Projected Deployment and Costs of Wave Energy in Europe

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Abstract

This paper presents an outlook of the development of wave energy (WE) in Europe. Growth projections are adapted from experience in onshore and offshore wind. Costs are broken-down into components and experience curves are applied. The levelized cost of energy (LCOE) is calculated and compared with other technologies using the EGC model described by of the IEA. World Energy Outlook 2009 projections are used for CO_2 and fossil fuel prices to 2030.

The reference scenario depict 0,7GW installed in the EU in 2020, 11GW in 2030 and 80GW installed by 2050 leading to a decrease of the LCOE to 22c€/kWh, 9.4c€/kWh and 4.8c€/kWh respectively (€$_{2008}$). Without externalities, WE could be competitive around 2030 compared to fossil-fuel generated electricity, or shortly after if CCS technologies become a reality. If local externalities (SO_2, NO_x, NMVOC and PM2.5) are accounted, WE would be competitive before 2030 in all scenarios. Several assumptions are described to obtain the results.

Other potentially significant externalities and macroeconomic impacts both in favour and against WE are not included in the results, due to the uncertainty associated and the scope of this study, but results in literature show that it would even advance more the competitiveness of WE.

Keywords: cumulative installed capacity, experience curves, externalities, levelized cost of energy, wave energy

1. Introduction

The new European Directive on renewable energies (RES) sets binding targets of 20% of RES share of primary energy and 20% of CO_2 emission reduction in 2020 with respect to 1990. In 2050, several scenarios project a decarbonization of 80% to 100% of the EU electricity. In 2007, the share of RES (including waste) only accounted for 7,8% of total primary energy demand in EU. In this context, a great effort for a massive deployment of RES is needed to accomplish the binding objectives.

Early stage energy technologies as wave energy are not included in the EU SET-Plan to 2020 and are struggling to cross the pre-commercial stage, also known as “the valley of death”, between prototype and the commercial stage. There are several barriers to the development of these technologies, such as the high investment needed to deploy first demonstration units combined with high risk, that require financial support as attractive feed-in-tariffs and public funding.

However, looking at medium/long term, promoting new technologies through adequate policies will not only decrease its costs through the learning process, but also induce a positive effect on national economies due to innovation and increased national competitiveness. Moreover, several papers in literature account for externalities not included on electricity production disturbing the real price of electricity.

This paper gives a vision of the potential evolution of the costs of wave energy if adequate policies are implemented. Potential WE deployment scenarios are presented based on the experience from the wind sector. The LCOE is calculated and projected assuming different discount rates for each component of the cost. Finally the results are compared to other technologies including some external costs not included in the price of electricity.

2. Methodology

2.1 Future wave energy deployment

Similarities in the development of renewable energy sectors have been observed in the last years. The EWEA report [1] shows that offshore wind growth is following a very similar deployment rate curve as onshore wind if this later curve is properly displaced 15 in the time axis as shown in Figure 1. By considering these growth curves as well as the pace of wave energy development since 1998, it is possible to produce a consistent scenario up to 2050. There is no reason why the growth of wave energy will be smaller than the one for offshore or onshore wind. Indeed the supply chain for WE is less demanding in terms of expertise and deployment vessels, since the equipment and the offshore operations are more conventional.

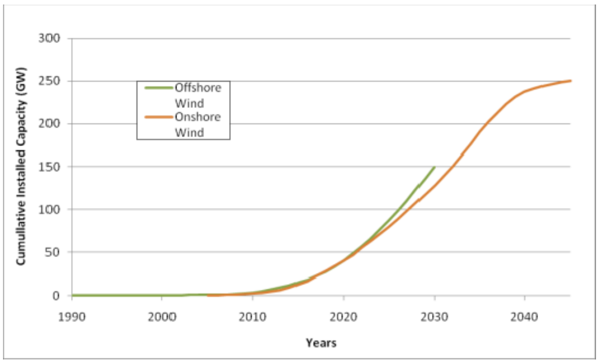

Figure 1: Offshore wind deployment in EU compared to onshore (offshore timescale, onshore increased 15 years).

Data for actual levels of cumulative capacity from 1990 to 2030 are obtained from three reports from the EWEA reports [1], [2] and [3]. 4 characteristic periods are defined corresponding to the sector development rate, in terms of the increase of the annual installed capacity: 1) Pre-commercial, 2) Industry Development, 3) Full Deployment and 4) Saturation.

The average increase of the annual installed capacity is obtained from linear regression for each period as shown in Figure 2.

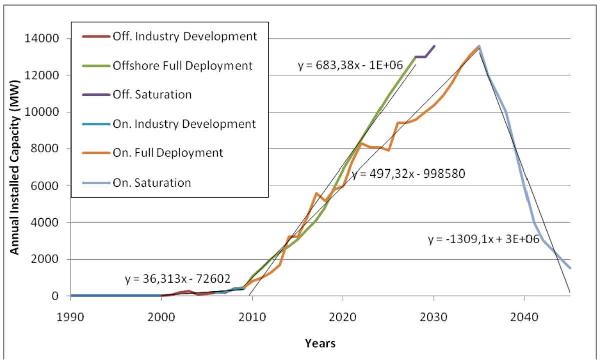

Figure 2: Linear regression applied to annual installed capacity increase for onshore and offshore wind in EU.

In this paper, it is assumed that trends in WE development can be similar to that of offshore wind to estimate the future pace of wave energy deployment based on past and future projections of wind energy. In fact, data of deployment of WE from 1998 up to 2014 based on planned developments shows similarities with the pre-commercial stage of offshore wind with a delay of 16 years.

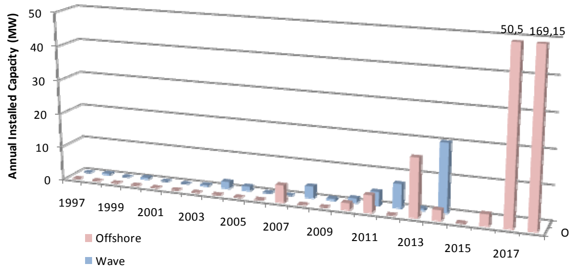

Figure 3: WE past and expected installed capacity from 1998 and 2014 compared to offshore wind (wave energy timescale, offshore increased 16 years.

A conservative reference scenario for wave energy deployment is projected assuming a ratio of deployment compared to offshore wind of 75% (i.e. 25% slower than offshore wind). One optimistic scenario is presented based on the EU-OEA roadmap for ocean energy, assuming the same rate of deployment as offshore wind (ratio equal to 100%), and one pessimistic considering deployment ratio of 50%. Data from offshore wind does not show saturation period so data from onshore wind is used for that purpose. As no data is available in literature on the saturation limits of installed capacity at EU level, the saturation limit for EU installed capacity is calculated assuming the theoretical average wave energy resource of 320GW [4], a specific significant impact (SIF) factor for each scenario and a maximum technology capacity factor (CF). Black & Veatch [5] defined the SIF for tidal energy in the UK of 20%, as the percentage of the total resource that can be extracted without significant economic or environmental impact. The results are presented in Table 1.

Scenario	Deployment Ratio	SIF	Max. CF	Max. EU Capacity
Reference	75%	10%	40%	80GW
Optimistic	100%	15%	35%	137GW
Pessimistic	50%	8%	35%	69GW

Table 1: Parameters determining the wave installed capacity in EU for three different scenarios.

2.2 The expected cost of wave electricity

The LCOE of a generic wave energy farm is calculated following the IEA EGC spreadsheet model [6]. This methodology calculates the LCOE depending on parameters shown in Table 2.

In this paper, an initial value is assumed for all the components of the LCOE for the 1st production model, and then learning rates (LR) are introduced to forecast reductions (positive) or increases (negative) in the different parameters when increasing the global manufactured capacity. The global manufactured capacity corresponds to the cumulative sum of the new and the replaced capacity in the EU and the rest of the world (ROW). It is assumed that in the rest of the world wave energy takes-off slower than in the EU, only starting in period 2 with a growth rate 10% of that the EU increasing to 100% in period 4.

Overnight costs include pre-construction, construction and contingency costs, excluding interest during construction. Investment costs are then calculated assuming the construction period and the discount rate. For the first production models, it is considered are considered between 3000-5000€/kWe depending on the scenario based on data found on literature [7] [8] and from experience of the 1st commercial plant installed in Aguçadoura, corresponding to 3 Pelamis units of 750kW each with a published cost of 4000€/kW [9]. Due to the large number of concepts and demonstration projects, the first production models are supposed to be installed when 40MW of cumulative installed capacity in the EU is reached, corresponding to the end of the pre-commercial phase. Learning rates are then applied to the overnight costs to forecast the future cost reduction. All monetary values are shown in $€_{2008}$ if not indicated.

Due to the lack of experience in operation & maintenance (O&M) of wave farms, annual O&M costs are calculated assumed a typical value for offshore wind of 4% of the overnight costs assuming [10] [11] [12]. The ratio of O&M costs and overnight costs is assumed to be constant along the years (but the annual value decreases depending on the learning in the overnight costs). Decommissioning costs of 5% of the overnight costs are also accounted following the indications of the EGC model but show small importance. An initial capacity factor and lifetime are applied to the first production units, increasing with a learning rate as shown in Table 2. Finally the cost of capital is introduced with a higher initial discount rate due to the high risk of first projects and then decreasing with a learning rate. The global cumulative capacity used in the experience curves corresponds to each of the previously mentioned deployment scenarios.

Parameter		Reference	Optimistic	Pessimistic
Capacity Factor	1st	20%	25%	15%
	LR	-5%	-3.5%	-7%
Discount Rate	1st	15%	10%	15%
	LR	6%	3%	5%
Overnight Costs (€/kWe)	1st	4000	3000	5000
	LR	9%	8%	8%
Constr. Period (years)	1st	2	2	2
	LR	10%	10%	10%
Lifetime (years)	1st	15	20	15
	LR	5%	5%	5%
Decomm. Costs (%overnight)		5%	5%	5%
Annual O&M Cost (%overnight)		4%	4%	4%

Table 2: Parameters defining the LCOE of wave energy using the EGC model including initial values for 1st units and learning rates to simulate experience curves

2.3 Comparison with other technologies

The forecasted wave LCOE is compared with the forecasted mean values of the IEA for coal steam cycle and gas combined cycle power plants projections described in [6] for 2015 and 2030, both without and with CCS technology (chemical absorption with 90% of capture). The parameters are defined in the following table. Between both dates, it is supposed a linear progression in all parameters. Discount rate is maintained relatively high at 10% due to the volatility of the fuel prices. It is 12% at the beginning for CCS technologies assuming more risk in the investment.

Parameter	Start	Coal	Coal CCS	CCGT	CCGT CCS
Capacity Factor	2015	85%	85%	85%	85%
	2030	85%	85%	85%	85%
Discount Rate	2015	10%	12%	10%	12%
	2030	10%	10%	10%	10%
Overnight Costs (€/kWe)	2015	2200	3400	900	1450
	2030	1900	2700	800	1150
Constr. Period (years)	2015	4	4	2	2
	2030	4	4	2	2
Lifetime (years)	2015	40	40	30	30
	2030	40	40	30	30
Decomm. Costs (%overnight)	2015	5%	5%	5%	5%
	2030	5%	5%	5%	5%
Efficiency	2015	46%	36%	57%	49%
	2030	54%	44%	63%	56%
Carbon Emissions	2015	100	10	50	5
	2030	100	10	500	5
Annual O&M Cost (%overnight)	2015	2%	4%	2%	4%
	2030	2%	4%	2%	4%

Table 3: Parameters for coal (steam cycle) and gas (combined cycle) with and without CCS (chemical absorption) [6]

Carbon and fuel prices are obtained from the predictions of the IEA World Energy Outlook 2009 in their Reference and 450 scenarios.

Price	Scen.	2008	2015	2020	2025	2030
Steam Coal (tonne)	*Ref*	120.6	91.05	104.6	107.2	109.4
	450	120.6	85.55	80.9	72.46	64.83
Natural Gas (MBtu)	*Ref*	10.32	10.46	12.10	13.09	14.02
	450	10.32	10.46	11.04	11.04	11.04
CO_2 (tonne)	*Ref*	(13)*		43		54
	450	(13)*		50		110

Table 4: Projected steam coal, natural gas and CO_2 prices to 2030 in the WEO reference and 450 scenarios [13]

2.4 Accounting some externalities

Finally, a review on the valuation of externalities associated to electricity power plants is performed. Large variability in the number, types and economic valuation of externalities are found [14]. ExternE project stand as the reference up to now, and only the average values included in its 2005 update ExterE-Pol report [15] (also included in IPCC 2007 report) have been used (see Table 5). For wave energy it has been assumed similar values as for offshore wind.

Pollutants	Hard Coal	Gas CC	Offshore Wind
(GHG)	(22.9)	(8.4)	(0)
SO_2	6.9	5	0
NO_x	10.5	1.0	0
NMVOC	0	0.3	0
PM2.5	5.5	0.3	0
Rest (upstream)	6	2	1.6

Table 5: External costs (€$_{2008}$/MWh) of current electricity systems associated with emissions from the operation of the power plant and the rest of the supply-chain [ext]

GHG effect is not included in the analysis as it is already accounted in the price of CO_2 emissions embedded in the calculation of LCOE.

Several publications in literature account for other externalities with significant impacts on the cost in other papers but they have not been accounted here until verified from more sources. They are mentioned in the discussion.

3. Results

3.1 Future wave energy deployment scenarios

Three different scenarios are presented following the methodology described in the previous section. Figure 4 shows the deployment of WE in the three scenarios compared to that of offshore wind in the EU. Assuming the growth rates described before, WE installed capacity peak around year 2040 in the reference and optimistic scenario 80 and 137GW respectively. The slower scenario also peaks before 2050.

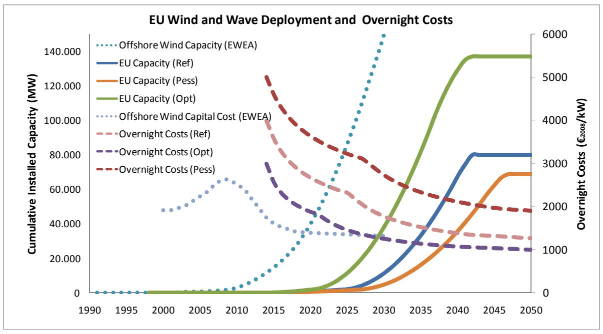

Figure 4: WE cumulative capacity in three different scenarios in the EU and projected unitary costs reduction estimated with experience curves, compared to offshore wind.

The overnight costs rapidly decrease, faster in the optimistic scenario that would attain similar costs as offshore wind around 2025-2030, and a bit slower in the reference and pessimistic scenarios. It is important to comment that the manufactured capacity in the EU and worldwide continues to increase once the saturation limit is reached due to replacement and a market growth in the ROW.

The LCOE is expected to be very high in the all the scenarios by 2014, due to high investment costs and discount rates of 10-15% that investors may require to involve in high risk projects. However, the cost will rapidly decrease as shown in Figure 5.

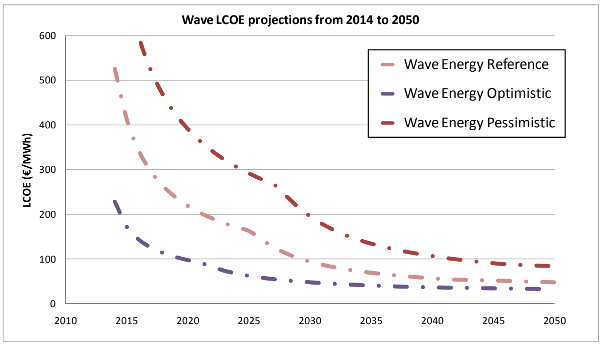

Figure 5: Example figure text.

Figure 6 shows a comparison of wave LCOE and the projected LCOE of coal steam cycle and natural gas combined cycle power plants for 2015 and 2030 in the reference and 450 scenarios published in the IEA WEO 2009. CCS technology is included only for the 450 scenario (in the reference scenario the price is considerably higher than without CCS). Figure 6 also shows the actual costs of some local externalities (CO_2, NO_x, NMVOC and PM2.5 both in the power plant and upstream in the supply chain for hard coal, CCGT and offshore wind (assumed to be similar as wave). The external costs are not included in wave, coal and gas curves, which represent the LCOE without externalities.

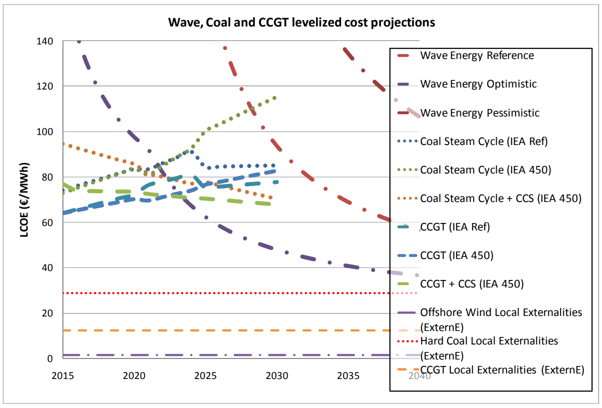

Figure 6: Wave Energy LCOE projections compared to projected costs for coal and gas power plants both with and without CCS in the reference and 450 IEA scenarios.

4. Discussion

The three deployment scenarios show that the investment costs could decrease rapidly assuming high investment costs between 3 and 5 M€/MW installed and learning rates of 8-9% typical of the wind industry. The IEA Wind Technology Roadmap ETP BLUE Map [16] scenario assumes a learning rate of 9% for offshore wind investment costs. The European Environmental Agency [17] states that typical progress ratios for wind turbines are 80-95% (or 20-5% learning rates), so the assumed learning rates appear to be reasonable if not conservative. Of course, leaning rates are only gross approximations of technological progress with consequent limitations. Some authors state the influence for learning not only of the cumulative capacity but also the R&D expenditures and the country innovation potential. However, this papers aims to be only a sketch of the potential of wave power not only in the long but in the medium term and not a deep technological development analysis.

In addition to learning rates, the initial overnight costs assumed appear to be also realistic and conservative. As stated before, the unitary cost of the 1st Pelamis commercial wave farm in 2008 was 4000€/kW and 1st production units are planned to be installed in 2014 in this paper. The fact that the Aguçadoura project did not carry on for a long time, does not imply that future costs should be much higher, rather than increasing experience in components of the device or limiting the lifetime or capacity factor (in this paper it is supposed an initial lifetime of 15 years and 20%, compared to typical published values of 20-25 years and 25-40% of CF). Yet, these initial costs appears should not be regarded as high rather than quite low considering the typical costs in the early stages of other renewable energy (RES) technologies such as solar PV, which in 2008 typical costs were around 5-6M€/MW and having already gone across a larger part of the experience curve than wave energy. First production models for those technologies had a much higher investment per capacity unit. However, solar PV is expected to have larger learning potential being a high-tech industry with large basic R&D in materials and components.

As was commented before, there is no reason why wave energy could not possibly deploy at the same rate as offshore wind. Offshore wind and ocean energy OE face similar challenges, even though the former is at a more advanced stage of development. Indeed the supply chain for wave energy is less demanding in terms of expertise and deployment vessels, since the equipment and the offshore operations are more conventional. Furthermore we see from the national targets that a significant number of countries is prepared for OE take off. Table 6 shows the national targets for OE by 2020 taken from the EU-OEA roadmap.

Country	**OE Target 2020 (GW)**	**Country**	**OE Target 2020 (GW)**
UK	2	*Spain*	0.1
Ireland	0.5	*Portugal*	0.3
Denmark	0.5	*Canary Is.*	0.5
France	0.8	***TOTAL***	**4,7**

Table 6: National targets in 2020 for OE installed capacity published in the EU-OEA road map [18].

The roadmap sets a target of 3.6GW in 2020 while the results of the projections here presented for the 3 scenarios range between 0,5GW the pessimistic and 1,8GW the optimistic, being 0,72GW the expected deployment in the reference scenario. OE is referred to wave, tidal, salinity gradient and temperature gradients, but the later two are still in an early stage and do not seem to reach large deployment in 2020.

After this brief discussion, the results pointing at the installed capacity and reduction in overnight costs presented in Figure 4 appear to be realistic. The projected costs reach 2M€/MW before 2030 in the reference scenario and a saturation limit of 80GW around 2040.

The LCOE is however an indicator much more complex to determine because it depends on many factors. Some of them depend greatly depend on the location of the farm, such as the capacity factor and the O&M costs, while the discount rate is dependent on the investor's decision. Thus, the values here represented are an average of the sector development and the LCOE of particular projects may differ substantially from the shown values. It is expected that the location swith best conditions (either in terms of high FIT, resource or grid availability) will be occupied first, lowering the LCOE of those projects. Also the high volatility in fossil fuel and CO2 prices implies high uncertainty in the future LCOE of gas and coal plants. The reference and 450 IEA WEO scenarios have been assumed here, but they may still differ greatly from reality. Also, there is an intense discussion on the future availability of competitive CCS technologies as the ones assumed in the IEA report [6].

After discussing the limitations implied in the study, the reference scenario shows that WE could be competitive assuming the actual evaluation of the price of electricity between 2030 and 2035. The optimistic lowers the break-even point to 2020-2025, while the pessimistic could reach somewhere between 2040 and 2050. It is intentionally named the "actual evaluation of the price of electricity" as it does not take into account externalities as the ones accredited by the ExternE-Pol and IPCC reports [15] [19]. If taken into account, wind and other RES are already competitive against fossil fuel generated electricity, and others such as wave energy could reach the break-even point far before expected.

The externalities used in this paper only account for average values of the ExternE-Pol evaluation of local effects (see table 5) and represent conservative estimations compared to other publications. Literature shows (as resumed in [11]) that the effects of these local externalities could be around an order of scale higher or lower depending on the location (especially of the proximity to high density of population). Also recent studies evaluate the impact of other externalities as energy security and depletion of resources accounting for very significant values (11-30$/MWh in the US [20]), the evaluation of price volatility, and the cost of energy dependence. The externalities mainly affect fossil fuel generated electricity. Other externalities should also be accounted for RES such as wave energy. The IEA [16] presents several estimates of the cost of balancing variable renewable integration, being the mean value for a 10% wind penetration (the maximum expected share for wave energy) around 2€/MWh. All these externalities have not being accounted in the results of the study due to the large complexity and variability in the results, but further work should be done to internalize them in the price of electricity as they may change greatly the order of merit in electricity generation.

Other potential benefits for the implementation of renewables are presented in several reports. There is also discussion on this issue, but the more consistent reports show positive effects in added value, employment, such as the EmployRES [21] project, due to lead market effect, increasing competitiveness and exports of the EU.

5. Conclusions

The three deployment scenarios presented in the study show a rapid increase in the cumulative installed capacity of wave energy leading to 60-137GW between 2040-2050, leading to a rapid decrease in investment costs from 4000€/kW in 2014 to 2000€/kW in 2025-2030 and 1400€kW in 2040 in the reference scenario. The LCOE in the reference scenario could rapidly decrease from around 40c€/kWh in 2015, closing to 20c€/kWh (2020), below 100c€/kWh in 2030 and reaching 50c€/kWh by 2050.

These results however involve large uncertainty and are based in many assumptions presented in this study. The aim of this work is only to draw possible paths of wave energy development. In this sense, future evolution in conventional power plant electricity costs from IEA data show that wave energy could be competitive around 2030. However, if externalities and macroeconomic impacts were accounted, wave energy could be competitive in the EU far before this date.

Acknowledgements

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