Renewable Energy 118 (2018) 627–643

Contents lists available at ScienceDirect

Renewable Energy

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

Co-located offshore wind and tidal stream turbines: Assessment of energy yield and loading

D. Lande-Sudall [a], [*], T. Stallard [b], P. Stansby [b]

[a] Western Norway University of Applied Sciences, Department of Mechanical and Marine Engineering, Inndalsveien 28, 5020, Bergen, Norway
[b] University of Manchester, School of Mechanical, Aerospace and Civil Engineering, Oxford Road, Manchester, M13 9PL, UK

ARTICLE INFO

Article history:
Received 30 September 2016
Received in revised form
21 September 2017
Accepted 21 October 2017

Keywords:
Co-location
Offshore wind farms
Tidal stream arrays
Hybrid
Environmental loads
Energy yield

ABSTRACT

Co-location of wind and tidal stream turbines provides opportunity for improved economic viability of electricity generation from these resources relative to projects exploiting each resource separately. Here co-deployment is assessed in terms of energy generation and loading of support structures. Energy yield is modelled using an eddy viscosity wake model for wind turbines and superposition of self-similar wakes for tidal turbines. A case-study of the Inner Sound of the Pentland Firth is considered. For 3.5 years of coincident resource data, 12 MW wind capacity co-located with a 20 MW tidal array results in a 70% increase in energy yield, compared to operating the tidal turbines alone. Environmental loads are modelled for a braced monopile structure supporting both a wind and tidal turbine, as well as for each system in isolation. Peak loading of the combined system is found to be driven by wind loads with greatest overturning moment occurring with the wind turbine operating at close to rated-speed and the tidal turbine close to its shutdown speed. Mean loads vary across the tidal array by 6% indicating no significant shielding effects are gained by co-locating in more sheltered regions of the array.

1. Introduction

In-line with the commitments signed by the 175 countries of the 2015 Paris Agreement recognising the need to significantly cut global greenhouse gas emissions [1], further expansion of large offshore wind farm deployments are expected. In the UK, electricity generated from offshore wind is currently around 17 TWh/yr [2] and is anticipated to reach over 90 TWh/yr[1] by 2030. However, the cost of electricity from offshore wind has failed to decrease as expected through experience alone [4]. Many planned wind farm locations require deployment in water depths greater than 30 m where traditional support structures may no longer be feasible and the required systems may have higher capital cost. As such levelised cost of energy is likely to remain higher than for gas or coal generation and large scale deployment of wind is likely to rely on continued government incentives. Deployment of other renewable technologies, such as solar and wave alongside wind farms (co-location) have been proposed as methods of cost reduction of electricity generation (e.g. Tina et al. [5] and Gao et al. [6]). In this study, co-location of offshore wind turbines with farms of tidal stream turbines is considered. Tidal stream turbines are a less mature technology than offshore wind or solar. However tidal arrays are currently being installed and there is the potential in the UK to generate an estimated 18 TWh/yr from the tidal stream resource [7] and average power of more than 2 GW from the Pentland Firth alone [8]. Co-location enables shared use of electrical infrastructure and, potentially, of support structures. There may also be benefits in terms of reduced variability of power from a co-located farm as opposed to operating a wind or tidal farm in isolation. Existing offshore wind farms have typically been installed in locations with low tidal stream velocities. As such, this study addresses co-location of wind turbines at sites being developed for tidal stream arrays, since a strong tidal stream resource will be required for tidal generation.

To assess economic viability of alternative design options at a preliminary stage of development, it is informative to assess how factors which directly influence revenue and capital expenditure may differ. Revenue from renewable energy projects is dependent on annual energy production and the accuracy with which this may be forecast is clearly vital. Capital cost is dependent on many factors

---

* Corresponding author.
E-mail addresses: david.lande-sudall@hvl.no (D. Lande-Sudall), tim.stallard@manchester.ac.uk (T. Stallard).

[1] Based on [3] prediction of 33 GW of installed capacity by 2030 and an average capacity factor of 33%.

https://doi.org/10.1016/j.renene.2017.10.063

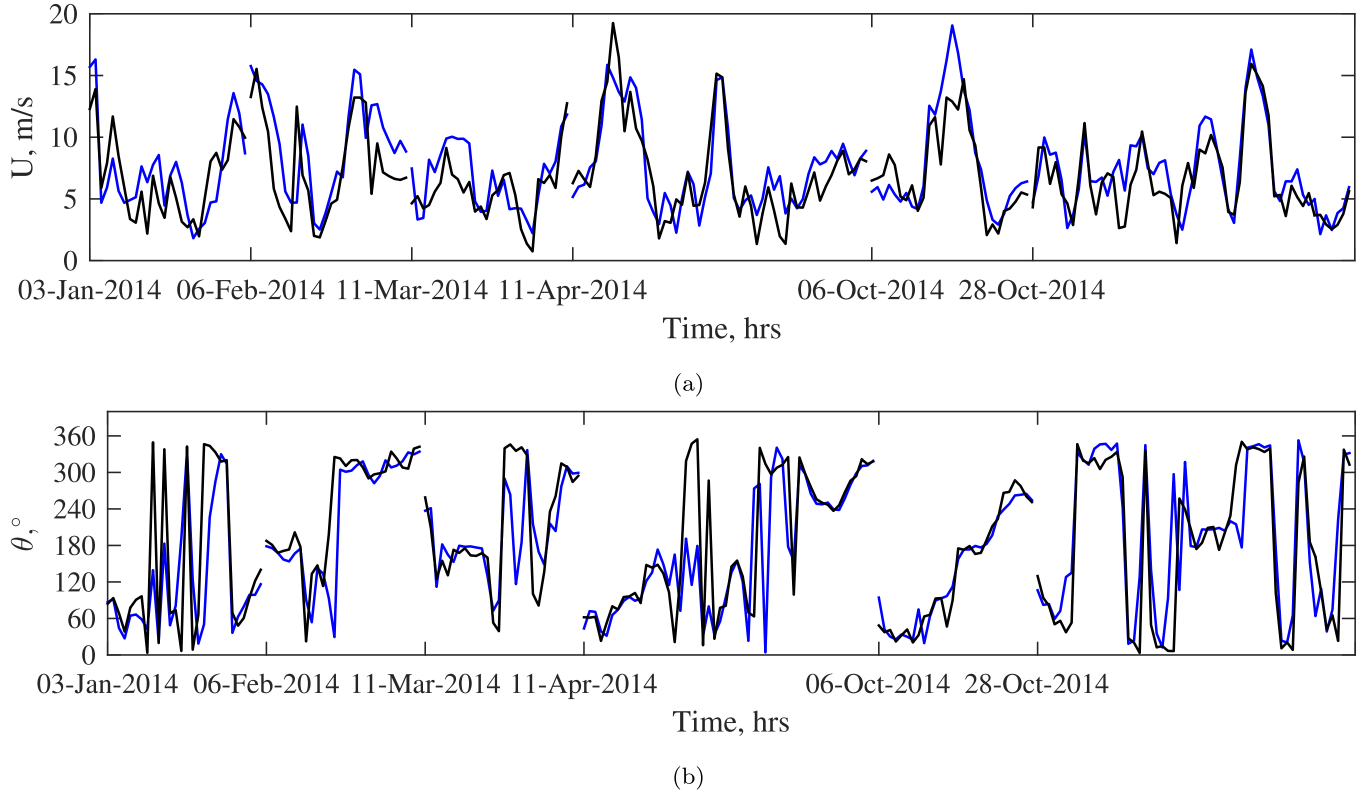
including dimensions, complexity and number of support structures, as well as site-specific installation costs. To this end, a model of the energy yield from co-located wind and tidal turbines is first presented, along with evaluation of time varying power for a case-study farm comprising 12 MW offshore wind power capacity co-located with 20 MW tidal capacity, situated in the Inner Sound of the Pentland Firth, Scotland. It is noted that the methodology could be applied to any site of interest. For the tidal stream array, the influence of a yaw operating strategy and shutdown criterion based on both current speed and significant wave height, H_s, is considered, since these directly influence yield and tidal turbine complexity. The second part of this paper assesses the environmental loads acting on a hybrid support structure for a wind and tidal stream turbine, since such loads affect structural dimensions. The loads are compared against those acting on support structures for wind and tidal turbines in isolation.

2. Wind farm energy yield model

AWS OpenWind [9] with a standard eddy-viscosity wake model [10] is used to model wind farm energy yield. A generic 3 MW power curve is specified for each turbine, with a rotor diameter of 100 m, rated speed of 12 m/s and shutdown set at 25 m/s. The thrust curve was from a 3 MW Vestas V90 wind turbine [11] in order to define the momentum extraction in the wake model. The wind turbines are assumed to operate with 100% availability, with no downtime due to faults or maintenance. A power matrix, specific to the farm layout and dependent on wind heading, is generated. This is used as a look-up table against hourly wind resource data to obtain time-varying power output.

Numerical Weather Prediction (NWP) data of wind resource at 10 m height is available from the UK Met Office UKV model [12] in a 6-hourly time-series for the periods 01 Jan 2012–30 Nov 2012 and 01 Jan 2013–24 Jun 2015 and at an approximately 1.5 km spatial resolution. This approximately 3.5 years of data is too short to account for the wind power variability over the life-time of the farm (e.g. decadal variability [13]). However, the approach used herein can also be applied to longer time-series, as more data becomes available. This analysis therefore provides an indication of the relative magnitude of wind to tidal energy yield, the power variability, and when used for analysing loads, the operational conditions of the turbines during peak load events. Since this dataset is at relatively coarse spatial and temporal resolution, a linear measure-correlate-predict (MCP) approach has been applied to the UKV data, using wind data from an hourly, 400 m resolution mesoscale Weather Research and Forecasting (WRF) model [14,15] employed over the Pentland Firth region. The WRF model is considered to provide a more accurate representation of the undisturbed wind speeds at the site and was configured according to [16] who previously validated the model against measured data from five met stations around the Pentland Firth. Initial and boundary conditions were from National Centres for Environmental Prediction (NCEP) Final (FNL) Global Analysis data at 1° × 1° spatial and 6-hourly temporal resolutions [17]. Five telescopic nested-domains, each of 78×78 compute nodes provided an outer domain resolution of 32.4 km, increasing in ratios of 3:1 to an inner domain resolution of 400 m on plan. In the vertical axis, 45 η levels were specified with ten levels within the lowest 250 m.

The WRF model has been run for an aggregate period of eight weeks and wind speed at 10 m level extracted to correlate with the UKV model data. The intervals considered comprised two, non-overlapping 14-day periods and four, non-overlapping 7-day periods (see Fig. 1). Each interval was selected such that the wind speed occurrence represented annual occurrence statistics defined



(a)

(b)

Fig. 1. Hourly time-series of wind speed (a) and direction (b) at 10 m elevation from both UKV (black) and WRF (blue). The figure shows data for six separate time-intervals, with the start date of each shown on the x-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)