Ocean energy in Europe: assessing support instruments and cost-reduction needs

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Abstract — **The SET-Plan declaration of intent for ocean energy has set ambitious targets for wave and tidal energy technologies. Tidal technologies are expected to reach a levelised cost of energy (LCOE) of 15 cEUR/kWh by 2025. To meet this target, technology costs need to be reduced by about 75 % from 2016 values. Cost-reduction of tidal technologies is expected to go hand in hand with technology deployment and further technology validation gained by the operation of first-of-a-kind tidal farms.**

In this paper we assess the learning investment needed to support the cost-reduction of tidal energy to meet the 2025 SET-Plan targets. The learning investment necessary to bring tidal energy to cost-competitiveness would be of about EUR 1.45 billion, requiring about 3.2 GW of installed capacity to achieve the LCOE target of 15 cEUR/kWh. Supporting the step growth for the sector requires the design of accompanying policies aimed at the industrialisation of the sector to support the creation of assembly and manufacturing facilities.

***Keywords*— Tidal Energy, Levelised Cost of Energy, Learning investment, Cost reductions, SET-Plan**

I. Introduction

The ocean energy sector has made considerable progress over the past few years. Significant developments have taken place in the EU and Canada, with the deployment of the first tidal energy demonstration farms, a milestone for the creation of the ocean energy market. In Europe, among the ocean energy technologies, tidal and wave energy are those poised to provide the most significant contribution in the short-term, with about 71 MW of tidal and 37 MW of wave energy capacity expected to be deployed within the EU by 2020 [1].

In 2016 Europe reinforced its commitment to the development of ocean energy technology. The SET-Plan Declaration of Intent has set out ambitious targets for the ocean energy industry [2], and ensures the support of the EU through research, demonstration and innovation actions. The roadmaps developed by the Ocean Energy Forum [3] and by the European Technology and Innovation Platform [4] for ocean energy have identified key actions for making ocean energy a commercial reality in the EU and on a global stage.

Besides technical and environmental challenges, the main barrier preventing large-scale ocean energy uptake in the EU is related to financial viability considerations.

The sector is therefore required to achieve significant cost-reduction in the next 10 to 15 years, and to achieve this it is extremely important that support schemes are tailored to the needs of the technology. In addition to existing support systems, novel R&D and financial instruments need to be identified to support the development of wave energy technology and to help reduce the risk associated with demonstration farms. The current cost of tidal and wave energy technology has to be reduced by 75% and 85% respectively to meet the targets agreed in the SET-Plan.

In this paper, we estimate the financing needs of tidal energy to understand what would be the investments needs in technology and enabling services (from public and private sources) necessary for the ocean energy sector to meet the SET-Plan targets by 2025. This analysis is complemented with an assessment of supply chain involvement that would facilitate the industrial roll out needed to match the different deployment trajectories.

An in-house developed levelised cost of energy tool (LCOE) is used to determine the required capacity to meet the SET-Plan targets. Baseline data is taken from the 1st array stage presented by OES [5]. The tool allows the assessment of the needed tidal installed capacity (break even capacity) and investments (learning investments) required to take tidal energy 15cEUR/kWh given a series of assumption, based on technology learning and R&D.

II. SET-Plan Targets

The SET-Plan declaration of intent for ocean energy [2] has set ambitious targets for wave and tidal energy technologies. Tidal technologies are expected to reach a levelised cost of energy (LCOE) of 15 cEUR/kWh by 2025 and of 10 cEUR/kWh by 2030. Wave energy technologies are expected to reach the same targets with a five-year delay, 15 cEUR/kWh in 2030 and 10 cEUR/kWh by 2035. In order to meet these targets, technology costs need to be reduced by about 75 % from 2016 values [1]. Cost-reduction is expected

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to go in hand with increased technology deployment and further technology validation gained by the operation of first-of-a-kind farms. These processes are expected to unlock cost-reduction through economies of scale (large industrial production) as well as through learning by research (improvement of technology through R&D).

In this paper we focus on determining the learning investment needed to support the cost-reduction of tidal energy to meet the 2025 SET-Plan targets. Learning investments usually refer to the support needed by a technology to become commercially viable or, as in this case, to reach a given benchmark.

III. Learning curves and cost reduction

Experience and learning curves have long been established as tool to assess the development, to understand cost-reduction mechanisms and to forecast market uptake of new energy technologies. The cost of energy is the most common and most important performance indicator of the competitiveness of energy technologies [6]. The forecast of future cost through the use of learning curves becomes essential to sustain the deployment of energy technologies and estimate the potential capacities [7]. Learning curves thus allow the analysis of the development cost of technologies as a function of cumulative production/capacity [8]. For this reason, learning curves are at the base of policies aimed at encouraging the evolution of renewable energy technologies [9].

Basic experience curves can be expressed as follows ([10], [7], [8]):

$$\boldsymbol{C(x_t) = C(x_0) \times (x_t/x_0)^{-b}} \qquad \textbf{(1)}$$

where x_0 is the cumulative capacity at time $t = 0$;
$C(x_0)$ is the cost of the unit produced at time $t = 0;$
x_t is the cumulative production or capacity at time $t;$
$C(x_t)$ is the cost of the unit produced at time t.

The learning parameter b expresses the rate at which the cost declines for each doubling of the capacity. This is related to the learning rate (LR) as follows:

$$\boldsymbol{LR = 1 - 2^b} \qquad \textbf{(2).}$$

The advantage of using the learning rate rather than the learning parameter is that a higher learning rate relates to a faster cost decrease.

Different factors concur in driving cost reduction[11], [12]:

- Learning by doing, which refers to the learning achieved through methodological improvements, increased efficiency and specialisation.
- Learning by research, as a result of R&D investments and introduction of new materials or components.
- Learning by interaction, achieved through knowledge sharing and knowledge diffusion.
- Learning by upscaling, referring to increase manufacturing capabilities.
- Learning by upsizing of the product, e.g. increased power rating of a turbine.

The concurrent factors are often summarised in one single learning rate. Single learning factor learning curves have been widely adopted to understand the cost-reduction of mature technologies, such as wind energy and photovoltaics ([13]–[16]), however they have limited application to emerging technologies since they do not provide a clear account of the learning by research.

One of the advantages of applying learning curves to ocean energy technologies is that they can be used to understand what is the required breakeven capacity at which a given cost target is met, and consequently they provide an indication of the additional costs required to reach it. These costs are the learning investments, which can be derived as follows [7]:

$$\boldsymbol{I = C(x_0)x_0 \left\{\frac{1}{1-b}\left[b\left(\frac{C(x_b)}{C(x_0)}\right)^{(b-1)/b} - 1\right] + \left(\frac{C(x_b)}{C(x_0)}\right)\right\}} \textbf{(3)}$$

where x_b is the breakeven cumulative capacity;
and $C(x_b)$ is the cost target to be met.

One of the disadvantages of using learning curves is that, while it provides a figure of the necessary investments to make a technology competitive, this methodology does not forecast when the breakeven capacity will be met[6].The breakeven time is dependent on deployment rates, and can be influenced by policy mechanisms designed to accelerate uptake of a given technology ([9], [15]).

The determination of learning investments is therefore linearly dependent on the current cumulative capacity and costs. Cost and performance indicators such as capital expenditure (CAPEX), operational expenditure (OPEX), and capacity factors are needed to estimate the current and future LCOE of ocean energy technology. Given their current state ([17], [18]), uncertainties over cost indicators are bound to affect the overall calculations. In particular, whilst learning rate for other energy technologies have been estimated through years of technology progression ([6], [13]), in the case of ocean energy technologies, learning rates have been applied based on experience drawn from offshore wind energy studies ([15], [19], [20]). Furthermore, the lack of design convergence witnessed in the sector generates further uncertainties with regards to the CAPEX and OPEX of technologies yet to be commercially viable, thus affecting estimates of breakeven capacity and required learning investments.

IV. Methodology and data sources

The aim of the paper is to investigate the learning investment needed and the associated breakeven capacity needed to meet SET-Plan targets. In order to reduce the number of uncertainties affecting the calculations the following assumptions have been made:

1. The analysis focuses mainly on tidal energy technologies meeting the 2025 SET-Plan targets. The ongoing deployments of tidal technology indicate that tidal energy technologies are more

advanced, thus reducing noise and uncertainties related to cost and performance indicators.

2. The analysis is based on the final estimated LCOE of tidal technologies. In this case, assumption on OPEX, capacity factors and availability of the technologies are needed. LCOE calculations employed in this work follow the methodology employed in [5], [21]. The needed LCOE reductions are analysed before investments that generate the learning,
3. Learning investments are calculated based on CAPEX, as commonly employed for emerging technologies [22].
4. We employ the indicators provided by the recent reports on cost of ocean energy by the IEA Ocean Energy System [5], and by ETRI [23].
5. A deployment scenario is simulated in order to understand supply chain requirements and make a comparison with currently announced projects. For this purpose a generic tidal turbine rated at 1.5 MW is employed. An exponential deployment rate, with installed capacity doubling for each year between 2017 and 2025.
6. For the purpose of the reference case the learning rate for CAPEX and OPEX is assumed to be the same, with no learning in terms of device performance (capacity factor).
7. An enhanced deployment scenario is also taken into consideration, accounting for enhanced economies of scale once turbine production is >250/year and with a capacity factor learning rate of 2% until cumulative capacity reaches 250 MW. This scenario aims to simulate learning by R&D and learning by doing.

The data employed and currently available in literature carry a level of uncertainty, for example, current CAPEX for tidal turbines ranges between 4400 EUR/kW and 12400 EUR/kW, while capacity factors can range between 19 % and 40 % As a result, the current LCOE for tidal energy technology ranges between 40 and 80 cEUR/kWh with a reference value of about 60 cEUR/kWh, for operation in average resources, as shown in Figure 1.

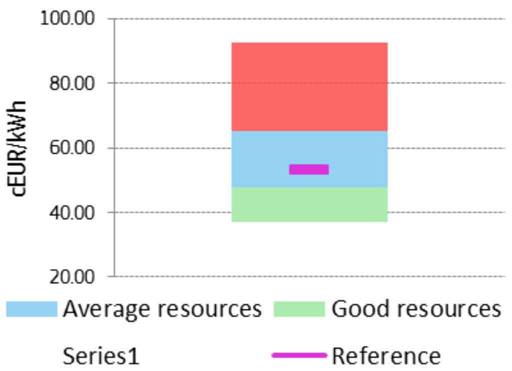

Figure 1 LCOE estimates for tidal energy technologies

A reference scenario was created based on the cost indicators available in literature ([5], [23]) and validated with cost of ongoing projects extracted from the annual reports of companies [24]. Reference values employed for this study are presented in Table 1.

TABLE 1 REFERENCE COST AND PERFORMANCE INDICATORS EMPLOYED.

Variable	Reference Value
CAPEX	7000 EUR/kW
OPEX (Fixed Operating and Maintenance)	6.5 % of CAPEX/year
Lifetime	25 years
Discount rate	10 %
Capacity Factor	36 %
Availability	88 %
Starting capacity [MW]	3.4
Learning CAPEX	10 %
Learning OPEX	10 %
Learning Capacity Factor	0 %

V. COST REDUCTION OF TIDAL ENERGY TECHNOLOGIES

Cost reduction trajectories for tidal technologies are presented in Figure 2 based on deployed capacity.

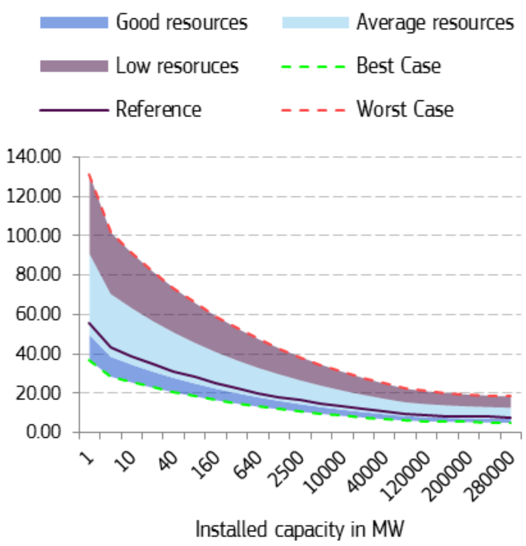

Figure 2 Cost reduction scenario for tidal energy

The choice of the discount rate (opportunity cost of capital), has a direct effect on determining the LCOE of tidal technologies and as a consequence the learning investment, as presented in Figure 3. For the purpose of this study, we employ a somewhat optimistic discount rate of 10%, taking into account that the first tidal farms are expected to receive partial support from public bodies. Discount rate for offshore wind projects has recently dropped to below 8% [25].

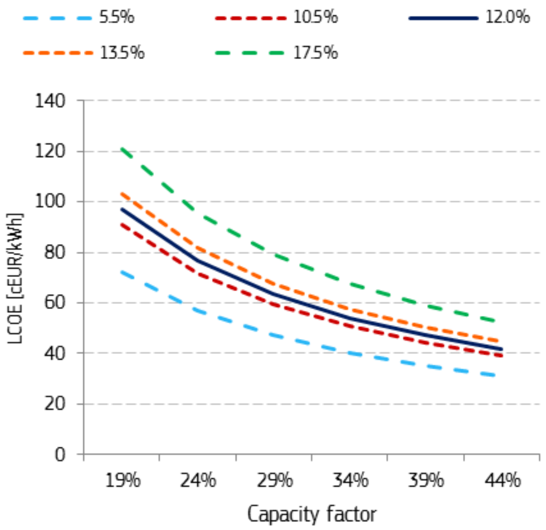

Figure 3 Effects of discount rate on LCOE

VI. Reference Case Analysis

In the reference case, the learning investment necessary to bring tidal energy to cost-competitiveness would be of about 1.45 billion EUR, requiring about 3.15 GW of installed capacity to achieve the LCOE target of 15 cEUR/kWh. This has been determined through reverse LCEO calculation to identify required Capex and then by applying equation (3).

An increase in CAPEX of 15 % (8000 EUR/kW), would push the learning investment to EUR 8.9 billion EUR and would require 11 GW of tidal technology to be installed by 2025. The pipeline of tidal projects in the EU is expected to reach 1.25 GW of installed capacity by 2025, about 33 % of the required capacity to reach the cost targets. A full overview of the learning investment required is presented in Table 2.

Table 2 Learning investment required in the various scenarios.

	Best Case	Good	Reference	Poor	Worst
CAPEX (EUR/kW)	6300	6645	7000	8044	9090
AEP (MWh)	3194	2918	2775	2612	2300
BEC (MW)	313	1705	3152	11424	112000
Learning Investment (mio EUR)	180	700	1450	8903	126,289
Capex at Target (EUR/kW)	3473	2720	2441	2000	1420
% Capex Reduction	45%	60%	65%	75%	84%

BEC identifies the break even capacity, or the capacity needed to reach the required cost target. AEP is Annual Energy Production
The differences between best case and worst scenario take into account increased Capex, Opex. In the best case scenario higher availability and capacity factor is taken into account compared to the other scenarios.

Table 2 also provide information on the required target cost of CAPEX once the SET-Plan cost target is met. Capital expenditure account for about 60% to 70% of the total LCOE of tidal energy farms. It is important to notice that, for non-floating systems (e.g. foundation based turbines), the device accounts for about 30% of the total LCOE. This bears significant implications with regard to innovation of tidal technologies and mostly with regard to cost-reductions that can be unlocked through economies of scale. As a matter of fact, while the cost related to installations can be reduced through learning by doing (as shown during the deployment of the 4th turbine of the MeyGen array [26]), reduction of the cost of turbines are to be achieved through upscaling and mass-manufacturing (Figure 4).

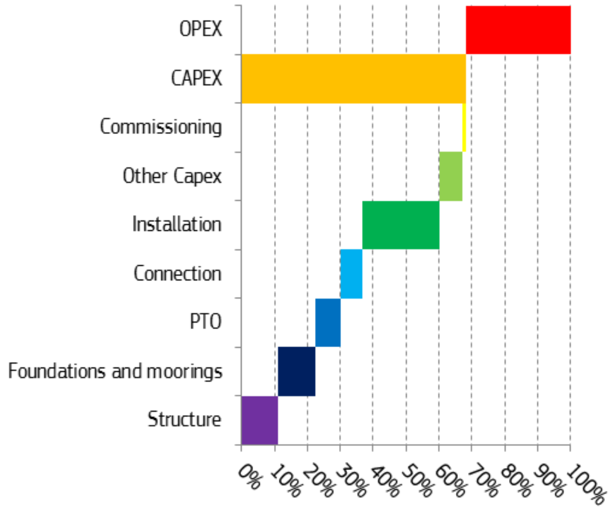

Figure 4 Breakdown of CAPEX and OPEX for tidal energy LCOE

A. *Timeline*

In order to understand how the deployment of tidal energy could take place, we assume an exponential growth between 2017 and 2025. We then compare the projected growth to the list of announced tidal energy projects in the EU to assess feasibility, as presented in Figure 5.

The forecasted exponential growth may not represent correctly the list of announced projects, however, it allows for a number of insights on the development and consolidation of the tidal supply chain. The following remarks can be made:

- 2017-2019, the forecasted growth matches the list of announced projects. We expect these projects to go ahead having received funding.
- 2019-2023, significant deployments have been announced for this period. Nevertheless, there is the need to develop a reliable supply chain for the sector to ensure that these projects can take place. The projected LCOE by 2023 is of 19 cEUR/kWh.

In order for the sector to reach the SET-Plan target, 2 GW of tidal energy projects need to be announced and deployed in the period 2023-2025. The growth witnessed in the wind energy sector indicates that from a technical standpoint this is achievable. Furthermore, a higher deployment rate can be expected if by 2023 tidal energy LCOE has reduced by 66 % from the current 60 cEUR/kWh to 20 cEUR/kWh, as could be expected in the announced project scenario.

B. Economies of scale

One of the key drivers for cost-reduction is the consolidation and the automation of the supply chain. Some tidal companies have already announced the construction of manufacturing and assembly plants for 2018 [27]. Research on cost-reduction drivers for wind energy has identified that significant cost-reductions occur with the increased number of turbines manufactured [7], [15], [28]. Considering the average rated power of tidal turbines to be 1.5 MW, Figure 6 presents the number of turbines required to meet the 2025 targets (purple line) or expected in the announced projects (blue line).

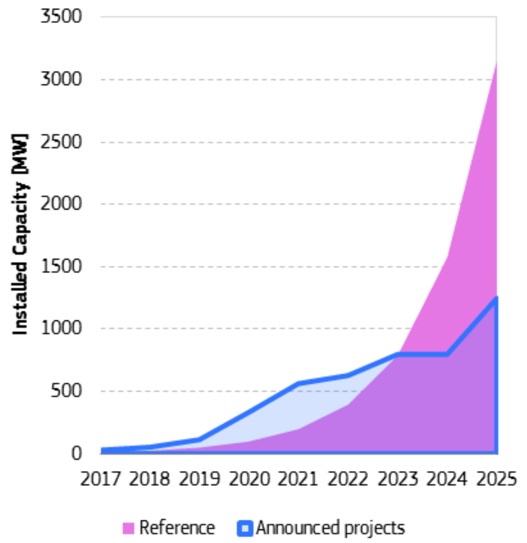

Figure 5 Projected growth and announced tidal energy projects in the EU between 2017 and 2025.

By 2020, the annual production of tidal turbines is expected to be above 200. However, the projected yearly production at the DCNS facilities, the first tidal manufacturing site announced, is between 25-50 turbines per year. Four facilities of this kind are needed to meet the 200 turbines per year goal, meaning that the key market players (Atlantis, Andritz and DCNS) should have all invested in manufacturing and assembly facilities in Europe. If this condition is met, steeper cost-reduction curves can be expected for the sector moving forward.

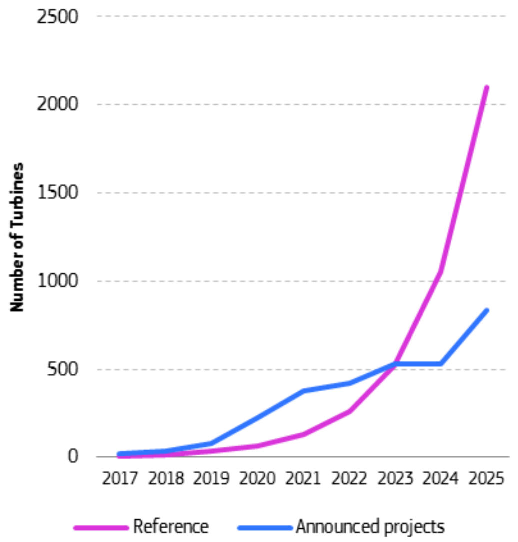

Figure 6 Expected number of turbines deployed

VII. ENHANCED DEPLOYMENT SCENARIO

An enhanced deployment scenario was taken into consideration in order to assess the effect of different learnings that could take place through the deployment of the first tidal energy farms. In particular, the following assumptions are made:

- Learning by research, e.g. increased performance of tidal turbine in the short term due to technology validation. A Capacity factor learning rate of 2% is used up to a total deployment of 250 turbines.
- Effects of economy of scale, once cumulative capacity is >300MW. The learning rate would then move from 10% to 18%. A strong cost-reduction was witnessed in the manufacturing of wind turbines [8].
- Learning by doing for OPEX and installation, increased know-how from demo plants, with a 0.25% increase in learning rate for each doubling of the capacity.

Figure 7 presents the results obtained from the simulation of the enhanced deployment scenario in comparison with the reference scenario. By taking into account the different learning listed above, breakeven capacity is reached at 420 MW of cumulative installation.

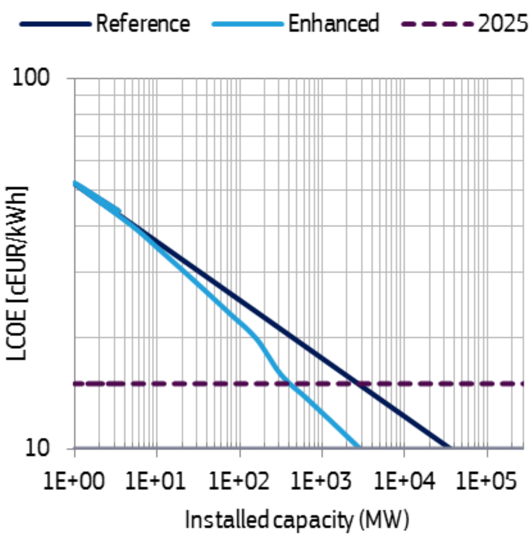

Figure 7 LCOE reduction in the reference and enhanced scenario. Dotted line indicates 2025 target.

The enhanced scenario offers the possibility to assess how different learnings can affect cost-reductions. In particular, significant cost-reduction can be expected with regard to installation, operation and maintenance of the first tidal energy farms.

VIII. CONCLUSIONS AND FURTHER WORK

In this paper we assessed the required capacity and learning investments for tidal energy to meet the 2025 LCOE targets of the SET-Plan Declaration of intent. 3.15 GW of projects needs to be installed to ensure that the 15 cEUR/kWh goal is reached. Public and private investment of EUR 1.45 billion Euro is needed to support the development. Currently, the tidal energy pipeline accounts for 1.25 GW of projects expected to become operational by 2025. Additionally, projects of 2 GW are needed to meet the targets.

Nevertheless, the current pipeline of projects would ensure a 60 % reduction of LCOE from the current level, the consolidation of the supply chain through investment in factories and further CAPEX reduction through economies of scale. This assessment relies on cost and performance data from literature. The consolidation of the sector and an increasing amount of information on capacity factors from ongoing projects will help in reducing uncertainties.

Through the analysis of the enhanced scenario it is possible to understand how different learning may help the sector grow rapidly. In any case, in order to sustain the growth of the sector predicted in both deployment scenarios, the pooling of resources beyond those currently available is needed. Strong supporting policies, and in particular, industrial policy aimed at the creation of assembly and manufacturing facility are required. Sustaining a rapid growth from now to 2025 offers the tidal energy sector the possibility to identify different learning avenues. The learning investments need to meet the 2025 targets may be justified by higher returns once the technology becomes cost-competitive.

Similarly, the methodology here presented is applicable in part to wave energy and other ocean technologies. The tool developed for this research will be used to continue monitoring and assess the learning of ongoing projects. As the know-how of the sector growths with new installations, our aim is to determine learning rates and curves based on real data rather than assumptions.

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