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Assessing the impacts of technology improvements on the deployment of marine energy in Europe with an energy system perspective[☆]

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ABSTRACT

Marine energy could play a significant role in the long-term energy system in Europe, and substantial resources have been allocated to research and development in this field. The main objective of this paper is to assess how technology improvements affect the deployment of marine energy in the EU. To do so the linear optimization, technology-rich model JRC-EU-TIMES is used. A sensitivity analysis is performed, varying technology costs and conversion efficiency under two different carbon-emissions paths for Europe: a current policy initiative scenario and a scenario with long-term overall CO_2 emission reductions. We conclude that, within the range of technology improvements explored, wave energy does not become cost-competitive in the modelled horizon. For tidal energy, although costs are important in determining its deployment, conversion efficiency also plays a crucial role. Ensuring the cost-effectiveness of tidal power by 2030 requires efficiency improvements by 40% above current expectations or cost reductions by 50%. High carbon prices are also needed to improve the competitiveness of marine energy. Finally, our results indicate that investing 0.1–1.1 $BEuro_{2010}$ per year in R&D and innovation for the marine power industry could be cost-effective in the EU, if leading to cost reduction or efficiency improvements in the range explored.

1. Introduction

Climate change and energy policies are strongly interlinked: energy-related greenhouse gases (GHG) emissions in the EU27[2] accounted for almost 80% of the total in 2011 ([1] and [2]). Moreover, 40% of 2010 GHG emissions could be attributed to energy industries alone (electricity and refineries mainly) [3]. To address the challenge, the EU is defining a new set of energy policies that will provide additional impetus to the decarbonisation of the power system. In Refs. [4], the European Commission addresses energy and climate change policies in concert, with a view to reaching a reduction of GHG emissions of 40% in 2030 with respect to 1990 levels. It recognises that the rapid development of renewable energy sources poses new challenges to the energy system, notably the integration of decentralised and variable production in the electricity system. The Communication also highlights the need to ramp up research and development (R&D) and innovation investments beyond 2020, while at the same time setting priorities to accelerate cost reduction and market uptake of key low-carbon technologies.

The power sector has a critical role to play in ensuring meeting short and long-term energy and climate objectives in the EU. Marine energy encompasses a group of low-carbon technologies that could play a significant role in the transition of the power sector in Europe, contributing to energy security as well as to the reduction in emissions of greenhouse gases. As indicated in Refs. [5], the sector could also generate 40,000 jobs by 2035. It is thus important to better understand how key parameters affect investment decisions in marine technologies in an energy system perspective.

☆ The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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The main objective of this paper is therefore to assess, within a systematic and coherent energy system framework, how technology cost and conversion efficiency affect the competiveness and deployment of marine energy technologies in the EU. Such analysis is intended to provide insights on priorities for R&D and innovation to accelerate the market readiness of marine technologies. To the best of our knowledge, no comprehensive assessment has yet been carried out exploring the role of marine energy for the medium and long term decarbonisation of the European energy system within an energy system perspective, though country-level studies adopting similar approaches do exist, for instance, for the United Kingdom [6]. A similar approach was used to determine the potential contribution of wave energy in the US energy system by using the NREL Re-EDS model as shown in Refs. [7], whilst the EIA [8] considered the potential contribution of wave and tidal technologies at global level, albeit showing limited contributions up to 2040.

The remainder of the paper is organised as follows. Section 2 briefly summarises the state of play of marine energy in the EU28,[3] and highlights the expected developments in the medium and long term. Section 3 outlines the key elements of the JRC-EU-TIMES model, describes the policy assumptions underlying the two decarbonisation pathways explored in the paper, and summarises the sensitivity analyses performed. Section 4 presents the main results, focussing on the impacts of marine technologies improvements on its deployment. Section 5 concludes the paper.

2. Marine energy: state of play

Wave and tidal energy technologies are the two forms of marine energy expected to provide significant contribution to the EU energy system in the next few decades [9]. Several European countries, in particular those located on the Atlantic Arc of the continent, benefit from vast resources and have a significant potential for the development of marine energy technologies. The United Kingdom, for example, has an estimated tidal energy economic potential of 18TWh/year, while 50TWh/year could become economically viable for wave ([10] and [11]). According to Ocean Energy Europe, wave and tidal technologies could reach up to 100 GW of installed capacity by 2050, with over 260TWh delivered to the grid [12]. However, in the past few years, 2020 projections have been significantly reduced from 3 GW of expected capacity [13,14] to 240 MW [15], with forecasts for the UK alone reducing from 1.95 GW [16] to 140 MW [17].

Despite reduced targets, Europe maintains a leadership position in the development of the marine energy sector and many European countries are at the forefront of innovation [18]. The United Kingdom, Ireland, France and Norway present hubs for both technology development and market mechanisms to facilitate the deployment of full-scale prototypes and devices, such as MEAD in the UK,[4] and the newly launched Offshore Energy Renewable Energy plan in Ireland [19].

A number of technologies are moving from prototype demonstration towards pre-commercial pilot arrays in order to prove reliability, survivability and affordability; however the high costs associated with ocean energy and technological fragmentation are currently hindering both access to finance and market uptake. As shown in Fig. 1, tidal technologies appear closer to commercialisation presenting a greater design convergence, having proved operation generating significant electricity supplied to the grid and with a series of array demonstration projects in the pipeline. On the other hand, wave technologies have yet to show the same level of reliability, and the current lack of design consensus is delaying the engagement with the manufacturing and supply chain to provide substantial cost-reduction and favour their market uptake [7].

While the performance of marine energy technologies is expected to improve steadily over time, their market-readiness and competitiveness will depend on whether such improvements lead to sufficient cost reductions and/or efficiency gains. The currently observed trends show the development of the sector to be below initial expectations. According to a recent report by the Strategic Initiative for Ocean Energy [20], cost of energy predictions for marine energy indicate that tidal technology could be competitive with other renewable energy sources (RES) when a cumulative capacity of 2.5–5 GW is reached, whilst wave requires 5–10 GW to ensure competiveness. There is therefore the need for stepping up efforts in innovation, R&D and demonstration to accelerate learning and cost reduction, thus enabling marine energy to play its role in the medium and long-term decarbonisation of Europe. Consolidating Europe's position as the leading centre for innovation is therefore critical.

3. Methodology and approach

3.1. The JRC-EU-TIMES model

This section briefly describes the key characteristics of the JRC-EU-TIMES model, its main inputs and outputs. Special attention is devoted to how the modelling framework addresses marine energy technologies. An extensive description of the model can be found in Ref. [21].

The JRC-EU-TIMES model is a linear optimization, bottom-up, technology-rich model generated with the TIMES model generator from ETSAP (Energy Technology Systems Analysis Program), an implementing agreement of the International Energy Agency ([22], [23]). It represents the energy system of the EU28 plus Switzerland, Iceland and Norway (EU28+) from 2005 to 2050, with each country constituting one region of the model. Each year is divided in 12 time-slices that represent an average of day, night and peak demand for every season of the year.

The equilibrium is driven by the maximization (via linear programming) of welfare, defined as the discounted present value of the sum of producers and consumers surplus. The maximization is subject to several constraints, including: upper limits on the supply of primary resources; constraints governing technology deployment; balance constraints for energy and emissions; and the satisfaction of energy services demands in the modelled sectors of the economy (primary energy supply; electricity generation; industry; residential; commercial; agriculture; and transport).

The most relevant model outputs are: the annual stock and activity of energy supply and demand technologies for each region and period; the associated energy and material flows, including emissions to air and fuel consumption for each energy carrier; operation and maintenance costs, investment costs, energy and materials commodities prices.

The main drivers and exogenous inputs are summarised in Fig. 2.

3.1.1. Energy services and materials demand

The materials and energy demand projections for each country are differentiated by economic sector and end-use energy service, using as a start point historical 2005 data and macroeconomic projections from the GEM-E3 model [25] as detailed in Refs. [21], and in line with the values considered in the EU Energy Roadmap 2050 reference scenario [26]. From 2005 till 2050 the exogenous

[3] As in,[2] plus Croatia.

[4] https://www.gov.uk/innovation-funding-for-low-carbon-technologies-opportunities-for-bidders#the-marine-energy-array-demonstrator-mead-scheme.

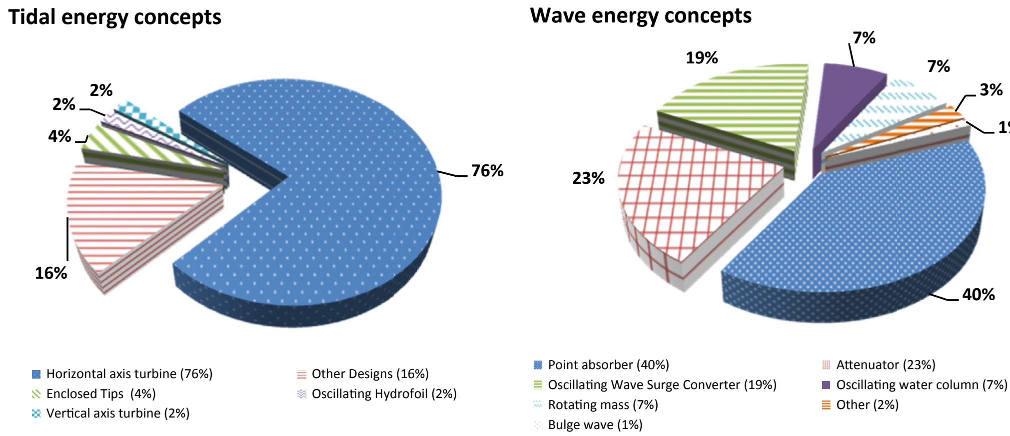


Fig. 1. Technology fragmentation in wave and tidal energy technology (Source: [18]).

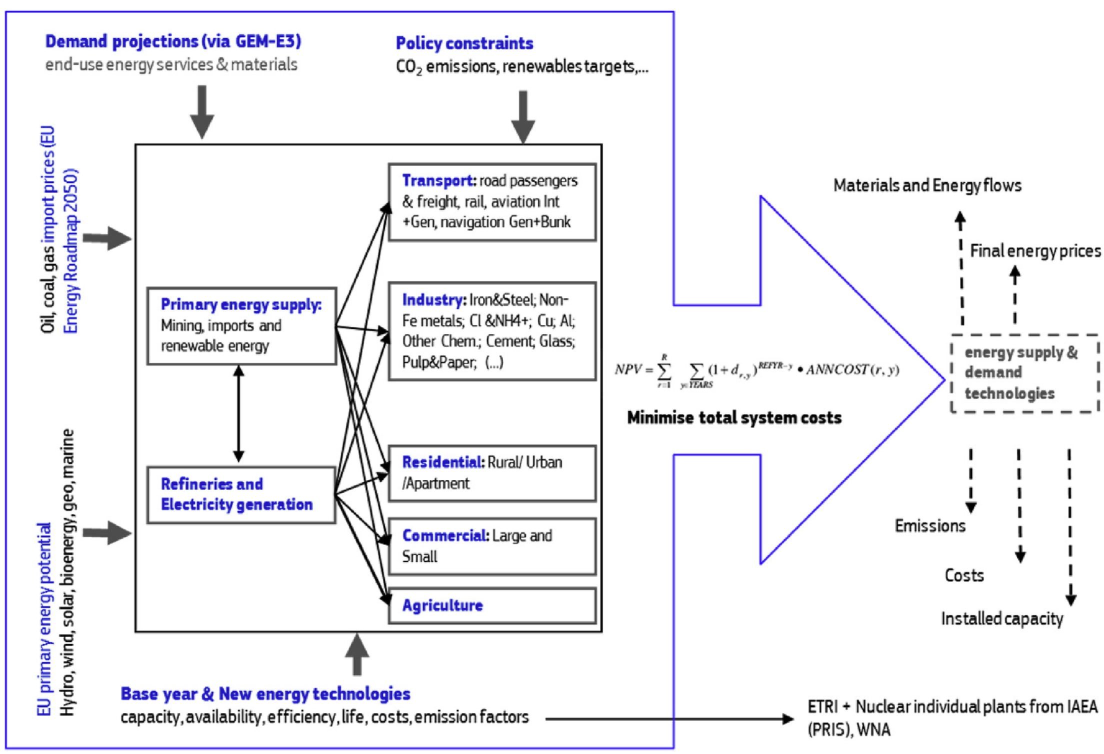


Fig. 2. The JRC-EU-TIMES model structure. (Source: [24]).

useful energy services demand grows 32% for agriculture, 56% for commercial buildings, 28% for other industry, 24% for passenger mobility and almost doubles (97%) for freight mobility. On the other hand, the exogenous useful energy services demand for residential buildings is 12% lower in 2050 than in 2005 due to the assumptions on improving the building stock's thermal characteristics.

3.1.2. Energy supply and demand

Country and sector-specific energy balances are derived from energy consumption data from Eurostat, determining the energy technology profiles for supply and demand technologies in the base year. Beyond the base year, new energy supply and demand technologies are compiled in an extensive database with detailed technical and economic characteristics.

The electricity production sector is divided in accordance to producer types and generating plant types. Main Activity Producers generate electricity and/or heat for sale to third parties, through the public grid, as their primary activity. Autoproducers generate electricity and/or heat, wholly or partly for their own use. Both types of producers may be privately or publicly owned. The types of plants are classified according to fuel input, technology group and whether the plant is electricity only or Combined Heat and Power (CHP). The categories of the plants follow closely the RES2020 [27] and Energy 2050 Roadmap [26] nomenclature. The most relevant source of the database for electricity generation technologies is [14], and the detailed figures, including technology costs, can be found in Ref. [21]. The technology-specific discount rates are aligned with the values considered in the PRIMES model as in Ref. [26]. The social discount rate is set at 5%.

3.1.3. Primary energy potentials and costs

The JRC-EU-TIMES model considers country-specific, current and future potentials and costs of primary energy (renewable and fossils), both imported and endogenous. Fossil primary energy import prices are exogenous, and aligned to the values considered in Ref. [26]. The extraction and conversion of primary energy resources are modelled explicitly. The prices of these commodities are endogenous, and depend on country-specific resource extraction and conversion costs. At this moment unconventional gas in Europe is not considered.

Bioenergy is also modelled explicitly. Moreover, in addition to production in the modelled regions, forestry residues can be imported. Bioenergy conversion pathways include first, second and third generation biorefineries. The direct use of ligno-cellulosic biomass is also envisaged.

Finally, a number of assumptions and sources are adopted to derive the renewable energy (RES) potentials in the EU28 for wind, solar, geothermal, marine and hydro (Table 1).

3.2. Marine energy in JRC-EU-TIMES and modelled scenarios

Two, aggregate, marine energy technologies are modelled explicitly: wave and tidal (without differentiating tidal stream and range). Their baseline techno-economic parameters are detailed in Table 2 and Table 3. These values have been elaborated based on a literature review and expert assumptions, and are aligned to the assumptions underlying [14]. The maximum electricity production of marine energy technologies in JRC-EU-TIMES is determined by their capacity/efficiency (or availability) factor. This aggregate factor represents both the hours of the year in which the renewable resources is available (e.g. waves or tides), and the necessary stops for maintenance [29]. For marine plants we consider in JRC-EU-TIMES a generic efficiency modelled as a capacity factor applicable to each country where marine energy is possible, as in Table 3, based on JRC own expert assessment. Fig. 3 depicts the maximum generated electricity per year at the regional level in 2050.

Predicting the evolution of techno-economic parameters for technologies is a challenging task. Learning curves are often proposed in the literature, as a means of estimating expected improvements of techno-economic parameters via learning-by-research and/or learning-by-doing (see, for instance [34], and [35] for energy technologies). Marine energy presents however specific challenges: the sector is still in its infancy, there is no active market yet, and the lack of convergence in the design, as well as the limited current installed capacity beyond the pilot level, make it difficult to estimate learning curves, either based on research or deployment or both. For this reasons, a learning rate of 12% was adopted, in accordance to bottom-up estimates provided by the Carbon Trust and SI Ocean report [36]. In addition, we did not model learning curves endogenously for several reasons: i) we perfom a partial study for only one group of energy technologies, whereas endogenous learning would have to apply to all technologies in an energy system model; ii) our model represents only EU, whereas technology learning is a global phenomenon, and iii) our model has perfect foresight and including endogenous learning curves, without additional assumptions on system inertia, could lead to over-investment in the early stages as this would lower their cost significantly in later periods.

Two different climate policy scenarios are considered, as summarised in Table 4. The Current Policy Initiatives scenario (CPI) includes the 20–20–20 policy targets ([30] [31] [32], and [33]). The CAP scenario is consistent with the medium and long-term CO_2 emissions reduction underlying [4], reaching a CO_2 reduction of 80% below 1990 values in 2050.

The two scenarios have the following assumptions in common: i) No consideration of the specific policy incentives to RES (e.g. feed-in tariffs, green certificates); ii) a maximum of 50% electricity can be generated from variable solar and wind, to account for concerns related to system adequacy and variable RES. Moreover, wind and solar PV cannot operate during the winter peak time slice; and iii) countries without nuclear power plants will not have these in the future (Austria, Portugal, Greece, Cyprus, Malta, Italy, Denmark and Croatia). Nuclear power plants in Germany and Belgium are not operating after 2020 and 2025 respectively.

For each scenario, we vary technology costs and capacity factor in turn. Technology costs are assumed to decrease in 5% step intervals with respect to the baseline levels from 2015 onwards (Table 2). The original evolution of the efficiency for both tidal and wave energy technologies implies an improvement of 5% every decade: for the sensitivity analysis, this rate of improvement is

Table 1
Overview of the technical RES potential considered in JRC-EU-TIMES.

RES	Methods	Main data sources	Assumed maximum possible technical potential capacity/activity for EU28
Wind onshore	Maximum activity and capacity restrictions disaggregated for different types of wind onshore technologies, considering different wind speed categories	[27] until 2020 followed by expert-based own assumptions	205 GW in 2020 and 283 GW in 2050
Wind offshore	Maximum activity and capacity restrictions disaggregated for different types of wind offshore technologies, considering different wind speed categories	[27] until 2020 followed by expert-based own assumptions	52 GW in 2020 and 158 GW in 2050
PV and CSP	Maximum activity and capacity restrictions disaggregated for different types of PV and for CSP	Adaptation from JRC-IET of [27]	115 GW and 1970 TWh in 2020 and 1288 GW in 2050 for PV; 9 GW in 2020 and 10 GW in 2050 for CSP
Geothermal electricity	Maximum capacity restriction in GW, aggregated for both EGS and hydrothermal with flash power plants	[27] until 2020 followed by expert-based own assumptions	1.6 GW in 2020 and 2.9 GW in 2050 for hot dry rock; 1.5 GW in 2020 and 1.9 GW in 2050 for dry steam & flash plants. 301 TWh generated in 2020 and 447 TWh in 2050
Marine	Maximum activity restriction in TWh, aggregated for both tidal and wave	[27] until 2020 followed by JRC-IET expert-based own assumptions	117 TWh in 2020 and 170 TWh in 2050
Hydro	Maximum capacity restriction in GW, disaggregated for run-of-river and lake plants	[28]	22 GW in 2020 and 40 GW in 2050 for run-of-river. 197 GW in 2020 and 2050 for lake. 449 TWh generated in 2020 and 462 TWh in 2050

Table 2
Economic characteristics of marine energy technologies (EUR2010/kW).

Year	Wave energy				Tidal energy			
	Specific investments costs (overnight)		Fixed operation and maintenance costs		Specific investments costs (overnight)		Fixed operation and maintenance costs	
	Ref.	Min.	Ref.	Min.	Ref.	Min	Ref.	Min
2020	4070	2035	76	38	3285	1643	62	31
2030	3350	1675	67	33	2960	1480	59	29
2040	3062	1531	57	28	2700	1350	50	25
2050	2200	1100	47	23	2200	1100	47	23

Ref.: cost assumptions in the baseline case.
Min.: cost assumptions in the most optimistic case (50% cost reduction).

Table 3
Technical characteristics of marine energy technologies.

Year	Capacity factor				Technical lifetime
	Wave energy		Tidal energy		
	Ref.	Maximum	Ref.	Maximum	
2020	0.22	0.35	0.22	0.45	30
2030	0.23	0.47	0.23	0.47	30
2040	0.24	0.50	0.24	0.47	30
2050	0.25	0.50	0.25	0.50	30

Ref.: capacity factor assumptions in the baseline case.
Min.: capacity factor assumptions in the most optimistic case (50% increase in capacity factor).

assumed to increase in 5% steps up to the maximum efficiency indicated in Table 3.

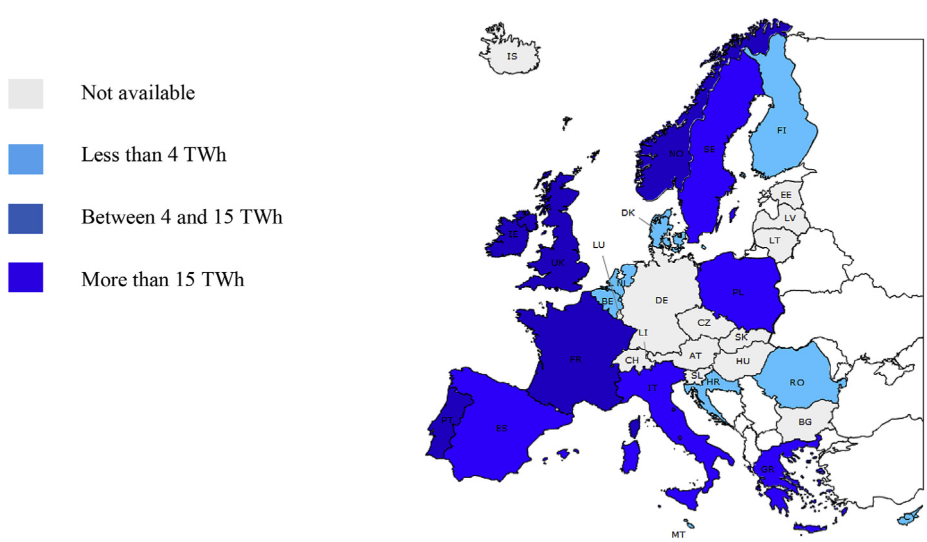
Within each policy scenario, we then compare the changes in the energy system brought about by the variations in either the technological costs or the capacity factor with respect to the baseline results of each of the two policy scenarios in turn.

Before the results we would like to point out that such long-term modelling approaches as of the JRC-EU-TIMES model inherently have significant uncertainties. These are not only depending on expectations on the future development of energy technologies, as well as their respective RES potentials, but also on macroeconomic evolution, willingness to invest in RES or CO_2 mitigation policies. Naturally, long-term modelling should not be used to forecast the future, rather to support energy planners and policy makers in envisioning possible alternatives with the best available information. In our model, the detailed assumptions on future techno-economic parameters for energy technologies in Europe are derived from expert opinion and/or available evidence and sectoral studies. These implicit assumptions are important drivers of the results – therefore providing further arguments for the sensitivity analysis approach adopted in this paper.

4. Results and discussion

New marine energy technologies do not become competitive by 2050 with the baseline cost and efficiency assumptions, unless a long-term mitigation cap is imposed (CAP scenario). Meeting the long-term CO_2 emission target calls in our model for the deployment of the full portfolio of low-carbon power technologies, including marine. In the CAP scenario in the EU28, 67.4 GW of new tidal energy capacity is installed in 2050, generating 155 TWh (Table 5). The total generated electricity is close to the maximum technical potential of 170 TWh.

In our model, with current estimates for techno-economic parameters, the CO_2 emission cap is met through two decarbonisation paths. Firstly, the electrification of the energy system. The share of electricity in final energy consumption increases from 20% in 2010



Marine energy is assumed not available in Iceland, due to its geographical characteristics.

Fig. 3. Maximum possible generated electricity from marine energy considering the maximum possible technical potential and generic capacity factor.

Table 4
Policy scenarios modelled in JRC-EU-TIMES.

Scenario name	20–20–20 targets[a]	Long term CO_2 cap	Other assumptions
Current Policies Initiatives (CPI)	Yes, ETS till 2050	No	Until 2025 the only new NPPs to be deployed in EU28 are the ones being built in FI and FR and under discussion in BG, CZ, SK, RO and UK.[b] After 2025 all plants under discussion can be deployed but no other.
Current Policies with CAP (CAP)	As CPI	80% less CO_2 emissions in 2050 than 1990 levels[c]	As in CPI

[a] The EU ETS target is assumed to continue until 2050. The national RES targets are implemented for 2020 and 2030 (the target for 2030 is the same as in 2020). There are no such targets after 2030. The minimum share of biofuels in transport is implemented from 2020 and maintained constant until 2050.
[b] This corresponds to the following plants: in Bulgaria (Belene-1, Belene-2); Czech Republic (Temelin-3, Temelin-4), Finland (Olkiluoto-3), France (Flamanville-3, Penly-3), Hungary (Paks-5, Paks-6), Romania (Cernavoda-3, Cernavoda-4), Slovakia (Mochovce-3, Mochovce-4) and UK (Hinkleypoint-C1, Hinkleypoint-C2, Sizewell-C1, Sizewell-C2).
[c] The 80% cap includes CO_2 emissions from international aviation and navigation.

to 35% in 2050 in the capped scenario, as opposed to 21% in the CPI scenario. Secondly, the large scale deployment of renewable energy sources electricity (RES-e) (Table 6). The share of RES-e increases from 25% in 2010 to 49% in 2030, and 66% in 2050. Electricity generated from solar and wind is the main source for the increase. In the CAP scenario, the share of wind and solar generated electricity increases from 6% in 2010 to 22% in 2030 and 49% in 2050. In comparison, the contribution of electricity generated from marine, which is considered more predictable than solar and wind, is substantially smaller, with only 3% of total generated electricity in 2050.

In the remainder of this section we explore the level of cost reduction of efficiency improvements that could bring about a large scale deployment of tidal energy, and assess the implication on the whole energy system. For this purpose, we define large scale deployment as a minimum of half of the maximum achievable potential, i.e. 59 TWh in 2020 and 85 TWh in 2050.

4.1. Deployment of marine energy technologies and implications at the EU level

At the outset, it is important to highlight that, in the current analysis, wave energy technologies never become competitive in the range of efficiency improvements or cost reductions explored. Tidal and wave technologies are perfect substitutes: they compete for the same marine resource, and provide the same output – low-carbon electricity – in the same countries. As in our scenarios, tidal energy is always cheaper than wave energy (with the exception of 2050, see Table 2), the potential for wave energy is not realised. The result is therefore driven by the underlying assumptions: an improved representation of the potentials for wave and tidal, taking into account the fact that the two are not always competing for the same marine energy nor are available in the same countries at the same level, could lead to different results. Baseline assumptions on the evolution over time of techno-economic parameters of other, low-carbon technologies also play a role in the relative competitiveness of wave energy, which is always more expensive than the marginal technology (tidal energy). With the modelling assumptions adopted in this research, wave energy would only become competitive for cost reductions higher than 60% of the reference technology costs in 2030 under a long term decarbonisation cap (CAP scenario), and assuming that the cost of tidal energy technologies does not improve beyond 50%. In the CPI scenario, the cost

Table 5
Tidal energy generated electricity (TWh) considering the baseline efficiency and costs.

	'2010	'2020	'2030	'2040	'2050
CPI	0.63	0.63	0.63	0.63	0.63
CAP	0.63	0.63	0.63	0.87	155.10

Table 6
Share of RES-e and solar& wind electricity (shown in brackets) in total electricity generation.

	2030	2050
CPI	42% (17%)	44% (23%)
CAP	49% (22%)	66% (49%)

reduction needed to make wave energy competitive in 2030 are even higher – 80% of the reference cost in that year.

The remainder of the paper will focus on tidal energy technologies. Fig. 4 shows the impact of changes from the baseline in investment and O&M costs and in the capacity factor on tidal energy generated electricity (Fig. 4)(a) and deployment (Fig. 4)(b) in 2030 (top) and 2050 (bottom) for the two scenarios.

Firstly, tidal energy technologies become cost-effective in the EU28 already in 2030 in the presence of a long term –80% CO_2 cap (CAP scenario) coupled with technological improvements. In the CAP scenario, tidal energy is deployed in 2030 starting from 15% efficiency improvements (CAPEFF) or cost reduction (CAPCOST). The deployment remains however limited: only cost reductions above 30% or efficiency improvements above 25% would lead to a total generated electricity of at least half the maximum potential. On the other hand, bringing forward the deployment of tidal energy to 2030 in the absence of a long-term CO_2 cap (CPI scenario) requires significant technological improvements (halving of the costs or at least 45% efficiency improvements) – but in all cases at levels well below 50% of the total generating potential.

Secondly, over the long-run (2050), tidal energy technologies would become competitive even in the absence of a long-term CO_2 cap for more modest technological improvements: with a mid-term CO_2 cap, cost reductions and efficiency improvements above 25% (CPICOST) and 10% (CPIEFF) would be sufficient. In all of these cases, though, generated electricity is well below half of the maximum potential of tidal energy – 0.9TWh in the CPI scenario. Only for cost reductions of at least 45% (CPI) and efficiency improvements of 15% (CPI) would tidal energy generate more than half of its technical potential.

Thirdly, in the absence of a long-term CO_2 cap (CPI), improving efficiency beyond 25% does not have significant *additional* impacts on the level of deployment in the long-term compared with the baseline with a mid-term CO_2 target (CPIEFF).

It is important to point out that, as the maximum capacity for Europe is defined on the activity rather than on the installed capacity, electricity generation can never exceed 170TWh in 2050. This level of activity is however achieved with very different installed capacities in the case of capacity factor improvements (Fig. 4)(b).

Changes in the deployment of marine energy impact the overall electricity generation mix, and this impact is stronger in 2030 than it is in 2050, in particular in the CAP scenario (Fig. 5). This is because

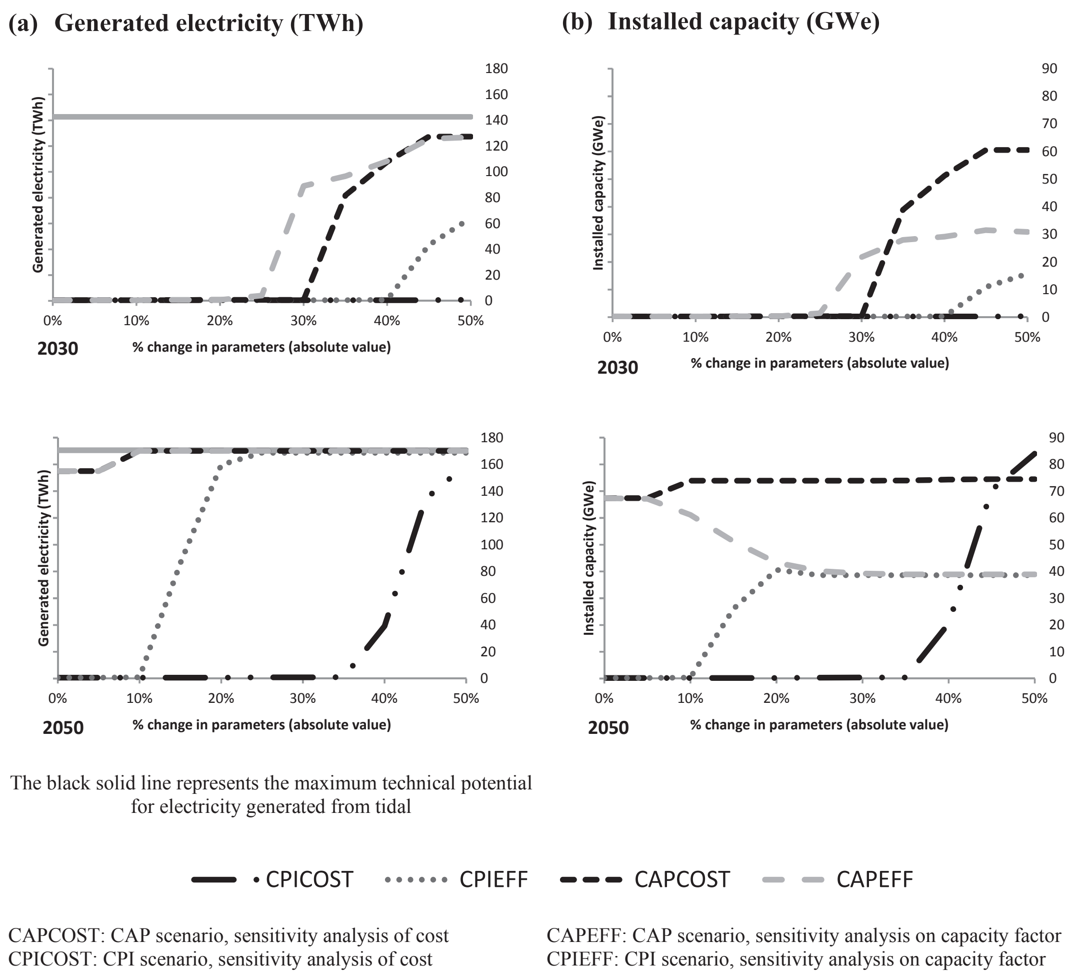


Fig. 4. Deployment of tidal energy for the two scenarios (CPI and CAP) for 2030 and 2050.

earlier deployment of tidal energy changes the merit order of electricity generation technologies and, therefore, substitutes both fossils and nuclear generation. In particular, the relative importance of thermal fossils (including coupled with carbon capture and storage) decreases with higher deployment of tidal energy, though the share of thermal fossils in total electricity production does not vary by more than 2% with respect to the baseline. While the deployment of renewable electricity generation (RES-e) technologies increases significantly, nuclear energy is hardly affected.

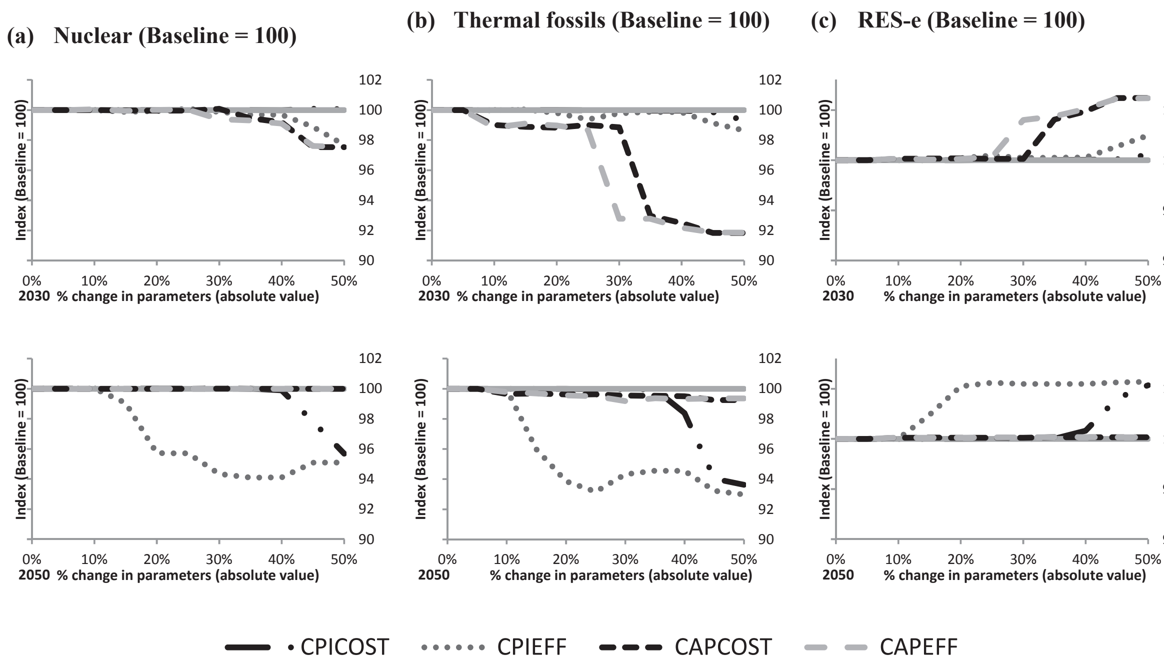
These changes in the electricity generation mix have, in turn, implications for the energy import dependency of the EU28, though the impact of the higher deployment of tidal energy remains marginal, i.e. a maximum 1% decrease of energy import dependency for EU28. On the other hand, the technological improvement of tidal energy has a significant effect on the share of solar and wind generated electricity when compared to the baseline, with a decrease in this share by up to 10% at EU level.

Overall, the impact of technological improvements on the cost of the energy system is small, as tidal energy technologies remain marginal even in the face of significant increases in their deployment. However, the direction of change is in line with expectations, with technological improvements leading to lower total energy system costs. In the long-term (2050), in the presence of the 80% CO_2 cap, reductions in the cost of tidal energy lead to an annual undiscounted saving for the whole of EU28 of 3–12 $BEuro_{2010}$ for a 10% and 50% cost reduction respectively. The impact of efficiency improvements is in the same range. When considering the effect over the whole time-horizon, with an overall discount rate of 5%, the savings in the total discounted system cost translate into an annual saving of 0.1–1.1 $BEuro_{2010}$. This amount can provide an indication of what could be invested in R&D leading to cost reductions or efficiency improvements of tidal energy technologies, while at the same time not implying additional costs to society, as higher investments in R&D would be compensated by corresponding savings in the total energy system costs.

Finally, it is interesting to note that, while investment costs increase with higher deployment of tidal stream and range, the additional fixed and variable costs decrease significantly, and more than compensate for the higher investment.

4.2. Deployment of tidal energy technologies — highlights of implications at member state level

The trends previously discussed for the EU28 are visible at country level. Fig. 6 depicts the deployment of tidal plants across EU28 member states for the years 2030 (left) and 2050 (right) for the CPI and CAP scenarios. The colours represent the fraction of the maximum technical potential that is deployed for a 50% improvement in efficiency. This is the most optimistic case for tidal deployment explored in the assessment: for most of the countries either there is no deployment without improvements of at least 35% in cost or efficiency, or the deployment patterns are very



CAPCOST: CAP scenario, sensitivity analysis of cost
CPICOST: CPI scenario, sensitivity analysis of cost
CAPEFF: CAP scenario, sensitivity analysis on capacity factor
CPIEFF: CPI scenario, sensitivity analysis on capacity factor

Fig. 5. Electricity generation mix.

similar or even identical to those observed in the 50% efficiency improvement case. We have also represented in the figure the relevance of tidal electricity, as percentage of national renewable electricity for the 20%, 35% and 50% cost reduction or efficiency increase.

Both the electricity generated from tidal energy and the fraction of deployed potential increase from 2030 to 2050, as tidal becomes cheaper and, for the case of CAP, as the CO_2 cap's stringency increases. The combination of years and CO_2 mitigation targets for the two mapped variables allows identifying for which countries new tidal plants are more cost-effective. This is the case of Cyprus, Malta, Italy, Denmark and The Netherlands, where the deployment of tidal energy becomes cost-effective (measured looking at the fraction of deployed potential in 2030 for CPI). These countries install tidal plants up to 94% of their maximum potential, generating up to 0.1 TWh, 3.4 TWh, 0.2 TWh, 2.4 TWh and 0.9 TWh respectively. The electricity generated corresponds to 1%, 6%, 1%, 9% and 1% of RES-e in these countries. In 2030 tidal electricity becomes cost-effective also in Ireland, with 77% of the maximum potential deployed corresponding to 8 TWh (24% of Irish RES electricity). The deployment in UK increases as well, up to 77% of the potential, i.e. 49 TWh (27% RES electricity). These values are for the 50% efficiency improvement, as in the medium term efficiency improvements have a higher effect than cost reductions.

New tidal plants become cost-effective up to the maximum potential in Greece, Portugal, Spain, France and Poland in 2030, but only in the CAP scenario and for cost reductions of at least 35% in Spain and Greece and at least 40% for Portugal and Poland. The share of tidal electricity in RES-e reaches 6–11%, depending on the country. Finally, for countries such as Lithuania, Sweden and Finland, tidal electricity is only cost-effective in 2050 while the long-term CAP makes tidal cost-competitive also in Croatia in 2050. However, the contribution of tidal in these countries is quite small, up to 6% of RES electricity.

In general terms, at country level, UK and Ireland seem to be the most sensitive member states to variations in cost and efficiency assumptions in the medium term. In 2050, all countries seem to respond in a similar manner to such variations, as the costs of plants are assumed to be lower by default due to the exogenous common assumption on technology learning.

It should be highlighted that the results at member-state level are highly dependent on the maximum technical potentials considered, for which there is substantial uncertainty. Several studies are underway to estimate tidal and wave potentials, in particular for the Atlantic Arc countries, including own work by the European Commission's Joint Research Centre. However, there is not yet harmonized data for the other member states with a maritime territory. In particular [37], mentions separated potential data for tidal energy for France, Germany, Ireland, the UK, the Netherlands, and Spain, which were not considered in this study. This more recent data could change the results substantially, especially for countries such as Poland or Lithuania, which do not have at the moment expertise on marine energy. Note however that, although the results of our assessment indicate that marine technologies are deployed to their maximum potential in these countries, the generated electricity is limited – less than 7TWh for Poland and 0.02 TWh for Lithuania, for example.

5. Conclusions

In this study we assessed the effects of technological improvement on marine power competitiveness, focussing on investment and O&M costs reduction and efficiency increases. We explored the cost-effectiveness of marine energy technologies until 2050 within the EU28 energy system. To do so, we used the JRC-EU-TIMES bottom-up linear optimisation model, assessing both the impacts of current expectations of marine energy technology evolution for tidal and wave plants, and more optimistic assumptions about the decrease in technology cost due to technology learning and efficiency improvements. We assessed these effects for two alternative

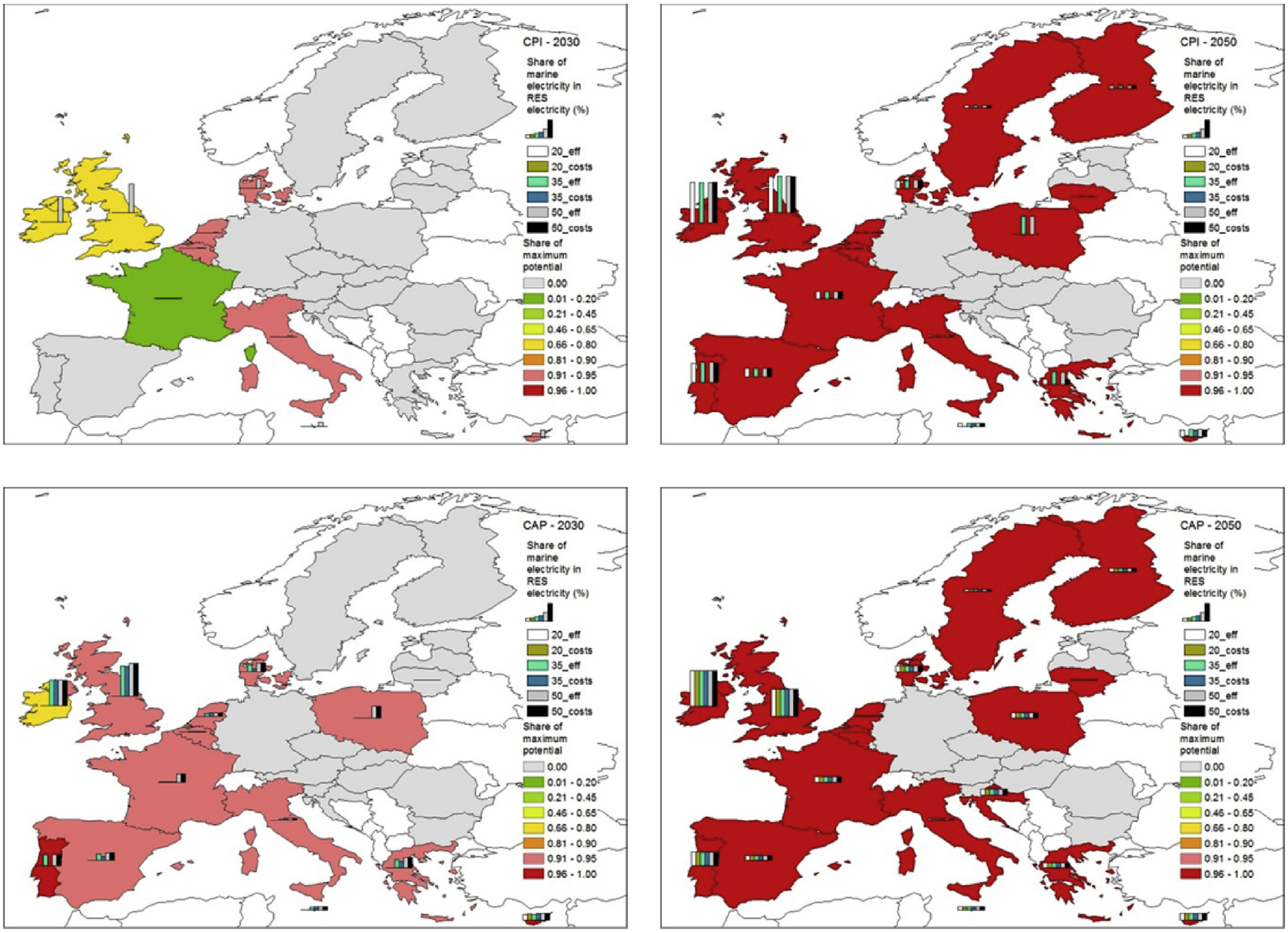


Fig. 6. National share of deployed maximum potential for 50% efficiency improvement (coloured background) and share of tidal generated electricity of RES-e (bar charts) for 20%, 35% and 50% variation in cost and efficiency for the years 2030 (left) and 2050 (right) for the scenarios CPI and CAP. White countries are out of the scope.

CO_2 mitigation policy scenarios.

Our analysis takes a simplified approach to R&D and innovation, since we assume that technological improvements on costs and on efficiencies can be decoupled. In reality, higher efficiencies or capacity factors could imply cost increases. Another limitation of our approach is the uncertainty associated with the maximum technological potential for marine power deployment in EU28+. At this stage, it is extremely difficult to obtain reliable data for all the member states and thus the effect of a higher (or smaller) technical potential on marine energy deployment should be further assessed. Further work with refined scenarios, including current developments in the sector, and updated country-specific potentials for wave and tidal energy will be undertaken to explore the robustness of the results. Finally, our analysis uses a simple cost-effective approach, whereas there are many other factors influencing marine technology deployment that we do not capture, such as job creation, environmental preferences or constraints, and competition with non-energy uses of the marine space. These aspects in reality influence the adoption of technology-specific policy incentives in several ways that are out of the scope of this paper. At a more general level, our modelling assumptions about the expected development of energy technologies in the future energy system of Europe, while based on expert opinion and, where available, sectoral studies, are subject to uncertainty. Nonetheless, this simplified approach allows us to provide insights on priority areas of the technology development for further research.

We conclude that, with the model assumptions applied in this research, the current expectations on marine techno-economic improvements and without considering specific technology policy incentives, it will be a major challenge to achieve the industry's targeted levels of deployment of 3.6 GW by 2020 and 100 GW by 2050 [13]. With the considered technology improvement expectations and from a purely cost-optimisation perspective, the total installed capacity in our model results in 2020 is 0.2 GW, while in 2050 installed capacity ranges from 0.2 GW to 74 GW depending on the CO_2 mitigation cap.

Marine energy technologies would still need to achieve technological improvements well above those currently expected in order to become competitive prior to 2050. For wave power technologies, we conclude that improvements in the costs and efficiency beyond 50% with respect to current expectations would be needed for the technology to be cost-effective in EU28. In our analysis, although we decreased the technology costs up to 50% and increased its capacity factor up to 50%, wave power remains uncompetitive. Only for cost reductions higher than 60% in a CAP scenario would wave energy become competitive, and only if the cost of tidal energy does not improve beyond 50% of expected costs in 2030. In the modelling framework used for this research, wave and tidal energy are substitutes, and this assumption is a key driver behind the result. This result is partly driven by the competition with tidal energy, which is cheaper, and partly by the modelling assumption that wave and tidal energy compete for the same energy potential. It is however also in line with the expectations of the industry, that indicates a minimum reduction of 80% in the cost of wave technologies for its market deployment [20]. Improved data on the maximum realisable potential for tidal and wave at the country level separately could help further investigate the competitiveness of wave energy.

In order to bring forward the deployment of tidal energy to 2030, substantial techno-economic improvements would be needed: with a mid-term CO_2 emission cap (CPI), tidal energy would be deployed in 2030 only with a 40% and higher improvement in the efficiency or at least 50% cost reductions. Our results point to the fact that improving technological efficiency is also key to ensure higher deployment of tidal energy, and it is more important than reducing costs. Therefore, focussing R&D and innovation efforts of improving efficiencies would seem to be more effective in bringing forward and accelerating the competitiveness of tidal energy. If an 80% overall long-term CO_2 cap (CAP) is in place, efficiency improvements or cost reduction higher than 30% and 25% with respect to those currently expected would not bring about significant *additional* deployment compared to reference. Similarly, in the long-term (2050), improving efficiency by more than 25% would only have minor impacts on the additional level of deployment of tidal energy in the CPI – whereas the saturation is reached much earlier for the CAP scenario (techno-economic improvements of 10% and above). While there is a need for further assessments under different conditions and/or techno-economic improvements, this sensitivity analysis does provide information that can help set R&D and innovation targets and priorities for the short and medium term.

In the presence of a medium and long-term CO_2 cap, the large-scale deployment of tidal technologies is useful in ensuring cost-effectiveness of the transition to a low carbon Europe. However, because of its smaller technical potential compared with other renewable technologies as wind, their additional deployment brings relatively small savings in terms of total EU28 energy system costs. Nonetheless, the results of our modelling exercise indicate that investing the equivalent of 0.1–1.1 $BEuro_{2010}$ per year in R&D and innovation for the marine power industry could be cost-effective over the long-term, provided it leads to cost reduction or efficiency improvements in the range explored. This is the range of annualised savings brought about in the total discounted system cost by an increasing deployment of tidal energy in Europe. The lower end of the spectrum is aligned with estimated financial resources mobilised in 2011 for research and investment on marine energy in Europe of $100MEuro_{2010}$. The higher end of the spectrum is, on the other hand, comparable to the investment in research and development for wind energy [18].

Accelerating the deployment of tidal stream and range technologies, while important as part of a low-carbon portfolio, has only limited impact on the energy system in terms of its affordability and security. More and earlier deployment of other low-carbon technologies is therefore needed, alongside policies to support the development of the marine energy industry. This should include electricity storage and smart grids, to enhance the stability of the electricity system and provide the flexibility needed with a high share of non-dispatchable electricity.

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References

[1] EEA, Trends and Projections in Europe 2013. Tracking Progress towards Europe's Climate and Energy Targets until 2020, EEA Report 10/2013, European Environment Agency, Copenhagen, 2013.
[2] EEA, Annual European Union Greenhouse Gas Inventory 1990-2011 and Inventory Report 2013. Submission to the UNFCCC Secretariat, EEA Technical Report 8/2013, European Environment Agency, Copenhagen, 2013.
[3] EEA, End-user GHG Emissions from Energy. Reallocation of Emissions from Energy Industries to End Users 2005-2010, EEA Technical Report 18/2012, European Environment Agency, Copenhagen, 2012.
[4] European Commission, A Policy Framework for Climate and Energy in the Period from 2020 to 2030. COM(2014) 15 Final. Communication from the Commission to the Council, the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, European Commission, Brussels, 2014, p. 18.
[5] European Commission, Blue Energy: Action Needed to Deliver on the Potential of Ocean Energy in European Seas and Oceans. COM(2014) 8 Final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions, European Commission, Brussels, 2014.
[6] H. Jeffrey, B. Jay, M. Winskel, Accelerating the development of marine energy: exploring the prospects, benefits and challenges, Technol. Forecast. Soc. Change 80 (2013) 1306–1316.
[7] M. Previsic, The Future Potential of Wave Power in the United States, United States Department of Energy – Wind & Power Technologies Program, 2012.
[8] U.S. Energy Information Administration, Annual Energy Outlook 2014 with Projections to 2040, U.S. Energy Information Administration, 2014.
[9] JRC-IET, Technology Map of the European Strategic Energy Technology Plan (SET-plan) Technology Descriptions, in: JRC Scientific and Technical Report, Institute for Energy and Transport of the Joint Research Centre - European Commission, 2013, p. 156.
[10] The Crown Estate, UK Wave and Tidal Key Resource Areas Project, 2012.
[11] G. Mork, S. Bartsow, M.T. Pontes, A. Kabuth, Assessing the global wave energy potential, in: OMAE2010 (ASME), 29th International Conference on Ocean, Offshore Mechanics, and Arctic Engineering, Shanghai, China, 2010.
[12] European Ocean Energy Association, Industry Vision Paper 2013, 2013.
[13] European Ocean Energy Association, Oceans of Energy. European Ocean Energy Roadmap 2010–2050, 2010. Brussels.
[14] JRC-IET, Technology Map of the European Strategic Energy Technology Plan (SET-plan) Technology Descriptions, JRC Scientific and Technical Reports, Institute for Energy and Transport of the Joint Research Centre – European Commission, 2011, p. 178.
[15] Bloomberg New Energy Finance, A Drop in the Ocean – Wave and Tidal Deployment to 2020, Marine Research Note, 2013.
[16] Renewable UK, Wave and Tidal Energy in the UK, State of the industry report 2011, 2011.
[17] Renewable UK, Wave and Tidal Energy in the UK, State of the industry report 2013, 2013.
[18] T.D. Corsatea, D. Magagna, Overview of European Innovation Activities in Marine Energy Technologies, JRC Scientific and policy reports, European Commission, Joint Research Centre, Luxembourg, 2013.
[19] E.a.N.R. Department of Communication, Offshore Renewable Energy Development Plan. A Framework for the Sustainable Development of Ireland's Offshore Renewable Energy Resource, 2014.
[20] D. Magagna, A. MacGillivray, H. Jeffrey, C. Hanmer, A. Raventos, A. Badcock-Broe, E. Tzimas, Wave and Tidal Energy Strategic Technology Agenda, SI Ocean, 2014.
[21] S. Simoes, W. Nijs, P. Ruiz, A. Sgobbi, D. Radu, P. Bolat, C. Thiel, S. Peteves, The JRC-eu-times Model. Assessing the Long-term Role of the SET Plan Energy Technologies, JRC Scientific and Policy Reports, Institute for Energy and Transport of the Joint Research Centre – European Commission, 2013, p. 376.
[22] R. Loulou, U. Remme, A. Kanudia, A. Lehtila, G. Goldstein, Documentation for the TIMES Model - Part I, Energy Technology Systems Analysis Programme (ETSAP), 2005.
[23] R. Loulou, U. Remme, A. Kanudia, A. Lehtila, G. Goldstein, Documentation for the TIMES Model - Part II, Energy Technology Systems Analysis Programme, 2005.
[24] S. Simoes, J. Cleto, P. Fortes, J. Seixas, G. Huppes, Cost of energy and environmental policy in Portuguese CO2 abatement—scenario analysis to 2020, Energy Policy 36 (2008) 3598–3611.
[25] P. Russ, J.-C. Ciscar, B. Saveyn, A. Soria, L. Szábó, T.V. Ierland, D.V. Regemorter, R. Virdis, Economic Assessment of Post-2012 Global Climate Policies – Analysis of Gas Greenhouse Gas Emission Reduction Scenarios with the POLES and GEM-e3 Models, JRC Policy Report, Institute for Prospective Technology

Studies of Joint Research Centre of the European Commission, 2009, p. 70.
[26] European Commission, Energy Roadmap 2050. COM(2011) 885 Final. Communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 2011. Brussels.
[27] RES2020 Project Consortium, The Pan European TIMES Model for RES2020. Model Description and Definitions of Scenarios, Intelligent Energy Europe Project no: EIE/06/170/SI2.442662, 2009, pp. 1–27.
[28] Eurelectric, Hydro in Europe: Powering Renewables, 2011.
[29] S. Simoes, J. Seixas, P. Fortes, G. Huppes, The savings of energy saving: interactions between energy supply and demand side policies – quantification for Portugal, Energy Effic. J. 7 (2014) 179–201.
[30] European Commission, Decision 406/2009/EC of the European Parliament and of the Council on the Effort of Member States to Reduce Their Greenhouse Gas Emissions to Meet the Community's Greenhouse Gas Emission Reduction Commitments up to 2020, 2009. Brussels.
[31] European Union, Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community, European Commission, Brussels, 2009.
[32] European Union, Directive 2009/28/EC of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources, 2009. Brussels.
[33] European Union, Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC, European Union, Brussels, 2012.
[34] C.O. Wene, Experience Curves for Energy Technology Policy, OECD/IEA, 2000.
[35] K. Schoots, F. Ferioli, G.J. Kramer, B.C.C. van der Zwaan, Learning curves for hydrogen production technology: an assessment of observed cost reductions, Int. J. Hydrogen Energy 33 (11) (2013) 2630–2645.
[36] S.I. Ocean, Ocean Energy: Cost of Energy and Cost Reduction Opportunities, 2013. Available at: http://siocean.eu/en/upload/docs/WP3/CoE%20report%203_2%20final.pdf.
[37] T.J. Hammons, Tidal Power in the UK and worldwide to Reduce greenhouse gas emissions, Int. J. Eng. Bus. Manag. 3 (2011) 16–28.