Marine current energy conversion: the dawn of a new era in electricity production

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Marine currents can carry large amounts of energy, largely driven by the tides, which are a consequence of the gravitational effects of the planetary motion of the Earth, the Moon and the Sun. Augmented flow velocities can be found where the underwater topography (bathymetry) in straits between islands and the mainland or in shallows around headlands plays a major role in enhancing the flow velocities, resulting in appreciable kinetic energy. At some of these sites where practical flows are more than 1 m s\(^{-1}\), marine current energy conversion is considered to be economically viable. This study describes the salient issues related to the exploitation of marine currents for electricity production, resource assessment, the conversion technologies and the status of leading projects in the field. This study also summarizes important issues related to site development and some of the approaches currently being undertaken to inform device and array development. This study concludes that, given the highlighted commitments to establish favourable regulatory and incentive regimes as well as the aspiration for energy independence and combating climate change, the progress to multi-megawatt arrays will be much faster than that achieved for wind energy development.

1. Introduction

The exploitation of natural and sustainable resources to meet our energy needs is paramount if societies are to reduce their ever-increasing emissions and pollution stemming from energy supplies derived from fossil fuels. Extensive activities around the globe are gearing up to reduce our reliance on such fuels by increasing the share...
of energy generated from renewable resources such as biomass, geothermal, ocean and wind energy. Major programmes in many countries are centred on the deployment of large-scale wind energy, be it onshore or offshore. If we consider the latter, the emphasis here is on the development of large-capacity turbines of more than 6 MW, and the installations on platforms geared to progress wind farm development further towards deeper water where the resource is larger. Such progress is likely to continue at a fast pace driven by resource availability, higher yields and available subsidies and the need to satisfy energy supply security and to meet international emission targets.

Moving further offshore, wind energy creates other opportunities to develop additional renewable resources to support the needs highlighted earlier. Our oceans, which cover more than two-thirds of the planet, present a vast amount of energy available in the form of waves, currents as well as temperature and salinity gradients. As examples, energy conversion from waves was considered by Clément et al. [1] and Falcão [2], whereas consideration of temperature and salinity gradients can be found in Damy & Marvaldi [3] and Brauns [4], respectively.

In this study, we limit the discussion to the consideration of marine currents or tidal stream energy conversion, which, in effect, exploits ocean resources and has some similarities in application to wind energy conversion. These similarities lie in the operating environment, weather variations, aspects of power capture and take-off, supply chain, and operation and maintenance to name but a few.

Exploitation of tides for the generation of electrical power is now a reality. Methods of extracting tidal energy fall into two categories: (i) barrages—water is impounded behind a barrier and then discharged in a controlled fashion through a conventional hydropower plant mounted within the barrier—this category includes barrages across tidal estuaries such as the 50 year old La Rance scheme [5] and the several discarded proposals [6] for a similar scheme on the River Severn; (ii) tidal current (stream) generators [7]—water flow is interrupted by some arrangements of hydrofoils to generate torque that drives a generator. The conversion device may be a ducted or non-ducted arrangement. Many of the current prototype designs have taken a similar configuration to wind turbines, comprising non-ducted, low-solidity, horizontal axis rotors. Such turbines are well suited to high sea flow conditions and can be configured as ‘fences’ or arrays of turbines sited across channels within appropriate and energetic sites in the oceans.

This study describes the salient issues related to the exploitation of marine currents for electricity production, highlighting aspects of resource assessment, conversion technologies and the status of leading projects in the field. The study also summarizes the important issues related to site development and some of the approaches currently being undertaken to inform device and array development.

2. Resource characteristics and assessment

Marine currents driven by the tides can carry large amounts of energy, especially around the UK’s shores. Other forms of marine currents stem from global oceanic circulation such as those encountered in the Florida Current in the Atlantic Ocean or the Kuroshio Current in the Pacific Ocean and those caused by variations in sea water density—such as in the Bosphorus Channel (Turkey). In many ocean areas, marine currents are considered to be too slow to exploit. However, augmented flow velocities can be found where the underwater topography (bathymetry) in straits between islands and the mainland and shallows around headlands plays a major role in enhancing the flow velocities, resulting in appreciable kinetic energy. Some of these sites, where practical flows are more than 1 m s\(^{-1}\), are considered to be economically viable for marine current energy extraction.

The tidal current resource is a consequence of the gravitational effects of the planetary motion of the Earth, the Moon and the Sun, which produce the tides that drive such currents. Hence, the resource is highly predictable, albeit variable in intensity. The consequence of this is that projects
that rely on such a resource offer an advantage over other renewable energy technologies—such as wind or wave energy—by providing quantifiable long-term energy yields that can be planned for and managed with the electrical grid.

In the UK, the resource was mapped around 2004 using support provided by the predecessor to the current Department of Energy and Climate Change in the form of an Atlas of UK Marine Renewable Energy Resources [8]. During this period, another more detailed study estimated that the UK has a total resource of around 90 TWh per annum, emphasizing that only about 20 per cent (18 TWh) could be exploited [9]. Other similar resource studies have been conducted for different countries, some of the results of which have been documented in the annual reports produced by Ocean Energy Systems [10]. It must be noted, however, that, in many of these estimates, there are considerable uncertainties in the quality of the data produced. However, such studies are constructive as, in the absence of detailed measurements at prospective sites, they set out an indicative assessment of the potential of the resource and the required market development and potential for its conversion technologies.

Resource assessment is critical for both estimating energy yield and assessing extreme design conditions over the expected lifetime of devices. In addition, a full understanding of site flow conditions is required so that energy extraction from the site can be quantified and any impacts of the energy extraction can be assessed [11]. This understanding can be gained through a combination of survey data and numerical modelling. For example, an ongoing project is being carried out at the University of Southampton for the Alderney Commission for Renewable Energy (ACRE) [12] in which the possible impact of large arrays of tidal turbines on local sandbanks is being examined. Figure 1 shows the impact on simulated flow velocity at a point where energy is extracted from a site (indicated by the rectangle on the inset map) close to Alderney, Channel Islands, UK. Tidal flows and energy extraction were simulated in TELEMAC-2D following the methodology outlined in Blunden & Bahaj [13], with validation provided by four acoustic Doppler current profiler deployments commissioned by ACRE. A snapshot of the spatial pattern of the impact of the array installation upon tidal current velocity magnitudes is given in figure 2. The plot in figure 2 shows differences in velocity at a particular stage of the tide, between when energy is extracted, compared with the natural state. In the analysis, only those differences larger than ±0.1 m s⁻¹ are included.

Figure 1. Complex effect of array upon both flow speed and flow direction: plotted on the hodograph are simulated flow velocity at a particular point in the domain (point indicated in inset map), in the natural state and with energy extraction (energy is extracted in the rectangular area on the inset map). (Online version in colour.)
Figure 2. Impact of array installation upon velocity magnitudes over a sandbank (dotted line) close to the Channel Islands. The visualization shows differences in flow speed at a particular stage of the tide, when energy is extracted (in the rectangular area), compared with the natural state. (Online version in colour.)

Site measurement surveys of flow conditions and bathymetry will need to be conducted in order to identify secondary effects such as turbulence, unsteady flows and wave/current interactions that may not be apparent from available coarse data or marine atlases. Careful planning of site array layouts is very important so that turbulence and wake effects generated by the devices and their support structures are addressed, and thus optimum energy yields can be achieved. As there are no marine current energy conversion (MCEC) arrays in existence today, there is a knowledge gap in the information needed for designs at a scale that can facilitate planning and installation of optimized configurations of arrays within a site. In order to capture this required information, it is anticipated that the first installations of arrays will be fully instrumented so that data at scale can be captured. This will provide the necessary data to allow the development and validation of array planning and design tools. In the absence of this, the industry is currently relying on knowledge generated through simulations and the studies of model turbines in circulating water channels [14,15]. The results from these can be used in conjunction with numerical simulations to appraise current array designs for future implementation at appropriate sites [16].

3. Technology development

(a) Energy conversion

Marine currents are akin to the wind energy resource, where the kinetic energy of the moving fluid can be extracted in a similar fashion using suitable turbine rotors. In most cases, wind energy conversion analysis and tools can be used to characterize the extraction of energy from marine
currents using, for example, a two- or three-bladed horizontal axis turbine. The power \( P_o (W) \) available from a marine current (in the absence of significant changes in depth or elevation) is given by

\[
P_o = \frac{1}{2} \varrho A v_o^3,
\]

where \( \varrho \) (kg m\(^{-3}\)) is the density of the fluid, \( A \) (m\(^2\)) is the cross-sectional area of the rotor under consideration and \( v_o \) (m s\(^{-1}\)) is the unperturbed speed of the fluid.

The \( P_o \) is proportional to the cube of the fluid velocity; hence, the energy yield is highly sensitive to variations in velocity. There are, however, some subtleties when considering MCEC, when compared with wind energy conversion. The power in the flow is proportional to the fluid density, which, for water, is about 800 times that of air. Hence, the power density (kW m\(^{-2}\)) for marine current energy converters will be appreciably higher than that produced by wind energy converters when considered at appropriately rated speeds for both technologies [17]. This also means that smaller and hence more manageable converters can be installed within the water layer where the bathymetry (water depth) is favourable for an optimal size of turbines to be deployed within the site. It must be noted that, unlike wind energy, in marine current energy the bathymetry places a constraint on the maximum size and hence the rated power of a marine energy converter or turbine.

(b) Conversion technology status

As indicated earlier, in most cases, the physical principles of marine current turbines have much in common with those developed for converting wind energy, but with the driving fluid being water rather than air. Most MCEC devices fall within the following types: horizontal axis turbines (similar to wind turbines), orthogonal flow turbines (axis can be vertical or horizontal), Venturi devices, shrouded variants of these aimed at concentrating the incident flow to a rotor and oscillating hydrofoils. The devices can be fixed rigidly to the seabed, mounted on a mooring or fixed to a moored platform.

Serious development of prototypes was initiated in the UK starting around the year 2000 through support from the government’s Technology Programme, run by the Department of Trade and Industry (DTI), and eventually passed to the new Department of Energy and Climate Change. This programme has now evolved and falls under the Technology Strategy Board’s (TSB) research and development-funding portfolio [18]. In 2010, the TSB set up the Marine Renewable Proving Fund (MRPF) with £60 M for both wave and tidal energy. The front runners benefiting from the early UK government programme are given in table 1, whereas table 2 shows global lead contenders.

(c) Routes to array deployment

(i) Site development

The data shown in table 1 represent the development of single devices, which in most cases was started by small-scale research and development companies. As indicated in table 1, some of the UK devices are at the prototype scale with device assessment being undertaken at test sites such as the European Marine Energy Centre (EMEC) in the Orkney Islands, UK [19]. Such assessments
Table 1. Lead devices in the UK and support provided by the UK government programmes. (1) This photograph is reproduced with the permission of Marine Current Turbines Ltd, a Siemens Business. (2) Image reproduced courtesy of Rotech Engineering Ltd. (3) Image reproduced courtesy of SMD Ltd. (4) Image reproduced courtesy of Pulse Tidal Ltd. (5) Artist impression of TGL turbine.

<table>
<thead>
<tr>
<th>Device</th>
<th>History</th>
<th>Initial Funding</th>
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</thead>
<tbody>
<tr>
<td>Lunar Energy</td>
<td>Founded 2001. Rotech tidal turbine 1 MW capacity. Tested at various scales in towing tanks (<a href="http://www.rotech.co.uk">www.rotech.co.uk</a>)</td>
<td>DTI: £2.25 M awarded £3.5 m in total. Not fulfilled owing to lack of match funding.</td>
</tr>
<tr>
<td>SMD Hydrovision</td>
<td>Founded 2005. Twin 500 kW counter-rotating generators. 2006 tested 10th scale at NAREC (<a href="http://www.smd.co.uk/products/renewables">www.smd.co.uk/products/renewables</a>)</td>
<td>DTI: £2678 M not fulfilled owing to lack of match funding.</td>
</tr>
<tr>
<td>Pulse</td>
<td>Founded 2007. First machine: pulse stream 100 kW installed in 2009. New design 1 MW, possible deployment in 20 m water (<a href="http://www.pulsetidal.com">www.pulsetidal.com</a>)</td>
<td>DTI: £878 k Npower Juice: £108 k European Union (FP7) grant: £3.2 M.</td>
</tr>
<tr>
<td>TGL</td>
<td>Founded 2005. Now subsidiary of Alstom 2012. First 0.5 MW machine tested for a few months at EMEC in 2010. Second 1 MW machine in development (<a href="http://www.tidalgeneration.co.uk">www.tidalgeneration.co.uk</a>)</td>
<td>Local development agency: approx. £75 k DTI/TSB: approximately £3.7 M, also undisclosed support from the UK’s Energy Technology Institute.</td>
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Under real conditions are devised to subject turbine design philosophies to various in situ testing regimes. Others have been undertaken independently by the companies themselves, such as the MCT’s SeaGen project at Strangford Lough, Northern Ireland, labelled as commercial prototypes, which already has over 2 years of operational experience [20].
Table 2. Depicts non-UK global leaders in marine energy conversion in terms of deployment. (1) Image reproduced courtesy of Ocean Renewable Power Co. (2) Image reproduced courtesy of Verdant Kris Unger/Verdant Power Inc. (3) Image reproduced with the permission of Kawasaki Heavy Industries, Ltd.

<table>
<thead>
<tr>
<th>Device History</th>
<th>Initial Funding</th>
</tr>
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<tbody>
<tr>
<td><strong>Ocean Renewable Power Company:</strong> founded 2004</td>
<td>total grants approx. £5 M</td>
</tr>
<tr>
<td>TidGEN 180 kW (<a href="http://www.orpc.co">www.orpc.co</a>)</td>
<td></td>
</tr>
<tr>
<td><strong>Verdant Power:</strong> founded 2001</td>
<td>unknown</td>
</tr>
<tr>
<td>1 MW pilot project with 30 turbines</td>
<td></td>
</tr>
<tr>
<td>(<a href="http://www.verdantpower.com">www.verdantpower.com</a>)</td>
<td></td>
</tr>
<tr>
<td><strong>Kawasaki Heavy Industries Ltd:</strong> founded 1878</td>
<td>unknown</td>
</tr>
<tr>
<td>tidal development from 2010? 1 MW turbine</td>
<td></td>
</tr>
<tr>
<td>planned EMEC berth 3 (<a href="http://www.khi.co.jp">www.khi.co.jp</a>)</td>
<td></td>
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</table>

Notwithstanding the important strides highlighted earlier and the successes in current technology development, experience in deployment and operation will now need to migrate to multiple devices of what can appropriately be termed first-generation technologies. However, array device deployment, although significant in the development of the technology, forms only one part of the complex interactions within a project scope that aims to develop a specific site. Site development tools are also needed to encompass many of the requirements of legislation; environmental analysis; stakeholder interaction; issues related to the technology deployment, commissioning, operation and maintenance; and proximity to ports and the grid. Some of these steps are summarized in figure 3.

**(ii) Support mechanisms**

Projects encompassing marine energy conversion deployment at array scale have been driven by fiscal instruments. In the UK, the government’s main market support mechanism is through the Renewables Obligation scheme [7,21]. Such incentives provide Renewables Obligation Certificates (ROCs) in the UK, whereas in other countries such as Canada a feed-in tariff (FiT)-type mechanism is promoted [22]. For the UK, enhanced support for marine energy projects (wave and tidal) will start to take effect on 1 April 2013 and was set at the five ROCs band with a 30 MW project capacity cap for deployment in the period leading up to 2017. This band is around two and half times the current support level given under the same scheme for offshore wind. In other countries such as Canada, the FiT is currently under discussion [22].
(iii) Project zones

The above-mentioned fiscal support mechanisms are aided by the creation of project zones aimed at developments that encompass multi-megawatt and multi-device arrays. Prime examples of these are (i) the Pentland Firth in the UK where such zones are championed by the Crown Estate (which owns the seabed around the UK shores) [7,23] and (ii) in Canada where the development of the Bay of Fundy project is driven by the Nova Scotia government [24]. The projects and deployment in the latter are currently under development. Initial indications estimate that single turbines will be deployed within the first ‘learning phase’ followed by arrays where cabling and power capacities allow. The planned development for a proposed 1000 MW of marine current arrays to be installed in the UK by 2020 is given in table 3. Table 3 also gives time lines and an indication of the project phases undertaken by site developers to fulfil the requirements for array-scale deployment.

(d) Informing array deployment

Although the projects mentioned earlier are extremely important for enhancing the status of technology development, currently no real data exist on large devices deployed in arrays in the sea. As mentioned earlier, project developers are currently relying on small-scale research and development routes to facilitate and inform designs of arrays [13,25,26]. Such knowledge will inform optimized site array designs, including consideration of wakes, the influences of turbulence and their impact on device spacing. This is crucial as well-planned and optimized sites will lead to projects that will result in the needed energy yields which are appropriate for a return on investment.

In addition, deployment in arrays can also be informed by simulation studies linked to laboratory-scale tests and analysis from single devices. Figure 3 shows such an approach that is structured to give an overarching connectivity between the various aspects encountered in the design and optimization of an array. Such analyses are used to predict the performance and energy yields including devices under yaw. To illustrate this approach, we consider an analysis

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**Figure 3.** Site development steps giving a brief indication of the scope of work to be undertaken by project developers.
Table 3. Planned development for a proposed 1000 MW of marine current installations by 2020 in the Pentland Firth, UK.

<table>
<thead>
<tr>
<th>project site and developer</th>
<th>capacity (MW)</th>
<th>project development and status</th>
</tr>
</thead>
</table>
| Inner Sound: MeyGen Ltd (Atlantis Resources Corporation Pte Ltd., International Power Marine Developments Ltd and Morgan Stanley Capital Group Incorporated) | 400           | -- projected capacity: 3891 MW devices, technology Atlantis and TGL  
--- phase 1a: 20 devices (20 MW) primarily for array demonstration purposes  
--- foundations: gravity-based or piled; type will be assessed and one will be used for both designs  
--- electrical connection: either buried beach or horizontal directional drilling through rock cable landings; substation and grid connection locations depend on environmental sensitivities and landfall  
--- phase 1b: 65 devices (+65 MW)  
--- phase 2: deploy the rest after experience from phase 1  
--- in 2012: 253 MW of grid capacity secured. Consent applications for phase 1 submitted. Transmission lines upgrade started  |
| Westray South: SSE Renewables Developments (UK) Ltd                                         | 200           | -- scoping report October 2011. Currently undertaking site investigation and project development planning activities, while in parallel commencing the Environmental Impact Assessment (EIA) and Navigational Risk Assessment (NRA) processes  
--- phase 1: 30–45 MW, possibly with different technologies. Consent and licence applications for phase 1 to be submitted by late 2013, with installation planned to begin 2016 (onshore infrastructure in late 2014)  
--- phase 2: is planned to be completed by 2020  
--- all the above is subject to consenting  |
**Table 3. (Continued.)**

<table>
<thead>
<tr>
<th>Project Site and Developer</th>
<th>Capacity (MW)</th>
<th>Project Development and Status</th>
</tr>
</thead>
</table>
| Cantick Head: Cantick Head Tidal Development Ltd (SSE Renewables Holdings (UK) Ltd & OpenHydro Site Development Ltd) | 200 | – Project briefing document published in April 2012  
– Currently undergoing project development and site investigation activities, as well as preparing for EIA and NRA processes  
– Phase 1: 30 MW from 2016/2017  
– Phase 2: increase to 200 MW by end of 2020  
– Technology: OpenHydro’s Open-Centre Turbine with a 16 or 20 m diameter  
– Fast turbine deployment using specialist barge to deploy both turbine and gravity base within 1 h  
– Possible offshore substation |
| Brough Ness: SeaGeneration Ltd (Marine Current Turbines Ltd) | 100 | – 66 devices over three phases over 4 years in an area of 4.3 km\(^2\) (99 MW)  
– Plan to (i) secure planning and environment consents for the site by 2015 and (ii) start construction in 2016  
– Phase 1 of deployment planned to start 2017 |
| Ness of Duncansby: Scottish Power Renewables UK Ltd | 100 | – Potential 95 MW capacity project  
– Plan for phase 1 at 30 MW capacity (no date given)  
– Technology Hammerfest Strom UK and Scottish Power Renewables (submerged 1 MW device)  
– The tidal resource and seabed surveys have been completed and the EIA has been submitted  
– No clear timeline or recent information available online |
Table 4. Turbine assumptions for the analysis.

<table>
<thead>
<tr>
<th>parameter</th>
<th>constraint</th>
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<tbody>
<tr>
<td>tidal current turbine diameter</td>
<td>10–20 m</td>
</tr>
<tr>
<td>tidal current turbine rated power</td>
<td>0.5–2.5 MW</td>
</tr>
<tr>
<td>turbine gear box and seals efficiency</td>
<td>constant 97% (considered optimistic)</td>
</tr>
<tr>
<td>generator speed</td>
<td>constant r.p.m.</td>
</tr>
<tr>
<td>generator efficiency</td>
<td>constant 95% (considered optimistic)</td>
</tr>
<tr>
<td>power and thrust coefficients</td>
<td>experiment curve fits</td>
</tr>
<tr>
<td>power control</td>
<td>blades pitch above rated speed</td>
</tr>
<tr>
<td>design tip speed ratio (TSR)</td>
<td>TSR = 4</td>
</tr>
<tr>
<td>velocity profile</td>
<td>uniform across turbine</td>
</tr>
</tbody>
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based on (i) results determined from towing tank experiments on a scale model of an 800 mm diameter horizontal axis tidal turbine [27] and (ii) site tidal data extracted from tidal diamonds data at both Portland Bill, UK (AC 2615 F) and at the Fall of Warness, Orkney Islands (AC 2250 E) using the analysis described in Blunden et al. [28]. The latter site is close to the EMEC test site in the Orkney Islands and represents what is assumed to be the expected result for turbines tested at the EMEC site. It must be noted that predictions at Portland Bill forecast a strong constant southerly flow component, making the flow conditions non-rectilinear (sometimes referred to incorrectly as ‘bi-directional’) in contrast to that at the EMEC site. Applying the assumptions summarized in table 4, the predicted turbine design conditions and power output are presented in figures 4 and 5.

**Figure 4**, for Portland Bill, represents an interconnected depiction of the predicted thrust on the turbine, the expected load factors and the resultant annual energy yields as a function of turbine diameter and rated power. The analysis has been performed for both (i) a non-yawing turbine with blades that pitch 180° when the tide changes direction and (ii) a yawing turbine that physically turns to maintain its direction perpendicular to the flow.

The predictions demonstrate a methodology for combining site conditions and the properties of turbines to give the expected energy yields from a specific site. This can be used to inform design approaches and for creating investment vehicles that can be combined with the fiscal support available to allow funds to flow for the exploitation of specified sites. In addition, decisions can be made about turbine design parameters that can exploit site conditions using either a conservative design and/or optimized revenue generation. For instance, it is possible to oversize a turbine for a particular site: if, because of depth restraints, a turbine with diameter of 16 m were chosen, then by increasing the rated power from 1.0 to 1.5 MW an extra 250 MWh would be produced (figure 4d) but the maximum load experienced would rise from 496 to 651 kN (figure 4b), and the load factor would be reduced from 0.31 to 0.23 MW (figure 4c). Obviously, these have implications for foundations and other system costs that will need to be put in place to allow for such a change and decisions would need to be made on whether such an approach is economically favourable.

The same analysis was conducted for the EMEC site, and the results are shown truncated in **figure 5**. Again, load factors and energy yields at this site are presented only for the case of a fixed orientation turbine. The results indicate that at this site, which is strongly rectilinear, a variable orientation turbine (which yaws to face the flow) is predicted to produce less than 1 per cent extra energy when compared with a fixed turbine. Hence, quantifying energy generation and income will inform whether such an approach is worthwhile and economic. In addition, the maximum energy yield for the simulated 16 m diameter turbine at the site is approximately 5 per cent less than that produced at Portland Bill owing to the EMEC site being less energetic.
Figure 4. Predictions for the turbine design speeds, thrusts and performance for both fixed orientation and yawing Portland Bill. (Online version in colour.)

Such analyses are invaluable for both linking device and site characteristics while keeping an eye on the energy yield and hence the economics of a project, and the investment necessary to exploit a site. Furthermore, array spatial planning will also have an influence on the achieved yield as device density and its resultant impedance within a specific site will also have an impact. As indicated in §2, resource assessment and the creation of a hydrodynamic model of the site will, in the absence of real site data, inform optimization of the spatial planning of arrays.
4. Conclusions

As highlighted in this study, the marine energy community has made major strides, achieving a lot in a very short period of time. Many seasoned observers believe that the present status of the technology is comparable to that of the emerging wind energy development in the 1980s. Therefore, in order to develop marine energy technology, deployment pathways will need to be found to reach the levels of acceptable multi-megawatt arrays. It is clear from projected deployment intentions that initial phases of deployments will be in sheltered sites. However, most of these sites will need the appropriate infrastructure such as proximity to the grid, ports and buy-in from stakeholders. The cost of such support is demonstrated within the Pentland Firth and Orkney Islands waters ‘round 1’ leases. In addition to £4 billion estimated cost of the 1.6 GW of potential capacity for different technologies (600 MW wave energy devices, 1000 MW tidal current devices), £1 billion will be required from public sources to develop and build new grid connections, harbours and other supporting infrastructure in the Orkney Islands and Caithness [23].

As highlighted within this study, plans for implementations at multi-megawatt array-scale development are forging ahead. In the UK and other countries such as Canada, there is also concerted support for the technology at ministerial and local government levels. Hence, given the highlighted commitments to establish favourable regulatory and incentive regimes as well as the aspiration for energy independence and combating climate change, the progress should be much faster than that achieved for wind energy development.

In the UK, however, there are further complications in relation to ROCs as, beyond 2017, the scheme will be replaced by a new government scheme enveloped within the Electricity Market Reform (EMR). Within the latter, there is a risk that marine energy (wave and tidal) will not get the same level of support as the current five ROCs. This is because the EMR is likely to be technology blind as it attempts to concentrate resources on technologies that maximize the amount of renewables/low carbon generation for the least cost. In particular, the need to achieve the European Union’s target of 15 per cent electricity from renewables by 2020 is anticipated to result in the expansion of offshore wind to up to 30 000 MW, compared with the few hundred megawatts likely to be achieved by the marine energy industry within that time frame [29]. Hence, a debate is now being generated to establish that marine energy technologies should be considered as having ‘other compelling arguments’ to warrant support at the higher levels [30]. Hence, there is a danger that leaving technology development entirely to market forces is likely to result in slower progress in large-scale deployment. Nevertheless, it is anticipated that the market incentives based on energy produced and the announced enhanced ROCs/FiT are likely to provide a viable industry in due course, provided that the technology is reliable at scale and within the operating environment.

**Figure 5.** Predictions of load factor and energy yield at EMEC for a fixed orientation turbine. (Online version in colour.)
Notwithstanding the above, judging by the various activities reported here and others around the world, and the consolidation provided by the entry to the market of large companies, electrical utilities and institutions such as the UK’s Crown Estate, there is further hope that the road to technology roll-out will not be long, hence the future for MCEC looks bright.

This work forms part of the Sustainable Energy Research Group’s studies in the ocean energy area. Full details of the Group’s programme can be found at www.energy.soton.ac.uk.

References