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The wave and tidal resource of Scotland

Simon P. Neill [a,*], Arne Vögler [b], Alice J. Goward-Brown [a], Susana Baston [c], Matthew J. Lewis [a], Philip A. Gillibrand [d], Simon Waldman [c], David K. Woolf [c]

[a] School of Ocean Sciences, Bangor University, Marine Centre Wales, Menai Bridge, UK
[b] University of the Highlands and Islands, Lews Castle College, Stornoway, Isle of Lewis, UK
[c] International Centre for Island Technology, Heriot-Watt University, Old Academy, Back Road, Stromness, Orkney, UK
[d] Environmental Research Institute, North Highland College, University of the Highlands and Islands, Thurso, UK

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ABSTRACT

As the marine renewable energy industry evolves, in parallel with an increase in the quantity of available data and improvements in validated numerical simulations, it is occasionally appropriate to re-assess the wave and tidal resource of a region. This is particularly true for Scotland - a leading nation that the international community monitors for developments in the marine renewable energy industry, and which has witnessed much progress in the sector over the last decade. With 7 leased wave and 17 leased tidal sites, Scotland is well poised to generate significant levels of electricity from its abundant natural marine resources. In this state-of-the-art review of Scotland's wave and tidal resource, we examine the theoretical and technical resource, and provide an overview of commercial progress. We also discuss issues that affect future development of the marine energy seascape in Scotland, applicable to other regions of the world, including the potential for developing lower energy sites, and grid connectivity.

1. Introduction

If there is one region of the world that is synonymous with marine renewable energy, it is Scotland. With 16,500 km of coastline and a population density of 64/km^2 [1], Scotland is in a strong position to make use of its abundant wave and tidal resources to generate meaningful levels of electricity [2]. Scotland sits on the western fringes of the northwest European continental shelf, exposed to waves propagating from the north Atlantic - the main source of its wave energy resource. In addition, numerous narrow channels, seaways and "firths" interspersed around Scotland lead to the formation of some of the strongest tidal currents in the world, with the Pentland Firth, in particular, often nicknamed the "Saudi Arabia of tidal power" [e.g. Ref. [3]]. As a consequence of Scotland's abundant natural marine resources, there has been much commercial progress of both wave and tidal energy projects in Scottish waters [e.g. Ref. [4]], and this progress has been facilitated by the formation, in 2003, of EMEC - the European Marine Energy Centre - in Orkney.

However, the exploitation of Scotland's wave and tidal energy resource from the most energetic sites is hindered by insufficient electrical grid infrastructure. The majority of promising wave power sites are situated around remote island locations, with the greatest tidal energy resource found in channels between islands, or between Scottish islands and the mainland. A strong grid infrastructure between these remote sparsely populated development sites and the main population centres further south is therefore imperative for the further development of projects and marine energy technology in the region.

This article, which reviews the marine energy resource of Scotland, is organised into three main sections - commercial progress (Section 2), tidal resource (Section 3), and wave resource (Section 4). Within each of the resource sections, sites that are currently leased for either tidal or wave energy development are briefly described, followed by a detailed regional assessment of the resource (i.e. encompassing locations that have not necessarily been leased), based on existing studies and new interpretations of numerical models combined with observations. Finally, the article concludes with a discussion of issues affecting future development of marine energy in Scotland, such as exploiting less energetic sites, and grid connectivity (Section 5).

* Corresponding author.
E-mail address: s.p.neill@bangor.ac.uk (S.P. Neill).

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2. Commercial progress

In this section, we explain the role of the European Marine Energy Centre (EMEC) on the development of the marine energy industry in Scotland, and provide an overview of commercial progress of tidal and wave energy.

2.1. European Marine Energy Centre, EMEC

The foundation of EMEC arose from a strong political commitment to foster a wave and tidal energy industry in Scotland. The Atlantic coast of Scotland, including the west coast of Orkney, has a strong wave energy resource. Accessible tidal stream energy sources in both Orkney and Shetland were identified by early research [5], including a specific site at Fall of Warness, Orkney. A combination of this natural environment and local industrial, academic and governmental support underpinned the selection of Orkney to host test centres. The European Marine Energy Centre (EMEC) was established in 2003, with the wave test centre at Billia Croo on the west coast opening and welcoming the Pelamis 750 device in 2004. The tidal test centre at Fall of Warness opened in 2006, and in 2008 Open Hydro was the first tidal turbine to deliver electricity to the UK grid. New developers continue to deploy at both EMEC sites, as detailed in the following sections. EMEC has expanded to offer a "scale wave site" and a "scale tide site", in addition to the original full-scale, open-sea sites. The template of EMEC has been adopted internationally, but the early establishment of the centre has undoubtedly benefited industrial development in Scotland, including the supply chain.

2.2. Tidal energy developments

At the time of writing, at least six "first generation" seabed-mounted, horizontal axis tidal turbines have completed testing at EMEC, as well as several other devices. MeyGen and Nova Innovation are now installing some of the world's first pre-commercial arrays off Caithness and Shetland, respectively, using machines of this type. MeyGen plan 6 MW of installed capacity in their first phase, using a blend of 1.5 MW units from Atlantis and Andritz Hydro Hammerfest [6]. Nova Innovation are installing five of their own 100 kW devices, and reported the first power supplied to the Shetland grid in March 2016 [7].

Four device developers have announced plans to test "second generation" tidal energy convertor (TEC) designs at EMEC in either 2016 or 2017: Nautricity with the CoRMaT, Sustainable Marine Energy with the PLAT-O platform (using Schottel turbines), Tocardo with their T2 design, and Scotrenewables with the SR2000. These technologies show two notable areas of evolution. Firstly, all are floating designs (optionally in the case of Tocardo), in contrast to earlier seabed-mounted devices; and secondly the emergence, from Schottel and Tocardo, of "bare" turbines sold as components, which are then integrated by others into full TEC systems. It is also interesting to observe a greater diversity of scale. Whereas most first generation machines were rated at 1 MW, new designs range from 100 kW (intended for arrays of many small devices, but also for small-scale off-grid applications) to 2 MW.

2.3. Wave energy developments

An enthusiastic commercial outlook for the wave sector from 2011/12 culminated with the intense full scale testing programmes of then leading developers Aquamarine Power and Pelamis Wave Power at the EMEC test site at Billia Croo, Orkney. This positive outlook was further boosted by the successful delivery of "the world's first commercial wave power station" in Mutriku, Basque Country, by Voith Hydro Wavegen [8]. However, these positive developments suffered severe setbacks with the decision by Voith, in 2013, to withdraw from actively pursuing developments in the wave energy sector, and more recently by the announcement of Pelamis Wave Power and Aquamarine Power calling in administrators and subsequently stopping trading in 2014/15. In effect, that means that the three Scottish based previously globally leading developers in the sector are no longer trading, and it has only been partially possible to capture the wealth of knowledge acquired during intense research, development and field testing programmes during the closures of business of said companies. In response to these developments, the Scottish Government set up Wave Energy Scotland (WES) in 2014 to facilitate a comprehensive R&D programme with a view to bringing wave power technology to commercial market readiness [9]. The initial WES technology development programme supported 16 projects related to power take off technology, and a further 8 projects to develop novel wave energy converter (WEC) technologies. As the programme evolves through the project development stages, the number of participants changes, as only the most promising developments continue to receive support.

Following on from the discontinuation of the previously planned large scale developments, the focus appears to have shifted towards the implementation of smaller projects. A number of novel WEC concepts and subsystem components are currently being developed in a co-ordinated way, funded and overseen by WES, and concepts such as Albaterns WaveNet are already being deployed in conjunction with the aquaculture sector, with a view to small scale power production for local site use. In another active project, the same developer is considering integrated energy solutions at island community scale [10], and given the constraints experienced by a weak electrical grid infrastructure, this appears to be an appropriate interim stage *en route* to up-scaling projects to commercial scale.

The willingness of the private and utility sector to invest in wave power technology and projects is currently at a low level, e.g. due to a high uncertainty on revenue predictions related to electrical infrastructure and transmission costs. Combined with limited confidence in successful project delivery in the near future, programmes that are currently underway by the Scottish Government, through WES, are anticipated to re-create and stimulate conditions that provide higher levels of certainty for investors, and are likely to see progression of a new generation of prototypes to commercial stage.

CorPower Ocean, will test a dynamically-tuned point absorber at EMEC in 2016 [11], and Laminaria have announced plans to bring their prototype to Orkney the following year [12].

3. Tidal resource

Scotland is separated from the North Atlantic by relatively narrow (approximately 100 km) shelf seas to the north and west (Fig. 1). The Pentland Firth and the Fair Isle Gap,[1] as well as channels through the Orkney & Shetland island groups, connect these shelf sea regions to the North Sea in the east of Scotland, and the North Channel connects the shelf seas to the Irish Sea. Scotland's tides are controlled by the tides in the North Atlantic which, being strongly semi-diurnal, can be described by the principal semi-diurnal lunar (M2) and solar (S2) constituents (Fig. 2). The tidal wave propagates northwards up the western edge of the continental shelf, then turns eastwards across the northern extent of Scotland, before travelling into the North Sea (see the co-phase lines in Fig. 2). Combining the

[1] The strait between Orkney and Shetland.

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