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Do tidal stream energy projects offer more value than offshore wind farms? A case study in the United Kingdom

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A B S T R A C T

Marine-based renewable energy could help the United Kingdom (UK) move towards a more sustainable and low-carbon energy system. Today, offshore wind is the prevailing marine renewable technology but there is growing progress towards developing others, such as tidal stream energy (TSE) turbines which capture kinetic energy from tidal currents. Using historical operations data from 18 wind farms and simulated generation data for two TSE sites in the UK, we estimate that TSE projects offer about $10/MW h more in net social benefits than offshore wind projects. This estimate includes the value of energy generated, value of reduced marginal CO_2 emissions, cost of visual changes to the landscape, and cost of energy generation forecast errors. However, relative to offshore wind, the increased cost of TSE projects far outweighs the increased social benefits. The levelized cost of energy (LCOE) of TSE projects is expected to be about $74/MW h to $330/MW h higher than offshore wind projects through 2050. Only with optimistic LCOE projections, small TSE projects (20 MW) may be competitive (when including increased net social benefits) with small offshore wind projects by 2020.

1. Introduction

Increasing renewable electricity generation is a priority in many countries (IEA, 2017). In 2009, the United Kingdom (UK) set a goal, in coordination with other countries in the European Union (EU), to meet 15% of UK's electricity demand from renewable energy by 2020 (compared to about 8.3% in 2015 (DUKES, 2016)). In further coordination with other EU countries, the UK parliament also passed a law to reduce carbon emissions by 80% by 2050 (below 1990 levels) with annual targets set with a 5-year carbon budget (The UK National Archives, 2008). Despite the recent referendum vote for the UK to leave the EU, the UK government appears committed to continuing these renewable and climate obligations. The most recent climate budget passed for years 2028–2032 requires carbon emission reductions of about 57% by 2030, a more aggressive reduction compared to EU requirements of 40% (Vaughan, 2016). It is expected that renewable energy will play a large role in meeting emission targets.

Most renewable energy generation in the UK comes from wind power (48% in 2015), followed by biomass (35%), and the rest from solar (9%) and hydro (7%) (DUKES, 2016). At the end of 2015, the UK had 9188 MW (MW) of wind capacity located onshore and 5103 MW located offshore. Furthermore, future wind development has enormous potential in the UK. The European Environment Agency (EEA, 2009) estimates that the total unrestricted technical potential for wind power in the UK is about 4500 terawatt-hours (TW h) for onshore and another 4500 TW h for offshore – enough to power all consumption in the UK 30 times over (net energy demand in 2015 was 302 TW h, (DUKES, 2016)). However, offshore locations may offer advantages over onshore ones. First, offshore wind projects generate more energy due to stronger and more consistent wind. In 2015, the average capacity factor of existing offshore projects was 39% compared to 28% for onshore projects (DUKES, 2016). Offshore projects are also farther from population centers, and thus avoid concerns about increased noise, shadow flicker, and other human disturbances associated with onshore projects (Devine-Wright, 2005; Ek, 2002; Wolsink, 2000). There is also evidence that close proximity to onshore projects can lower residential property value, although these effects have been debated in past literature (Gibbons, 2013; Heintzelman and Tuttle, 2012; Hoen, 2010). Furthermore, recent work by Graziano et al. (2017) showed that locally sourced off-shore could potentially have important income and employment consequences for the UK's economy.

Because of these advantages, offshore wind capacity will likely surpass that of onshore. According to the Crown Estate, which controls commercial access to UK's seabed, there are about 4500 MW of new offshore wind projects currently under construction for operation by 2020, and an additional 10,000 MW of leases granted for future development (The Crown Estate, 2017).

Despite their benefits in helping to reduce carbon emissions, both onshore and offshore wind projects present several challenges. Wind

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projects generate electricity intermittently and often in unpredictable patterns (Sovacool, 2009). This presents a challenge to merchant wind farm operators, who sell energy into wholesale markets at least one hour before delivery. Missing delivery targets due to generation forecast error can carry penalties. For example, Lueken et al. (2012) find that 20 wind farms in Texas incur about $4/MW h in additional costs due to forecast error. The value of wind energy generated also depends on timing. Correlation of hourly wind energy generation with high wholesale energy prices (J.V. Lamy et al., 2016) as well as with high marginal emission reductions (Siler-Evans et al., 2013) can vary substantially by project location. Furthermore, one of the biggest challenges facing wind projects is aesthetics. There is an extensive body of literature that explores the perceived social costs of wind projects due to their impact on landscapes (Dimitropoulos and Kontoleon, 2009; Ek and Persson, 2014; Krueger et al., 2011; Ladenburg and Dubgaard, 2009). Even offshore wind projects, although farther from population centers than onshore projects, can be visible at distances beyond 40 km from shore (Sullivan et al., 2013). Lastly, there are concerns about the potential ecological impact of both onshore and offshore wind turbines, such as adverse interaction with birds, bats, and marine animals (Bailey et al., 2014; Bergström et al., 2014; Erickson et al., 2014; Loss et al., 2013; Stewart et al., 2007).

Other marine-based renewable technologies offer similar advantages to offshore wind, while avoiding some of their drawbacks. For example, tidal stream energy (TSE) projects capture kinetic energy from tidal currents that flow during the transition between high and low tide, which occurs twice per lunar day (24 h and 50 min). Unlike wind speed, tidal current speed is highly predictable using harmonic simulation tools (Blunden and Bahaj, 2006; Neill et al., 2012; Zhong and Li, 2006), which greatly facilitate energy generation forecasting. Another advantage is that, unlike offshore wind, TSE projects have little impact to the ocean landscapes since most TSE turbine technologies are fully submerged, and thus are not visible from shore (Polagye et al., 2010). Furthermore, the UK has abundant TSE resources, totaling about 95 TW h (The Crown Estate, 2012) in technical potential – enough to meet 31% of UK's net electricity demand (302 TW h in 2015, (DUKES, 2016)). It is important to point out that TSE turbines are not the same as tidal lagoon projects (also known as tidal barrage or tidal range), which are artificial walls containing embedded turbines built across an estuary or bay, such as the Swansea Bay project proposed in Wales (The Economist, 2017). Tidal lagoon projects are easily accessible for operation and maintenance since they are attached to the mainland (which helps to lower costs), but they also require large infrastructure changes to the estuary/bay and can only be sited in areas with suitable mainland geography. Unlike tidal lagoon, TSE projects are made up of stand-alone turbines fixed to the seabed, much like offshore wind turbines. TSE turbines are fully submerged, don't require large infrastructure changes to the landscape, and have less local environmental impact than tidal lagoon projects (Pelc and Fujita, 2002). Our work does not include tidal lagoons and instead focuses on TSE.

The TSE industry has recently started to gain traction. We estimate that about 20 MW of demonstration and pilot phase projects are currently deployed globally, with another 1600 MW of commercial phase projects in development for operation by 2022 (see Appendix A for a list of existing TSE projects across the world). However, ecological impacts of TSE projects are still widely uncertain since there are few projects in operation. It is expected that many of the same concerns regarding offshore wind projects (namely, impact to marine life) also apply to TSE projects (OES, 2014; Polagye et al., 2010, 2014).

The major challenge facing marine-based renewable projects like TSE, and to a lesser extent offshore wind, is cost. The current levelized cost of energy (LCOE) for offshore wind projects is about $175/MW h and $500/MW h for TSE projects[1] (Wiser, 2016; OES, 2015), compared to an average wholesale market index price of $60/MW h in the UK from 2012 to 2014 (2016$, (Elexon, 2017)).

Electricity end-users are not directly exposed to these higher costs. Instead, the UK government provides incentives for renewable technologies to increase renewable penetration and help new technologies move down the learning curve. This support is primarily realized through a "contract-for-difference" (CfD), which locks in a price ("strike price") offered to specific renewable technologies over a period of 15 years (BEIS, 2017a). The recent CfD strike price for offshore projects delivered by 2021/2022 was $136/MW h compared to $388/MW h for TSE projects. Total awards have a limited budget of $361 million so applicants must bid and compete on price to win CfD contracts (BEIS, 2017b). Furthermore, there is increased concern that financial support for renewables will decrease in the near future due to recent political changes (Vaughan, 2017). This puts more pressure on renewable projects to demonstrate economic competitiveness, and calls into question whether the large difference in CfD strike prices for one technology over another (TSE vs. offshore wind) is justified. However, the total net social benefits of TSE projects may be higher than those of offshore wind projects, which would help justify a higher public willingness-to-pay (i.e., government incentives) for the technology. This question is the underlying premise of our paper.

We aim to identify whether the difference in net social benefits between TSE and offshore justifies a difference in subsidies (i.e., CfD strike price) between the two technologies, which is currently about $252/MW h. We quantify the increased net social benefits (in $ / MW h) that TSE projects offer over offshore wind projects (i.e., "TSE social benefit premium"). For the net social benefits calculation, we consider differences between offshore wind and TSE regarding the value of energy generated, marginal CO_2 emission reductions, predictability in power generation, and visual impact on the landscape. We also discuss the ecological impacts of the two technologies based on past literature, but do not attempt to quantify or compare their associated social costs. We then compare LCOE cost projections between the two technologies through 2050 to see if/when TSE projects would be able to compete with offshore wind, given that TSE projects receive increased subsidies equal to our estimated TSE social benefit premium. Our calculations rely on generation data from 18 operational wind farms across the UK and modeled tidal current speed data from two TSE sites at the European Marine Energy Center (EMEC, 2017).

Our study is the first to quantify and compare net social benefits between offshore wind and TSE projects. We focus on TSE projects as opposed to other marine renewable technologies (ocean wave, tidal range/ lagoon, ocean thermal energy, and salinity gradient) because TSE projects have a unique combination of high resource potential in the UK (95 TW h, (The Crown Estate, 2012)), limited visual as well as environmental impact,[2] and commercial viability within the next 5 years (see Appendix A).

Several studies compare the characteristics of different marine renewable technologies, such as offshore wind and TSE. However, these studies typically focus on environmental impacts or capital costs, do not consider project performance (emission reductions, energy value, predictability, or visual impact), and often present only qualitative comparisons (Frid et al., 2012; Inger et al., 2009; Johnstone et al., 2013; Pelc and Fujita, 2002; Uihlein and Magagna, 2016).

The rest of this paper is organized as follows: in the next Section, we discuss our methods and the data we relied upon, in Section 3, we present results, and in Section 4, we conclude.

2. Methods and data

Our method relies on five steps outlined in Fig. 1. First, (1) we estimate net social benefits of both offshore wind and TSE projects and

[1] As a point of reference, the Swansea Bay tidal lagoon project is expected to have an LCOE up to around $300/MW h (Private Eye, 2017).

[2] Relative to tidal range/ lagoon projects, which are likely to induce more environmental and landscape changes (Pelc and Fujita, 2002).