Technological Forecasting & Social Change 80 (2013) 1306–1316

Contents lists available at SciVerse ScienceDirect

Technological Forecasting & Social Change

Accelerating the development of marine energy: Exploring the prospects, benefits and challenges

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ARTICLE INFO

Article history:
Received 14 February 2011
Received in revised form 20 December 2011
Accepted 17 March 2012
Available online 24 April 2012

Keywords:
Marine energy
Ocean energy
Renewable energy
Accelerated development
Energy policy
Innovation

ABSTRACT

Energy system scenarios and modelling exercises may under-represent the learning potential of emerging technologies such as marine energy. The research described here was devised to represent this potential, and thereby explore the possible role of marine energy in future energy systems. The paper describes a scenario for the accelerated development of marine energy technology, and the incorporation of this scenario into wider scenarios of UK energy system decarbonisation from now to 2050. The scenarios suggest that the accelerated development of marine energy could contribute significantly to the decarbonisation of energy supply in the UK, especially over the medium to long term. However, this is predicated on sustained innovation, learning and cost reduction over time. Encouragingly, a number of recently established policy support programmes are now beginning to stimulate the development of marine energy in Scotland, the UK and beyond. As the paper discusses, building on these initiatives, and 'realising' the accelerated development of marine energy, present a number of challenges, and will increasingly require international efforts. However, the potential rewards are very substantial.

1. Introduction

The broad acceptance that greenhouse gas emissions such as carbon dioxide (CO_2) are responsible for climate change has made decarbonisation an energy policy priority in the UK and internationally (e.g. [1,2]). At the same time, energy security has also gained increasing attention in UK energy policy (e.g. [3]). With the UK and other countries setting ambitious targets for decarbonisation, and with rising concerns for security of supply there is now an urgent focus on energy system change, and, as part of this, finding ways to accelerate the development and deployment of secure sources of low carbon energy.

Responding to the climate change challenge, UK and Scottish governments have set out legally binding frameworks for the progressive decarbonisation of the UK economy from now to 2050, with ambitious interim targets for the decade to 2020 [2,4]. There are also highly ambitious Scottish, UK and European targets for renewable energy deployment [5–7]. In striving to meet such ambitious targets, there is a potentially important role for a number of emerging supply technologies, including marine energy.

In the short term, over the next decade, marine energy is expected to make some relatively minor contributions to energy system change in the UK and internationally. The British Wind Energy Association [8] has – perhaps rather ambitiously – suggested that 3 GW of marine capacity could be deployed in the UK by 2020 and at the European level, the European Ocean Energy Association has suggested that marine energy could reach 3.6 GW of installed capacity in the EU by 2020 [9].

However, over the medium to long term, there are indications that marine energy could make a much more significant contribution. The UK has a particular interest in marine energy, and the potential to sustain an internationally leading role in the

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0040-1625/$ – see front matter © 2012 Elsevier Inc. All rights reserved.
doi:10.1016/j.techfore.2012.03.004

marine energy industry. The Carbon Trust [10] estimated that around 15–20% of UK electricity demand could eventually be met by marine energy.

With a sense of increasing urgency for decarbonisation, there are strong interests in seeking to accelerate the pace of development of low carbon technologies such as marine energy. However, marine energy is still an emerging technology, and there is a need for substantial further research, development and demonstration efforts to allow for learning and cost reduction before it can make major contributions to energy supply.

This paper explores the opportunities and challenges associated with efforts to accelerate the development of marine energy technologies, and the potential impact of accelerated development on the decarbonisation of the UK energy system. A scenario of accelerated marine development is first devised, and then a series of wider scenarios of UK energy system change from now to 2050 are constructed which incorporate assumptions of the accelerated marine development. Consideration is also given to the wider institutional and policy challenges of accelerated marine technology development.

2. Overview of marine energy innovation

Marine Energy – also referred to as ocean energy – is defined here as wave and tidal current energy; tidal barrages and other ocean energy technologies are not considered in this paper. After the energy crisis of the 1970s there were a number of marine energy R&D programmes established internationally. In contrast to wind energy, these efforts were not sustained, and there was only very limited innovation in marine energy from the mid-1980s to the late-1990s. Over the last decade, however, drivers such as climate change and industrial development have renewed policy interest and public and private investment, prompting a resurgence in marine energy innovation. This has led, in turn, to the emergence of a variety of prototype device designs for both wave and tidal power. This resurgence was led by small and medium enterprises (SMEs) and university consortia. However, more recently, large power companies and large public-private programmes have become increasingly involved. For a more detailed overview of UK-based marine energy innovation, see Ref. [11].

Wave and tidal energy resources are quite distinct, and there are a number of design concepts in development for both. For wave energy, there is a wide variety of device concepts including oscillating water columns, overtopping devices, point absorbers, terminators, attenuators as well as flexible structures. Tidal current energy exhibits less design variety, with most prototype designs based on horizontal axis turbines, but vertical-axis rotors, reciprocating hydrofoils and Venturi-effect devices are also being developed. Two UK-based companies have recently installed full-scale marine devices: Pelamis Wave Power in Orkney, Scotland and Marine Current Turbines at Strangford Lough in Northern Ireland (Fig. 1).

At present, the UK has an internationally leading position in the emerging marine sector — reflecting a significant natural resource, research capacity, related skills in offshore engineering and a relatively strong funding and policy support framework. There has also been a growth in interest in the development of marine energy internationally, and now over a dozen countries have dedicated support policies for marine energy [12]. Even with this growing international interest, a significant proportion of all marine energy developer companies and support facilities is based in the UK. Internationally, the UK is seen as having an important leadership role by other countries entering the sector.

Research capacity in the UK has seen significant expansion recently from initiatives such as the SuperGen Marine programme, supported by the publicly-funded UK Engineering and Physical Sciences Research Council [11], and the involvement of organisations such as the UK Energy Technologies Institute, a major public-private initiative, as well as the Technology Strategy Board, a non-departmental government body. UK research groups also play a key role in a number of EU-funded marine energy consortia and research projects [11]. At the same time, many other countries' energy research programmes are now taking an active interest in marine technology, both in Europe and beyond, and future research and development efforts are likely to become increasingly international.

In addition, a number of marine energy test centres have been established in the UK and beyond, such as the full-scale test centres at the European Marine Energy Centre (EMEC) in Orkney, Scotland and Wave Hub in South West England, as well as drive-train test facilities at the National Renewable Energy Centre (NaREC) in England and others in continental Europe, such

Pelamis Wave Power Marine Current Turbines

Fig. 1. Full scale marine energy devices.
Sources: PWP, MCT.

as the Biscay Marine Energy Platform (bimep) in Spain [11]. Test centres are also being established in the US and Canada. This growing international interest has also seen the development of international standards for marine energy through the International Electrotechnical Commission Technical Committee 114 [13] and the development of a framework for international collaboration through the International Energy Agency's Ocean Energy Systems Implementing Agreement [14].

Despite this burgeoning UK and international interest, marine energy technology is still emerging, and device developers are working through a series of steps in a development chain. This chain starts with testing at model-scale in tank facilities, then progresses to developing hydrodynamic models to design larger-scale models for larger tanks or offshore, and using the results from these tests to verify the modelling before moving to full-scale prototype design. This development chain is time consuming, typically taking several years, and requires significant funding at each stage, with step-change increases in development costs at each stage of the chain.

Therefore, in addition to specific breakthroughs in devices and components, accelerated development of marine energy would also aim to speed up the development chain, so as to progress emerging technologies' market readiness more quickly. This may involve, for example, institutional and regulatory reforms such as the development of test and design protocols and procedures to reduce the reliance on device-specific tank testing at different scales. The USA and Ireland have acknowledged this issue and have adopted a stage-gate funding approach at the US Department of Energy's Water Power group and Sustainable Energy Authority of Ireland [12].

3. Accelerated development of marine energy

To develop a scenario of the accelerated development of marine energy from now to 2050, a review was first carried out of the present 'state of the art' in the marine industry, key research challenges and priorities – including potential incremental technical improvements and 'step-change' breakthroughs – established and recently introduced policy support mechanisms, and the wider context for marine development and deployment both in the UK and internationally.

3.1. Marine research challenges and priorities

Despite significant recent advances in the development of wave and tidal energy devices, there are still a number of substantial engineering, economic and institutional challenges to be overcome before they are considered commercially deployable at scale. The Marine scenarios in this paper focus more heavily on technological innovation challenges than the institutional and economic challenges. These challenges can be understood as a series of issues confronting efforts to accelerate the development of the sector; they include:

- *Design variety and consensus*: marine energy innovation activity is spread over a wide variety of concepts and components. Over the shorter term, the lack of design consensus in both wave and tidal current energy technology fields is likely to restrict the pace of development and learning. At the same time, there may be significant longer-term advantages from retaining design variety [15].
- *Parallel support for incremental and radical innovation*: closest-to-market large-scale wave and tidal current prototypes (of around 1 MW units) using more conventional designs and components receive the bulk of financial resources and innovation efforts across the sector as a whole — especially from the private sector. While the testing of these more mature prototype designs is vital to capture learning-by-experience, there is a parallel need to support innovation in more radical options which may enable step-change performance improvements and/or cost reductions over the longer term. Given the longer timescales for this more radical innovation, public funding has a continued leading role to play here.
- *Feedbacks between learning-by-doing and learning-by-research*: because of the early stage of marine energy technology development, there is currently only limited experience in real operating conditions. One aspect of accelerated development is the feeding-back of data and experience on prototype performance and operating experience into earlier phases of the innovation chain. In practice, the transfer of experience is likely to be limited by commercial competition.
- *Shared learning for generic technologies*: there are a number of 'generic' technologies and components which have application across the sector, such as foundations, moorings, marine operations and resource assessment. While these offer opportunities for shared/collaborative learning, the support and transfer of generic knowledge and components are limited by commercial competition [11].
- *Knowledge and technology transfer from other industries*: other industry sectors, such as, but not limited to, offshore engineering and offshore wind, offer potentially important opportunities for knowledge and technology transfer. Enabling this transfer depends in part on a better understanding of the 'adaption costs' – the costs of transferring components and methods to the marine context – and also, identifying and taking advantage of specific opportunities for collaboration with other industries or supply chain partners.

3.2. Marine energy support policy

A number of specific support mechanisms for marine energy development have recently been established by UK and Scottish Governments and intermediary organisations and agencies such as the Carbon Trust and Energy Technologies Institute. However, these sector-specific 'niche' support policies are often not represented in high-level scenarios of energy system change. These policy support measures are starting to catalyse deployment of prototype devices and demonstration arrays. The following outlines some of the key UK policy support mechanisms and strategic plans for marine energy (for a fuller review, see Ref. [11]).

3.2.1. Support for research, development, demonstration and deployment (RDD&D)

- The *Renewables Obligation* (RO) and *Renewables Obligation* (*Scotland*) (RO(S)), the main support mechanisms for renewable energy in the UK. Since 2008, the RO and RO(S) have provided enhanced support of wave and tidal power [17,18]:
  - UK RO 'banding' provides 2 Renewable Obligation Certificates (ROCs) per MWh to wave and tidal energy devices [17].
  - The RO (Scotland) banding provides 3 ROCs per MWh to tidal energy devices and 5 ROCs per MWh to wave energy devices [19].
- The UK Government's *Marine Renewable Deployment Fund* (25% capital grant for qualifying projects and an enhanced payment of 10 p/kWh in addition to the normal ROC payment).
- The UK *Marine Renewables Proving Fund* is a £22.5 million capital grant initiative from the Carbon Trust (with funding from the UK Government's Department for Energy and Climate Change, DECC).
- The Scottish Ministers' *Wave and Tidal Energy Support (WATES) Scheme* (40% capital grant for qualifying projects and an enhanced payment of 10 p/kWh in addition to the ROC payment).
- The Scottish Government's *Wave and Tidal Energy: Research, Development and Demonstration Support fund* (*WATERS*) introduced in 2010 and replaces the previous WATES Scheme (£12 million from Scottish Government as capital and operational support for the deployment of wave and tidal energy devices (up to 25–50% depending on the nature of the R&D and the size of the company) plus an additional £3 million in European funding to support projects in the Highlands and Islands).
- The *Scottish Marine Supply Obligation* was an obligation placed on energy suppliers to provide a percentage of generation from marine renewables, towards a proposed 75 MW ceiling. This support mechanism was discontinued in 2009 when the Scottish Government introduced the enhanced RO banding for marine energy.
- The UK's Technology Strategy Board (TSB) is a non-departmental government body that aims to drive UK innovation. The TSB has started a research and development funding programme for innovative, collaborative wave and tidal stream energy technologies with two funding calls in 2010.
- The UK's Energy Technologies Institute (ETI) is a partnership between the UK government and international companies that aims to bridge the gap between laboratory-proven technologies and full-scale commercial systems. Marine energy is one of the ETI's priority areas and they have funded a few marine energy research projects in 2009–2010.
- *SuperGen Marine* is a publicly funded research consortium with 5 core University partners in the UK with an aim "to increase knowledge and understanding of device-sea interactions of energy converters from model-scale in the laboratory to full size in the open sea" [20].
- Carbon Trust's *Marine Energy Accelerator* has invested £3.5 million in grant funding to accelerate progress in cost reduction of marine energy (wave and tidal stream energy) technologies.
- The *Saltire Prize* is a £10 million international innovation prize offered by the Scottish Government to accelerate the commercialisation of marine energy.

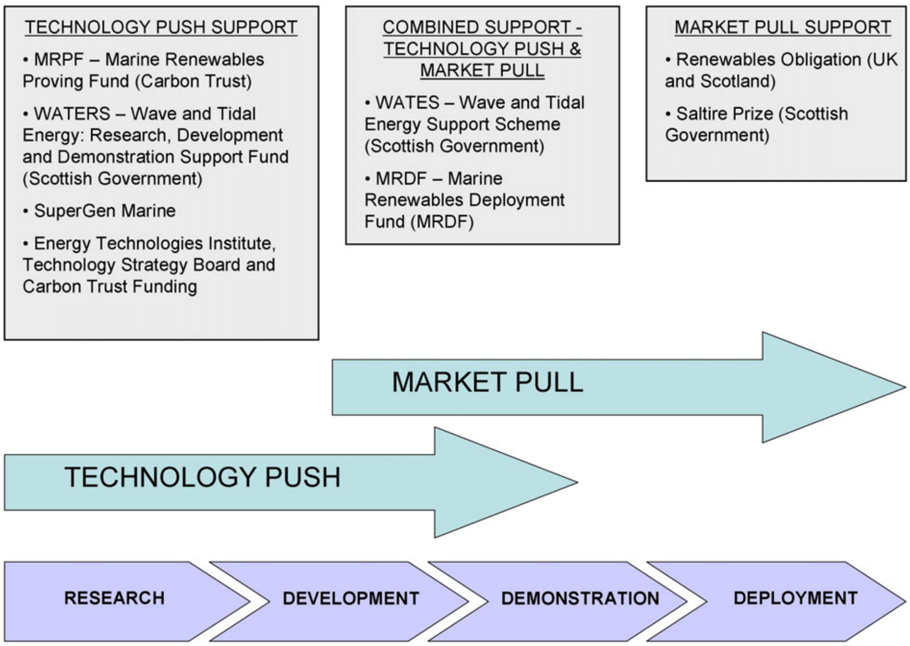

Fig. 2. UK marine energy support mechanisms.

The funding mechanisms in place for marine energy represent a range of both technology push and market pull support. Interestingly, there are also a few combined support mechanisms for marine energy such as WATES and MRDF in which there is both capital grant support (technology push) as well as enhanced market payments (market pull) (Fig. 2).

3.2.2. Strategic planning and roadmapping

- The UK Energy Research Centre's *Marine Energy Technology Roadmap* describes measures needed to support the deployment of 2 GW of marine capacity for the UK by 2020 [21].
- The UK Government's *Marine Action Plan* sets out a vision for the marine energy sector out to 2030, and actions needed from the public and private sector to facilitate the development and deployment over this period [22]. The Plan outlines a scenario of marine development out to 2030 (Fig. 3).
- The *Scottish Marine Energy Roadmap*, developed by the Scottish Government, provides an assessment of the current status and future potential of marine energy in Scotland, and recommends actions to ensure growth of the sector [23].
- The *Oceans of Energy: European Ocean Energy Roadmap 2010–2050* was developed by the EU's Ocean Energy Association and brings together the marine renewables industry in Europe to identify the development potential and barriers [9].

3.3. Policy experimentation and learning

The mixture of different policy support mechanisms listed above indicates a high level of policy commitment and support for marine energy in the UK, Scotland and beyond. At the same time, the sheer number of recent policy initiatives, and the number of revisions to existing policy mechanisms, suggest a process of experimentation and learning within policy and stakeholder communities about how best to support an emerging technology such as marine energy, in terms, for example of relative emphasis on technology push (through RD&D support) or market pull (through tariff support).

The high turnover of policy initiatives and revisions in this area can also be seen as reflecting the setting of highly ambitious overall policy targets for climate change mitigation and renewables deployment over the next decade (to 2020) and beyond (to 2050) [2,4], and also highly ambitious targets for renewable energy deployment at Scottish, UK and European levels [5–7].

For marine energy, a more particular driver of political expectations and interest, especially at Scottish and UK levels, is the opportunity for domestic industry creation by maintaining a position of international leadership. As a number of policy papers and statements testify, Scottish and UK politicians perceive an opportunity for industry building (and associated R&D and supply chain capacities) analogous to those associated with the fostering of wind energy in Denmark since the 1970s [24].

Under such high political and stakeholder expectations and a tendency for 'appraisal optimism' in assessing the potential for emerging technologies, especially over the shorter term [25], some recent policy initiatives to promote marine energy have reflected unrealistic expectations. For example, two recent policy initiatives – the Scottish Government's Marine Supply Obligation (MSO) and the UK Government's Marine Renewables Deployment Fund (MRDF) – both embedded high, and in retrospect rather unrealistic expectations of the short-term commercial status and deployability of marine energy.

In both cases, the failure of these 'market-pull' initiatives to promote technology deployment as expected led to further policy reforms. At the UK level, the Renewables Advisory Board's Marine Sub-Group was set up to consider the lack of take up of the MRDF. The subsequent policy response involved a rebalancing of the policy framework to place a greater emphasis on capital

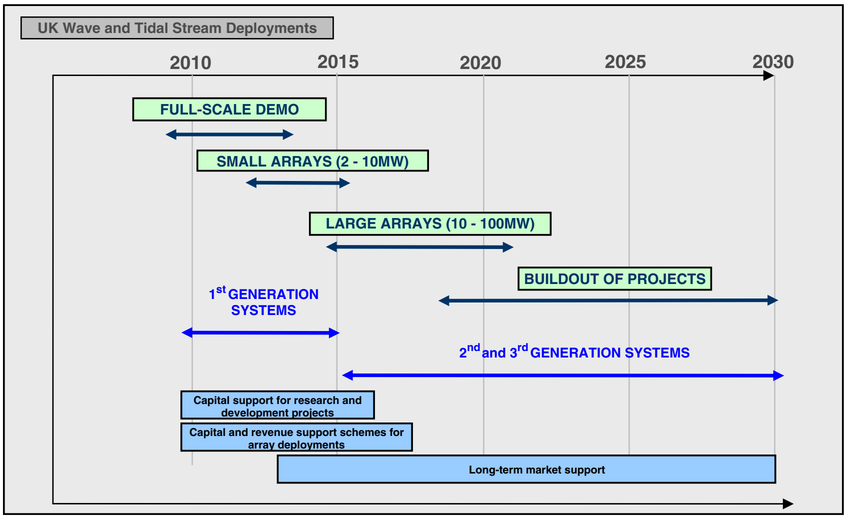

Fig. 3. UK Marine Energy Deployment Plan to 2030.
Source: Ref. [22].

support (technology-push) measures, with the introduction of the Marine Renewable Proving Fund (MRPF) by the Carbon Trust (and also the support of the Technology Strategy Board). The MRPF is aimed at enabling marine prototype projects to progress to the point at which they could qualify for the Marine Renewables Deployment Fund (MRDF), which in turn is intended to help the marine sector bridge the so-called 'valley-of death' [26] and reach the point at which it can take advantage of the nearer to market support offered by the Renewables Obligation. In Scotland, the MSO quota mechanism was replaced with the 'banding' of the RO(S) so as to provide significantly enhanced 'market niche' support for the first tranche of marine energy projects in Scotland.

Clearly, the high levels of policy and stakeholder expectations regarding marine energy present challenges as well as opportunities, Some of the policy initiatives associated with these expectations and interests have reflected unrealistic assumptions about the technology's level of maturity and readiness for deployment, and there has been a period of policy experimentation, learning and revision in efforts to effectively support the accelerated development of the marine energy sector. This process of policy learning is in some respects encouraging, and perhaps inevitable, in the construction of an overall system of support which combines together capital grants, market subsidy, innovation prizes and coordination actions.

4. Marine energy accelerated development scenarios

This section of the paper describes how a scenario of the accelerated development of marine energy technologies was devised here, as part of a wider research exercise which developed scenarios of accelerated development for several promising low carbon technologies. Different combinations of these technology acceleration scenarios were then assembled together at the system level, and scenarios of UK energy system development from now to 2050 were generated using an energy systems model, the UK Markal MED model. These UK energy system scenarios are constrained to follow an overall emissions trajectory consistent with either 60 or 80% CO_2 reductions by 2050 (relative to 1990 levels) (see Table 1).[1] (For more information on the scenarios see Ref. [27]).

4.1. Low Carbon baseline scenario

As part of the wider research work presented in this special issue, a Low Carbon scenario of UK energy system development was devised to follow a decarbonisation pathway from now to 2050, but without any assumptions of accelerated technology development. In the Low Carbon 80 scenario (with 80% CO_2 reduction by 2050), marine energy only plays a marginal role in electricity generation, with 5 GW deployed by 2050 (Fig. 4). Clearly, this scenario falls far short of UK and Scottish policy ambitions for marine energy deployment, and marine roadmaps produced by the marine development community. However, the Low Carbon scenario, as a least cost scenario, makes no attempt to represent the possible role of dedicated marine and wider renewables support policies, and private sector investment, in supporting technology acceleration.

4.2. Accelerated marine energy development scenario description

The progress of marine energy technology is highly uncertain, and like all scenarios, the scenario of accelerated marine development devised here is highly sensitive to assumptions regarding capital cost and technical performance. As such, the Marine scenario provides one *possible* development pathway, assuming high but plausible levels of technological progress.

Learning rates provide a measure of the cost reductions achieved with cumulative deployment of a given technology by presenting the percentage reduction in costs associated with each doubling in installed capacity of the technology in question [28]. While learning curves have been devised for a number of energy technologies, there are deep uncertainties around the application of learning curves to emerging technologies [29], and there is little robust historic cost data with which to devise learning rates for marine energy.

However, detailed 'bottom-up' engineering analysis carried out by the Carbon Trust has suggested that long term learning rates could be up to 15% for wave energy and 10% for tidal energy [10]. In describing the series of technological changes required

Table 1
Marine energy accelerated development scenarios.

Scenario name (% CO_2 emission reduction by 2050 shown in brackets)	Description
Low Carbon (60 and 80)	Low Carbon baseline scenario, with no technologies accelerated
Marine (60)	Marine energy acceleration scenario; no other technologies accelerated
Renew (80)	Four renewable energy technologies are accelerated in parallel (bioenergy, wind, marine and solar pv)
Acctech (80)	Seven supply technologies are accelerated in parallel (bioenergy, wind, marine, solar pv, nuclear power, carbon capture and storage and hydrogen and fuel cells)

[1] All of the single technology acceleration scenarios follow a CO_2 emission reduction pathway consistent with 60% reduction by 2050, while the aggregated scenarios follow a more ambitious pathway after 2020, consistent with an 80% decarbonisation ambition by 2050.

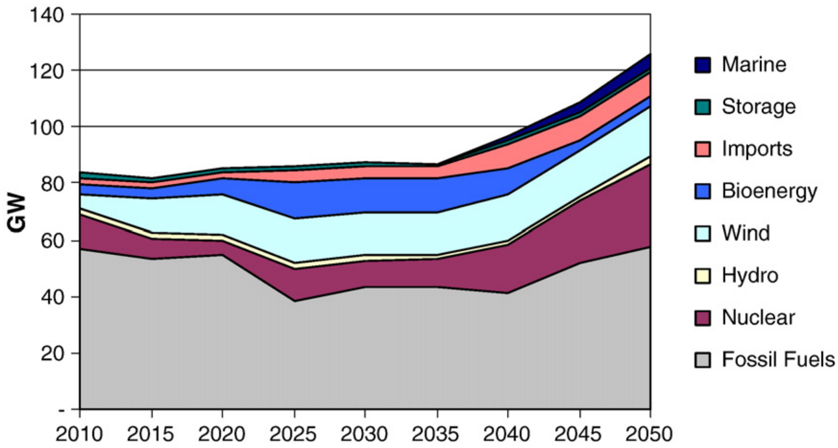

Fig. 4. Installed capacity in Low Carbon 80 scenario. Note: fossil fuels category consists of gas, oil, coal and coal CCS.

to sustain these rates, the Carbon Trust highlighted the importance of step-change improvements arising from radical shifts in designs and components, as well as more incremental learning [10].

The marine energy scenario devised here assumes that, over the short term, learning at the levels suggested by the Carbon Trust happens largely with protected niches created by UK support measures described in the previous section. Given the UK's leading position in marine energy development, domestic innovation support policies have the potential to influence the overall progression of the sector in the short to medium term. Using plausible niche deployment figures from 2010 to 2015, and learning rates and initial capital cost figures derived from the Carbon Trust [10], 'accelerated' learning curves for wave and tidal were produced for the present study.

The cost figures emerging from the short term niche learning scenario were then used as the assumed cost of marine technologies by 2015. After 2015, annual cost reduction rates were imposed, equivalent to a global learning rate of 10% for both wave and tidal current. These were projected forwards from 2015 to 2050. The impact of this accelerated development scenario on levels of deployment seen in UK energy system scenarios is described and discussed in the following section.

4.3. Accelerated development scenario results

In the *Marine* scenario, with marine energy accelerated alone (and all other technologies under non-accelerated assumptions), marine energy becomes a significant contributor to UK electricity generation, with first deployments seen shortly after 2010, and over 20 GW of marine technology installed by 2050 (Fig. 5). By 2050, marine energy supplies 67 TWh annually, almost 15% of all electricity generated in the UK. Clearly, this suggests that technology acceleration could make a major difference to the prospects for marine energy technology in the UK (Fig. 5).

The overall pattern in the Marine scenario is of a gradual increase in deployment up to 2030, and then a step-change increase after 2030. Initial technology deployment in the Marine scenario is predominantly from tidal current devices, but wave energy (which has a larger resource base in the UK) comes to dominate the marine energy contribution after 2030.

In *Renew* and *Acctech* scenarios, which have multiple energy supply technologies accelerated in parallel, marine energy makes a much greater contribution to the supply mix than in the *Low Carbon* non-accelerated equivalent scenario (Fig. 6). In the *Acctech* scenario, marine deployment undergoes rapid expansion after 2030, with over 20 GW of installed capacity achieved by 2050, similar to that seen in the *Marine* scenario. However, there is a slightly later pattern of marine deployment compared to the single technology *Marine* scenario. By 2050, any further deployment of marine technologies is restricted by assumed resource constraints.

Other system-level scenario variants were also generated to consider the possibility of particular technologies failing to commercialise or be deployed. In the *Acctech (no CCS)* scenario, carbon capture and storage technology – a technology which plays a major role in UK energy system decarbonisation after 2020 in the Low Carbon scenario – is assumed to be unavailable. As a result, marine technology deployment is significantly expanded in the 2030s – with almost 15 GW installed by 2035 – suggesting marine acceleration could offer a potentially important source of UK energy supply diversity in the context of technological uncertainty regarding CCS.

5. Discussion and implications

Achieving the high and sustained levels of innovation and learning assumed in the marine energy accelerated development scenario depends on creating and sustaining a highly effective marine energy innovation system. In practice, there are significant technical, economic and institutional challenges involved in providing this (Fig. 7).

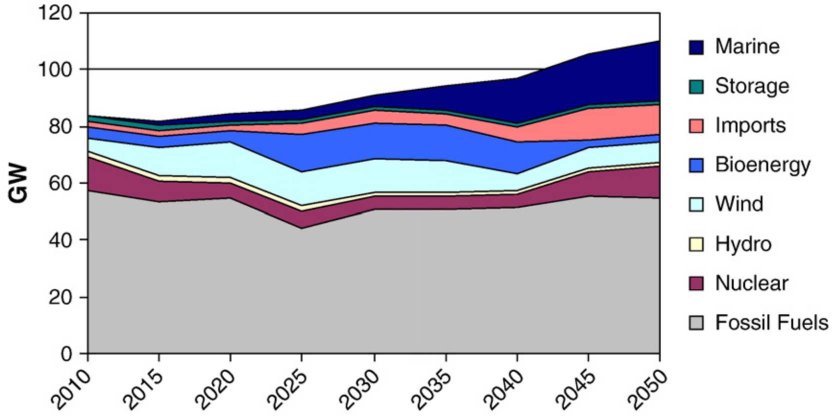

Fig. 5. Installed capacity in Marine scenario. Note: fossil fuels category consists of gas, oil, coal and coal CCS.

As discussed earlier, a combination of environmental, security and industrial policy concerns has driven a number of initiatives to support marine innovation over the past decade, in the UK and Scotland, and now increasingly internationally. These developments have enabled considerable early momentum to build up in the marine energy innovation system. At the same time, the experiences of policy experimentation, learning and reform suggest that achieving an appropriate policy support system is by no means straightforward. A coherent, adaptive approach to policy, across UK and international arenas, is needed to provide an appropriate combination of support mechanisms and encourage effective distribution of investments as the sector matures.

Additionally, the technology deployment levels envisaged in the UK energy system scenarios described above present their own challenges; clearly, these cannot be delivered by the existing supply chain infrastructure for marine energy in the UK, and will require major investment in specialised and dedicated installation equipment. Some of this investment is already underway — for example, some technology developers have already taken delivery of dedicated marine energy installation barges.

The UK Government is also starting to recognise the importance of supporting the development of infrastructure for offshore energy, as seen with the UK Government pledge of a £60 million investment in port facilities for offshore wind turbine manufacturers. The UK is strongly committed to offshore wind deployment over the next decade and beyond [20], and there are significant potential benefits and synergies here for marine energy. The development of offshore wind energy infrastructure over the next decade such as ports, installation vessels, under-sea cables and mooring systems, could provide significant secondary benefit for the less mature marine energy sector.

The level of deployment seen in the accelerated Marine scenario is broadly consistent with sector expectations and targets as portrayed in roadmaps. For example, the UKERC Marine Roadmap is based on a 2 GW deployment target for 2020, a level seen in the *Marine* single technology acceleration scenario. However, some other longer term ambitions for the sector appear to be predicated on more substantial cost reductions and/or technology performance improvements than those reflected in the accelerated Marine scenarios presented here.

For example, the scenarios described here impose an upper limit of installable marine capacity of around 21 GW, based on an estimate of the technically and economically exploitable marine energy resource in the UK [10]. However, improved resource characterisation and capture device technology may increase the exploitable resource. For example, it has been suggested that deeper water tidal current resources may be exploitable in the longer term and that the overall installable capacity of marine

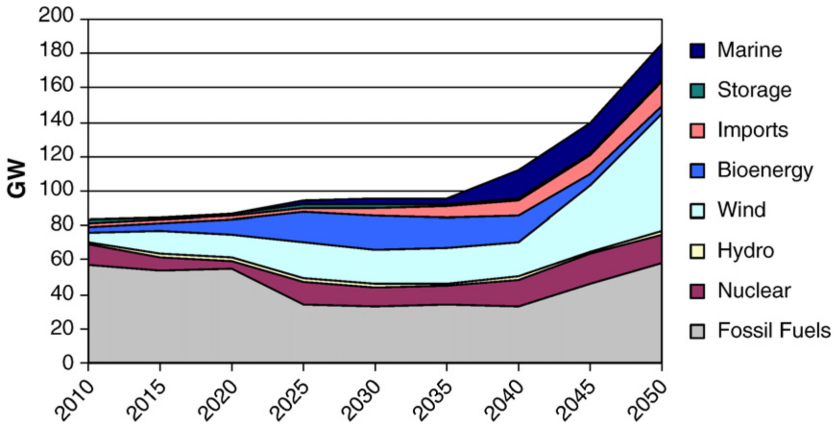

Fig. 6. Installed capacity in Acctech scenario. Note: fossil fuels category consists of gas, oil, coal and coal CCS.

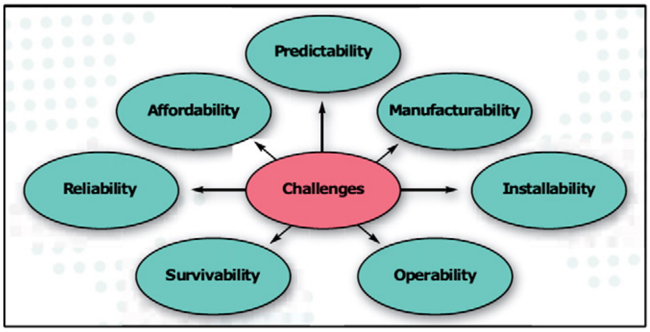

Fig. 7. Generic challenges involved in marine energy technology acceleration.
Source: Ref. [21].

may be closer to 30 GW rather than 20 GW [30]. Given the aggressive assumptions of technological improvement in the Marine scenario presented here, taking advantage of such additional capacity is likely to become an attractive longer term proposition — enabling continued increases in the marine energy capacity over time.

The scenario results imply that the marine energy industry and its enabling infrastructure mature after 2030, with much greater deployment capacity needed by this time. The split between wave and tidal energy – with tidal energy providing the largest initial contribution, but with wave energy dominating accelerated deployment after 2030 – is broadly consistent with the sectors' perception of the present-day maturity and future potential of the technologies. However, achieving the build rates seen in the scenarios presented here would also require wider developments such as site licensing and regulation, supply chains, and availability of major project financing.

In the *short term* (up to 2020) there are considerable deployment challenges, including planning and legislation, skills shortages and availability of installation vessels. Another challenge may be related to intellectual property protection [16]. Despite a level of headroom, grid reinforcement may also become a significant challenge during this period. This has been recognised by the UK Government in the Marine Energy Action Plan [22] which highlights the need for supply chain coordination; the Plan recommends that in addressing the challenges the marine sector exploits synergies with offshore wind regarding skills and supply chain. The Plan also recommends that the UK Government and devolved administrations give priority to providing an appropriate regulatory framework and preparing guidance for developers on the regulations and process of consenting and licensing.

Over the next decade, the cost reductions embedded in the Marine scenario are predicated on niche-learning, with progressive cost reduction and design consensus, as a small number of 'first generation' wave and tidal device designs become *de facto* 'industry standards'. In this scenario, there is also likely to be a consolidation of developer firms, as mergers and acquisitions bring together some small developers and allow hybrids of the best technologies to emerge and reduce costs. On a technical and engineering level, the UK Marine Energy Action Plan suggests that cost reductions should be achieved through a number of fundamental changes in areas such as the engineering design of devices, installation, operation and maintenance [22].

In the *medium term* (2020–2035) planning and regulatory barriers should by now be largely addressed. Despite the capacity built up in the preceding period, skills and infrastructure (such as ports and vessels) may be challenged by the steep ramp-up in build rate envisaged in this period. Given the remote nature of many of the marine resources, major grid reinforcements will be a significant challenge during this period with an increasing need for an offshore grid. In Scotland, the National Planning Framework has identified the need for a sub-sea grid to harness marine energy resources [31], and the Scottish Marine Roadmap explores strategies for grid infrastructure deployments [23].

Over the *longer* term (after 2035), it is implausible to describe the direction of marine energy innovation in any detail, but achieving the kinds of sustained learning that are embedded in the Marine scenario is likely to require the introduction of 'second generation' technologies capable of more efficient resource extraction and conversion. The introduction of more disruptive innovations embodying novel approaches to marine energy extraction is almost impossible to predict. However, while it is conceivable that some disruptive technologies could be introduced relatively quickly, they are more likely to mature in the medium and longer terms.

In the meantime, there is a need for support measures and policy strategies which allow more unconventional and disruptive technologies to be researched, developed and tested. Supporting RD&D on more radical and higher risk technologies is an important enabler of innovation over the longer term, and there is an important role here for publicly funded long term R&D programmes. Sustaining the learning assumed in the Marine scenario over the long term will also require the development of a much more internationalised marine energy industry – and associated innovation system – over the medium and longer terms.

Institutional and infrastructure barriers (such as supply chain constraints, planning constraints and grid reinforcement) may have been largely addressed in the long term. However, resources in deeper waters or more difficult locations may become exploitable by this time, presenting new technical or infrastructure challenges. In addition, competition for material and financial resources from other energy and non-energy sectors could impose longer term constraints on the sector.

6. Conclusions

There are high policy and stakeholder expectations about the potential of marine energy to provide secure low carbon energy in the UK and beyond. However, marine energy is an emerging technology with considerable uncertainty regarding the pace and direction of its development. While there is considerable scope for marine energy accelerated development over the medium and longer terms, securing technology acceleration is far from straightforward, and faces a number of technical, institutional and policy challenges.

In exploring the potential benefits and challenges of marine acceleration, this paper considered the present status of marine energy technology, and the range of policy support measures, including R&D programmes, capital support for testing and demonstration, market subsidies and infrastructure support, that are now being introduced to promote the development and deployment of the technology. Unlike many other areas of low-carbon innovation, the UK has a leading position in the emerging marine sector, with a significant resource and research base, related skills in offshore engineering, a significant proportion of all developer companies and support facilities, as well as a highly active policy support and roadmapping framework.

The policy and stakeholder expectations now associated with marine energy bring their own challenges. Under high political and stakeholder expectations, some earlier Scottish and UK policy initiatives imposed what proved to be overly ambitious short term goals with regard to the level of technology readiness in the sector, and this has led to a period of policy learning and reform so as to try to better align technical, economic and policy dynamics over time.

The paper also discussed a number of the challenges and tensions involved in long-term innovation system building. These include: a short-term interest in design consensus versus a longer term interest in design variety; a related need for parallel support for incremental innovation for more mature designs (where private sector investment can play a major role) and disruptive innovation of more radical concepts (where public investment is likely to be more important); the capturing and sharing of innovation in generic technologies; the strengthening of feedbacks between devices at different innovation stages; and the exploitation of opportunities for knowledge and technology transfer from other industries, including offshore engineering and especially, offshore wind. Common challenges – but also key enablers – here are commercial competition and intellectual property protection.

After reviewing these challenges and initiatives, the paper presented a scenario of accelerated marine energy progress, characterised by a major short term contribution of UK-supported niche learning, and then significantly internationalised learning and support thereafter. Under accelerated development assumptions, marine energy was seen to play an important role in scenarios of UK energy system decarbonisation from now to 2050. Marine energy supplies almost 15% of all electricity generated by 2050, and additional exploitable resource may allow for further increases to this figure.

Realising this scenario will require sustained support for its development over time. A coherent and adaptive approach to policy, in the UK and internationally, will be needed to encourage effective investments as the sector matures. In particular, there is a need to strike an effective balance, over time, between technology-push and market-pull mechanisms, to allow for design consensus, but at the same time avoiding 'lock-out' of breakthrough technologies which may allow for step-change improvements over the longer term. Put differently, marine acceleration requires a co-evolution of development and deployment, with learning-by-experience associated with early deployments, alongside learning-by-research to enable step changes in technology performance and cost. There are also considerable investment needs in infrastructure and support, including supply chains, installation capacity and electricity networks.

Despite the technical, economic, institutional and political challenges involved, the scenarios presented here suggest that marine energy acceleration can contribute significantly to UK energy system decarbonisation. They also suggests that acceleration may offer significant benefits for supply diversity (especially in a context of uncertainty facing other low carbon supply technologies) and also industry creation, given the UK's 'first mover' status. In sum, technology acceleration could make a major difference to the prospects for marine energy technology in the UK and beyond.

While the UK marine energy innovation system can be a major engine of progress over the shorter term, securing accelerated marine progress over the medium and longer terms will rely increasingly on the internationalisation of efforts and rewards. As well as gradually improving more mature devices, these global efforts, especially from public programmes, need to be directed toward the commercialisation of next generation technologies. Marine technology acceleration is a multi-faceted, multi-national challenge, but it promises significant benefit both for those involved in its development, and also wider society.

Acknowledgements

This research formed part of the programme of the UK Energy Research Centre and was supported by the UK Research Councils under Natural Environment Research Council award NE/C513169/1.

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