Ocean & Coastal Management xxx (2016) 1–11

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Large scale three-dimensional modelling for wave and tidal energy resource and environmental impact: Methodologies for quantifying acceptable thresholds for sustainable exploitation

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ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form
3 November 2016
Accepted 24 November 2016
Available online xxx

Keywords:
Marine renewable energy
Tidal stream
Waves
Environmental impact
Sustainability

1. Introduction

1.1. Background

In the context of increasing societal concerns about the effect of traditional energy sources based on the combustion of fossil fuels on the earth's climate, Marine Renewable Energy (MRE) is a relatively new sector showing considerable promise, particularly in highly populated areas of northern Europe where other (e.g. some terrestrial) renewable energy sources have either fulfilled their potential or are likely to encounter significant challenges as a result of lack of free/available resource, environmental or socio-economic impact, etc.

The MRE sector comprises a number of different technologies (see Magagna and Uihlein, 2015). In order of degree of readiness, these include offshore wind, tidal energy, wave energy and a few emerging technologies such as salinity gradient and thermal energy conversion. The latter have been piloted already (in some cases, for quite some time) but their current technology readiness level (see review by Magagna and Uihlein, 2015) suggests that they are still some way off becoming commercially viable.

Offshore wind is the most mature offshore MRE sub-sector, building upon the widespread deployment of onshore wind farms. By 2015, offshore wind had reached a generating capacity of >5 GW in United Kingdom waters. Across Europe, the total adds up to >10 GW and some 700 MW in the rest of the world (source: Offshore Wind Factsheet 2015; http://www.renewableuk.com/en/publications/index.cfm/offshore-wind-factsheet). The potential effects of offshore wind farms on the physical environment are relatively straight-forward to measure and model. The main effects on the physical environment relate to the effect of energy extraction on the wind field, which reduces e.g. the amount of energy available to mix the water column, and the physical effect of the turbine support structures on the flow and wave fields. Their main direct biological effect during the operational phase is their potential interaction with birds, although other effects have been proposed (e.g. support structures can serve as artificial reefs for native or invasive species). Some construction methods produce levels of underwater noise that can be of concern regarding marine mammals and, potentially, fish.

The tidal MRE sector includes a number of different technologies that exploit tides to generate electricity. They include tidal stream devices, where turbines placed within the tidal stream exploit the

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http://dx.doi.org/10.1016/j.ocecoaman.2016.11.025
0964-5691/

kinetic energy of the tidal flow to generate electricity, and dam-like structures with turbines, such tidal lagoons and barrages (closed dams) or turbines in open dams perpendicular to the tidal flow. Most Tidal Energy Converters (TECs), e.g. for tidal stream developments, are typically horizontal axis bladed turbines (although other designs exist) and therefore share some similarities with wind turbines. However, TECs are yet to reach the required level of technical maturity for routine large scale commercial deployment, although they show promise, particularly in areas where the resource is most abundant, such as parts of the coastal waters west and north of Scotland (The Scottish Government, 2013).

Wave energy converters (WECs), in contrast to TECs, are diverse in design, although they all share the same source of energy to generate power: the combined wind seas and ocean-swells as they approach coastal areas, where their potential for exploitation is currently concentrated (for economic reasons). The lack of convergence towards a preferred design has been identified as an obstacle to the commercial development of the waves sub-sector and poses some practical challenges when it comes to investigate its potential environmental impact.

1.2. Study area

The main geographic focus of this work is the Pentland Firth and Orkney Waters (PFOW) area (Fig. 1), comprising waters around the Orkney Islands off the north Scottish coast and the 10–12 km wide channel (the Pentland Firth) that separates this archipelago from the Scottish mainland. The Pentland Firth is significantly deeper than the bays and channels among the islands, which are generally less than 25 m and rarely exceed 40 m. Depths in the main Pentland Firth channel typically reach 60–80 m and even >90 m on the western side. The Inner Sound, south of the Island of Stroma in the Pentland Firth, is somewhat shallower (ca. 35 m). The M_2 tide that propagates clockwise around the British Isles results in an approximately 2 h phase difference between the west and east ends of the Pentland Firth and sets up a hydraulic gradient that generates strong tidal currents which can reach 5 m s^{-1}. Tidal currents are also forced around headlands and through other channels within the Orkney Islands, where spring flows can exceed 3.5 m s^{-1}. The amount of extractable tidal stream power in the area has been the subject of a number of studies with wide-ranging estimates. For the Pentland Firth, the higher limit has been estimated as 4.2 GW averaged over the spring-neap cycle (Draper et al., 2014) but more recent work reports a more realistic scenario of around 1.5 GW (O'Hara Murray and Gallego, 2016a,b).

The wave regime in PFOW is dominated by Atlantic swells and the influence of low pressure systems that travel primarily from west to east across the North Atlantic. Therefore, wave conditions are most severe in the exposed coastal areas to the west. The seasonal range of average wave resource in the area has been estimated between <10 (summer) and 50 kW (winter, top range of the estimate) (Neill et al., 2014).

The PFOW area is rich in geological features, coastal landscapes and seascapes that collectively support diverse habitats and species, many of which are considered rare and/or vulnerable. There are four designated Special Areas of Conservation (SAC; European Union designation) in Orkney and three SACs on the adjacent north coast of the Scottish mainland, for the protection of marine and coastal habitats. Another 29 sites (some with marine elements) have been designed as Sites of Special Scientific Interest (SSSI; national designation) and three nature conservation Marine Protected Areas (MPA) were formally designated in the area in 2014 (Pilot Pentland Firth and Orkney Waters Working Group, 2016).

The marine environment also has great social and economic importance for the Orkney Islands and adjacent areas of the north of Scotland. Fishing is a long-established industry in the area, targeting a wide range of pelagic (herring, mackerel), demersal (including cod, haddock, whiting, saithe, monkfish) and shellfish (including prawn, *Nephrops*, lobster, brown and velvet crab, whelk and scallop) species. The Scottish Sea Fisheries Statistics 2015 (The Scottish Government, 2016) indicates that there were 132 Scottish based active fishing vessels in the Orkney area and a further 93 in the adjacent north Scottish mainland area of Scrabster (all vessel sizes). The combined value of landings in 2015 by Scottish based vessels in the area was in excess of £39M. Fishing is an integral part of coastal and island communities as a source of employment and as an important link to maintaining associated services, thus contributing to community sustainability. The PFOW area is utilised by a variety of other vessels with various cargoes, passenger ferries and recreation. Aquaculture is also relatively important, although aquaculture sites have so far been located largely in sheltered waters of no primary interest for MRE exploitation. The marine and coastal area in the PFOW supports a wide range of activities associated with recreation, sport, leisure and tourism that make a significant contribution to the local economy and the sustainability of remote communities. Many of these activities are based on the wildlife, the scenery or are water-based, and rely on a clean, safe and diverse marine environment. Key interactions are expected to take place between the MRE sector and the fishing industry, shipping and navigation and the natural environment, and to be key elements of environmental impact assessments and the licensing/consenting process. There may be interactions with other sectors but these are anticipated to be minor.

1.3. Legislative framework

The Scottish Government has set a target of a largely decarbonised electricity generation sector by 2030, with a renewable electricity target of 100% of the Scottish consumption equivalent by 2020. MRE developments in Scottish waters are subject to licensing conditions. Part Four of the Marine (Scotland) Act 2010 gives Scottish Ministers responsibility for licensing activities within inshore Scottish waters (up to 12 nm), as well as for offshore waters (12–200 nm) under the Marine and Coastal Access Act 2009 for non-reserved activities such as MRE developments. Developers in Scotland need to apply for licences or consents under a number of regulations which include the Electricity Act (S36) 1989, the Coast Protection Act 1949 and the Food and Environment Protection Act 1985. The licensing landscape in Scotland has been simplified recently to provide a largely one-stop-shop that allows simultaneous application for the relevant consents. In addition to a marine licence, a project will require approvals or consents from other authorities such as The Crown Estate, a landed estate under The Crown Estate Act 1961, which leases the seabed within the UK 12 nm limit and the rights to non-fossil-fuel natural resources on the UK continental shelf.

Although the specific details will vary between countries, most applicable national environmental legislation in Europe is directly transposed from European Union legislation and it is often similar to other international legislation, commonly based on international conventions, so the information we present here will be of wider applicability beyond the Scottish context. The primary instrument for monitoring and managing the quality of Scotland's coastal waters out to 3 nm from the coast is based on the European Union (EU) Water Framework Directive (WFD; EC (2000)). The PFOW area is largely classified as 'good' status under the WFD. The waters on the eastern portion of the Pentland Firth are of 'high' status, as well as several "transitional waters" in the PFOW area (Pilot Pentland Firth and Orkney Waters Working Group (2016)).

Please cite this article in press as: Gallego, A., et al., Large scale three-dimensional modelling for wave and tidal energy resource and environmental impact: Methodologies for quantifying acceptable thresholds for sustainable exploitation, Ocean & Coastal Management (2016), http://dx.doi.org/10.1016/j.ocecoaman.2016.11.025