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Evaluation and comparison of the levelized cost of tidal, wave, and offshore wind energy

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In the current context of environmental degradation and depletion of fossil fuels, marine energy has emerged as an alternative to traditional energy resources. However, being in an initial step of development, extracting energy from the ocean is often regarded as difficult and uneconomical. The existing models for assessing marine energy costs are often oversimplified, leading to uncertainties that may hold investors back and slow down the market penetration of this renewable. Therefore, an accurate prediction of marine energy costs is fundamental to drawing conclusions about its competitiveness. Among the different possibilities of marine energy, this paper focuses on the economic analysis of tidal, wave, and offshore wind energy. The individual costs involved in the construction of these offshore energy parks and operation and maintenance tasks during their lifetime are determined. With this information, the levelized cost (€/MW h) is calculated for offshore wind, wave and tidal energy (€165/MW h, €225/MW h and €190/MW h, respectively). It is found that these renewables have a higher energy cost than traditional energy sources; however, considering factors such as the learning rate or externalities enhances their competitiveness. In the second part of this paper, combined energy systems, such as hybrid converters, are presented as a future solution to boost the development of marine energies. The synergies between these renewables are outlined, as well as the cost savings that can be achieved through diversified energy systems. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4932154>]

I. INTRODUCTION

The depletion of traditional energy resources and the degradation of the environment as a result of the fossil fuels consumption have led the European Union to undertake to transform Europe into a highly energy-efficient, low-greenhouse gas (GHG) economy, committing therefore to reducing CO₂ emissions and energy consumption by 20% and to achieving the target of a 20% of the total energy consumption of the EU made up of renewable energy.¹ It is anticipated that more than 30% of electricity will have to be generated from renewable sources by 2020.² In this context, marine energy has emerged as one of the most attractive solutions to the world's energy challenges.³ The main argument that supports the substantial use of this kind of energy is its enormous potential for electricity production,⁴⁻⁷ since it is demonstrated that the offshore resource is enough to supply current EU electricity consumption.⁸ Nevertheless, the main barriers to the development of marine energies are: (i) the early stage of development of the technologies,⁹⁻¹⁹ (ii) the uncertainties regarding the environmental impacts,²⁰⁻²⁸ and (iii) the high costs involved.²⁹⁻³⁴ Among the different options, this paper is focused on offshore wind, tidal, and wave energy.

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Offshore wind energy presents a number of advantages relative to its land-based counterpart, such as the larger available resource, lower turbulence, and negligible visual impact.^{35,36} Besides, the technological similarities between them have facilitated the development of offshore wind energy and its market penetration—the installed capacity in Europe was over 8 GW at the end of 2014.³⁷ On the contrary, tidal and wave energy are still in an initial stage of development but both presents promising prospects in the near future due to the enormous available resource. The total European wave energy resources are estimated to be of the order of 320 000 MW (Ref. 38) and the corresponding European marine tidal current energy resource is estimated to be sufficient for 13 700 MW of generation capacity.^{29,34,39}

Being a young industry, the accurate prediction of the energy cost is fundamental to attracting investors and boosting the development of these renewables. However, the lack of available information results in a large scatter in the current economic predictions.⁴⁰ Most of the documents that have been published on this subject are focused on the analysis of its commercial attractiveness as a private investment. Indeed, the vast majority of the offshore wind energy economic literature has focused on metrics such as initial investment and operation and maintenance (O&M) costs to assess financial competitiveness between technologies.^{29,41–45} And the same applies to tidal^{29,46,47} and wave energy.^{31,46,48–50} Other studies analyze the effects on the economy of a concrete country which decides to promote a new renewable energy such as wave power.^{30–32}

In this line, the aim of this paper is to determine the levelized cost of wave, tidal, and offshore wind power—a decisive parameter when comparing the profitability of different sources of energy.^{41,42,45,46,51} This economic indicator corresponds to the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value (PV) equivalent. For this purpose, all the necessary elements for the economic assessment are analyzed: preliminary, construction, operation and maintenance, and decommissioning costs. In the second part of this study, combining different renewable in the same marine space is presented as a promising solution to reduce costs and avoid other problems inherent to renewables such as the power variability. The existing synergies between marine energies are analyzed, as well as the feasible cost savings.

II. COSTS: BACKGROUND OVERVIEW

In order to calculate the levelized cost, it is necessary to identify the different individual costs that have to be included. The cost associated with permissions and licenses is difficult to estimate, since the regulatory framework is yet to be established and it is expected to be highly country-specific.⁵² The capital cost encompasses the purchasing and installation of the different elements needed to install the energy farm. No less important is the cost of the required maintenance labors through the lifetime of the energy farms, since they are installations located in the harsh sea conditions. Finally, the decommissioning cost has to be included. In addition, to calculate the levelized cost, it is necessary to know the capacity factor of each technology to determine the power output, and the discount rate—the return on investment required to attract project investors—to obtain the present value of each cost.

A. Offshore wind energy cost

The preoperating cost involves all the expenses incurred on preliminary studies, projects, environmental impact assessment, consenting procedures, etc., as well as the direction and coordination of the aforementioned activities. It will depend on a number of factors, such as the location, as policies vary from one country to another, or the size of the installation. Therefore, there is a wide range of values for this cost reported in the bibliography (Table I). It is considered that this cost ranges between €500 000 and €2 000 000⁸ and it is usually expressed as a percentage of the capital cost (CAPEX). Moreover, the permitting and sitting fee is considered to be \$37 per kW installed, i.e., it is assumed to be around 37 times the capacity of the generator in the unit of dollar.⁴⁶

TABLE I. Pre-operating and licenses costs.

Category	Cost	Source
Preoperating cost	10% CAPEX (€)	31 and 53
	€500 000-€2 000 000	8
Licenses and permissions	0.037 × Installed power in W (\$)	46
	2% wind turbines cost (€)	31 and 53

As for the capital cost of offshore wind projects, it can be divided into three categories:³³ (i) turbine; (ii) foundation; and (iii) electric installations: inner park cabling, export cable linking the Offshore Wind Park (OWP) to the shore, and offshore substation with foundations. Table II compiles the range of different values of the capital cost used in the literature.

The split of total investment cost into single cost categories is often discussed in the literature. All reports agree that wind turbines involve the highest cost. For instance, Ref. 56 shows that costs of the wind turbines, transformer substation, building works, and other activities constitute 69.77%, 6.71%, 14.69%, and 8.83%, respectively. In the same line, others such as Ref. 57 or 55 consider that approximately 75% of the total cost of energy for a wind turbine is related to upfront costs such as the cost of the turbine, foundation, electrical equipment, grid-connection, and so on.

With regard to O&M cost, due to the lack of long term operational data (post 10 years), there is no empirical evidence to cite long-term offshore O&M cost. Despite that, the literature compiles some values for this cost based on the experience from other offshore installations such as oil platforms (Table III). The breakdown of the O&M cost^{58–60} is shown in Table IV.

Finally, a wind turbine needs to be dismantled at the end of its lifetime. Some reports assume no dismantling costs at all because the residual value of the wind turbine will compensate for the decommissioning cost. In other studies, it is considered to be in the range 0.5%–1% (Ref. 64) of the capital cost, and others (Ref. 33) assumed M€0.2/MW. As regards the energy production from typical offshore wind turbines, the capacity factor of the installation is commonly accepted to range between 32% and 43%.⁶²

TABLE II. Capital cost of an offshore wind energy farm.

Source	Capital cost
BWEA ⁵⁴	\$3450–\$5850/kW
Ernst and Young ⁴⁴	\$4500/kW
Krohn <i>et al.</i> ⁵⁵	\$2000–\$2700/kW
Heptonstall <i>et al.</i> ²	£2000/kW

TABLE III. Synthesized and supplemented operation expenditure estimations.

Source	Cost per installed MW	Cost per MW h	Year
Junginger ⁶¹	£27 000–£59 400	£8.8–£19.36	2005
DECC ⁶²	£24 165–£68 310	£7.9–£22.30	2005–2008
KPMG ⁶²	£80 865	£26.40	2007
Ernst & Young ⁴⁵	€38 000	€12.39	2007
Risø ⁶³	€49 005	€16	2008
Ernst & Young ⁴⁴	€45 000	€14.67	2009
Douglas Westwood ⁶³	£40 500–£67 500	£15.41–£21.23	2010
EWEA ⁵⁵	...	\$17	2009

TABLE IV. Breakdown of O&M cost of a typical offshore wind farm.

Categories	€/MW h	%
Maintenance	8.8	40.00
Administration and miscellaneous	5.5	25.00
Insurance	3.3	15.00
Rent	3.3	15.00
Electricity	1.1	5.00

B. Tidal energy costs

The predevelopment cost is assumed to be the same than in offshore wind energy farms since both are installations located in a marine environment.²⁹ After the energy farm is planned and all permissions are obtained, the next stage is the construction and start up of the plant. According to Refs. 65 and 66, the capital cost ranges between £1400/kW and £3000/kW. That is well in line with the latest available data sets presented in Refs. 3 (£3220/kW) and 67 (€5250/kW).

Furthermore, Refs. 68 and 69 analyse the distribution of the capital cost and it states that the device cost for horizontal axis tidal turbines is similar to offshore wind turbines, and it is about 50% of the capital cost. Whereas in Ref. 29, the cost of the turbine is considered to be around 30% (Table V). This difference demonstrates the existing uncertainties in tidal energy cost as being this technology in its infancy.

Ongoing maintenance costs include O&M costs, insurance costs, decommissioning costs, and others. They are estimated to be between \$191 000 and \$302 000 annually in Ref. 67. In the same line,³ considers an O&M cost between £121 000/yr and £315 000/yr. The average of \$232 250/yr will be used in this analysis. Apart from the different costs, the capacity factor is usually considered around 30% in the literature.^{29,65}

C. Wave energy costs

As well as in the case of tidal energy, preoperating cost is assumed to be the same than for offshore wind energy. As regards the capital cost, it refers to the amount needed for purchasing the Wave Energy Converters (WECs) and all the necessary elements for constructing the wave energy plant, as well as for their installation (Table VI). After analyzing and comparing different studies and sources,^{69–71} it can be inferred that the cost of the WECs lies between M€2.5 and 6 per installed MW. As for the mooring system, the most usual is CALM (Catenary Anchor Leg Mooring) and its cost is commonly calculated as 10%–20% the WECs cost.^{29,31,48} Finally, there is the electric installation, which includes the underwater and onshore cable, and the rest of the elements like the substation (Table IV).

With regard to the operation and maintenance cost, it is considered to be €30/MW h.⁷⁶ Besides, it is necessary to take into account that ten years after the set-up of the installation, the WECs have to be removed from the sea to carry out a complete revision, which is estimated to cost about 4.2% of the initial expenditures.⁷³ Finally, the decommissioning cost is usually considered around 0.5%–1% of the initial investment.⁸ The most frequent values for the capacity factor range from 20% to 50%.^{71,77,78}

TABLE V. Breakdown of capital costs.

Distribution of the capital cost	Percentage of total cost
Turbine (and structure)	30%–50%
Installation	16%–30%
Electrical installation	15%–20%

TABLE VI. Summary of initial costs.

Element	Cost	Source
WEC & installation	M€2.5–6.0/MW	54, 65, and 70
Mooring system	10% WECs cost €0.265/N	29, 48, 53, and 72 47 and 66
Mooring installation	€50 000/day	73
Underwater cable	10% CAPEX	31 and 49
Cable installation	€2.07/m	74
Electrical substation	≈M€1.2	75

III. LEVELIZED COST

The levelized cost of energy (*LCOE*) allows the comparison of energy generation technologies on the basis of weighted average costs. Among the different models to calculate *LCOE*, the discounting method is used in this work (Eq. (1)): the stream of (real) future costs and (electrical) outputs, identified as C_t and O_t in period t , are discounted back to a *PV* by applying the discount rate (r), which is often considered as a 10% for this kind of inversion.^{2,79–81} The discounting method is recommended for Ref. 29 and used in Refs. 42 and 65

$$LCOE = \frac{PV(Costs)}{PV(Output)} = \frac{\sum_{t=0}^n C_t / (1+r)^t}{\sum_{t=0}^n O_t / (1+r)^t}. \quad (1)$$

According to the values of *LCOE* obtained (Table VII), wave energy presents the highest cost, whereas offshore wind is the most economical and tidal power has a medium value but closer to offshore wind energy. These data are well in line with previous estimates found in the literature. For example, Ref. 2 states that the levelized cost of offshore wind energy ranges from £89/MW h to £193/MW h,⁸² considers a range between £140 and £250/MW h for tidal power, and⁸³ a levelized cost from €180/MW h to €490/MW h—greater scattering—for offshore energy farms.

The explanation of the differences between the *LCOE* of these three offshore renewables lies in the stage of development. Indeed, offshore wind energy is at commercial stage and there are already some farms around the world that are providing electric power to the grid, while wave energy technology is in an initial stage and most of the WECs are prototypes that have not been tested in large scale. When comparing the *LCOE* values obtained with those of other traditional electricity generation technologies (Table VIII), it is clear that currently producing a MW h by marine renewable energy is more expensive than by non-renewable technologies. Therefore, marine energy is only profitable at present if favored by subsidies, which are essential to achieve the desired technology development and percentage of participation in the energy mix. Recent studies^{84,85} concluded that an initial strike price of €220–300/MW h (2012 prices) for offshore wind energy, €390–420 for tidal stream energy, and €420–450 for wave energy is required to catalyze the industry and allow the necessary economies of scale a learning to be

TABLE VII. Levelized cost (€/MW h).

Technology	<i>LCOE</i> (€/MW h)
Offshore wind	165
Tidal	190
Wave	325

TABLE VIII. Levelized cost estimates for ten electricity generation y technologies.^{29,40}

Technology	<i>LCOE</i> (€/MW h)
PWR nuclear (pressurized water reactor)	49.96
CCGT (combined cycle gas turbine)	43.17
IGCC coal (integrated gasification combined cycle)	36.59
IGCC coal with CCS (carbon capture and storage)	55.76
Retrofit coal	44.40
Pulverized fuel	32.57
Pulverized fuel with CCS	50.79
CCGT with CCS	59.78

realized. These higher prices in comparison to traditional energy technology (€200/MW h in average⁸⁶) may lead to a negative response from the common users. In this context, raising environmental awareness of society would be fundamental.

Furthermore, over time it is expected that projects can reach economies of scale and then promoters could realize greater investments based upon tested technology. At this stage, it is likely that costs would be reduced and, consequently, investors could obtain profits and promoters could operate in market prices similar to other common renewable energies. There are not many studies examining the impact of learning curves on the profitability of marine energy park. Despite that, most of them agree on a learning rate of 85%–90% within the next 10 years.^{31,61,83,87,88} If this is considered even in a pessimistic scenario a reduction of the levelized cost of wave energy around 22% may be obtained.⁸⁹ Decisions about energetic planning are usually based on the generation cost of each source of energy, forgetting the other stages in energy production. There exists a new tendency that consists in including externalities—positive or negative consequence of an economic activity that is experienced by unrelated third parties—when calculating the energy cost. For example, it is estimated that carbon emissions in wave energy are 6 gCO₂/kW h,⁹⁰ whereas the average value for traditional energy resources is 250 gCO₂/kW h,⁹¹ a remarkable difference that should be included when calculating the energy cost. Besides the environmental externalities, there are others that should be also considered, such as the effect that renewable have in the supply security reducing the risk of supply cuts of conventional fuels, or the creation of new jobs and integration into the economic fabric. In this sense, oil and coal technologies for electricity production have associated high external costs (60 and 58.33€/MW h, respectively) in comparison with other non-renewable sources energies like natural gas (€15/MW h). The difference is still greater in the case of wind, which is associated with external cost of a mere €1.75/MW h. Pressurized water reactor (PWR) nuclear technology is a special case. The measured external costs are much lower than all fossil fuels despite being considered environmentally dangerous. This is due to the fact that nuclear power generation emits fewer greenhouse gases and the conventional methods used when calculating the externalities do not consider neither the inherit danger of nuclear technology—in the case of an accident occurs—nor the problem of the radioactive waste. There are some handicaps that make difficult to value them, e.g., the difficult to estimate the probability of occurrence of an accident or the uncertainties about the way that nuclear power plants store their waste. All in all, if the externalities^{92–95} were included in the calculation of the energy cost, the *LCOE* values for traditional energy and renewables would bring closer (Fig. 1). This would open up the range of possibilities of marine energy when the costs decreased through economies of scale and experiences.

IV. COMBINED ENERGY SYSTEMS

Recently, it has been suggested by some authors that resource diversity may be used to manage the variability of renewable power and lower the system integration costs of

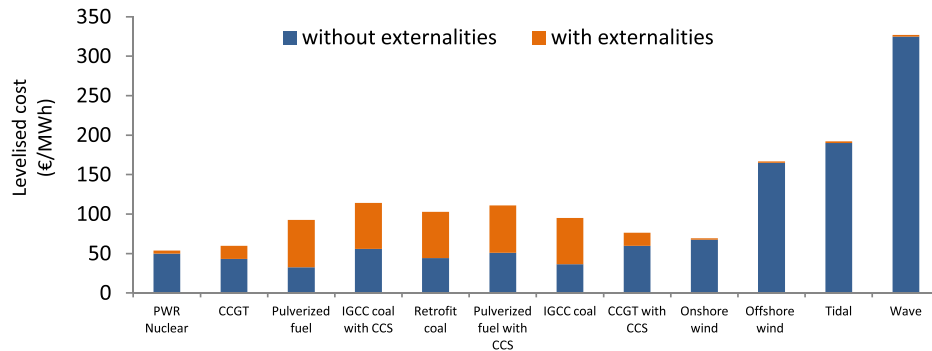


FIG. 1. Levelised cost (€/MWh) of different technologies including external costs.

renewables.⁹⁶ In this context, taking advantage of different marine resources in the same area has recently emerged as a viable option to enhance marine energy competitiveness.^{89,96–101} The *diversified or combined systems*^{98,102,103} allow the existing synergies between these renewables to be realized.^{101,104,105} First, a better use of the marine resource would be made^{105–107} by increasing the yield per unit of marine area. Moreover a reduced capital cost per MW installed might be achieved because of common elements like the electrical installation.^{108–110} In the same way, cost savings in maintenance tasks would be expected due to sharing strategies and other factors such as the shielding effect of WECs^{26,111–114} over the offshore wind farm,^{115–119} which increase the weather windows for O&M.^{120–122} In fact, some studies, e.g., Ref. 64, found cost reductions between 12% and 14% for both the capital and maintenance costs. Besides, it would be an opportunity to smooth the power output avoiding the inherent variability to renewable by taking advantage of the existed phase shifts between waves and winds or the greater predictability of tidal energy.^{40,98,102,103,109} Moreover, including novel technology such as wave energy converters and tidal turbines in installations at a commercial stage like offshore wind farms could shorten the time for achieving cost reduction through economies of scale for these novel technology components.¹²³

According to the degree of connectivity between the offshore wind turbines and WECs, there are different possibilities for a combined wave and wind array:¹⁰⁵ (i) co-located wind-wave energy; (ii) hybrid converters; and (iii) energy islands (Figure 2). Co-located systems^{98,124} are the simplest option at the present stage of development of wave and offshore wind technologies.^{125–127} These systems combine an offshore wind farm with a WEC array with independent foundation systems but sharing: the same marine area, grid connection, O&M equipment and personnel, port structures, etc.¹⁰⁰

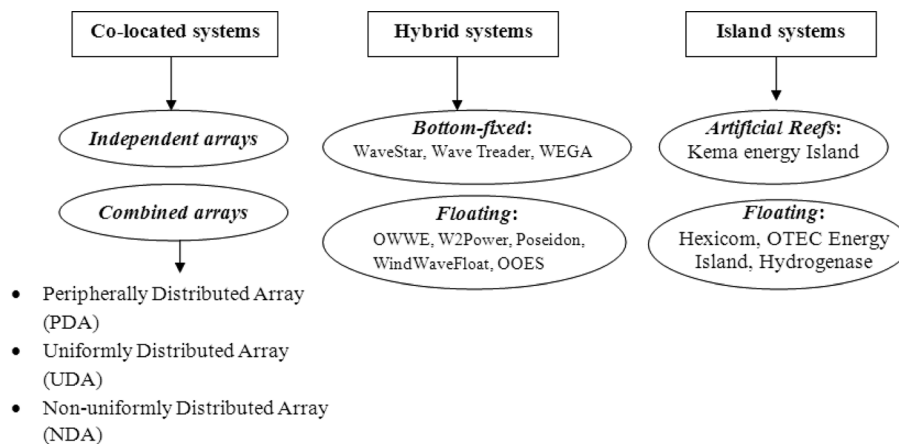


FIG. 2. Classification of combined wave-wind technologies.

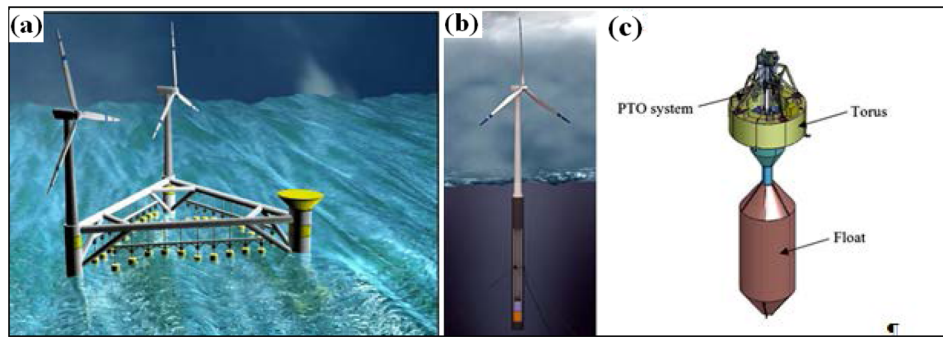


FIG. 3. (a) W²Power, (b) Hywind, and (c) Wavebob.

However, the future is about moving from standalone device to hybrid systems. The majority of offshore wind projects have been installed using monopile foundations, which is currently feasible for water depths of up to 35 m, but there are no technologies proven in water depths over 50 m.^{128,129} This limit increases the use-use conflicts between offshore energy installations and traditional sea functions, such as shipping or fishing, since they are commonly present near shore or in shallow depths, which are at the same time the suitable areas for low-cost offshore renewable farms. Therefore, Floating Offshore Wind Turbines (FOWTs) become an economically viable option in waters deeper than 50 m that could overcome the challenge to find space for offshore renewable projects that balances the need for low cost renewable energy against the needs of these other sea use functions. One of the major problems of FOWTs are the significant motions that they are subject to, which reduce the aerodynamic performance of the turbine, as well as induce structural loading not encountered with fixed foundations. One solution would be to use a WEC on the floating platform to absorb wave energy and reduce these turbulences.¹²⁵ There are different possibilities and prototypes, but most of them are still in development. Figure 3(a) corresponds with an FOWT that integrates two conventional offshore wind turbines on a triangular semi-submersible floater,¹³⁰ which has a greater efficiency (16% more) and a lower capital cost (31% less) and reduces their life cycle cost in 12%–26%. Figures 3(b) and 3(c) correspond with a combination of Hywind and two-body floating WEC,⁹⁹ which increases the wind power production around 6% with regard to the wind power production by one standalone wind turbine. Additionally, wave power is absorbed by the WECs, increasing 10%–15% the total power output.⁹⁹ In brief, wave energy is considered a high risk investment because the technology is unproven. Offshore wind is expensive but proven. Combining them defrays the costs in the riskier venture while adding to the potential return on investment from the proven technology.

In the case of tidal and offshore wind energy, there is less information about their combined systems. As in the case of wave and wind energy, tidal turbines can be combined with offshore wind turbines by using the same foundation or by linking the tidal turbine to the offshore wind turbine foundation instead of drilling/anchoring at another location. The simplest way to develop tidal stream energy is to borrow from horizontal axis wind turbines.

V. CONCLUSIONS

Renewable energies are crucial in combating against climate change and the dependence of fossil fuels. Marine energy has emerged as one of the alternatives with better prospects, thanks to the enormous resource available. However, this technology is often regarded as uneconomical. In this context, the first part of this study was dedicated to analysing marine energy economics and to compare the *LCOE* obtained with that of other conventional energy sources. Among the different alternatives, this paper focused on tidal, wave, and wind offshore power. Wave energy presents the highest costs (€325/MW h) on account of the initial stage of wave technology—prototypes that have not been tested a large scale. However, this novel renewable is expected to become more competitive through the practice and economies of scale—a

learning rate between 10% and 15% is expected in the following 10 years. To this end, it is important for governments to support its development with subsidies to attract investors. At the other extreme of renewable energy *LCOE* is offshore wind (€165/MW h), which has been at a commercial stage for more than a decade. However, it is still more expensive than traditional energy sources. For its part, tidal energy is closer to wind energy costs due to the technological similarities between tidal converters and wind turbines. Furthermore, a new tendency for the calculation of energy costs by including the so-called externalities was also considered in this study. This is a most realistic analysis which modifies the conclusions about renewable energy profitability substantially. In fact, the *LCOE* of traditional resources increases up to 70%, reducing the difference with marine energy by 50%. Conventional sources such as coal or fuel presented levelized costs greater than onshore wind energy and closer to offshore wind and tidal energy when externalities were considered. Therefore, these external costs are important to planning the energy use over the long term, and ignoring them would leave society exposed to the full range of side effects associated with fossil fuel usage. In a second part of this study, combined energy systems were proposed as a way of enhancing the competitiveness of marine energy by taking advantage of the mutual benefits of their combination and thus boosting the joint development of these renewables. It was concluded that combined farms provide an excellent opportunity to increase the power production from renewables in a cost-competitive way, to achieve a more sustainable use of the resource and to reduce supply uncertainties due to the variability inherent to the resource. Furthermore, it was stated that an important effort in the development of hybrid converters should be made to enhance the synergies between offshore wind and wave or tidal energy. Through them the available resource in water depths could be turned into exploitable increasing the suitable locations for deploying offshore farms, which would be important in the case of crowded areas.

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¹Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance).

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