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Challenges and opportunities for sustainable offshore wind development: Preliminary findings from a literature review and expert survey

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November 2020

No. 122

SRI PAPERS

SRI Papers (Online) ISSN 1753-1330

First published in 2013 by the Sustainability Research Institute (SRI)

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Challenges and opportunities for sustainable offshore wind development: Preliminary findings from a literature review and expert survey

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Contents

Abstract

This study shares the initial outcomes from a structured literature review on challenges and opportunities for sustainable offshore wind development, complemented by results from a global survey held among offshore wind experts in governmental, industry, civil sector, and research and innovation organisations.

Key words: offshore wind; sustainable development; clean growth; renewable energy; research and innovation priorities.

Submission date [02-11-2020]; Publication date [03-11-2020]

About the Author

Dr Anne Velenturf is a Research Impact Fellow in Circular Economy and Sustainable Offshore Wind Development. She is an interdisciplinary researcher working across the Schools of Civil Engineering and Earth and Environment. She works on the interface of academic research and practice, using her expertise in participation process management, knowledge exchange and impact delivery for challenge-led research that supports the implementation of a sustainable circular economy.

Anne currently delivers the EPSRC Knowledge Transfer Secondment project "A Sustainable Circular Economy for Offshore Wind" in partnership with the Offshore Renewable Energy Catapult and the Department for International Trade. She has led the £7M Resource Recovery from Waste programme funded by NERC, ESRC and the Department for Environment, Food and Rural Affairs. She also delivered projects on market research, business model innovation, regional and national circular economy implementation, and various projects to create a policy environment that is more amenable to a sustainable circular economy.

Anne has published in a variety of media on circular economy and is a regularly invited speaker. You can access her research via her profile at https://eps.leeds.ac.uk/civil-engineering/staff/850/dr-anne-velenturf

1. Introduction

The deployment of low carbon infrastructure such as wind and solar farms is a major strategy for the reduction of greenhouse gas emissions with the aim to limit global temperature rises well below 2°C (UNFCCC 2019). While low carbon infrastructure used to be surrounded with a narrative of high costs and questions around reliability and uptake, it is now seen as a “backbone of global development and climate strategy” (IRENA 2020).

Offshore wind (OSW) has rapidly become a preferred technology. In 2019 a total of 27GW OSW was in operation globally with a further 7GW under construction (WFO 2020). The WFO (2020) report assessed that the UK holds the largest market with close to 10GW operational capacity and that China is expected to take over the leading position during the 2020s. A steady growth of OSW is expected. For example, the UK aims to install at least 30GW and up to 40GW by 2030, with further ambitions to grow capacity to 75-175GW by 2050. The maximum global wind resource from OSW is estimated at 39TW (Soukissian et al 2017).

Renewable energy has the potential to contribute to climate change mitigation and sustainable development (Karakosta et al 2013). However, with the increasing scale of the OSW sector, new sustainability challenges are emerging around for example energy storage, resource security, geo-technology and securing social benefits for local communities. Sustainable development is most commonly defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987). Stamford and Azapagic (2012) speak of the relative sustainability of OSW and how the potential can be improved within the dynamics of a changing energy system.

A search for literature on a comprehensive review of challenges and opportunities for sustainable OSW development returned blank (Scopus search in April 2020). It is important to assure that OSW is indeed sustainable and remains sustainable with the growth of the sector. This study aimed to identify and prioritise challenges and opportunities for sustainable OSW development from the perspective of on-going research and innovation.

2. Methods

This research consisted of a structured literature review followed by a survey among OSW experts.

2.1 Literature review

A review of academic literature was carried out starting with two Scopus searches:

1. Search terms “sustainability” and “offshore wind” and “challenge”, returning 20 publications (2 April 2020).
2. Search terms “sustainability” and “offshore wind” and “opportunity”, returning 11 publications (29 April 2020).

One publication appeared in both searches. In total 30 publications were reviewed, the list has been included in the appendix. The publications were initially assessed for accessibility and relevance to sustainable OSW development. Four publications held limited relevance for this study but were subjected to a quick review anyway to gather any important challenges and opportunities. One publication only had one section on OSW specifically and this section was reviewed. One article was academically poorly conceived and hence not reviewed in detail. Seven publications could not be fully accessed and contents from abstracts only could be taken on board. The remaining 27 articles were reviewed in depth through a structured process by searching first for literal mentions of “challenge” and “opportunity”, followed by a full read of the publication to derive all challenges and opportunities.

The challenges and opportunities were then organised into four categories – social, economic, technical and environmental – and any overlapping categories thereof. They were then organised by theme to allow for the articulation of 67 challenges and opportunities from across the academic literature on sustainable OSW development.

2.2 Expert survey

2.2.1 Preparation

The review results were transferred into an online survey with questions on pages relating to the following categories: environmental, social-environmental, social, social-economic, economic, techno-economic, technical, techno-environmental and fully integrated (i.e. covering social, economic, technical and environmental aspects), with subsections on challenges and on opportunities. Participants could add up to three additional challenges and opportunities within the respective subsections of each category, and they were then asked to prioritise the top three based on demand for research and innovation. Participants also had the chance to add any other challenges and opportunities at the end of the survey.

Participants were asked to recommend publications for the benefit of this study. It was hoped that this would help to surface any holistic overview of sustainable OSW development challenges and opportunities from academic literature and publications from public, private and civil sector organisations, if there were any.

The survey received ethical approval from the University of Leeds. All participants were made aware of the purpose, research objectives and envisaged outputs from the survey. Data management assurances were communicated as well. Participation was anonymous but access to the survey was controlled and by invite only to ensure participants were experts in OSW. Participants were offered the opportunity to ask any questions ahead of taking part and before entering the survey they had to give informed consent.

2.2.2 Data collection

The survey was piloted which confirmed that it took up to one hour to complete. This is unusually extensive and will have limited the number of responses received, compounded by the unusual period under Covid-19 lockdown with many people having reduced availability or indeed none at all for example due to being furloughed. Data were collected over a period of four weeks in May-June 2020. In total 29 participants completed the survey.

The survey included questions to determine the broad geographic location of the experts and the nature of their organisation (Figure 1). Participation was skewed towards Europe with further coverage from North-America, South-America, Asia and Australia. Experts were contacted in Africa but they, in part understandably given the limited preparations for OSW developments, felt that this study held limited relevance to them. The distribution across types of organisations was somewhat skewed towards academia while responses from governmental and non-governmental bodies were relatively limited.

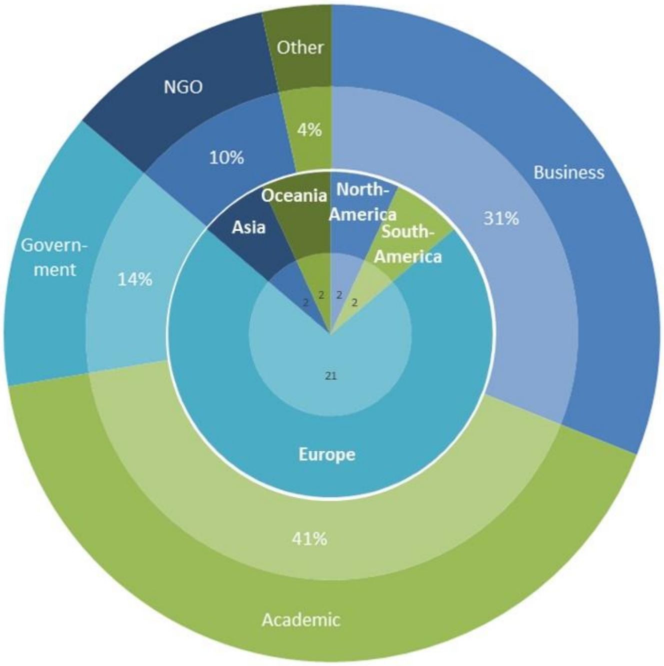

Figure 1: In total 29 experts in diverse organisations completed the survey, the majority being in Europe and minimal coverage around the world was ascertained.

2.2.3 Data analysis

Data analysis was structured to keep expert views from Europe and the rest of the world separate. The OSW sector in Europe is well established compared to other parts of the world and this might have impacted on the views articulated by the experts.

Data were prepared with a tracked reorganisation of the additional challenges and opportunities to be consistent with the earlier defined categories and themes, yet remaining sensitive to the notion that experts may have conceptualised the categories (environmental, social, etc.) differently which could offer valuable insights in itself. All additional challenges and opportunities went through a process of open coding and similar ones were then grouped together, and then either added to existing challenges and opportunities or presented as entirely new suggestions.

Within each category data on the prioritisation of challenges and opportunities were scored with expert's first priority receiving a score of 3, second priority scored 2 and third priority scored 1 point. The number of participants (n) was determined for each category separately, given that experts could choose to skip categories about which they felt to have limited expertise. An expert was counted as contributing to a category if any additions were shared and/or if any scores were given to prioritise challenges and opportunities. Average scores for challenges and opportunities were calculated and transferred into bar charts for comparison.

3. Results

A total of 45 challenges and 22 opportunities for the sustainable development of OSW were identified from academic literature (Figure 2). About two thirds of these could be categorised under a single dimension of sustainability, with the remainder being on the interface of two or more dimensions. This indicates demand for interdisciplinary solutions.

Overall there were more challenges than opportunities, 45 and 22 respectively. Technical and economic – and related categories such as techno-environmental and social-economic – challenges and opportunities were the most prevalent. The environmental, and related, category was the smallest. The relatively high frequency of technical and economic challenges and opportunities compared to the environmental and social may simply be a reflection of the subject areas within which studies were published, with nearly half being in energy and engineering.

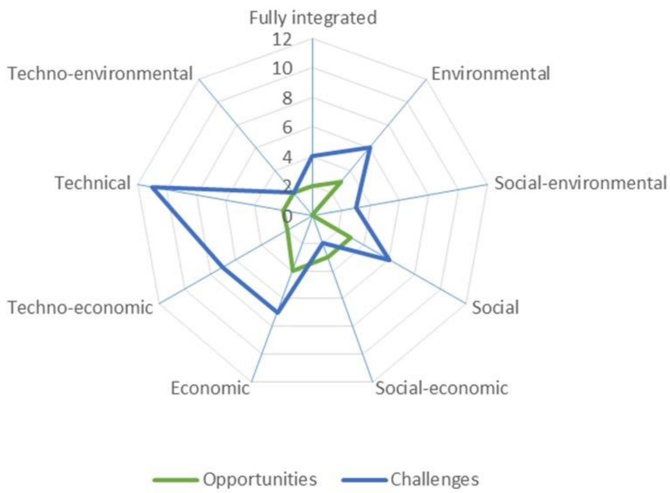

Figure 2: Overview of the number of challenges and opportunities for sustainable offshore wind development in the different categories.

3.1 Environmental

3.1.1 Environmental challenges

Overview of literature review results, with integrated nuances from survey

Cumulative ecological impacts: The cumulative ecological impacts are a challenge to assess (Kannen et al 2013). OSW can have adverse impacts on the marine environment and industry should expand gradually to comply with the precautionary principle, eliminating uncertainties regarding nature conservation before moving forward (Koller et al 2006). Adhering to the precautionary principle is challenging under circumstances of exponential expansion of OSW such as in the UK. Academia can play a role in the inter/transdisciplinary modelling of the cumulative impacts of large scale OSW taking a co-design approach that aims for ecosystem-based management (Kannen et al 2013). Stamford and Azapagic (2012) conclude that OSW (and nuclear) have the lowest environmental lifecycle impacts. Survey participants within Europe and around the world confirmed that it is challenging to assess the overall sustainability impacts throughout the project lifecycle considering material, energy and water usage, emissions and pollution, and unintended consequences to the marine environment, especially because not all potential environmental impacts are known, can manifest themselves over very long timescales, and technologies and models to collect and assess data need further development.

- **Impacts on geohydrology:** OSW farms can change flow patterns that in their turn can change the coastal morphology (Soukissian et al 2017).
- **Impacts on biodiversity:** Biodiversity is affected throughout the lifecycle of an OSW farm, including commissioning, operation and decommissioning. Disturbances to biodiversity include underwater noise, underwater habitat changes such as electromagnetic field effects, flow pattern changes, and entanglement risks from cables and mooring lines (Soukissian et al 2017). A survey participant from outside of Europe stressed the risk for habitat loss of endangered species. Above water, birds may avoid OSW farm areas and when birds do enter the area then there is a collision risk although technological solutions are thought to mitigate this impact (Soukissian et al 2017). The survey underlined the risks to migratory species. In addition to these challenges, there are also opportunities for biodiversity for example with the introduction of whole new structures on which biodiversity can take hold (Wilson and Elliott 2009). A survey participant from Europe added, however, that there is no hard evidence to prove that leaving infrastructure at end of use is better than removal. Another participant mentioned impacts for fishing which can be positive and negative.

Long term effects of climate change: Climate is driving the available wind resource for OSW (Contestabile et al 2017). Moriarty and Honnery (2012) argue that wind speeds are forecasted to reduce due to temperature differences between the poles and equator becoming smaller. JBA Consulting (2019) presented modelling results at Offshore Wind Connections 2019, which highlighted that this could pose a risk to OSW around the UK. The survey revealed another challenge resulting from climate change in the form of sea level rise affecting onshore and offshore infrastructure.

Resource use: Questions are being raised around the sustainability due to the resource demand of OSW infrastructure (Morrissey and Heidkamp 2018), especially given the rising demand for similar resources across low-carbon sectors (Jensen et al 2020). Survey participants within and outside of Europe added to this challenge that the resource extraction and manufacturing impacts on the environment, exacerbated by rising material demands for energy storage facilities and grid developments.

Waste and recycling: Stamford and Azapegic (2012) argue that the impact of material usage on the environmental sustainability of OSW is relatively high compared to other power supply technologies that rely of fuel resources that have a combined environmental impact from both the operation and use of fuels (e.g. oil, gas, nuclear). The use of metals in particular has an adverse impact on the water, human and eco-toxicity of OSW compared to other technologies. In the absence of empirical results there seems to be a high optimism within OSW literature regarding a) the absence of direct wastes from turbine operation and low chemical waste generation in the whole supply chain (Karakosta et al 2013) and b) the recyclability of all materials including metals (e.g. Stamford and Azapagic 2012, Topham and McMillan 2017) and even the management of composites, which would arguably offset most of the negative environmental impacts associated with the extraction and early processing of materials from which OSW components are made. However, there are many issues around end of use management and recycling (Purnell et al 2018, Jensen et al 2020), and particularly regarding the growing amount of blade waste from blade replacements and decommissioning operations (Lichtenegger et al 2020).

Priorities for research and innovation

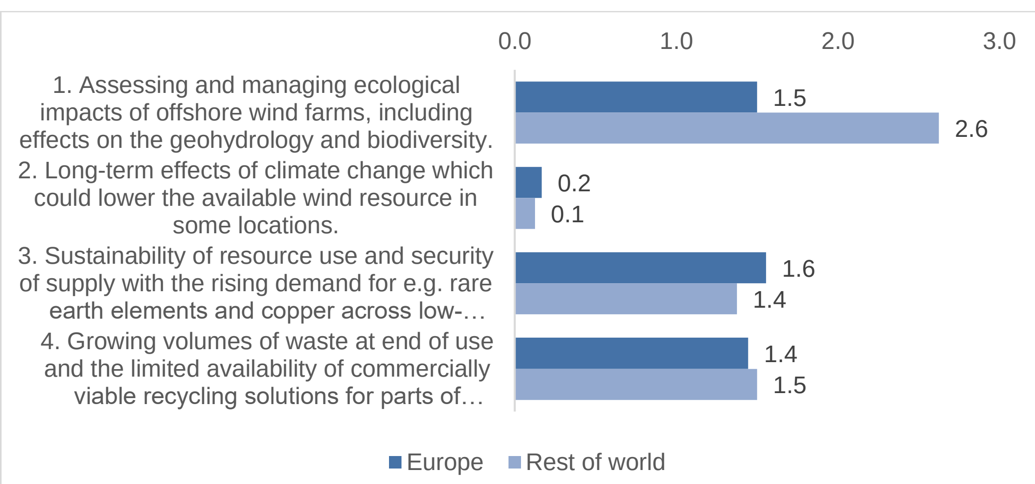

Figure 3: Environmental challenges (Europe n=18; Rest of world n=8)

3.1.2 Environmental opportunities

Overview of literature review results, with integrated nuances from survey

Climate change mitigation: OSW can contribute to sustainable development and mitigating climate change (Koller et al 2006, Stamford and Azapegic 2012), by reducing dependency on oil and natural gas (Amran et al 2020). Whole lifecycle greenhouse gas emissions are an important sustainability criterion (Karakosta et al 2013) – including CO_2, CH_4, nitrous oxides, chlorofluorocarbons, water vapour – but Apergis et al (2010) argue that renewables have not yet significantly contributed to reducing CO_2 emissions. The leakage of sulphur hexafluoride gas is a growing concern given the extreme global warming potential, though not linked to OSW directly (Widger and Haddad 2018).

Reducing use of space: Reduced surface use is considered an environmental benefit. OSW occupies less land and greenfield than other power supply solutions (Stamford and Azapegic 2012). OSW reduces land use conflicts by moving power generation into the sea where there is generally more space for development (Koller et al 2006, Contestabile et al 2017, Soukissian et al 2017). This effect can be even greater with the use multi-functional systems (Contestabile et al 2017). The benefit of saving land surface was also recognised by survey participants outside of Europe, leaving more land for alternative developments. Note, however, the growing conflicts between users of an increasingly busy marine space. This is a recurring opportunity covered from multiple angles within this publication.

Fuel reserves: OSW reduces dependency of power supply on finite fuel reserves (Stamford and Azapegic 2012). Survey participants from within and outside of Europe built on this, confirming the opportunity to reduce dependency on biomass, nuclear, fossil fuels, and avoid the environmental impacts such as greenhouse gas emissions, pollution, and habitat destruction from extraction.

Additions from survey

Nine additions were made that turned the challenge of impacts on biodiversity around and, instead, added the opportunity that OSW offers to increase biodiversity. Increasing the distance from shore was seen as an opportunity to minimise impacts on biodiversity and fisheries, while OSW farms could or already are functioning as marine conservation areas, artificial reefs and regenerating fish stocks. OSW farms together could form a network of eco-corridors.

Priorities for research and innovation

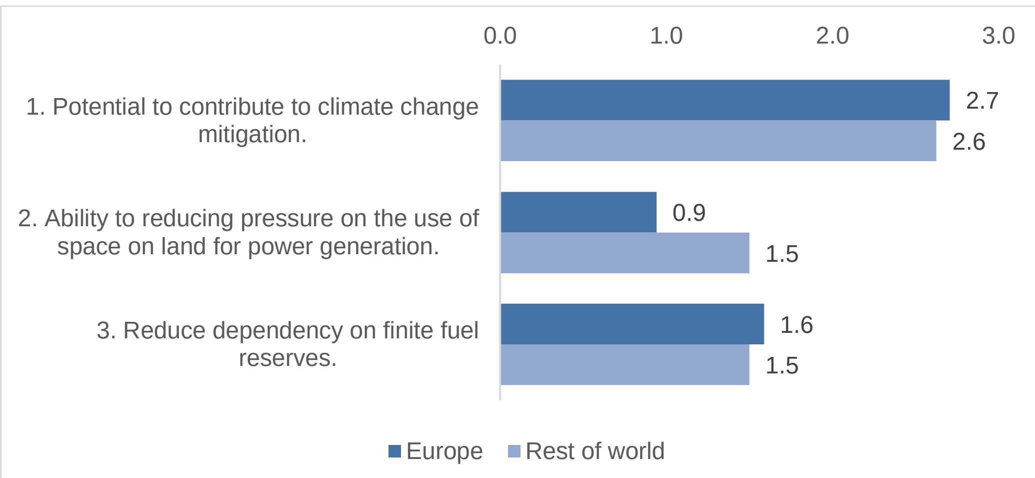

Figure 4: Environmental opportunities (Europe n=17; Rest of world n=8)

3.2 Social-environmental

3.2.1 Social-environmental challenges

Overview of literature review results, with integrated nuances from survey

End-of-use management: When OSW infrastructure reaches end-of-use the components should preferably be reused or recycled as per regulations following the waste hierarchy and polluter pays principle (Topham and McMillan 2017, Jensen et al 2020). Governance and industry practice on ‘decommissioning’ need to be established further. For example, reuse performance is limited in the North Sea oil & gas sector in the UK (in part due to considering reuse and recycling under one banner while they are entirely different processes requiring a different approach before and during decommissioning operations) and this should be prevented for OSW (Velenturf et al 2020). In regions falling under OSPAR regulations, sites should be left in a similar condition as before deployment of OSW while in other countries leaving structures in situ is an option (Topham and McMillan 2017), and there is an on-going discussion about whether leaving infrastructure in place at end-of-use can offer better environmental value in some cases (Smyth et al 2015).

Marine spatial planning: Coastal areas will transform further with more marine renewable energy, adding to pressure from human activity, and there is a need for spatial planning to manage environmental sustainability (Azzellino et al 2013). There is demand for long-term marine spatial planning and to combine this with short/ mid-term policy and managing interactions with other uses of the marine environment (Kannen et al 2013, Soukissian et al 2017); confirmed by a survey participant from Europe and nuanced by responses from outside of Europe, as OSW developments are seen as a risk to the livelihoods of local populations depending on fishing. In the decommissioning of oil & gas infrastructure in the North Sea a lack of marine planning was considered to hold back potential to reuse and repurpose assets for example for OSW (Velenturf 2020).

Social perceptions: The impacts on the biophysical surroundings can also affect people, for example through visual and noise disturbance (Karakosta et al 2013). This impacts on social perceptions of OSW development. Social perceptions on OSW differ between locations. OSW is generally more accepted the further away from the shore and out of view and hearing distance it is (Karakosta et al 2013, Contestabile et al 2017, Ahsan and Pedersen 2018, Morrissey and Heidkamp 2018), but in places such as in the Mediterranean opposition can be persistent because OSW is considered a risk to tourism income (Soukissian et al 2017). Public acceptance is considered an important sustainability factor (Karakosta et al 2013). Social perceptions should be investigated and knowledge should be exchanged across the EU (Soukissian et al 2017). A survey participant from Europe emphasised the importance of education on the benefits of OSW.

A participant from outside of Europe noted a lack of understanding from nature conservation groups about the benefits of OSW for the overall protection of the environment.

Priorities for research and innovation

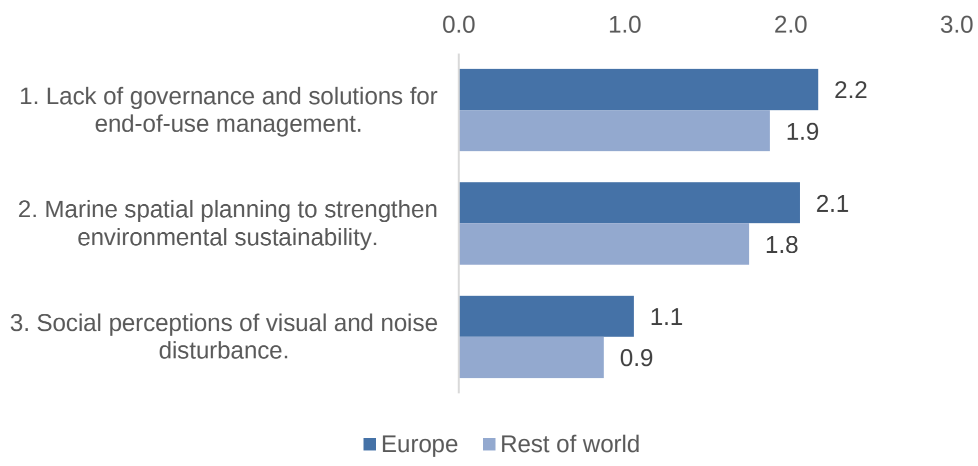

Figure 5: Social-environmental challenges (Europe n=18; Rest of world n=8)

3.2.2 Social- environmental opportunities

Overview of literature review

None

Additions from survey

Survey participants added several remarks regarding public perception. One argued that turbines can be considered admirable and aesthetically pleasing structures. Others stuck to the existing narrative that OSW is further away from land and causing less visual and noise pollution, thereby being more palatable for people. It was argued that any remaining concerns could be ameliorated with the potential for jobs, environmental benefits and cheaper energy supplies. However, a respondent from outside of Europe emphasised that the benefits must go beyond payment of royalties and has to constitute participation of communities in public-private cooperation. Similarly, OSW operators could grow public acceptance by playing an active part in environmental actions.

The potential for growing acceptance through the creation of synergies was articulated further by participants from all corners of the world, in the form of e.g. creating artificial reefs in support of the fishing industry and nature conservation, tourism including educational tourism to OSW farms, transport and marine electric mobility, hosting research infrastructure/ sharing data and, eventually, the creation of new floating sustainable communities or man-made islands. This opportunity is strongly visible in the fully integrated opportunities as well.

The transition away from fossil fuels and towards OSW reduces pressure on land for power generation in densely populated coastal communities.

A trade off with the lower energy costs due to OSW growth was noted by a participant from Europe, because per capita energy use has to decrease all the while switching to renewables as well. The transition to renewable energy offers the opportunity to reduce energy consumption altogether. This is also important in following the energy hierarchy and the position of growing OSW in relation to that. While OSW energy has a better sustainability potential than for example fossil fuels, the energy can still be used in unsustainable manners and would not necessarily contribute to achieving environmental gains and net zero – while OSW offers the opportunity, achieving and proving this is still a challenge.

Priorities for research and innovation

No figure because no opportunities from review.

3.3 Social

3.3.1 Social challenges

Overview of literature review, with integrated nuances from survey

Identifying and engaging stakeholders: OSW development involves multiple actors at different stages of the lifecycle, there is spillover between the phases, and actors, resources and activities are interdependent – all of which justify co-creation as a logical approach (Brink 2017). The marine environment is used by different actors with diverse perceptions, values and attitudes (Kannen et al 2013). It is challenging to map a project's primary stakeholders to evaluate their needs, expectations and influencing abilities – both during development of an OSW farm and the O&M stage (Soukissian et al 2017, Ahsan and Pedersen 2018). While stakeholder engagement is integrated into OSW ISO standards, is it considered a major challenge (Ahsan and Pedersen 2018) perhaps due to the difficulties to orchestrate all interests, views and understandings of concepts (Wever et al 2015).

Uncertain and inadequate regulations: Regulations form a challenge for different reasons with likely geographic and cultural variations. Chen (2011) reports demand for more regulation to deploy OSW in China. Topham and McMillan (2017) note a lack of specific regulations which increases uncertainty in decommissioning processes and this may be the reason why, in the UK, decommissioning plans for OSW tend to be inadequate (Topham and McMillan 2017, Jensen et al 2020). Drunsic et al (2016) discussed specialised regulations on vessels in the US, the Cargo Preference Act, which forms a challenge for OSW deployment. Soukissian et al (2017) argue that environmental impact assessments are challenging because it involves checks to prevent adverse effects to MPAs and meeting Natura 2000 directives. Participants from Europe mention underdeveloped environmental permitting regulations, policy integration to include carbon taxation and subsidies, and the dynamic political situation.

Approaches and criteria for marine spatial planning: There is a need for more marine spatial planning, and criteria to assess sustainability of various human activities, to balance various uses of the marine space and nature conservation (Azzellino et al 2013).

Azzellino et al (2013) argue that quantitative marine spatial planning criteria are requested to evaluate sustainability of conflicting human activity in the Danish North Sea. Survey participants from Europe confirm this, highlighting challenges around cumulative impacts of OSW farms in marine spatial planning and estimating the impacts as a result of policy and regulation. Participants from outside of Europe mention the importance of liaising between users of the marine space, and note the risk of opposition against OSW when the impacts are unclear. Moreover, social impacts have to be integrated into marine spatial planning as well.

Getting involved in ocean zoning and nature conservation: Industry is often not involved in ocean zoning development, especially at international level, but they are majorly affected. This is due to lack of understanding of movement behind ocean zoning, industry being stuck in sectoral processes and less in multi-stakeholder processes where zoning is discussed, and a lack of means to involve broader ocean business community on marine management and sustainability issues especially at global level (Holthus 2009). Locally, allocation of areas as MPAs is a challenge for deploying renewables at sea in the Mediterranean, but also an opportunity when co-locating MPAs with power facilities because they can keep other marine activities away (Soukissian et al 2017).

Cross-sectoral learning: OSW decommissioning requires learning across sectors, bringing together techniques developed for onshore wind and oil & gas (Topham and McMillan 2017). While remaining a challenge, some countries are better placed to build upon expertise developed for the exploitation of hydrocarbon reserves which could be transferred to OSW and other ocean-based renewables due to their industrial history (Henry et al 2015). A survey participant from outside of Europe adds that the efficient and fast information sharing between academia and industry can help.

Learning from experiences in a dynamic and competitive context: Experience in both the commissioning (e.g. in China – Chen 2011) and decommissioning is limited (Topham and McMillan 2017). During operation, competition between subcontractors that offer O&M to operators is strong because a) the number of subcontractors in the market is growing and b) operators have a powerful position in relation to subcontractors, and this limits willingness of subcontractors to share information to improve services which adversely impacts on O&M costs minimisation and maximising energy generation (Ahsan and Pedersen 2018). Ahsan and Pedersen (2018) continue to argue for vertical coordination in the supply chain to share information via meetings and platforms, but experience with this is lacking in the sector. Building on the findings from Ahsan and Pedersen (2018), it is clear that it is the speed of OSW deployment that makes it challenging to learn and improve in between projects. In the case of decommissioning, experiences are limited to a small number of OSW farms and no standard methods are developed yet (Topham and McMillan 2017, Jensen et al 2020).

Additions from survey

A participant from outside of Europe raised the concern of a developing underclass of workers that are poorly paid while carrying out hazardous work, similar to developments in other energy sectors.

Priorities for research and innovation

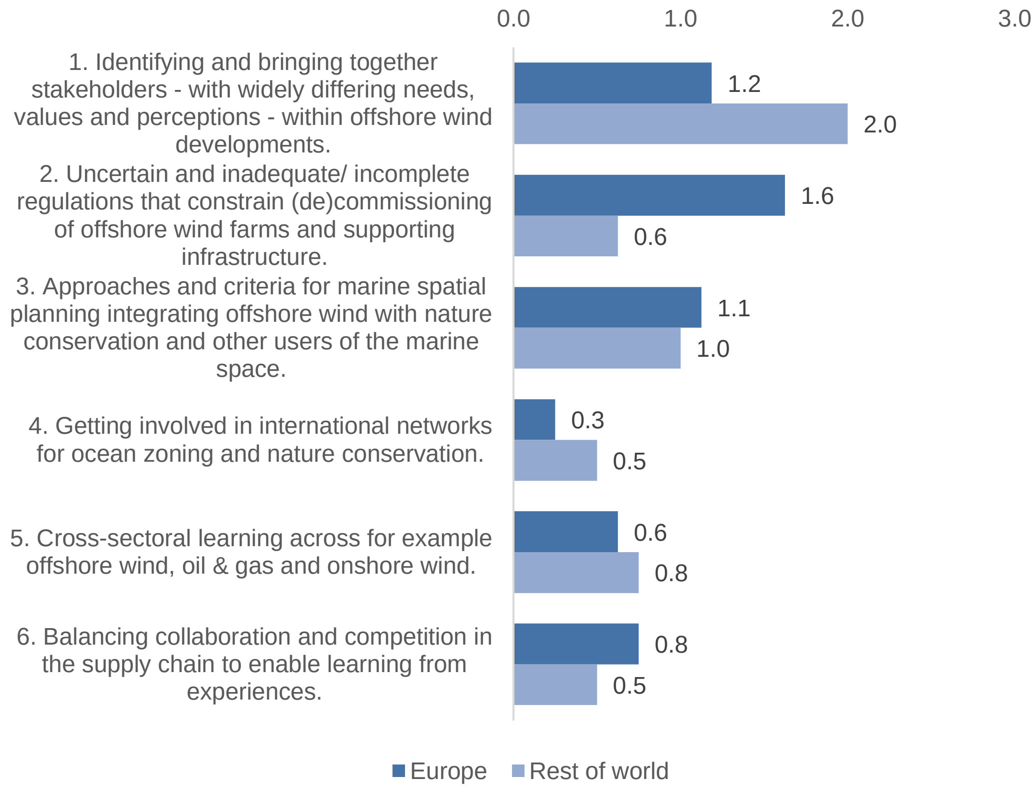

Figure 6: Social challenges (Europe n=16; Rest of world n=8)

3.3.2 Social opportunities

Overview of literature review, with integrated nuances from survey

Proactive and integrated stakeholder engagement: Integrated approaches to managing marine space would enable the early detection of potential areas of conflict and associated actions to mitigate and/or negotiate between stakeholders (Azzellino et al 2013). Proactive engagement of stakeholders is an opportunity to capitalise on local knowledge and avoid or overcome local opposition. Brink (2017) refer to this as 'frontloading' the coordination with local experiences, continuous local learning, cross-fertilisation of ideas, and alternative preparation and planning. Similarly, Soukissian et al (2017) argue for a site specific social impact assessment and involving stakeholders in the whole process to explain the impacts and benefits for them. It is indeed evident that residents become more positive about OSW when they understand the impacts better (Morrissey and Heidkamp 2018). Other factors that help limiting opposition is the location of OSW out of view and hearing distance, and linking OSW to projects that help to reduce costs such as desalination for fresh water supply (Contestabile et al 2017, Morrissey and Heidkamp 2018).

Spatial decision support systems: Spatial decision support systems could enable efficient exchange of information between experts, decision makers and other stakeholders, to enable the integrated management of marine space rather than single sector management (Azzellino et al 2013).

Understanding policy processes: The processes that shape policies are often overlooked but understanding them offers opportunities to successfully drive OSW uptake (Normann 2015). Conversely, a lack of understanding can lead to linking OSW to inappropriate agendas such as in the case of Norway where OSW was linked to the dip in the oil market, but the dip did not last long enough for OSW to take hold.

Additions from survey

A participant noticed the synergies as all opportunities can be seen as strongly interlinked, but they can also hold each other back.

Building on the challenge of cross-sectoral learning, there is also the opportunity to support learning across OSW, oil & gas and onshore wind, for example through a centre of excellence, which can also help in the transition away from fossil fuels and the creation of jobs.

Priorities for research and innovation

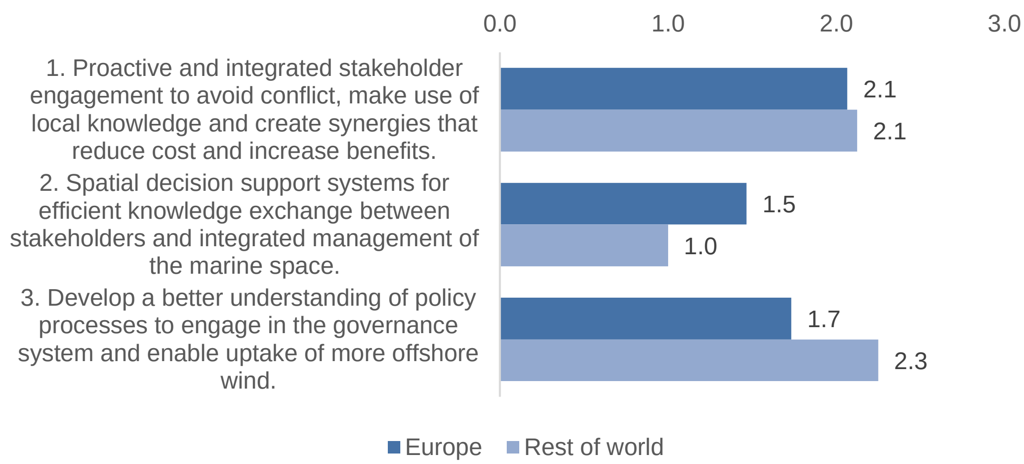

Figure 7: Social opportunities (Europe n=15; Rest of world n=8)

3.4 Social-economic

3.4.1 Social-economic challenges

Overview of literature review, with integrated nuances from survey

Skills access: Access to local wind power expertise and skills can be a challenge such as in the UK (Offshore Wind Connections 2019 – communications by Vestas, Siemens, Humber LEP) and parts of the Mediterranean (Soukissian et al 2017), while in other regions access to a readily skilled workforce is an opportunity (Morrissey and Heidkamp 2018). Survey participants from Europe brought to the fore that there is a chicken and egg issue, in that the creation of local supply chains can be challenging in Europe and this impacts on the benefits that can be created for local communities. At the same time finding skilled workers can be difficult. The creation of jobs and a skilled workforce were mentioned a number of times, with concerns raised about on-going digitisation and an aging engineering workforce. The reskilling of oil & gas industry staff for OSW is perceived to be challenging. Participants from outside of Europe agreed on the challenges to train local workers, from e.g. onshore wind and oil & gas sectors, to work in OSW. Without local workers the potential to generate local economic benefits is constrained. Others noted the use of a poorly paid underclass of migrant workers which is not sustainable and also limits regional job creation close to OSW developments.

Staff safety: Safety risks around personnel movements, working at heights, and working with high voltage and currents (Ahsan and Pedersen 2018, Morrissey and Heidkamp 2018). Others would, however, argue that OSW has a relatively low accident rate compared to other power supply technologies, and certainly a low large accident risk (Stamford and Azapegic 2012). Survey participants suggest, however, that a wider perspective including more of the construction and operational aspects should be taken into account. A participant from outside of Europe suggested that staff safety could be guaranteed better with more monitoring of OSW installations.

Additions from survey

Social justice in supply chains was raised as a concern, linking the sourcing of copper and rare earth elements to slave and child labour as well as the displacement of indigenous people.

Realising a just transition is a challenge, expressed by for example uncertainties around using the reducing cost of OSW to equally reduce energy bills and thereby enhance peoples' lives.

The challenges around establishing local supply chains and creating local jobs have a knock-on effect on the strength of local economies and development of other industries.

Priorities for research and innovation

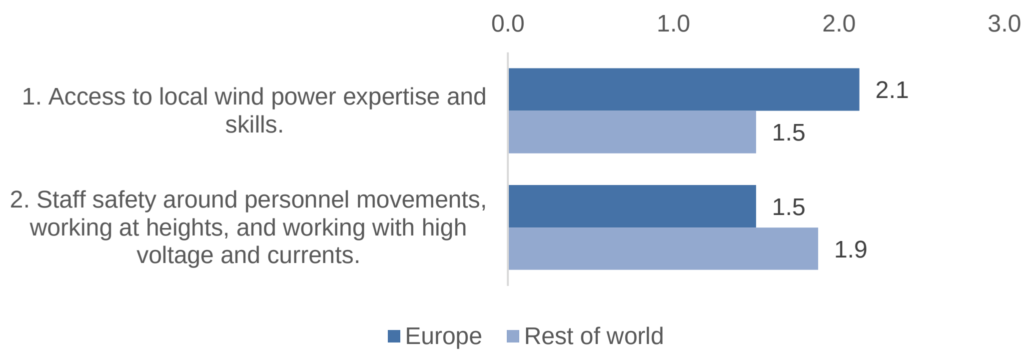

Figure 8: Social-economic challenges (Europe n=16; Rest of world n=8)

3.4.2 Social-economic opportunities

Overview of literature review, with integrated nuances from survey

Population growth: More renewable and sustainable energy is being installed to meet the increasing consumption of a growing population, such as demonstrated by Amran et al (2020) in the case of Saudi Arabia. While this offers opportunities for renewables sectors, the rising demand is a challenge from the perspective of environment (Scott and Barrett 2015) and also economically to meet demand for renewable energy in time (Amran et al 2020).

Energy security: OSW integrated with other renewables offers opportunities for countries to increase energy security and become self-sufficient (Contestabile et al 2017, Amran et al 2020), which is important for economic stability (Amran et al 2020). Survey participants noted that OSW can help island communities to become more resilient and enable local improvements in developing countries.

Job creation: OSW can drive economic growth and create jobs, and it is considered an important aspect in sustainability assessment (Karakosta et al 2013), but estimates of job-potential are not available everywhere and jobs may not be evenly distributed due to the clustering of low-carbon technologies (Soukissian et al 2017, Morrissey and Heidkamp

2018). Comparison of power supply technologies showed that OSW has a high direct and indirect employment potential (Stamford and Azapegic 2012). However, as a participant from Europe noted, the potential to create jobs depends on the industrial diversity of a region (which determine for example the potential services that can be offered to the OSW supply chain, sites that can be adapted for OSW manufacturing etc, and presence of workers with relevant skills). Industries and technologies evolve and this requires adaptation in the skills available in a region, as demonstrated by the many answers from experts around the world regarding the reskilling of oil & gas workers. OSW offers potential for more jobs in environmental monitoring and performance too.

Additions from survey

Realising OSW has the benefit of avoiding fines from the EU for missed renewable energy targets.

OSW offers new opportunities for local supply chains, such as to increase local contents across the entire OSW lifecycle including decommissioning (in its broadest sense). OSW can also drive innovation and support for onshore wind and other industries.

OSW can increase energy generation in remote areas, thereby creating opportunities for other industries to establish themselves.

Political support for OSW is important in order to get going (as demonstrated in for example the USA recently).

OSW could develop new ownership and business models that are more equitable, and thereby create new models for workers in the energy sector too.

Priorities for research and innovation

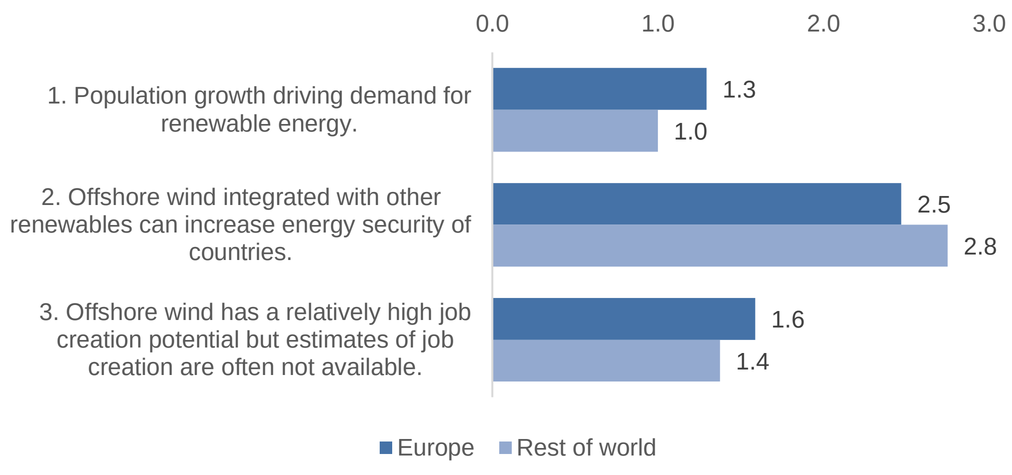

Figure 9: Social-economic opportunities (Europe n=17; Rest of world n=8)

3.5 Economic

3.5.1 Economic challenges

Overview of literature review, with integrated nuances from survey

Unstable markets: Creating stable market conditions to enable development, with an important role played by governments, e.g. in the EU via the Renewable Energy Directive which obliges every country to prepare national plans and forecasts for deployment; conversely, dynamic regulatory, policy and market conditions as well as financial and political instability constrain market development (Soukissian et al 2017). This suggests that the economic crisis following Covid-19 poses a high risk, exacerbated in the UK by the departure from the EU.

Market structure: The structure of conventional electricity markets is a barrier for OSW (Karakosta et al 2013).

Funding and finance: Access to stable and affordable funding and finance is important to reduce cost and enable deployment of OSW, and this requires support from the banking sector and government (Pal et al 2017, Soukissian et al 2017, Ahsan and Pedersen 2018).

In some places there is a lack of incentives that hold back deployment (Karakosta et al 2013), confirmed by a survey participant from outside of Europe.

International trade: While supply chains in some parts of the world have been established, such as in Europe, it is difficult for other markets to establish a manufacturing base such as in India – due to raw materials being subject to higher import duties than importing components – and in the US – which will have to break into markets by reducing costs by increasing efficiency and competitiveness e.g. for complex logistics (installation and transportation infrastructure) and equipment (specialised equipment and supply chain management for large components that are produced in batches) (Drunsic et al 2016, Pal et al 2017). If manufacturing capacity does increase, however, it can be a driver for OSW deployment (Karakosta et al 2013).

Port infrastructure: In the US limited port infrastructure is a challenge for the establishment of OSW manufacturing and development (Drunsic et al 2016). It is unclear whether this challenge is replicated in other locations as well, but a survey participant from outside Europe confirmed that development of local ports and logistics for OSW is a challenge that increases costs and dependency on other regions.

Costs and cost uncertainty: Costs throughout the lifecycle of OSW – from manufacturing to deployment, operation, maintenance and decommissioning – are still too high in some markets and subject to inefficiencies and uncertainties, and this constrains use of available wind resources (Shaker and Patton 2014, Henry et al 2015, Pal et al 2017, Ahsan and Pedersen 2018) while a lack of design for decommissioning can unexpectedly increase costs (Topham and McMillan 2017, Jensen et al 2020). Viability of OSW may still rely on feed-in-tariffs (Soukissian et al 2017) and costs have to be reduced to assure affordability for consumers and business sustainability (Rohrig and Lange 2008, Ahsan and Pedersen 2018, Amran et al 2020).

Complex supply chain: From Ahsan and Pedersen (2018) it can be derived that the supply chain structures is OSW are complex because stakeholders can play multiple roles depending on the project. For example, operators can also be OEMs and OSW farm owners, or only operate as OEM for a project, or function as third party O&M provider.

Tendering processes tend to be challenging for subcontractors and could be eased with common standards for all subcontractors (Ahsan and Pedersen 2018). At end of use, operations tend to be site specific with different market conditions and contractual terms (Topham and McMillan 2017).

Additions from survey

In Europe, support to establish local OSW supply chains and OSW farms is a challenge politically and in the energy transition, as fossil fuels still receive incentives and benefit from a lack of meaningful global carbon pricing.

While the focus still is on decreasing costs, potential for further reductions may be reaching a limit in Europe. Current auction prices for offshore leasing are too low for original equipment manufacturers to manufacture competitive products and continue research and development into for example more efficient manufacturing methods, while the growing scale of components produced with traditional materials and methods becomes too expensive to manufacture, transport and install (although one respondent thought costs would continue to decrease due to OSW growth). From outside of Europe it was perceived that competition among original equipment manufacturers and installers is limited and competition may decrease further with the uptake of larger turbines, and this may disadvantage onshore and offshore markets.

Globally, challenges were raised regarding the whole energy system and the energy transition in terms of the relative competitiveness of OSW compared to other energy technologies that can suddenly become cheaper (such as hydrogen) or that are already more affordable in places (such as onshore wind and solar); Integration with electric vehicles; and OSW owned by fossil fuel companies causing conflicts of interest.

Priorities for research and innovation

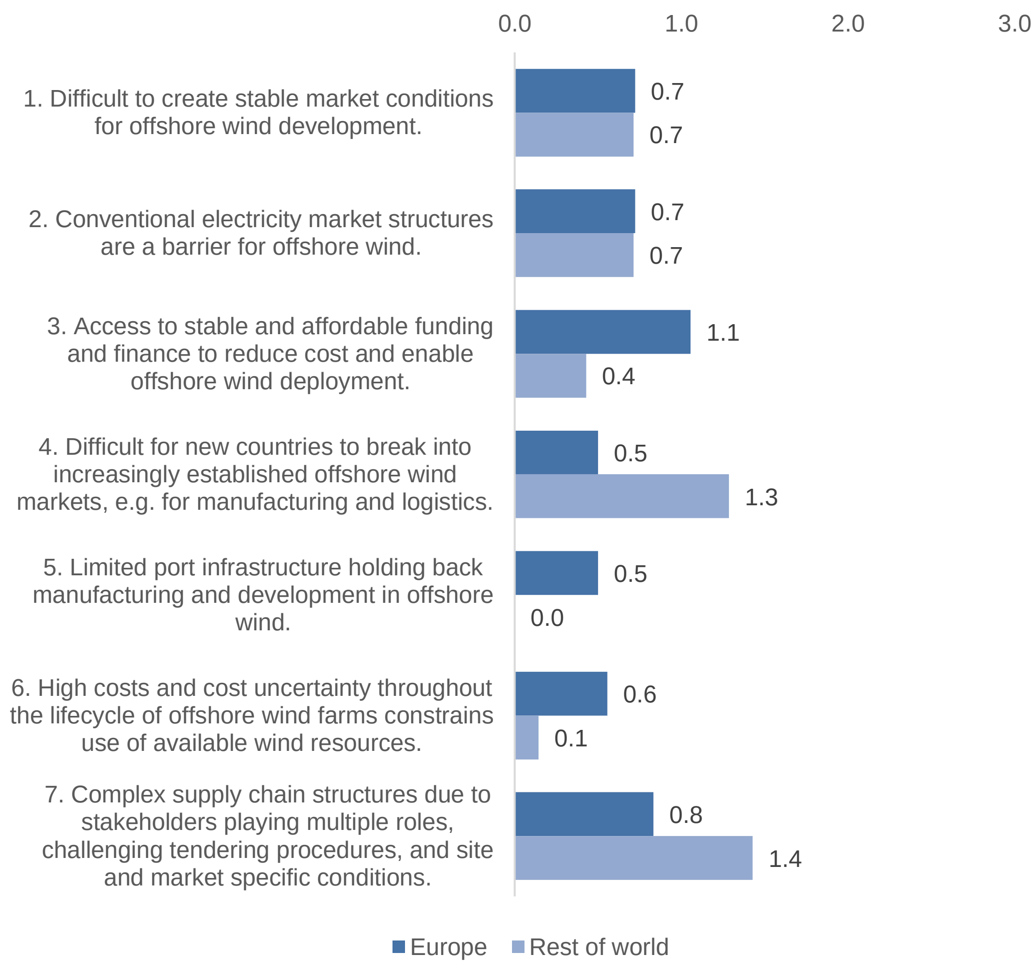

Figure 10: Economic challenges (Europe n=18; Rest of world n=7)

3.5.2 Economic opportunities

Overview of literature review, with integrated nuances from survey

Economies of scale: OSW offers opportunity to reach economies of scale by accessing stronger and more consistent wind resources further away from the shore and developing larger scale OSW farms (Contestabile et al 2017, Soukissian et al 2017, Ahsan and Pedersen 2018). Increasing performance, operational time and reliability, related to larger turbines and technological advances, is a driver for OSW deployment (Stamford and

Azapagic 2012, Karakosta et al 2013). OSW is forecasted to continue growing significantly until 2050 in Europe (Lichtenegger et al 2020).

Reducing LCOE: LCOE can be reduced by deploying larger turbines, realising more OSW farms, increasing the energy capture rates, and ensuring an appropriate and efficient policy framework (Simani 2015, Soukissian et al 2017). The literature proposes two seemingly opposing network strategies to reduce LCOE (levelised cost of energy): increasing competition (Soukissian et al 2017) and joint stakeholder action (Ahsan and Pedersen 2018).

Fossil fuel prices: High fossil fuel price can be a driver for more renewables (Henry et al 2015) but Normann (2015) argues that this may be an inappropriate policy target which, in Norway, has proven to be a negative risk for OSW.

Short development time: Compared to other electricity infrastructure, OSW has a short development time and new sites can be commissioned fast (Stamford and Azapegic 2012).

Additions from survey

OSW offers opportunity for ethical investment (suggested by participant from Europe).

OSW can be part of a sovereign wealth fund based on renewables (suggested by participant from Europe).

Priorities for research and innovation

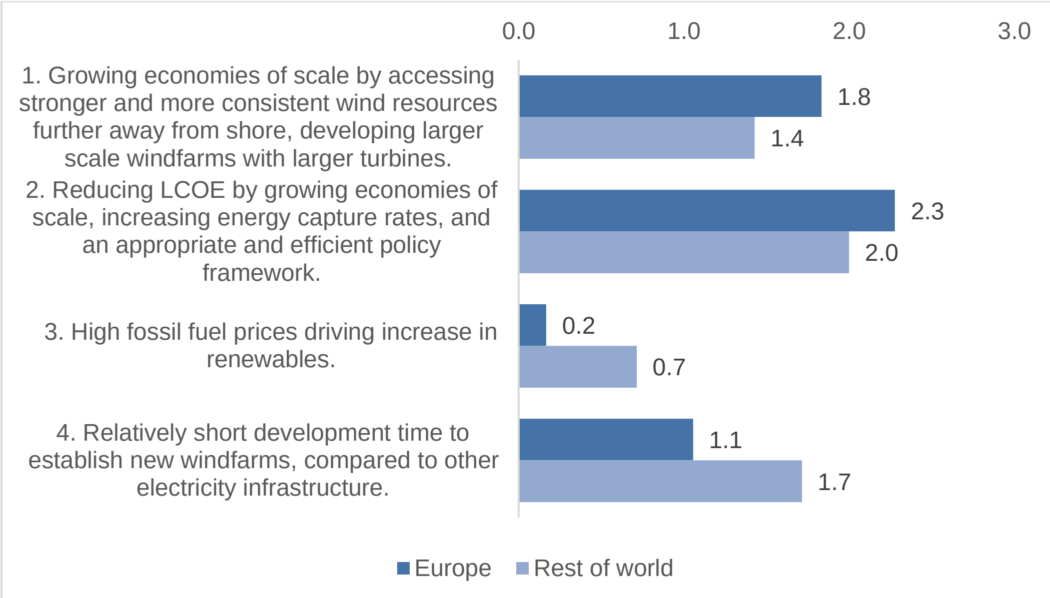

Figure 11: Economic opportunities (Europe n=18; Rest of world n=7)

3.6 Techno-economic

3.6.1 Techno-economic challenges

Overview of literature review, with integrated nuances from survey

Grid capacity, connectivity and integration: Renewables and nuclear require extra grid capacity, this is a challenge cutting across the whole energy system and if another technology would take up grid space first (e.g. nuclear, 60 years; solar PV, 35 years) then there could be less space for OSW for the lifetime of that technology (Stamford and Azapagic 2012). Renewables increase the demand for the grid to offer operating reserve capacity (unused capacity on grid to balance out predicted short-term changes in demand and supply), in the UK to the tune of 4.78GW with 5.8GW wind in 2011/12 to 8.13GW with 30.6GW wind in 2025/26 (Stamford and Azapagic 2012). Globally, grid capacity is a limiting factor in many locations, space on the grid alongside availability of an onshore connection and tools to manage integration of intermittent supply are crucial for OSW (Rohrig and Lange 2008, Chen 2011, Karakosta et al 2013, Contestabile et al 2017, Pal et al 2017, Soukissian et al 2017, Ahsan and Pedersen 2018, Morrissey and Heidkamp 2018). This is a trade-off with agglomerations i.e. the clustering of low-carbon technologies (Morrissey and Heidkamp 2018).

Intermittency: While OSW power generation is less variable than onshore wind (Soukissian et al 2017), there is still a challenge of intermittency. There is a challenge with the integration of renewables into the grid due to fluctuating and intermittent power generation, which was expected to affect the grid security, operation of other power plants, and the economy of the whole supply system in Germany (Rohrig and Lange 2008) – and in other countries too (Karakosta et al 2013). Energy storage (Soukissian et al 2017) and multi-functional platforms e.g. combining wind and wave power (Contestabile et al 2017) could offer solutions. A participant from Europe argued that wind and solar energy can be forecasted very well now and should not be considered intermittent but rather as variable power plants.

Inventorying wind resource: There is an on-going demand for the inventorying of 'wind resource' i.e. the potential capacity that could be realised depending on wind patterns (see e.g. Soukissian et al 2017, Amran et al 2020). Chen (2011) argues that such inventories are not carried out sufficiently in China and this risks developing OSW farms that may not be economically viable.

Distance from shore: Moving OSW further away from the shoreline increases challenges because it makes transport and O&M more complicated and time consuming and increases costs (Brink 2017, Ahsan and Pedersen 2018) and, as a participant from outside of Europe added, requires the use of more fuel (and this has environmental implications as well). This poses challenges to current instrumentation techniques.

Fault detection and control: Requirements for safety, reliability and availability are increasing because unexpected malfunctions can lead to enduring shutdowns until repairs can be carried out – exacerbated by marine and weather conditions (Simani 2015). There is demand for advanced fault detection and control systems to maintain system sustainability and keep turbines operating until repairs can be carried out (Shaker and Patton 2014, Simani 2015). This would limit the financial risk of component failure (e.g.

gearboxes, generators and transformers) and keep power generation going (Ahsan and Pedersen 2018). A participant from Europe suggested demand for real-time monitoring and management capabilities.

Vessel availability: There is a shortage of vessels and for vessels with the right equipment for construction, O&M and decommissioning (also with competition for vessels for oil & gas decommissioning) and this increases costs (Topham and McMillan 2017, Ahsan and Pedersen 2018).

Uptake of recovered materials from blades within supply chains: There are no connections between solutions to recover materials from blades and end-users (Lichtenegger et al 2020). Uptake is further held back by the low cost of virgin materials and low demand for recycled fibres, low cost of landfilling (in some locations), and the lack of consistent supply of waste materials (Lichtenegger et al 2020). A better insight into the waste arisings is required to develop solutions (Lichtenegger et al 2020), and this can be supported by better data systems (Purnell et al 2018) – the variations and fluctuations of waste arisings between countries requires solutions across the wider geographic area, to link supply of waste with demand for recovered materials at the lowest transport cost possible (Lichtenegger et al 2020).

Additions from survey

Hydrogen can add flexibility to connect OSW into the whole energy system, but reducing the cost of green hydrogen production from OSW is a challenge.

The growing scale of OSW infrastructure raises demand for new construction and operation methods.

Reducing LCOE for floating wind was perceived as a challenge by one respondent from Europe, but floating wind was generally seen as an area of opportunity.

Continuing the reduce costs puts pressure on innovation capacity (see economic challenges) and, according to a participant from Europe, government support is required to support innovation and the adoption of innovations in supply chains.

Priorities for research and innovation

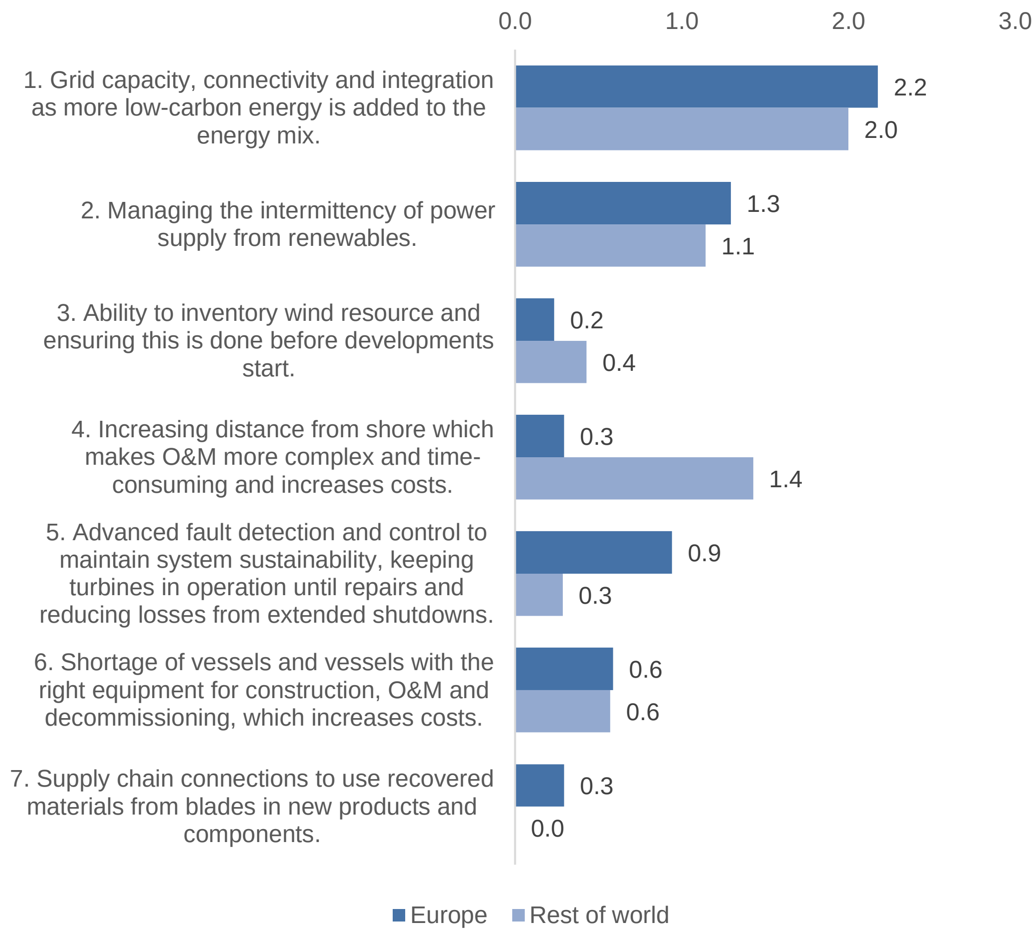

Figure 12: Techno-economic challenges (Europe n=17; Rest of world n=7)

3.6.2 Techno-economic opportunities

Overview of literature review

Battery costs: There are interactions between renewable energy and EV sector developments, because the drive for more EV is anticipated to reduce costs of batteries and this would make energy storage for renewables more affordable (Soukissian et al 2017); although one could argue that greater demand for resources could increase costs too.

Multi-functional infrastructure: Multi-functional structures that for example combine wave and OSW power can lower development costs and reduce costs and risk during operation by sharing components, infrastructure and maintenance (Contestabile et al 2017, Soukissian et al 2017). It can also be a solution to manage variability of power generation (Azzellino et al 2013, Contestabile et al 2017).

Additions from survey

Additions from the survey were rich in opportunities for innovative grid solutions and the integration of OSW energy into the whole energy system:

- Participants from Europe emphasised the potential for smart distributed networks, with improved grid monitoring and AI management systems, to allow for more flexibility and less energy losses from OSW power. The OSW sector could also offer more services to the grid system and electricity markets.
- Another strategy is to make more use of the geographic dispersion of wind and the integration of balancing areas. This may be particularly effective when connecting various countries, different climate zones and types of renewables, as suggested by a participant from outside of Europe.
- Others, from Europe, highlighted the potential for power-to-X to integrate OSW energy into the energy system in the form of hydrogen instead and take pressure away from grid networks. It was argued that hydrogen from OSW would only be competitive at scale and is in need for more investment in innovation.

- Smart wind farms could produce power or hydrogen on demand.

In Europe, innovation in materials and structures was seen as an opportunity to reduce costs by easing commissioning processes and mitigating for the lack of appropriate vessels.

Participants from within and outside of Europe argued for the recycling of materials, which may be able to reduce costs of end-of-use management, but supply chains for “decommissioning” are still to be developed.

Finally, the wind industry operates in an insular manner but other infrastructure industries could benefit from wind expertise on large composite blades.

Priorities for research and innovation

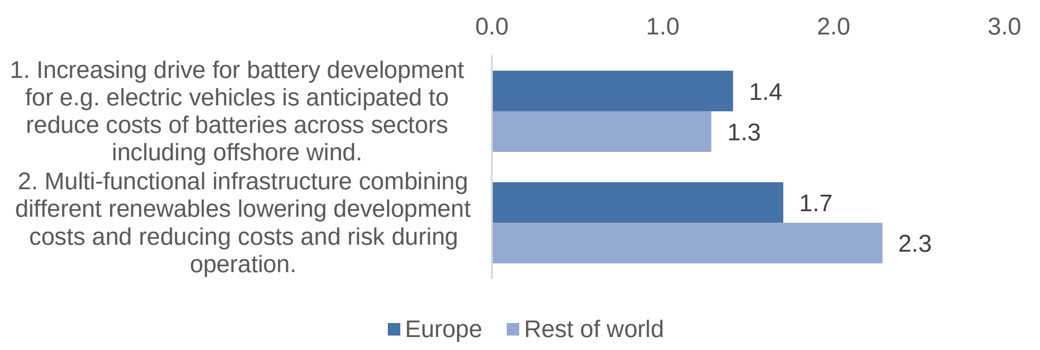

Figure 13: Techno-economic opportunities (Europe n=17; Rest of world n=7)

3.7 Technical

3.7.1 Technical challenges

Overview of literature review, with integrated nuances from survey

System efficiency: Concerns have been raised about the efficiency of energy supply. Contestabile et al (2017) raise the challenge around ‘wave-to-wire’ efficiency. Challenges around grid connections such as the landing place of OSW export cables and space on the grid – in addition to grid management challenges – are plentiful. A survey participant from Europe highlighted the demand for the provision of better real-time data on electrical performance. A participant from outside of Europe noted the importance of developing extra high voltage power evacuation facilities for OSW. Others, in the literature, have raised concerns about the energy efficiency of converting OSW power to hydrogen, reflected in a survey response raising a challenge about the integration with offshore electrolysis. Depending on the country and its particular energy supply systems, different solutions may offer better efficiencies, economic viability and social acceptance. For example, without established grid infrastructure it may be easier to convert power to hydrogen and use fuel distribution systems that are already in place (e.g. in the Maldives as an extreme example).

Plant flexibility: OSW is considered to have a relatively low plant flexibility because it can only supply electricity, whereas other energy technologies may be able to provide fuel, heat as well as power (Stamford and Azapegic 2012). This may change, however, with the introduction of hydrogen.

Complexity of (de)construction: OSW are complex construction projects (Brink 2017), particularly due to the large scale of OSW infrastructure and their increasingly complex engineering (Simani 2015). Moreover, OSW has been focused on setting up new projects with less attention for decommissioning, and this makes operations at end of use more difficult (Topham and McMillan 2017, Jensen et al 2020).

Lower velocity turbines: There is limited innovation for turbines that can operate at lower wind velocity, for OSW deployment in for example India (Pal et al 2017).

Data systems: There is demand for better data systems (Soukissian et al 2017). Informatics is seen as a future area of technological development (Borthwick 2016, Soukissian et al 2017). Data system challenges also came forward in survey responses from outside of Europe, with demand raised for a central database on continuous turbine data, the absence of which poses challenges for lifetime extension and end-of-use planning (which are constrained by the limited historical SCADA data on blade operational lifespan and repairs, exacerbated by limited standardization between original equipment manufacturers) but proprietary systems pose barriers to establish such a system.

Energy storage: Energy storage is a future area of technological development (Borthwick 2016, Soukissian et al 2017). A survey participant from Europe brought the potential for non-battery storage to the fore, using compressed air, raised or spinning weights, heat stores and hydrogen.

Advanced materials: The use of advanced materials is a future area of technological development (Borthwick 2016, Soukissian et al 2017). A survey response from Europe detailed a challenge further, as ineffective leading edge coatings can lead to a reduction in annual energy production.

Lifetime extension: Reduce structural loads to increase lifetime of components and whole turbine structures (Simani 2015).

Scour research: Scour reduces structure's stability at the foundation which has knock-on effects onto the cables which may have to bend beyond their design limits; bigger foundations are being used against scour for security reasons but at the same time scour increases with bigger diameter monopiles; scour appears to be worse in shallower waters with more mobile sediments; demand for better sensor techniques immediately from moment of construction onwards to understand the challenge better and enable development of anti-scour measures (Michalis et al 2013).

Blade waste management technologies: There is a lack of sustainable solutions to recycle reinforced composites that blades are mostly made of (Jensen et al 2020, Lichtenegger et al 2020). By 2050 it is forecasted that there will be 450GW wind capacity generating 325,000 tonne/ annum in blade waste alone, most will emerge from onshore in Germany and offshore in the UK (Lichtenegger et al 2020). There is a high variation in allowed blade waste management and the associated costs, e.g. blades are being landfilled in places in pieces but this carries a high cost in the UK and it is banned entirely in other locations (e.g. Germany). Incineration of blades for energy recovery presents various drawbacks, first of all because the glass fibres are not flammable and leaves a large volume of residues to dispose of at the end of the process, and it has adverse effects on the flue gas cleaning system (Beauson and Brondsted 2016). Burning in cement kilns is another pathway and mechanically recovered fibres can be integrated into concrete. There is some potential to reuse blade sections in alternative applications (Wind Europe 2020). There are social-economic barriers that hold back solutions.

Additions from survey

Floating wind design of structures and systems, operation and control, and mooring were all listed as challenges by participants from Europe.

Potential to reuse infrastructure from the oil & gas sector for OSW – e.g. pipelines for hydrogen, storage facilities and platforms – was raised as a challenge.

Priorities for research and innovation

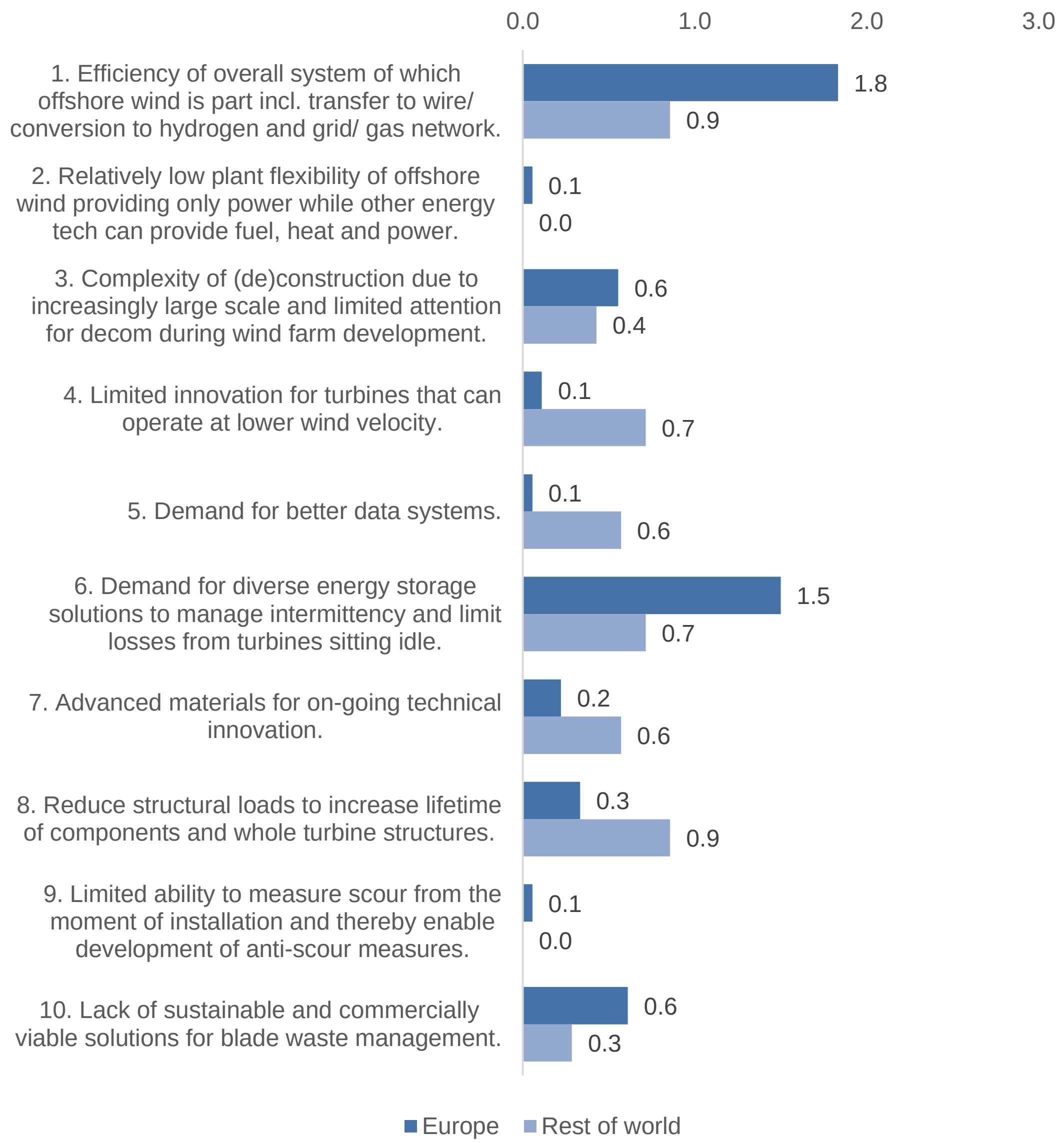

Figure 14: Technical challenges (Europe n=18; Rest of world n=7)

3.7.2 Technical opportunities

Overview of literature review, with integrated nuances from survey

Design for decommissioning: Sites can be designed up front to enable a retrofit with bigger turbines at end of use such as practiced in The Netherlands (Velenturf et al, Unpublished data), in case refurbishing or repowering is not feasible (Topham and McMillan 2017).

Robotics for remote O&M: Use of robotics offers opportunities for OSW with increasingly remote O&M, and this requires further technological developments (Borthwick 2016, Soukissian et al 2017).

Floating wind: Floating wind could ease decommissioning operations because it avoids the use of the increasingly heavy foundations (Topham and McMillan 2017). Floating wind was raised as an opportunity by survey participants from Europe, opening potential to develop in deeper waters, use multi rotor solutions, develop floating substations and integrate with offshore gas for hydrogen production.

Additions from survey

Opportunities were raised by participants from within and outside of Europe to use alternative materials and designs, replacing critical materials and materials that are difficult to reuse or recycle, developing vertical axis turbines and gain higher efficiencies with reduced system loads.

Operations and maintenance could benefit from the presence of secure 5G networks, the development and roll-out of advanced remote monitoring systems, multi-functional self-monitoring systems for data on loads and environment; informing advanced O&M strategies and transport planning and transfer of people.

There are opportunities to develop more energy storage in the form of high capacity local energy storage and using non-battery storage e.g. compressed air, heat stores, and spinning weights or raising weights.

Outside of Europe, reuse of oil & gas infrastructure was raised as an opportunity, for example reusing gas pipelines for hydrogen and synthetic fuel production, reusing ports, ships and crew accommodation, etc. Similarly, there is high potential to retrain staff from oil & gas to continue operating the infrastructure.

Priorities for research and innovation

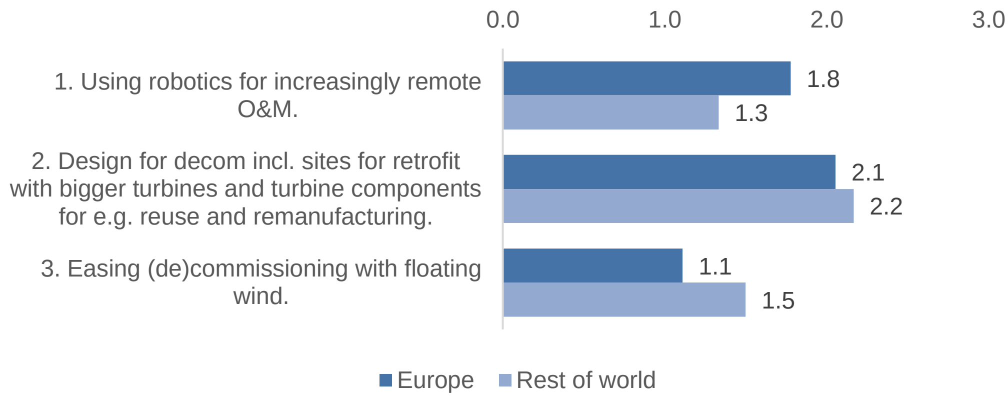

Figure 15: Technical opportunities (Europe n=18; Rest of world n=6)

3.8 Techno-environmental

3.8.1 Techno-environmental challenges

Overview of literature review, with integrated nuances from survey

Site specific conditions: Each location is unique and OSW farm design, (de)construction and operations must be adapted to the site specific conditions. This has mostly to do with weather, water depth, soil and time of the year (Brink 2017, Topham and McMillan 2017, Morrissey and Heidkamp 2018). Each project requires bespoke solutions over the lifetime of the OSW farm. Growth of OSW offered opportunities and challenges for site investigation industry, covering geophysical, geotechnical and environmental aspects – it is challenging because sites are dynamic and can have sensitive environmental conditions that make it difficult to collect data (Jenner et al 2002). Survey participants from within and outside of Europe confirmed that OSW resource assessment requires location specific geotechnical and geophysical studies and, once a location with a suitable wind resource has been identified, that site and technology specific baseline data on site ecology must be collected (to inform licence applications) which can be challenging and expensive.

Marine environment: The marine environment poses challenges throughout the lifecycle of OSW farms due to the logistics and diverse weather conditions (Shaker and Patton 2014, Topham and McMillan 2017). Decommissioning of OSW takes longer than oil & gas and hence it is more prone to varying weather conditions which impacts on the costs (Topham and McMillan 2017).

Additions from survey

A diversity of additional techno-environmental challenges was suggested (participant(s) location):

- SF6 – a potent greenhouse gas used in switchgear – must be replaced (Europe)
- Materials used in OSW components is still dependent on fossil fuels, such as the polymer resins used in blades (rest of world)
- Cumulative impacts from cables onshore and offshore (Europe)
- Associated OSW infrastructure onshore for construction, O&M and decommissioning (Europe)
- Development of local microclimates as a result of very large OSW farms (Europe)
- Understanding the impacts of the marine environment on component durability (rest of world)
- Understanding the impacts of submerged components on the marine environment through for example the leaching of coatings and disturbance of the sea bed (Europe)

Priorities for research and innovation

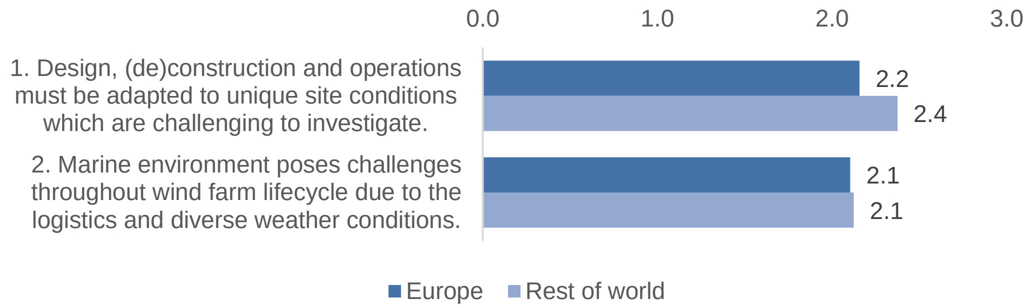

Figure 16: Techno-environmental challenges (Europe n=19; Rest of world n=8)

3.8.2 Techno-environmental opportunities

Overview of literature review

Less turbulence: OSW near shore can be exposed to relatively high turbulence levels, and moving OSW further away from the coast solves this challenge (Contestabile et al 2017, Ahsan and Pedersen 2018).

Site location for amenable environment: Optimise the siting of OSW farms, integrated with planning for other uses (e.g. transport, fishing) for environmental sustainability (Azzellino et al 2013). In Trinidad and Tobago, for example, the low wave heights, consistent wind and open waters near continent are all amenable to OSW (Henry et al 2013).

Additions from survey

Building on the additional techno-environmental challenges, the following opportunities were proposed (all are answers from participant(s) located in Europe):

- Development of offshore hubs (to reduce onshore infrastructure)

- Development of materials that are marine inert to avoid contamination of local environment
- Floating OSW turbines and cables to reduce impact on the subsea environment and possibly provide conditions for artificial marine habitat

Priorities for research and innovation

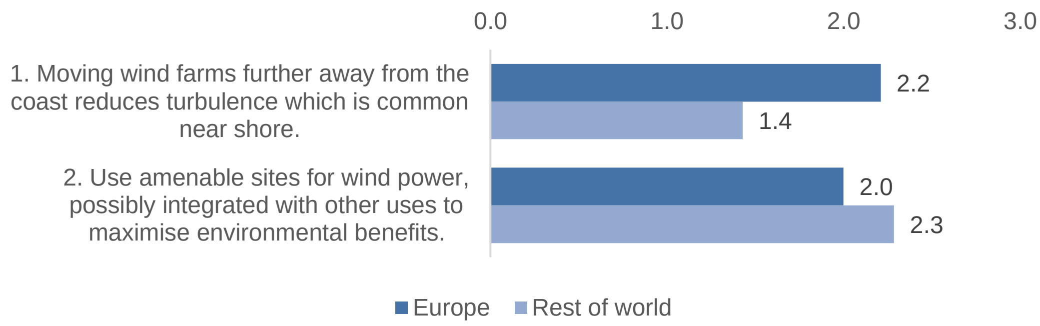

Figure 17: Techno-environmental opportunities (Europe n=19; Rest of world n=7)

3.9 Fully integrated

3.9.1 Fully integrated challenges

Overview of literature review, with integrated nuances from survey

Underexploited wind resources: In many locations around the world that would be suitable from a geotechnical perspective for OSW, OSW is hardly developed at all and/or not fully exploited including e.g. the US and Mediterranean (Shaker and Patton 2014, Drunsic et al 2016, Soukissian et al 2017). This review found environmental, social and economic reasons for this.

Whole system assessment: Uptake of large scale OSW should be subject to whole system assessment including forecasting capabilities, covering social, environmental, institutional and legal, and economic aspects, because OSW transforms continental shelves through socio-political decisions that are driven by climate change and a need for economic development (Kannen et al 2013).

Whole energy system: OSW develops within a dynamic whole energy system that is moving away from fossil fuels and competing with other alternatives such as various renewables and nuclear power (Normann 2015, Karakosta et al 2013). While this is a challenge, it is also an opportunity from the whole system perspective to optimise the electricity mix, bearing in mind that all power technologies have trade-offs (Stamford and Azapagic 2012).

Competition for space: While OSW reduces competition for space on land, it can still be constrained by – and impact on – different uses of marine space including e.g. in the Mediterranean: Economic (tourism, transport, fishing, aquaculture, mineral resources, oil & gas); Nature (Nature 2000, Ramsar); Security (military areas); and Cultural (sites of cultural heritage) (Azzellino et al 2013, Soukissian et al 2017). Floating wind may offer opportunities to move outside of areas of the sea that already have a competing use. With the growing use of the marine space there are growing challenges to manage conflicts and take a more holistic approach to marine planning. This an argument made in favour of decommissioning as well, to free up space and materials for new applications (Invernizzi et al 2020).

Additions from survey

All additional challenges that were raised could be integrated with those identified from the literature.

Priorities for research and innovation

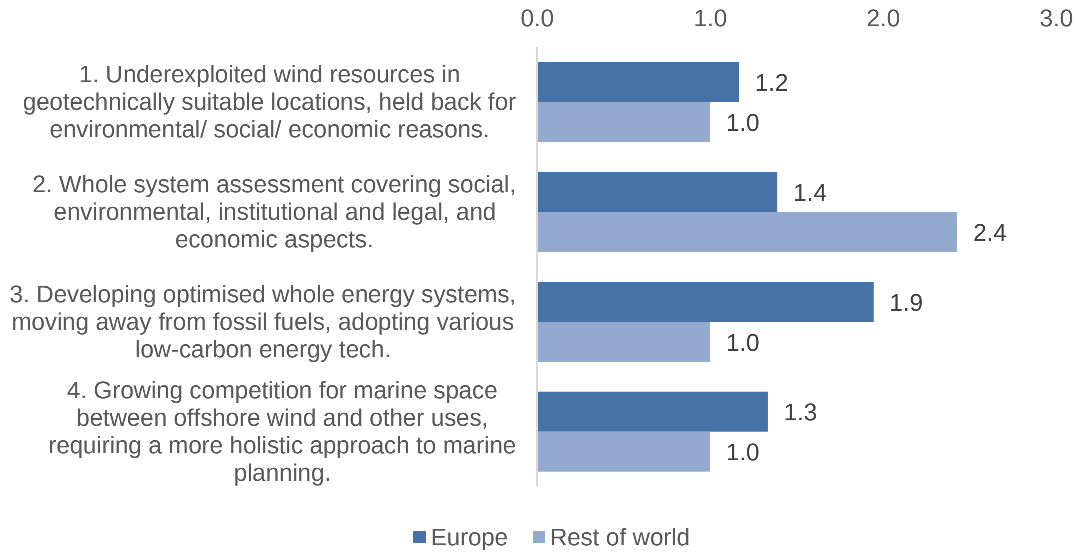

Figure 18: Fully integrated challenges (Europe n=18; Rest of world n=7)

3.9.2 Fully integrated opportunities

Overview of literature review, with integrated nuances from survey

Whole system design with multi-functional structures for multiple challenges: Each location faces different challenges depending on its geography, infrastructure, etc. and deployment of a site specific set of renewables in a particular way can help solve such challenges in an integrated manner. For example, on the Maldives a combination of wave and OSW power offers an integrated approach to address flooding, emergency situations, groundwater pollution, freshwater shortages, speculation, and fossil fuel dependency, with multi-functional structures and multi-use systems for power, desalination and coastal defence (Contestabile et al 2017). Similarly, the dispersed islands around Mediterranean Sea face higher energy costs and depend on energy intensive desalination for fresh water supply (Soukissian et al 2017). High energy costs and environmental impact of desalination for fresh water supply is also an issue in Saudi Arabia, and renewables could offer solutions (Amran et al 2020). Desalination systems powered by renewables may be worthwhile investigating for the UK, given the growing drought problems in the East of

England. Moreover, multi-functional structures can reduce conflict around the use of marine space, e.g. in the case of combining OSW with aquaculture (also suggested by multiple survey participants from Europe and the rest of the world), but this opens new technical challenges such as foundation design combined with cages as well as social challenges regarding legal arrangements and lack of experience in establishing such collaborations (Wever et al 2015). Multi-functional structures and combining renewables can lower cost (Azzellino et al 2013, Contestabile et al 2017, Soukissian et al 2017). Survey participants from around the world offered a great number of additional suggestions to this challenge from the integration of OSW with aquaculture to CO_2 sequestration and bioenergy, hydrogen production offshore, charging stations for e-mobility in the marine sector and production of synthetic fuels for heavy duty transport and industrial process heat generation, desalination plants, and the creation of new islands where communities or whole cities could be established off-grid.

Wind resource: Globally, the maximum global wind resource from OSW was estimated at 39TW (Soukissian et al 2017). For example, the UK has access to a steady wind resource with suitable average wind speeds (Morrissey and Heidkamp 2018, Sorenson 2020). The UK could provide itself with 100% renewable power by 2050 and export as well to the EU, and this could strengthen the position of the UK in trade negotiations with e.g. the EU which would benefit from the UK's wind resource to realise a sustainable energy system (Sorenson 2020). Exploiting the global wind resource is held back by various challenges and can be helped by several opportunities.

Additions from survey

All additional opportunities that were raised could be integrated with those identified from the literature.

Priorities for research and innovation

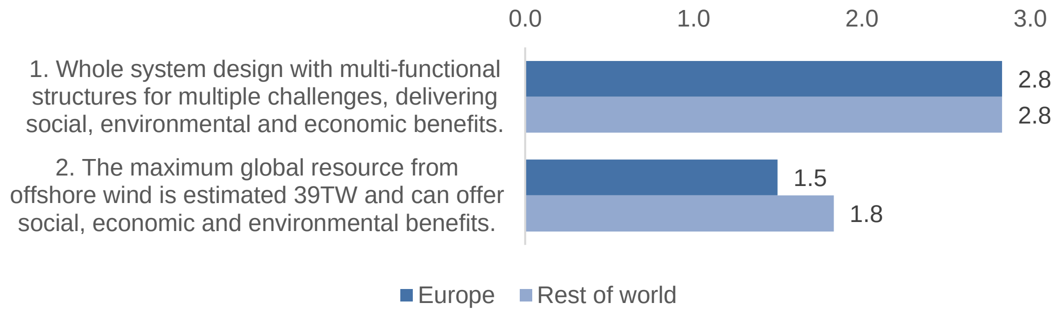

Figure 19: Fully integrated opportunities (Europe n=18; Rest of world n=6)

Acknowledgements

My sincere thanks go to the experts who generously contributed their time to take part in this study. I am also grateful to Drs James van Alstine and Imogen Rattle who reviewed the survey and Matt Thorpe who piloted it.

The study on sustainable offshore wind development was part of the Geoscience and The Energy Transition project funded by the University of Leeds.

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Appendix: Bibliography for offshore wind development challenges and opportunities

Search results from Scopus on 2 April 2020, with search terms “sustainability” and “offshore wind” and “challenge”, presenting publications in English only:

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Search results on Scopus on 29 April 2020 for “offshore wind” AND “sustainability” AND “opportunity”, presenting publications in English only:

1	Azzellino, A., Ferrante, V., Kofoed, J.P., Lanfredi, C., Vicinanza, D. (2013) Optimal siting of offshore wind-power combined with wave energy through a marine spatial planning approach International Journal of Marine Energy, 3-4, pp. e11-e25.
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