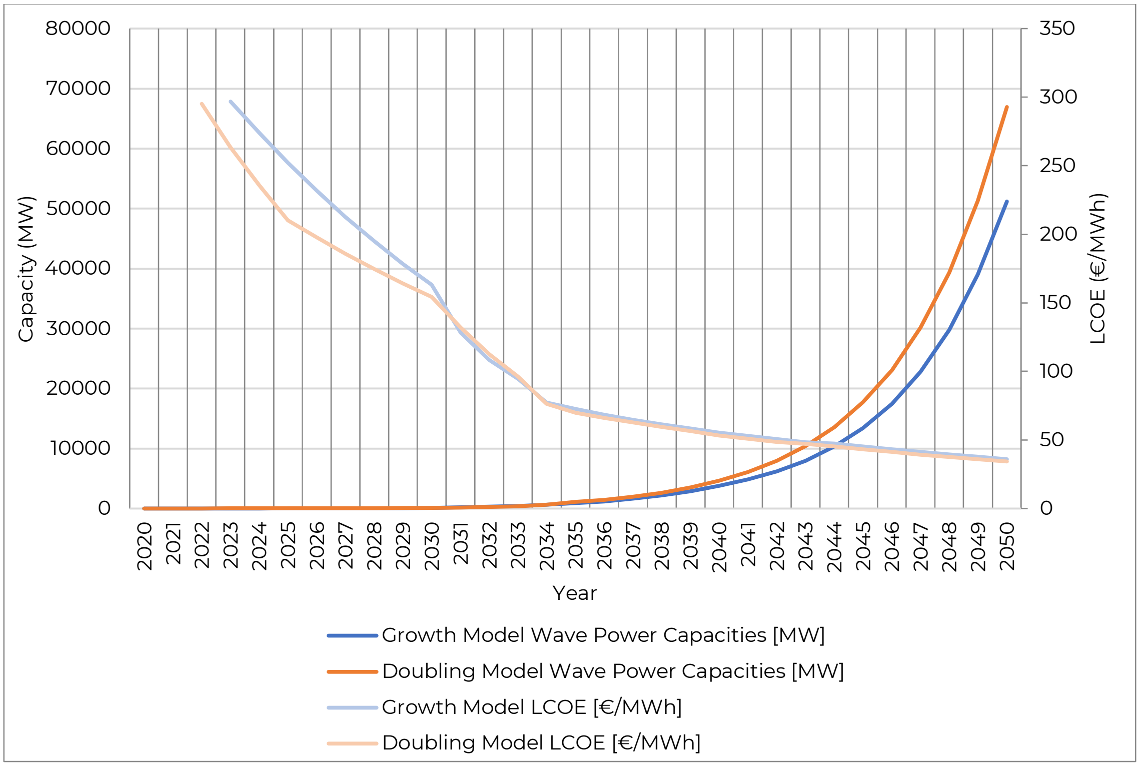

Figure 15: Projected wave capacities (MW) using growth and doubling models and the projected LCOE.

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5.3 Projections for wave and learning rates based on bottom-up database

Figure 16 shows the bottom-up projection for wave energy deployment up to 2050, based on the current and previous deployment of individual projects. Growth remains slow but is expected to rise rapidly from 2030 to ~13 GW in 2050. The data supporting these curves that can be seen in orange/grey was taken from the UK Energy Technologies Institute (ETI, UKERC, 2014) that provided a high and low growth forecast until 2050 with associated technology development transition stages, with the high and low forecasts resulting in 8/4 GW respectively for 2030 and 20/10 GW by 2050. A later start to deployment sees the bottom-up curve increase later on but still achieves a final position between the two scenarios at commercial scale.

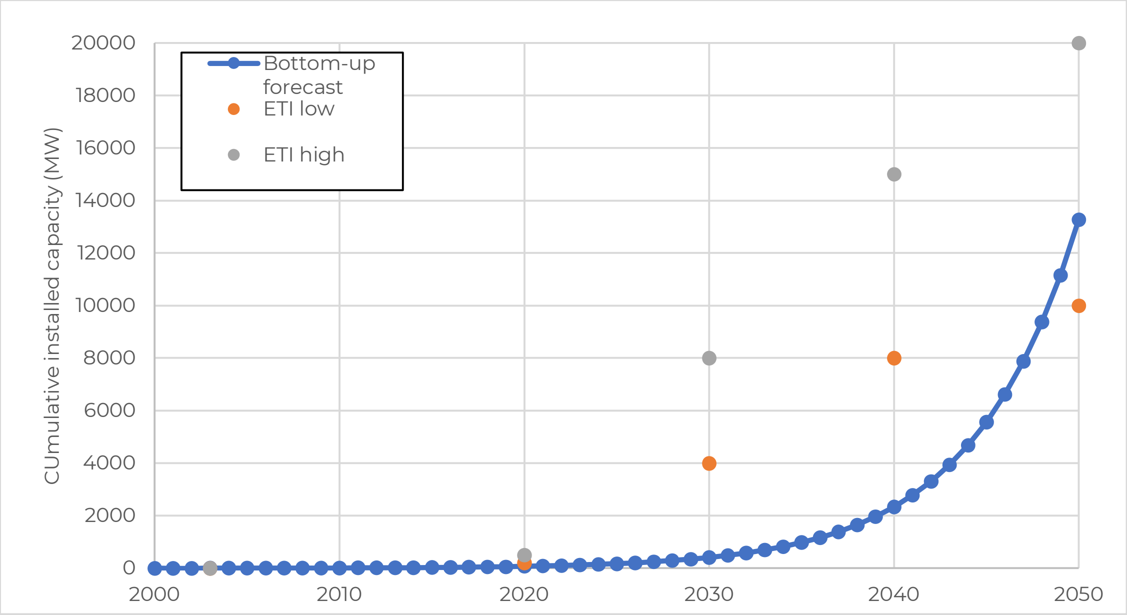

Figure 16: Wave energy projections based on the bottom-up approach to deployment, with ETI report values. Source: Author's work, (ETI, UKERC, 2014)

LCOE graphs for wave energy are presented in Figure 17 and Figure 18. The first shows LCOE reductions against cumulative installed capacity on a log scale. Report predictions from (ETI, UKERC, 2014), (OEE/IRENA, 2023) in red, and an average across all researched value in blue. The bottom-up curve in grey represents the forecast capacity calculated in this study (blue curve from Figure 16) with LCOE predictions from (OEE/IRENA, 2023). The bottom-up projected LCOE is the most optimistic but follows the pattern of defined report values well, with an expected LCOE of 180 €/MWh with 100 MW installed capacity, and 91 €/MWh at 1 GW and 46 €/MWh at 10 GW.

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LCOE against year is provided in the second Figure 18, with the grey bottom-up curve again showing an optimistic projection with 118 €/MWh by 2030 and 41 €/MWh by 2050 and follows the trend set by report values well. The average curve is less smooth due to the average values across all report types that predict varying LCOE across the expected future of wave energy.

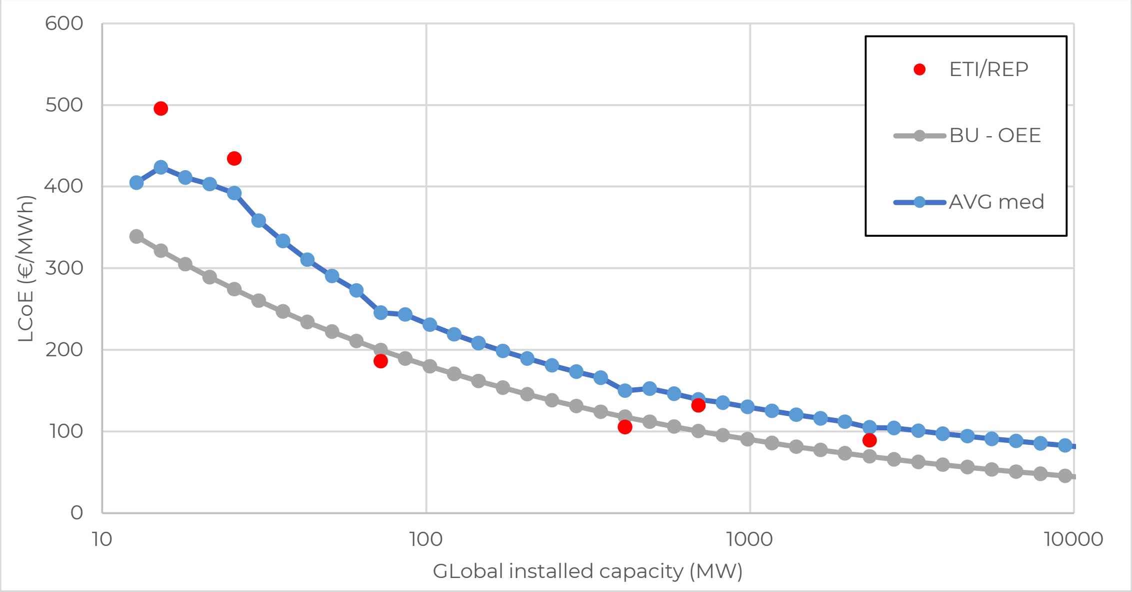

Figure 17: Wave energy LCOE with cumulative deployment (OEE/IRENA, 2023), (ETI, UKERC, 2014)

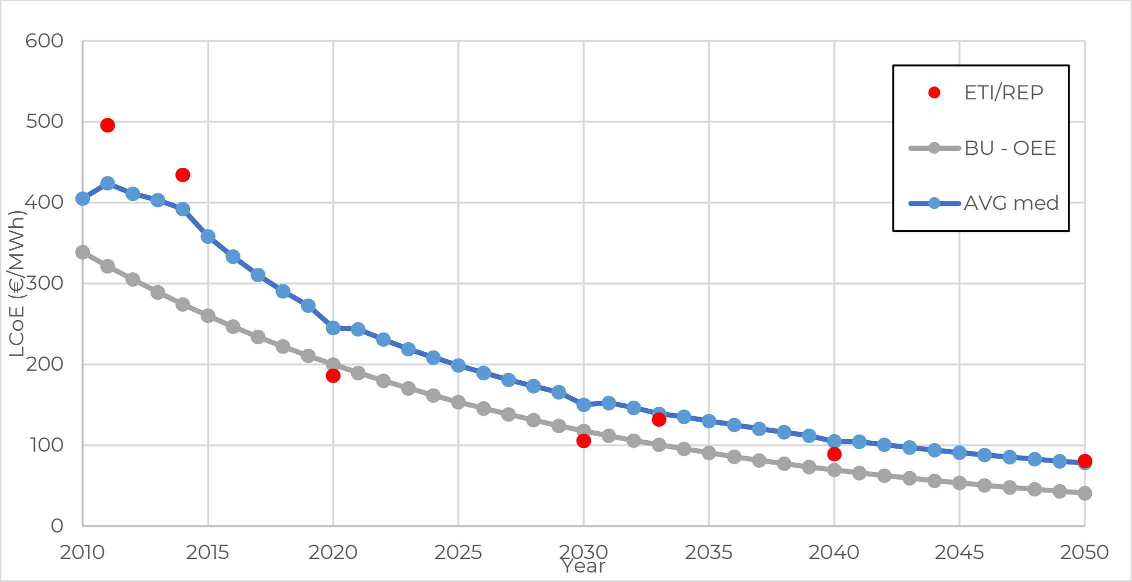

Figure 18: Wave energy LCOE projection until 2050 (OEE/IRENA, 2023), (ETI, UKERC, 2014)

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Table 4 - CAPEX, OPEX and other system CAPEX used to formulate wave LR (Source: (COGEA , WavEC, 2018), (LiftWEC, 2023))

	CAPEX	OPEX	BOP	Development
Units	€/kW	€/kW/year	€/kW	€/kW
2010	6835	82	1025	205
2017	6184	77	935	184
2023	5309	70	813	156
2030	4500	60	1075	114
2040	4399	-	929	81
2050	1600	56	815	81

The learning rates obtained for wave energy technology are in Figure 19. Of note CAPEX data witnessing high expected cost reductions with increasing future capacities at 8% LR across from 2010-2050, rising to 9-11% when considering under 2030, or above 2030 respectively and is within the LR range defined in Table 3. O&M LR is just under 5% in the "All" scenario, possibly due to commercial-scale O&M scale effects not yet being fully realised in practice. Overall LR are positive and are highest for the generator at 13%, D&C at 11% and the mooring system at 10% in the All scenario. Generally, the under 2030 LR yields the lowest values which is expected at the early stages of technology development and at a pre-commercial phase of deployment.

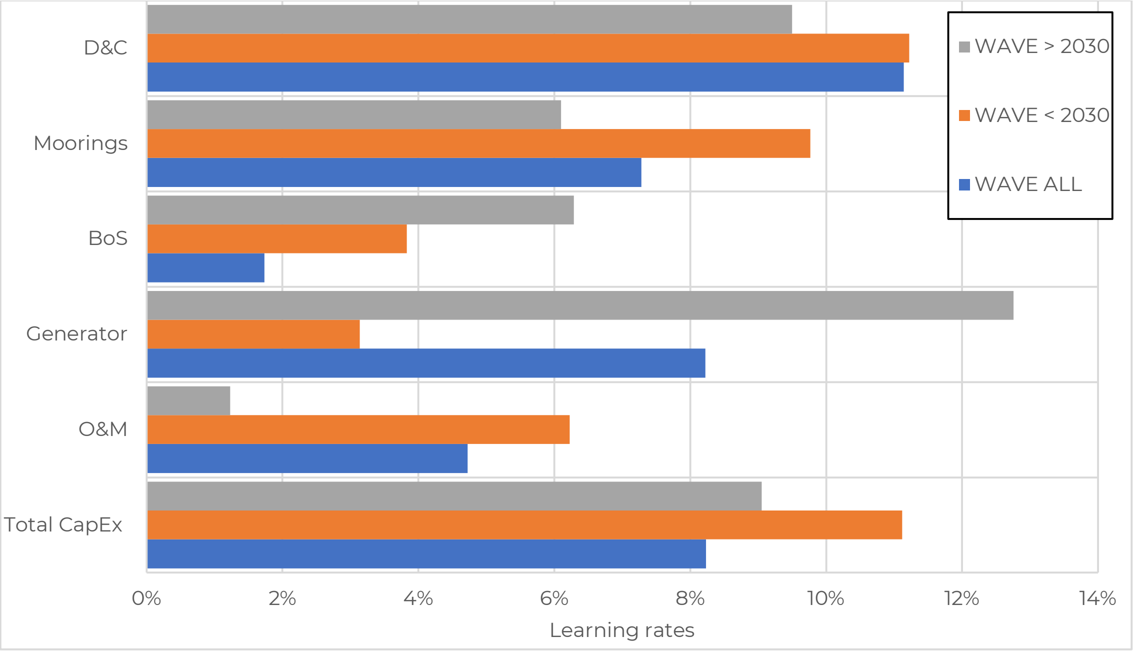

Figure 19: Learning rates for wave energy devices for different cost groups

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5.4 Key conclusions

Due to limited reports in the wave energy sector, a wider divergence of deployment results is observed from the analysis conducted within this chapter, although the estimated LCOE still converge. Some of the key conclusions are as follows:

Deployment:

From publicly available reports it is projected that in Europe wave may achieve between 178 and 494MW by 2030. Globally, 180 GW may be achievable by 2050 under favourable market conditions. Using fixed offshore wind as the reference technology, the future projections for wave energy for 2030 is 93MW, for 2040 is 4.7GW and for 2050 is 67GW. The bottom-up projections using a database compiled for this deliverable, projects ~400MW by 2030, growing to ~13GW by 2050.

LCOE:

Publicly available sources estimate LCOE between 110 to 150 €/MWh by 2030, and that wave could reach 40 €/MWh by 2050. The analysis using fixed offshore wind as the reference technology and LR derived from Corpower Ocean's current LCOE model and sales forecast, the LCOE is estimated to 154 €/MWh in 2030, 53 €/MWh in 2040 and 34 €/MWh in 2050. The bottom-up approach results in LCOE of 118 €/MWh in 2030 and 41 €/MWh in 2050. Furthermore, the bottom-up approach also identifies an LCOE of 180 €/MWh with 100 MW installed capacity, and 91 €/MWh at 1 GW and 46 €/MWh at 10 GW.

Learning Rate:

LR on LCOE in public source are estimated to between 15% and 18.6%. LR on CAPEX is estimated to between 9.3% and 11.4% and on OPEX to 9.4%. The current LCOE model and sales forecast shared by CorPower Ocean for the purpose of this report is divided into 3 phases and corresponding LR is calculated: Phase 1 between 10MW and 600MW a LR on LCOE of 19.9%; Phase 2 between 600MW and 20GW a LR on LCOE of 12%, and beyond 20GW a LR on LCOE of 11.2%. The LR calculated based on the bottom-up database give an overall LR on CAPEX of 8% and on OPEX of 5%. On individual components, overall LR are positive and are highest D&C at 11%, the generator 8.5% the mooring system at 7% in the All scenario.

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6. Offshore Solar

6.1 Industry projections

The first offshore solar project was developed by Oceans of Energy in 2019 with an initial size of 50kW and scaled to 0.5MW by 2023, off the Dutch coast (OOE, 2020). In 2024, another offshore solar developer SolarDuck a 0.52MW pilot project in the Dutch North Sea together with RWE (Offshore, 2024). A number of offshore solar projects are currently in the pipeline in the Netherlands, which will see offshore solar combined with offshore wind: a 0.5 MW offshore solar project in summer 2025 Hollandse Kust Noord operated by Crosswind (Shell & Eneco) (offshoreWIND.biz, 2023), a 5 MW offshore solar project in Hollandse Kust West by Oranjewind (RWE & Total Energies) (offshoreWIND.biz, 2024), and a 50 MW offshore solar project in IJmuiden Ver Beta by Zeevonk (Vattenfall & CIP) (offshoreWIND.biz, 2024).

Current LCOE or costs for offshore solar are difficult to find in publicly available reports, however, in 2021 the public EU-SCORES deliverable D7.9 (Exceedence, 2022), reported a cumulative deployment of 0.3 MW offshore solar. DNV (2021) estimated the LCOE in the same year to be 354 €/MWh. Specific projections for deployment and LCOE or costs for offshore solar are also difficult to find, however, in 2023 the Dutch government set a target of 3GW by 2030 (Taiyang News, 2023). DNV (2021) estimate that LCOE will decrease and reach somewhere near ground-mounted solar parks for which the estimate in the Netherlands is 50 €/MWh in 2030 and 40 €/MWh in 2050. Oceans of Energy also provided estimates on their LCOE and their expected cost reductions. These are based on their own estimated LR, experience and scaling factors in system size, to drop below 120-150 €/MWh once 4 MW of global installed capacity is deployed, and that by 2030 LCOE could drop to below 50 €/MWh. Oceans of Energy state that they are focused on the combination of offshore wind and offshore solar due to the complementary energy patterns. They estimate a market size in the 1000's of GWs of offshore solar, if offshore solar can be successfully integrated with offshore wind farms.

DNV (2022) furthermore suggest that by 2030, Floating PV (FPV) and offshore solar may grow to between 10 and 30 GW by 2030, but do not give an estimate of the share for either FPV or offshore solar. As an aside, in 2021 FPV had a cumulative installed capacity of 3.8 GW (Silalahi and Blakers, 2023).

Although FPV and offshore solar are sometimes combined in literature, the two applications are very different. FPV refers to PV on inland lakes and reservoirs and is similar to ground mounted (or rooftop mounted) solar PV, using much of the same equipment. In contrast, offshore solar requires different considerations to that of inland PV, due to the interactions with the marine environment and the offshore engineering & operations required (Innovation Engie, 2024).

Nevertheless, it is prudent to briefly investigate the development trajectory of onshore PV and FPV when also talking about offshore solar.

Onshore PV (ground and rooftop mounted) already had 39 GW cumulative deployed capacity in 2010, and has since grown to 1,412 GW in 2023 (IRENA, 2018)

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(IRENA, 2024). It is expected that by 2050, Onshore PV will have a cumulative deployment of 15,300 GW (DNV, 2023). LCOE in 2010 was reported to be 423 €/MWh, dropping to 47 €/MWh in the same timeframe, and is expected to be approximately 20 €/MWh in 2050 (IRENA, 2023). The PV modules is a key cost driver for Onshore PV (DNV, 2022), which has had LR of 26% between 1976 and 2023 and is expected to drop to 17% by 2050 (VDMA, 2024) (DNV, 2022). These are summarised in Table 5

FPV had some early pilots already in 2007, with more substantial projects between 2012 and 2015, with a cumulative installed capacity of 68MW in 2015 (DNV, 2022). By 2018, the 1 GW threshold has been reached. As already mentioned, by 2021, FPV cumulative deployment had reached 3.8 GW (Silalahi and Blakers, 2023). The corresponding LCOE in year 2021 is estimated to 62 €/MWh. No specific LR was found for FPV, however, DNV (2022) surmise that the key cost driver for FPV is also the PV modules and therefore expect similar LRs.

No specific LR for offshore solar was found in publicly available information, although the EU-SCORES public deliverable D7.9 uses a LR of 17%, derived from DNV (2022).

Table 5: Learning rates for PV modules from public sources

Learning Rate	On item	Reference
25% (btw 1976 and 2023)	PV module cost	VDMA, 2024. International Technology Roadmap for Photovoltaics (ITRPV) 2023 Results
17% by 2050	PV module cost	DNV, 2022. The Future of Floating Solar: Drivers and barriers to growth

6.2 Projections for Offshore Solar using Reference Technologies

To project the cumulative deployment of offshore solar this section uses the methodology earlier described DMEC's in house Growth Forecast Model (Pillet, Lehner, Stark, & van der Zant, 2023). Predicting the developments in the offshore solar is challenging since less market research has focused on the industry and existing research often combined insights from PV industry (Rooftop PV, Utility-Scale PV, Inland Floating PV, Building-Integrated PV) while the reality is much more complex since there are considerable particularities to take into account. For this specific projection, two sectors are used as references instead of only one as in the methodology of the previously presented projections for floating wind and wave. These two referenced sectors, as different as they certainly are, exhibit some similarities with offshore solar, that can provide valuable insights.

The primary reference is the 31 years of deployment data (1991-2022) in the offshore wind sector. Both industries operate in offshore environments, facing unique challenges such as harsh weather conditions and logistical complexities. The lessons learned from the offshore wind sector are instrumental in understanding the deployment potential and technical hurdles offshore solar.

The second reference is the onshore floating solar PV sector. This sector shares similarities particularly in terms of the scalability of the solution. Offshore solar has a much greater potential for scalability compared to offshore wind, while the onshore floating solar PV sector is a much more relevant point of comparison in this regard. The data is not as extensive as for the other sectors, but 15 years of data (2007-2022) has been collected for this report.

For the starting point, 2024 was chosen, since several important projects have been deployed. This includes 0.3 MW by Oceans of Energy deployed 12 km offshore in the North Sea in 2021 (Exceedence, 2022), 0.5 MW of Solar Duck's Merganser (RWE, 2024), China's first semi-submersible offshore photovoltaic power platform of 0.4 MW delivered by CIMC Raffles (Raffles, 2023) and so far, 0.024 MW out of 0.3 MW of SolarinBlue technology as a part of Sun'Sète project (SolarinBlue, n.d.). That brings the starting value to 1.224 MW.

By applying the growth curves obtained looking into the cumulative capacities from these two sectors—offshore wind and onshore floating solar, the results presented in Figure 20 were generated. The results suggest that by 2030 installed capacity of offshore solar could reach up to almost 13 MW and by 2040 up to 11 GW. Since the sector is fairly young the projections further into the future could be quite challenging with too many assumptions and uncertainties.

To calculate the corresponding LCOEs, the LR of 17% has been applied. This value was adopted from the publicly available EU-SCORES Deliverable 7.9 (Exceedence, 2022). As stated in this deliverable, the LR was derived from DNV 2022 report. For the starting LCOE we considered that Oceans of Energy's 0.3 MW project had an LCOE of 354 €/MWh as shared in the same report. These assumptions calculate a LCOE between 128.6 €/MWh and 130.1 €/MWh in 2030 and between 21 €/MW and 26.5 €/MW in 2040. However, it should be noted that considering fixed learning rate might not be completely realistic since the technology improvements only go so far. Also, with time the developments would be going further offshore and further from existing electrical infrastructure which might cause flattening of the learning curve.

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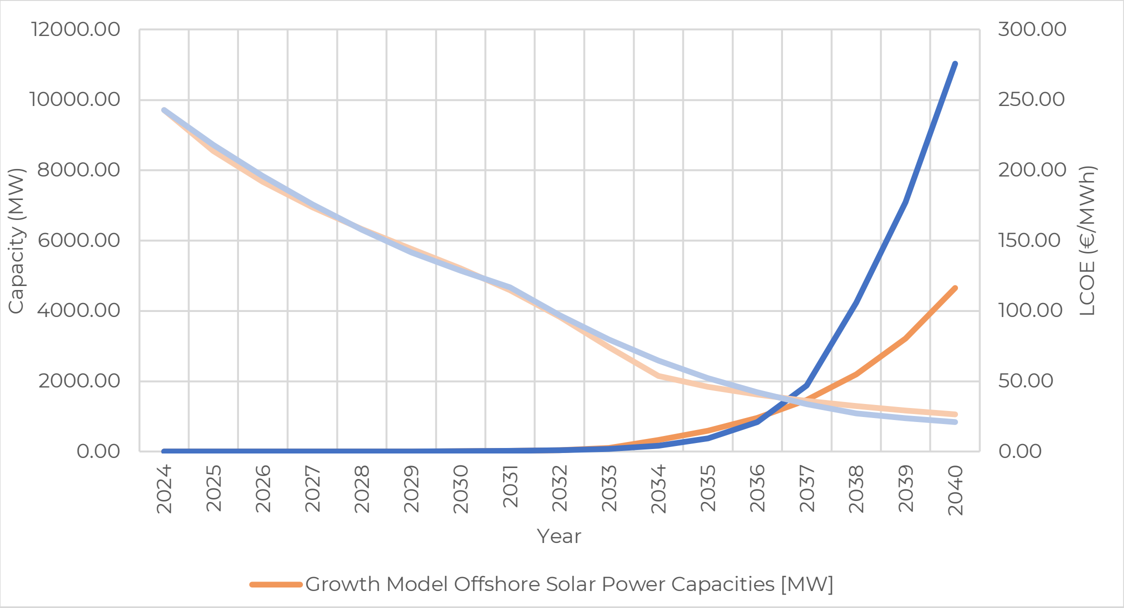

Figure 20: Projected offshore solar capacities (MW) using growth model (orange) and doubling model (grey) along with the projected LCOE

6.3 Projections for offshore solar and learning rates based on bottom-up database

The projection of expected offshore solar capacity from current installations and planned future projects to 2050 is shown in Figure 21. These projections are taken from early-stage projects and their current installed deployments. The three scenarios: low, medium, and high relate to the spread of future desired installations from developers, mainly from stated aspirations from 2030 that have been extended forward through polynomial curve fitting to the data points to 2050. The two predictions are expected to diverge from 2030 where the broad expected deployment ranges are expected to be installed. Expected growth ranges from 30-40GW from the low-high scenarios, respectively.

LCOE is expected to drop significantly from DNV's 2021 estimate of 354 €/MWh (DNV, 2021) to around 50 €/MWh as seen in Figure 22. Bottom-up LCOE projections were made from existing literature and the greater range of results can be seen in the spread of data. The literature generally agrees well with the average trend and is expected to follow a similar cost reduction pathway to the results from industry reports.

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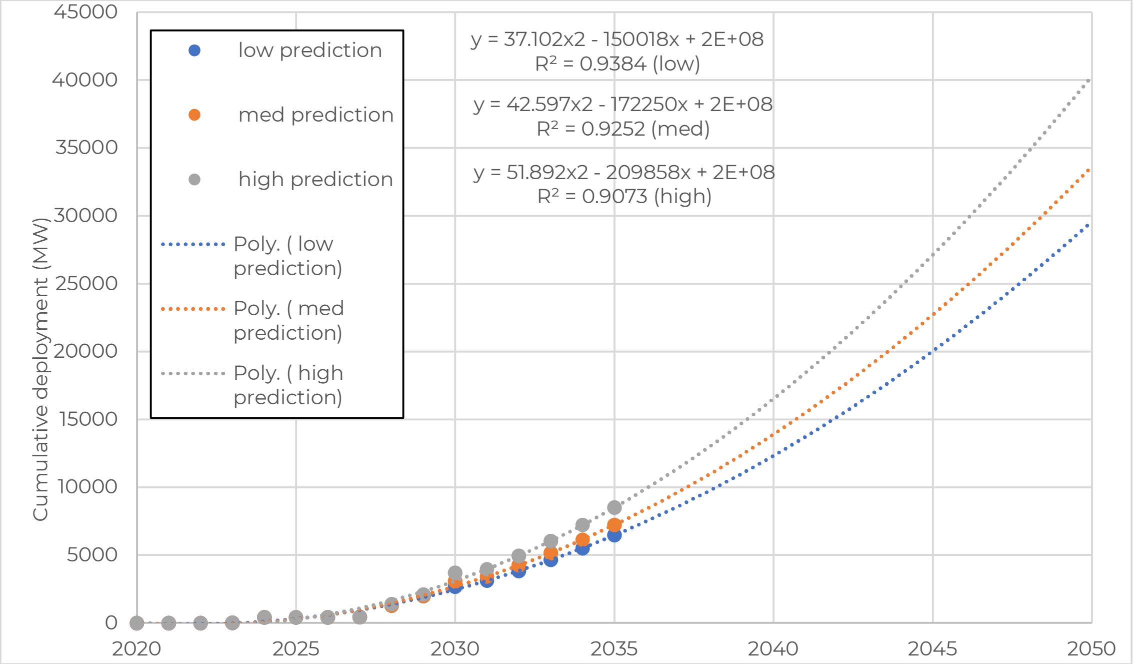

Figure 21: Bottom-up projections for offshore solar capacity until 2050. Source: Author's work

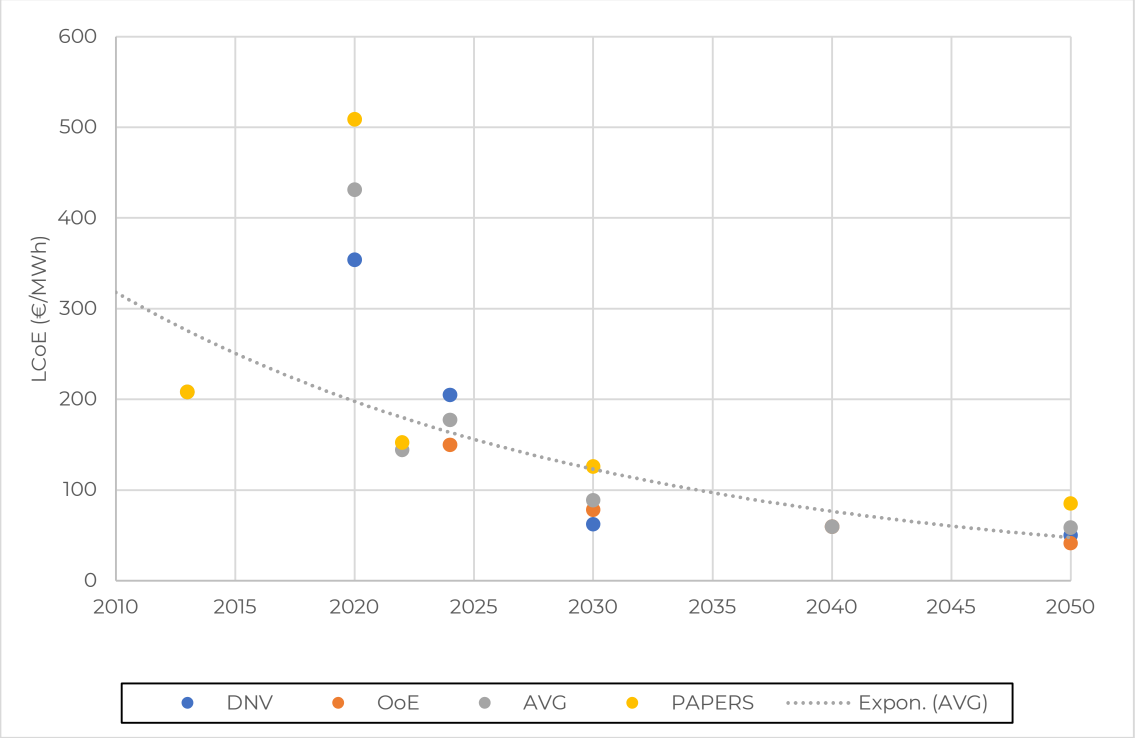

Figure 22: LCOE projections for offshore solar. Source: (DNV, 2021), (OOE, 2021), (Ghigo, 2022), (Trapani, 2013), (López, 2024), (Tina, 2023), (Keiner, 2022)

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Table 6 - CAPEX, OPEX and other system CAPEX used to formulate offshore solar LR (Source: (Ghigo, 2022), (Keiner, 2022), (Tina, 2023), (Trapani, 2013))

	CAPEX	OPEX	BOP
Units	€/kW	€/kW/year	€/kW
2020	5000	60	2000
2026	2190		1130
2030	1911	33	571
2035	2104	35	
2040	2554		600
2050	332	13	500

The learning rates for offshore solar are displayed in Figure 23. All LR for offshore solar are derived from literature and therefore represent an initial study into offshore solar cost reductions, before extra costs through agency reports are published and validated.

Overall CAPEX LR is 6%, with 9% under 2030 and 5% from 2030 onwards. As is expected, most of the higher LR are found in orange (< 2030) where capacity is low and doubling rates will be highest. Some results go against this pattern such as for BoS and platform, and this is often due to a lack of cost data, or published work CAPEX varying in value but not in cost year, leading to high LR. High LR was also found for the mooring system and platform, again due to closely grouped CAPEX results. As research into this field, especially in costs, is generally new, these LR at a sub-system level should be taken as initial results and could change with updated costs with future work. The general trend of LR is 6% and 5% for CAPEX and OPEX respectively, and high cost-reduction components including platform and moorings also show high results which is to be expected.

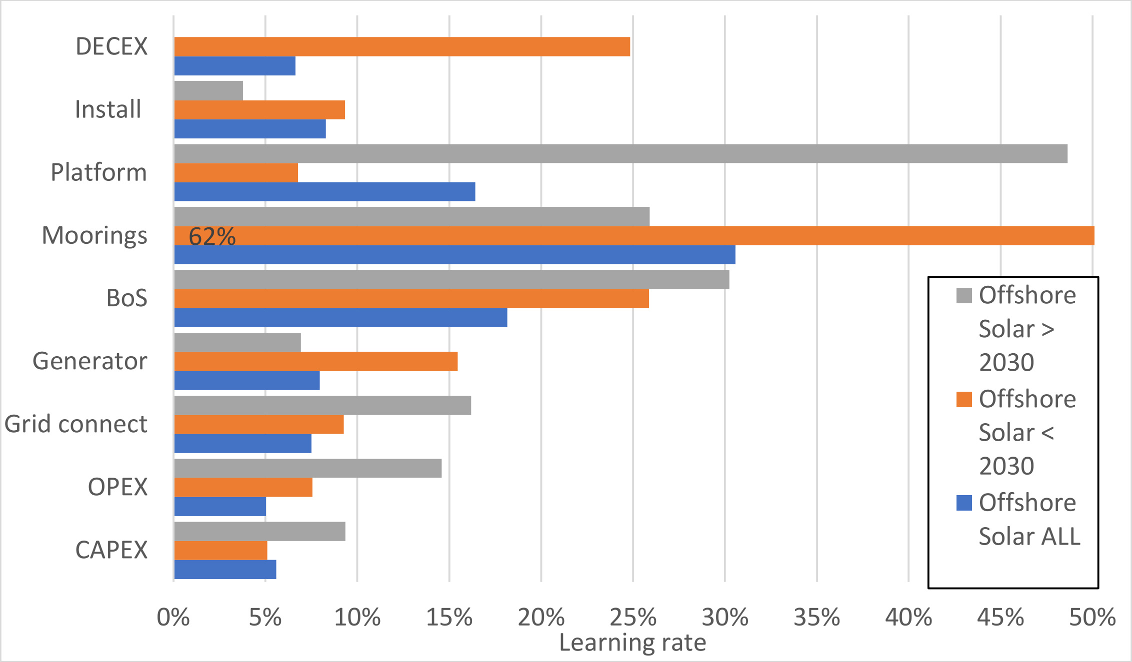

Figure 23: Offshore solar subsystem level learning rates

6.4 Key conclusions

There is currently very limited data on specifically offshore solar PV in the public domain. A limited number of reports discuss floating solar PV which includes both inland lake and reservoirs and offshore solar, with most of the attention on inland floating PV due to the currently significantly larger cumulative deployment. Some of the key takeaways that could be extracted from the analysis conducted are as follows:

Deployment:

Projections in public reports suggest between 10 GW and 30 GW of FPV by 2030, but do not give a number for the offshore solar contribution. Using a combination of fixed offshore wind, onshore PV and FPV, as reference technologies projections for offshore solar found that deployment could reach 13 MW by 2030 and 11 GW by 2040. Projections beyond 2040 using reference technologies has not been carried out, due to too many uncertainties and assumptions. The projections using the bottom-up database compiled for this deliverable, shows a range of between 1.6 and 3.5 GW by 2030, and between 17 and 30 GW by 2050.

LCOE:

Publicly available information on LCOE states that in 2021 LCOE was 354 €/MWh and is expected to reduce to reach similar LCOE of ground-mounted PV, which in the Netherlands is expected to be 50 €/MWh by 2030 and 40 €/MWh by 2050. The key driver in cost reduction is the PV panels, which have seen high LR of 40%

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between 2006 and 2023. The reference technology method uses LR of 17% and estimates below 130 €/MWh in 2030 and 26 €/MWh in 2040. Due to the limited number of projects a bottom-up approach to LCOE projections was not possible, instead using public references to project LCOE; by 2030 the corresponding LCOE is estimated to reach ~120 €/MWh and by 2050 the corresponding LCOE is expected to reach ~43 €/MWh.

Learning Rates:

In the public domain LR on PV modules were found to be as high as 40% between 2006 and 2023. Oceans of Energy however have shared a 17% LR on LCOE in the previous EU-SCORES D7.9 deliverable. The LR presented in the section on the bottom-up approach are derived from literature and are estimated to an overall LR on CAPEX of 6% and on OPEX of 5%. These numbers represent an initial study into offshore solar cost reductions, before extra costs through agency reports are published and validated.

7. Hybrid Systems and Combined Learning Rates

Hybrid systems combine two or more renewable energy technologies either through shared colocation or through combined platforms. In this study, only co-located devices in shared farms are considered that separate energy generation technology but make use of shared infrastructure such as grid connections, power cables and mooring devices. It is expected that developed and more mature technology including bottom-fixed offshore wind will host other, less mature technology such as offshore solar until these nascent industries reach commercial maturity.

Figure 24 shows the maximum LR across all technologies studied in this task and serves to highlight where LR synergies may be found. CAPEX rates range from 6-12% and is closely grouped across the four technologies. OPEX rates range from 4-9% and is also closely grouped, although as with grid connection, offshore solar tends to produce higher LR away from the other three technologies. Highest LR is for cost groups including moorings and platform, and for technologies especially FOW and offshore solar.

The main takeaway is the high variability of LR, that could indicate possible benefits within certain technologies but also could highlight some uncertainties within subsystem costs, especially as most cost reporting at present includes the current high prices that should alleviate in the next few years, with the timeframe for offshore solar especially narrow that can affect LR. These should be further refined and supplemented with new cost data once new reliable CAPEX is produced for these emerging technologies.

Figure 25 has hybrid learning cost reductions in the form of LCOE over time. The LCOE reduction curves of wave and offshore solar were applied to offshore wind (OW) and floating offshore wind (FOW) which have higher installed capacity

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currently, and could serve as ideal candidates for hybrid farms. Also shown are cost reduction curves are for single technologies (e.g. wave, offshore solar) on their own with their medium-projected capacity, with no extra capacity addition from hybrid farm co-location. This cost reduction of wave and offshore solar is then applied to the technology if 10% of either offshore wind or floating offshore wind technology, to represent larger farms and more mature technology accommodating a smaller emerging one yet to achieve commercial viability. Wave and offshore solar with no hybrid farm scenario both start at around 330-335 €/MWh, wave reduces to 131 €/MWh by 2030 and 76 €/MWh by 2050. For offshore solar, costs drop at an increased rate to 61 €/MWh by 2030 and 34 €/MWh by 2050.

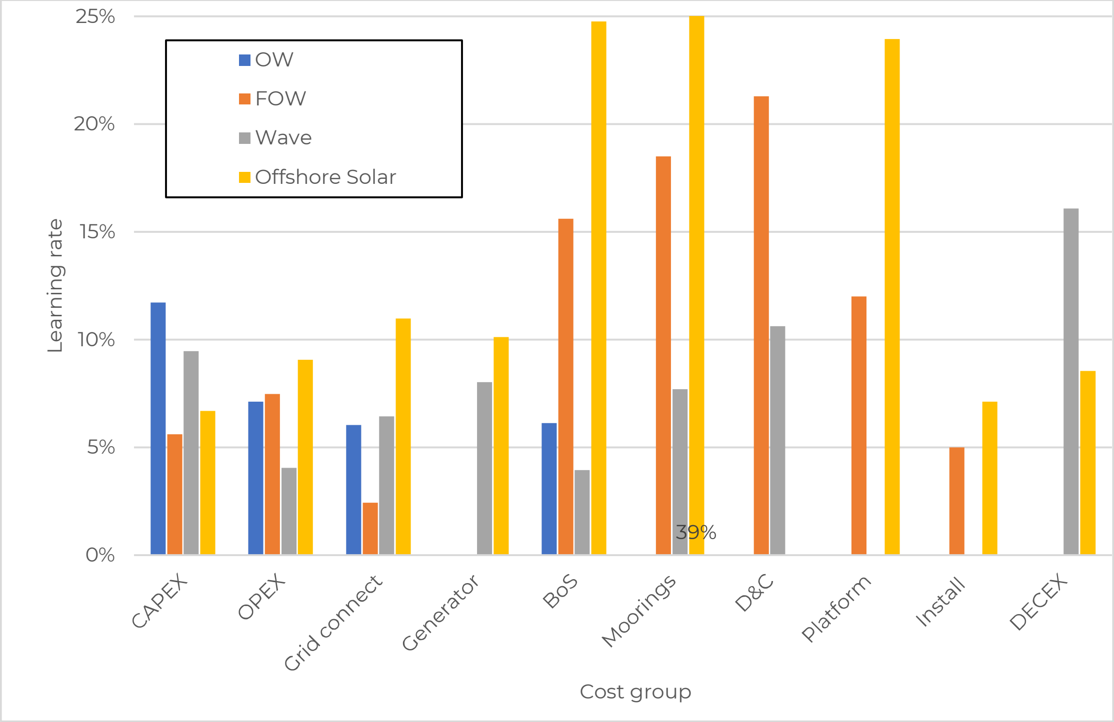

Figure 24: Learning rates across the four technologies at subsystem level

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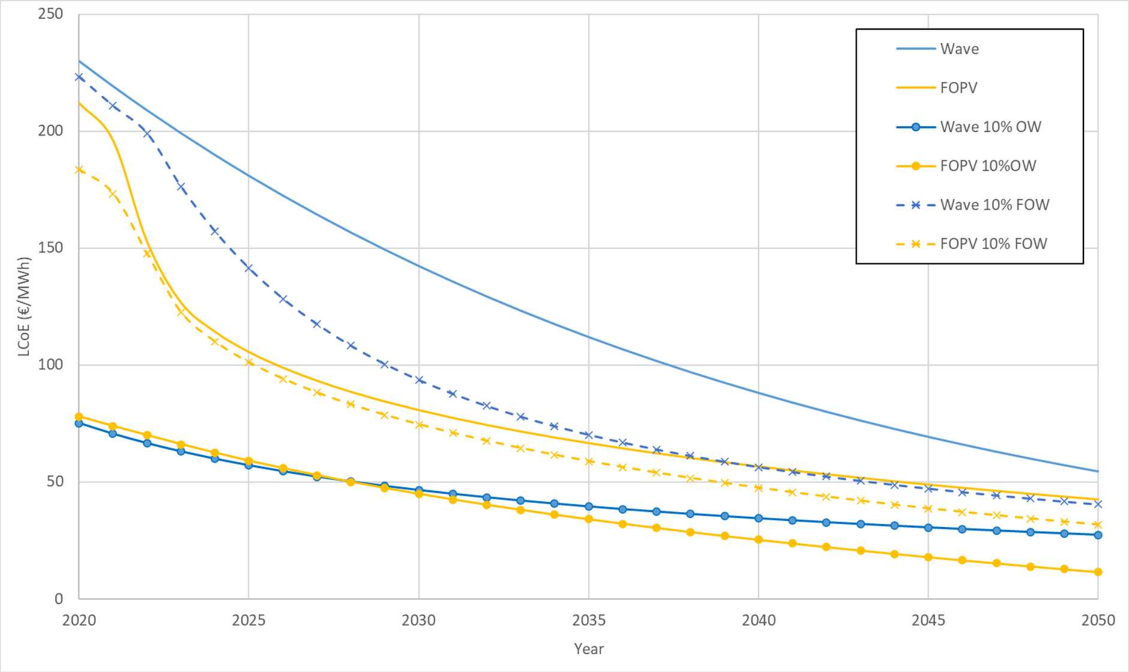

Figure 25: Hybrid farm LCOE reductions

When 10% of FOW capacity is shared in hybrid farms, wave starts at a relatively high LCOE due to the slow start of FOW in the 2020s but then reduces as cumulative deployment of FOW increase, reducing to 94 €/MWh by 2030 and 40 €/MWh by 2050. For offshore solar using hybrid farms with 10% of expected FOW capacity, LCOE starts lower with a rapid reduction due to the expected fast deployment of both technologies, reaching 75 €/MWh by 2030 and 32 €/MWh by 2050.

Offshore wind is already a dominant and mature technology that has witnessed rapid growth and general low costs. As such, a 10% share of capacity of an already mature and established technology results in low initial LCOE of ~78 €/MWh for both emerging technologies. The already developed and high rate of deployment means the curve of cost reduction does not follow the same drop as other scenarios, at ~45 €/MWh by 2030 and a divergence of 11-27 €/MWh for offshore solar and wave respectively by 2030. This high-level study shows that the cost reduction potential of the two nascent technologies is high but deployment is needed to realise these LCOE targets involving hybrid farms.

7.1 Key Conclusions:

Although a brief investigation into combined learning rates on hybrid systems has been conducted, it is clear that a combination of mature technologies with less mature technologies may be advantageous both from overall learning rates as well as accelerated cost reduction pathways, for the less mature industries until these industries reach commercial maturity. However, to realise these LCOE targets on hybrid farms, deployment is necessary.

8. Summary and Key Conclusions

The aim of this D7.12 White Paper on expected Learning Rates has been to identify future cumulative deployment levels, levelised cost of energy and learning rates for floating offshore wind, wave and offshore solar sectors. The paper also briefly investigates hybrid learning rates of different technology combinations.

This white paper explores each of the technologies separately through a number of different approaches. Firstly, identifying projections from the industry perspective on deployment, levelised cost of energy and learning rates. Second, using reference technologies to project deployment growths, and applying publicly available learning rates to project LCOE. Thirdly, using a bottom-up database compiled for this deliverable to, in so far possible, project deployments, future levelised cost of energy along with estimate learning rates.

Overall, the floating offshore wind sector, as compared to wave and offshore solar, has more publicly available information and good alignment is found between the different approaches to project deployment and corresponding LCOE, as well as between publicly available learning rates and the learning rates calculated using the bottom-up database.

The wave sector has less publicly available information as compared to floating offshore wind, likely due to floating offshore wind being the more commercially advanced technology. This scarcity of information is evident from the results of the three approaches, which shows larger ranges in the results for projected deployment, although the projected levelised cost of energy reduction largely follows similar downward trends.

The offshore solar sector was found to have the least available public information, and is incorporated within the broader term Floating solar PV, which also includes inland lakes and reservoirs. No specific future projections were found for offshore solar in the public domain. Using reference technologies and the bottom-up database methods proved equally complicated with tentative results.

For hybrid multi-MW farms, it was found that combining more mature technologies such as fixed offshore wind with less mature technologies such as offshore solar and wave until these nascent industries reach commercial maturity may result in positive overall learning rates and accelerate cost reduction pathways.

The key figures from the analysis of floating offshore wind, wave and offshore solar have been extracted from the main deliverable and are summarised in Table 7 and Table 8:

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Table 7: Projections for deployment and corresponding LCOE based on industry projections, using reference technologies, and using bottom-up compiled database for floating offshore wind, wave and offshore solar.

Floating Offshore Wind		2030	2040	2050
Industry projections	Deployment	6-14 MW	-	270 GW
	LCOE	>100 €/MWh	-	43 €/MWh
Reference Technologies	Deployment	2GW	51GW	116-750 GW
	LCOE	121-170 €/MWh	58-89 €/MWh	32-48 €/MWh
Bottom-up database	Deployment	41 GW	-	252 GW
	LCOE	100 €/MWh	-	35 €/MWh

Wave		2030	2040	2050
Industry projections	Deployment	178-494 MW	-	180 GW
	LCOE	110-150 €/MWh	-	40 €/MWh
Reference Technologies	Deployment	93 MW	4.7 GW	67 GW
	LCOE	154 €/MWh	53 €/MWh	34 €/MWh
Bottom-up database	Deployment	400 MW	-	13 GW
	LCOE	118 €/MWh	-	41 €/MWh

Offshore Solar		**2030**	**2040**	**2050**
Industry projections	Deployment	-	-	-
	LCOE	50 €/MWh	-	40 €/MWh
Reference Technologies	Deployment	13 MW	11 GW	-
	LCOE	> 130 €/MWh	26 €/MWh	-
Bottom-up database	Deployment	1.6-3.5 GW	-	17-30 GW
	LCOE	120 €/MWh	-	43 €/MWh

Table 8: Learning rates in publicly available information and calculated learning rates using the compiled bottom-up database

LR on FOW	**Publicly Available**	**Bottom-up calculated**
LCOE	14.1%	-
CAPEX	7.8% (avg)	6%
OPEX	-	7%

LR on Wave	**Publicly Available**	**Bottom-up calculated**
LCOE	15-18.6%	-
CAPEX	9.3-11.4%	8%
OPEX	9.4%	5%

LR on offshore solar	**Publicly Available**	**Bottom-up calculated**
LCOE	-	-
CAPEX	-	6%
PV Modules	40%	-
OPEX	-	5%

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