The implications of energy systems for ecosystem services: A detailed case study of offshore wind

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Abstract

Globally, the deployment of offshore wind is expanding rapidly. An improved understanding of the economic, social and environmental impacts of this sector, and how they compare with those of other energy systems, is therefore necessary to support energy policy and planning decisions. The ecosystem services approach provides a more holistic perspective of socio-ecological systems than traditional environmental impact assessment. The approach also makes possible comparisons across disparate ecological communities because it considers the societal implications of ecological impacts rather than remaining focused on specific species or habitats. By reporting outcomes in societal terms, the approach also facilitates communication with decision makers and the evaluation of trade-offs. The impacts of offshore wind development on ecosystem services were assessed through a qualitative process of mapping the ecological and cultural parameters evaluated in 78 empirical studies onto the Common International Classification for Ecosystem Services (CICES) framework. The research demonstrates that a wide range of biophysical variables can be consistently mapped onto the CICES hierarchy, supporting development of the ecosystem service approach from a broad concept into an operational tool for impact assessment. However, to improve confidence in the outcomes, there remains a need for direct measurement of the impacts of offshore wind farms on ecosystem services and for standardised definitions of the assumptions made in linking ecological and cultural change to ecosystem service impacts. The process showed that offshore wind farms have mixed impacts across different ecosystem services, with negative effects on the seascape and the spread of non-native species, and positive effects on commercial fish and shellfish, potentially of most significance. The work also highlighted the need for a better understanding of long term and population level effects of offshore wind farms on species and habitats, and how these are placed in the context of other pressures on the marine environment.

Keywords

Offshore wind farms; ecosystem service assessment; environmental impact; impact assessment; Common International Classification of Ecosystem Services (CICES)

1. Introduction

Almost 1,500MW of offshore wind capacity was installed in European waters in 2014, bringing the total to 8,045MW in 74 offshore wind farms [1]. The UK has over half of Europe's capacity, and in 2014 offshore wind contributed 4% of UK electricity generation mix, compared to 5% for onshore wind [2]. Offshore wind farms have been installed in 11 countries across Europe (particularly the UK, Germany and Denmark), and there is an emerging trend in Asia: China installed 229MW of offshore capacity in 2014, and Japan has 12 projects (totalling 874MW) in the planning pipeline [1].

There is a need to understand the economic, social and environmental impacts of this rapidly expanding sector, and to compare them with those of other energy supply options, in order to support specific planning decisions and the development of wider energy policy. However, there is debate as to whether the existing Environmental Impact Assessment (EIA) process is adequate, particularly for renewable energy. The EIA framework emphasises negative impacts, and is less effective at evaluating positive and non-local benefits, such as climate change mitigation [3]. The ecosystem services approach moves beyond evaluating impacts only in terms of harm caused by human activity [4]. It considers more holistically the integrated socio-ecological system [5], potentially providing an enhanced framework for impact assessment.

The ecosystem service approach focuses on the benefits society receives from the environment, and considers the delivery of environmental goods and services across four main categories: i) Provisioning services (food and raw materials); ii) Cultural services (direct uses such as recreation as well as the less tangible contributions to wellbeing made by interaction with the environment); iii) Regulating services (including flood protection, waste/toxin remediation and carbon sequestration); and finally iv) Supporting, or intermediate, services, which underpin the delivery of all other services [6,7]. The first three categories are described as final ecosystem services, as they contribute directly to the supply of goods and benefits that affect human welfare [7]. Progress in the ecosystem services approach has included the development of systems to classify individual ecosystem services within these broad categories (e.g. the Common International Classification for Ecosystem Services (CICES) [8]). This potential to standardise the process and outputs of evaluations may be an advantage in the adoption of the ecosystem service approach to impact assessment, as it allows results to be compared across different studies.

In addition to comparability across studies, a key strength of ecosystem service assessments is that the approach makes possible comparisons across disparate ecological communities. It considers the societal implications of ecological impacts rather than remaining focused on the specific species or habitats. For example, changes to fish and crop yields can both be considered in terms of impacts on food production, or changes to the extent of saltmarshes or forests can be evaluated according to the respective change in carbon sequestration. This is key to the evaluation of the relative impacts of diverse energy supply options, which will affect different ecosystems in different locations.

The capacity of the ecosystem service approach to frame environmental impacts in societal terms may also better support communication of these impacts to stakeholders and decision-makers [5], and facilitate making trade-offs against other social and economic costs and benefits. The ecosystem service approach is also the foundation of monetary valuation, allowing impacts to be reported in a single metric which can support the use of quantitative comparison tools such as cost benefit analysis.

A method for assessing the impacts of different energy systems on ecosystem services has been proposed and piloted [9,10]. However, this proof of concept considered a limited data set, as a result of the limitations of the approach used for systematic data sourcing. This paper provides a more comprehensive evaluation of the implications of offshore wind farms for ecosystem services. In doing so, it further tests the concept of an ecosystem services approach to energy impact assessment by considering a wider range metrics and an expanded hierarchy of the ecosystem services onto which the services map, compared to the work of Papathanasopoulou et al. [10]. This extension of Papathanasopoulou et al.'s [10] work contributes to the further practical evaluation that is needed to allow the ecosystem services approach to develop from a concept to operational tools. It also provides a detailed empirical assessment of the impacts of offshore wind farms on ecosystem services, with outputs that have the potential to be easily compared with similar evaluations of alternative energy supply options. The focus of this review is on local impacts; there is no meaningful way to attribute climate change mitigation at the scale of individual OWFs, and the implications for ecosystem services more widely from the development of a decarbonised electricity sector are beyond the scope of this paper.

2. Method

A review of 78 publications in the peer-reviewed and grey literature was undertaken to establish the environmental and socio-economic parameters considered in assessment of the impacts of offshore wind farms (OWFs). A formal systematic review process (e.g. [11]), was not followed in identifying this literature as the objective of the review was to identify the largest possible body of studies to permit a comprehensive evaluation of the application of an ecosystem services approach to energy impact assessment, not to facilitate replication. The publications reviewed were sourced using academic and internet search engines (including Web of Science, Scopus, Open Grey and Google Scholar), with the main search terms combining *offshore wind farm* (and alternatives) with general terms such as *ecosystem service* and *environment* as well as descriptors for key species, habitats, coastal uses and potential impacts on cultural services (e.g. *fish, benthic, recreation, seascape*). Wider social and economic impacts such as job creation were not considered as they do not relate to ecosystem services. Further sources were identified through 'snowballing' from the reference lists of articles identified through the search process, and by using expert knowledge of the literature. Each publication was scored against quality assurance criteria used in Rapid Evidence Assessment [12] and those achieving less than a 'moderate' score were excluded.

The review considered primary evidence from empirical research on OWFs or from very closely related experiments involving, for example, playback of recorded OWF noise or cables with equivalent electromagnetic properties. Studies that speculate on potential impacts based on experiences of other offshore infrastructure (such as other pile driving or seismic activity, piers, or artificial reefs), which have often featured prominently in previous reviews of OWF impacts (e.g. [13-15]), were excluded. Reports from statutory monitoring programmes were generally avoided, as questions have been raised about the reliability of the data as the approaches, methods and data analysis are not always fit for purpose [16-18]. The main elements considered in the review were: i) the principal ecological or socio-economic focus of the study; ii) the specific variable(s) evaluated in the assessment; iii) the metric(s) used; and iv) the direction of impact. Some publications considered more than one variable, and where this was the case, each element was considered separately. The location of the study, the scale at which impacts were considered, and the OWF lifecycle stage were also recorded.

The experience of Papathanasoupoulou et al. [10] suggests that most research on the impacts of energy technologies is not carried out in an ecosystem services context. Therefore, a process was required to map the results as reported in ecological and social metrics onto an ecosystem services framework. Following Papathanasopoulou et al. [9], the framework for this mapping process used the Common International Classification for Ecosystem Services (CICES, [8]) version 4.3, a system that seeks to standardise the classification of ecosystem services in order to support environmental accounting and wider ecosystem service assessment. CICES is a hierarchical classification, with the main categories of ecosystem service (provisioning, regulating, cultural) described as ‘sections’, which are successively expanded into divisions, groups, and classes (Table 1).

The environmental accounting focus means that CICES considers only final ecosystem services that directly link to goods and benefits that are valued by people. However, many of the impacts of energy developments affect the underlying environmental processes that provide these final services. In order to accommodate these impacts, the CICES classification was supplemented by the Millennium Ecosystem Assessment [6] category of supporting services. No attempt was made to attribute species- or community-level changes to particular supporting services such as food web dynamics or nutrient cycling mainly because each species/community is likely to support ecosystem maintenance in several ways. The exact role of particular species and the linkages between ecological communities and specific services remain uncertain. This complexity and uncertainty perhaps explains the absence of a standard classification system for supporting services.

Table 1. The typology used by the Common International Classification of Ecosystem Services (CICES)

Division	Group	Class
Section: Provisioning		
Nutrition	Biomass	Cultivated crops
		Reared animals & their outputs
		Wild plants, algae & their outputs
		Wild animals & their outputs
		Plants & algae from in-situ aquaculture
		Animals from in-situ aquaculture
	Water	Surface water for drinking
		Ground water for drinking
Materials	Biomass	Fibres & other materials from plants, algae & animals for direct use or processing
		Materials from plants, algae & animals for agricultural use
		Genetic materials from all biota
	Water	Surface water for non-drinking purposes
		Ground water for non-drinking purposes
Energy	Biomass-based energy sources	Plant-based resources
		Animal-based resources
	Mechanical energy	Animal-based energy
Section: Regulation & Maintenance		
Mediation of waste, toxics & other nuisances	Mediation by biota	Bio-remediation by micro-organisms, algae, plants, & animals
		Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, & animals
	Mediation by ecosystems	Filtration/sequestration/storage/accumulation by ecosystems
		Dilution by atmosphere, freshwater & marine ecosystems
		Mediation of smell/noise/visual impacts
Mediation of flows	Mass flows	Mass stabilisation & control of erosion rates
		Buffering & attenuation of mass flows
	Liquid flows	Hydrological cycle & water flow maintenance
		Flood protection
	Gaseous / air flows	Storm protection
		Ventilation & transpiration
Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat & gene pool protection	Pollination & seed dispersal
		Maintaining nursery populations & habitats
	Pest & disease control	Pest control
		Disease control
	Soil formation & composition	Weathering processes
		Decomposition & fixing processes
	Water conditions	Chemical condition of freshwaters
		Chemical condition of salt waters
	Atmospheric composition & climate regulation	Global climate regulation by reduction of greenhouse gas concentrations
		Micro & regional climate regulation
Section: Cultural		
Physical & intellectual interactions with biota, ecosystems, & land-/seascapes	Physical & experiential interactions	Experiential use of plants, animals & land-/seascapes in different environmental settings
		Physical use of land-/seascapes in different environmental settings
	Intellectual & representative interactions	Scientific
		Educational
		Heritage, cultural
		Entertainment
		Aesthetic
Spiritual, symbolic & other interactions with biota, ecosystems, & land-/seascapes	Spiritual &/or emblematic	Symbolic
		Sacred &/or religious
	Other cultural outputs	Existence
		Bequest

Expert judgement was used to map the impacts as reported in the reviewed studies onto the ecosystem services classification (after [9]). The mapping process generated a qualitative output based on potential changes to ecosystem services, as there remains too much uncertainty in the linkages between species, habitats and ecosystem services for a quantitative approach to be attempted. Impacts were recorded as the direction of the potential change in ecosystem service provision: positive, negative, no change and uncertain. This latter category reflects where there is: i) no clear trend in the effects reported within the study; or ii) where the observed response does not translate directly into a well-defined impact, for example changes in abiotic parameters such as current speed which will have complex cascade effects.

3. Results

The literature reviewed showed that most research effort on the environmental and cultural implications of OWFs has focused on marine mammals, birds, public attitudes, benthic communities and fish populations, with some consideration of abiotic factors and non-native species (Table 2). The vast majority (95%) of the assessments took place in the northeast Atlantic, with over half originating from the UK and Denmark alone. The scale of impacts considered by the studies was also limited: two thirds assessed site-level impacts, with a further 18% evaluating local changes (i.e. extending up to tens of kilometres beyond the boundary of the site). The few studies evaluating impacts at a national level concerned public or stakeholder perceptions of, for example, visual impact, and assessments of regional-scale impacts considered migratory birds and the potential spread of non-native species. In terms of lifecycle stages, two thirds of the publications considered operation only, 20% both construction and operation, and the remainder just the construction phase. A wide variety of approaches were taken to assessing the cultural and environmental impacts of OWFs, with nearly 200 variables evaluated across the studies, although some common trends in the use of certain metrics were detected (Table 2).

Explicit use of the term ecosystem services when discussing the context and results of the impact assessment was rare, and only employed by studies considering cultural issues. The only ecosystem services to be assessed directly were the effect of offshore wind turbines on people’s perception of seascapes and sense of place. In the remaining studies, the motivation for the research was outside the ecosystem services paradigm, and so the impacts were measured in biophysical metrics and were not considered in terms of societal implications. In most cases, the studies measured the abundance, biomass or behaviour of a particular species (such as commercial fish, harbour porpoise, or mussels) but evaluation of corresponding direct ecosystem service indicators – respectively, the effects on catch potential (and hence food supplies), the public’s response to any impacts on charismatic species, and rates of waste/toxin filtration, sequestration, storage or accumulation – were not undertaken. Similarly, where hydrodynamic changes were observed these were reported in terms of, for example, the extent of wakes, not directly as mass and water flows. Also, the provision of nursery habitat was considered only in terms of the presence of juveniles at OWF foundations, not relative to the wider provision of appropriate habitat or how the use of foundations by juveniles translates into population level effects.

Table 2. The type of variables considered, and examples of metrics used, in 78 publications on the environmental and cultural impacts of offshore wind farms

Focus	Variable type	Number of studies[1]	Typical metric	References
Charismatic macrofauna				
Birds	Abundance/distribution	13	Individuals per unit area/time	
	Avoidance behaviour	12	Deviation from normal trajectory, percentage of individuals avoiding OWF footprint	
	Habitat loss	3	Percentage change	[44,71, 78-91]
	Collision/mortality rate	7	Number per year, percentage of population	
	Other behaviour/health	9	Prey availability and capture rate, likelihood of flight/landing, change in body mass	
Harbour porpoise	Abundance/distribution	17	*Direct measures*: individuals per unit area *Indirect measures*: acoustic activity	[59, 60, 62-65, 68, 70, 71, 75, 77]
	Other behaviour/health	4	Breathing rate, surfacing behaviour	
Seals	Abundance/distribution	6	Individuals per unit area/time	
	Population effects	1	Breeding success	[58,59,61,71-74,76,77]
	Other behaviour/health	5	Turbine interactions, surfacing behaviour	
Socio-economic issues				[48-55]
Public & stakeholder attitudes	Preferred OWF design	11	Willingness to pay	
	General perceptions	19	Qualitative	
Benthic community				
Existing benthic community	Abundance/distribution	10	Individuals per unit area, percentage cover	[22,23,28,33,41,42,44,45,71, 94, 96,97]
	Community structure	11	Species diversity, species richness	
Colonisation of foundations	Abundance/distribution	6	Individuals per unit area, biomass	
	Community structure	4	Number of species	[23-25,92,93,95]
	Influence on water column	3	Change in chemical composition	
Fish populations				
Commercial fish	Abundance/distribution	6	Individuals per unit area/time/effort	[19-21,26-32]
	Other behaviour/health	8	Mortality, movements, condition, response to EMF	
Other species	Abundance/distribution	16	Individuals per unit volume/effort, biomass	[22,28,34,43,44,71]
	Community structure	9	Species diversity, species richness	
Abiotic factors	Water movement	9	Current speed, wake generation	
	Sediment composition	3	Grain size, organic matter content	[38-42]
	Scour	2	Depth of scour hole	
Non-native species	Presence	3	Number of species present, probability of transport	[45-47]

[1.] This does not equate to the number of studies, as some studies considered more than one variable

Table 3. Mapping information on the environmental and social impacts of offshore wind farms onto an ecosystem services framework derived from the Classification for Ecosystem Services (CICES) v4.3 and Millennium Ecosystem Assessment (MEA).

	CICES/MEA category				**Relevant offshore wind farm impact**	**Variable type**
	Section	***Division***	***Group***	***Class***		
CICES	Provisioning	Nutrition	Biomass	Wild animals and their outputs	Commercial fish populations	Abundance/distribution other behaviour/health
	Regulating	Mediation of waste, toxics and other nuisances	Mediation by biota	Filtration/sequestration/storage/ accumulation by micro-organisms, algae, plants, animals	Colonisation of turbine foundations by mussels	Abundance
		Mediation of flows	Mass flows	Buffering and attenuation of mass flows	Sediment remobilisation/transport	Water movement, scour Sediment composition
		Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Maintaining nursery populations and habitats	Turbine foundations providing habitat for juveniles	Abundance/distribution
			Pest and disease control	Pest control	Distribution of non-native or problematic species	Presence
			Atmospheric composition and climate regulation	Global climate regulation by reduction of greenhouse gas concentrations	Abundance of species with high carbon sequestration potential	Abundance
	Cultural	Physical and intellectual interactions with biota, ecosystems, land/seascapes	Physical and experiential interactions	Physical/experiential use of plants, animals and land-/seascapes in different environmental settings	Changes in recreational use due to visual impact	Preferred OWF design general perceptions
			Intellectual and representative interactions	Scientific	Subject matter for research	Number of studies
				Aesthetic	Sense of place	Preferred OWF design, general perceptions
		Spiritual, symbolic and other interactions with biota, ecosystems, land/seascapes	Other cultural outputs	Existence	Enjoyment of seascapes Populations of fish, birds and marine mammals	Abundance/distribution, habitat loss, behaviour, health, collision rate/mortality, population effects
MEA	Supporting				Diversity, richness, and abundance of benthic species and non-commercial fish	Abundance, distribution, community structure influence on water column

These findings support the initial assumption that evaluating the impacts of OWFs for ecosystem services requires a mapping process to allow assessments of biophysical metrics to be considered in ecosystem service terms. The wider variables assessed within the reviewed literature provide information relevant to ten particular CICES classes as well as the MEA supporting services category (Table 3). As expected, only qualitative reporting of the direction of impacts is possible, and the lack of robust, direct evidence of impacts on ecosystem services reduces confidence in the findings.

However, the evidence does suggest that OWFs have the potential to increase delivery of certain ecosystem services through, firstly, the maintenance of nursery populations and habitats of commercial fish and shellfish (Figure 1). The increased biomass of mussels at OWF foundations may also provide additional benefits through enhanced mediation of waste and toxins, and the uptake of carbon dioxide. There is also some evidence of potential positive impacts on the provision of biomass for nutrition (via OWFs supporting commercially important species), although this is not conclusive, as other studies have suggested that commercial fish populations would be unchanged or possibly negatively affected. OWFs may also have negative impacts on pest control, by providing a mechanism for the transport of non-native and nuisance species, and on cultural services, particularly through reduced enjoyment of the seascape. The effects on other ecosystem service categories tended to be mixed or uncertain, particularly in terms of whether observed changes in marine mammal and seabird behaviour would lead to effects on a scale that may impact existence values, and also for supporting services generally. Finally, the volume of research that has been generated by OWF development has, in itself, the positive effect of increasing scientific knowledge of marine systems. These findings are discussed in more detail in the following sections.

3.1 Provisioning services

3.1.1 Wild animals and their outputs

Concerns have been expressed that the noise of pile driving during OWF construction and the electromagnetic fields (EMF) generated by operational OWF cables could affect commercial fish species, although there has been little empirical research in these areas. When noise levels equivalent to pile driving were played back to sole larvae in a laboratory experiment there was no effect on mortality [19]. Caged cod and sole in shallow coastal waters did exhibit significant, if highly variable, behavioural responses to simulated pile driving noise, which indicated that the animals tend to move away from the source but may become habituated to it [20]. A similar field-based experiment suggested that dogfish and rays will alter their behaviour in the proximity of cables with similar EMF properties to those used in OWFs, but the observed behavioural responses were not predictable or universal [21].

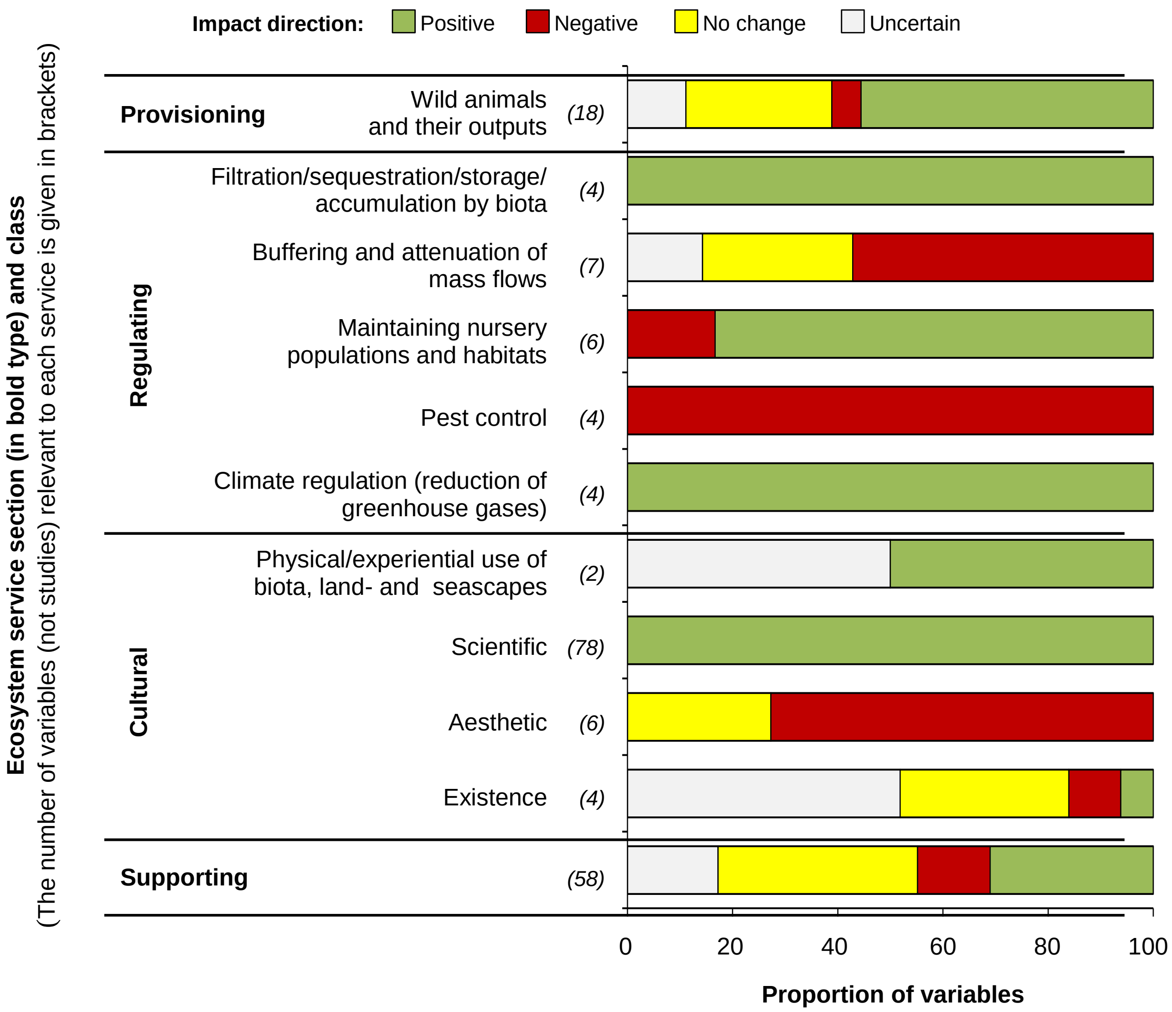

Figure 1. The potential direction of impacts on ecosystem services from offshore wind farm development (after [10]).

Conversely, it has also been suggested that commercial species may benefit through artificial reef effects, where OWFs provide an attractive habitat due to the availability of shelter and the prey species that have settled on the foundations. Some of these sessile prey species are themselves potentially harvestable; in particular mussels, which have been shown to be present in high abundance on monopile structures [22-25]. The abundance of cod, pouting, and eel has also been shown to increase in proximity to OWF foundations [26-28], with evidence of cod spending long periods within OWFs, [29, 30], staying very close to the turbines [29], and feeding on the benthic communities established on them [31]. The cod and pouting found near turbine foundations have also been shown to be in good condition, suggesting that OWFs do not act as an ecological trap [32].

The observed positive effects on commercial fish do not extend to all species in all circumstances. Sole have been shown to associate with OWFs, although there is no evidence that they are particular attracted to turbine foundations, as appears to be the case for cod [30]. OWFs do not affect the abundance of flounder [28] and the abundance of dab has been shown to decline [33]. Declines in whiting following OWF construction were attributed to wider population effects over the monitoring period, as in general, no significant changes were detected in the abundance or distribution of pelagic and demersal fish between the OWF and control sites [34].

3.2 Regulating Services

3.2.1 Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants and animals; Global climate regulation by reduction of greenhouse gas concentrations

The increased abundance of mussels observed at OWF foundations [22-25] may deliver other ecosystem services in addition to providing a potential food source. In particular, the presence of mussels is likely to increase the capacity of the system to remediate waste and also to sequester carbon (at least temporarily) compared to subtidal sand and gravel sediments [35-37].

3.2.2 Buffering and attenuation of mass flows

The creation of sediment plumes during OWF construction is a key issue raised within Environmental Impact Assessments and subsequent statutory monitoring. Once in place, the obstruction created by turbine foundations will continue to affect water flows, and hence the capacity of the system to retain sediment. Remote sensing and modelling studies have shown that large, turbid wakes are present downstream of individual turbines, which may extend for over 1km [38,39]. The development of scour pits at the base of OWF foundations, particularly in sandy sediments, provides further evidence that their presence affects sediment transport [39,40]. Although transport of sediment away from the area has been shown to occur, there is a lack of conclusive evidence that OWFs have any significant effect on the composition of the sediment around the turbines [41,42].

3.2.3 Maintaining nursery populations and habitats

There is evidence that OWF foundations may serve as a particularly successful nursery ground for edible crab. A marked increase in the number and biomass of juvenile edible crab on turbine foundations was observed at one OWF over three years of post-construction monitoring, with the final surveys showing the presence of juveniles from three year classes [42]. Other studies have also found juvenile edible crab associated with barnacle and mussel habitats on turbine pilings [25], and the structures are probably also an important nursery for masked crab and northern sea urchin [42].

OWF foundations are also used by young fish, particularly whiting which have been observed in very large shoals, feeding on amphipods on the turbine pilings [25]. Large aggregations of juvenile cod have also been recorded at OWF foundations [27], and tagging individual fish has demonstrated that juvenile cod spend long periods within OWFs [30]. A positive short-term effect on juvenile sand eels has been observed and related to a reduction in the sediment silt/clay fraction following construction [43]. However, in the long-term the effect on *Hyperoplus lanceolatus* sandeels (adults and juveniles) is negative, perhaps as a result of a change in predator density [43].

3.2.4 Pest Control

OWFs may have a negative effect on pest control by supporting increases in the abundance or range of non-native or nuisance species. OWF foundations have been shown to host populations of non-native species, at locations that represent an extension of the species range [44,45]. A further modelling study has also indicated that OWFs in the Irish Sea could act as stepping stones to allow larvae from species in Northern Ireland to reach the Scottish coast [46]. Modelling also suggests that OWFs in the Baltic may support the transport of moon jellyfish larvae [47], a native species that has negative impacts on fishing, tourism and coastal power stations when present in high densities.

3.3 Cultural services

3.3.1. Physical/experiential use of plants, animals and land-/seascapes in different environmental settings

The environmental impacts of OWFs may have implications for the welfare of people who make direct recreational use of the areas, species and habitats affected through, for example, watching birds or other wildlife. Although possible impacts on birds and marine mammals have been studied (and will be discussed further under the Existence section, below) there has been no assessment of whether there has been any subsequent impact on the availability or enjoyment of wildlife watching. However, the artificial reef effects of OWFs may bring benefits through the development of new recreational opportunities, and tourists visiting a French beach were shown to have a positive value for potential OWF-associated recreational activities [48].

The effect of OWFs on seascapes is a key issue, but most of the research reviewed did not relate any impacts directly to recreational uses such as walking or boating, and so this issue is considered in terms of sense of place impacts (see Aesthetic, below). Where perceptions of OWFs were considered in terms of recreational use, it was found that the perspectives of users varied according to the timing and frequency of beach walks: while the vast majority of respondents had a very positive attitude to existing OWFs, those visiting the beach most frequently were generally more negative towards OWFs than less frequent visitors, particularly those using the beach in winter [49].

3.3.2. Scientific

The 78 studies reviewed in this paper indicate the level of academic interest in the environmental and cultural impacts of OWFs. The body of knowledge generated from this research improves understanding across ecological, social and economic disciplines, and is of itself a positive impact of OWF development.

3.3.3. Aesthetic

There is strong evidence that OWFs are perceived to reduce the visual amenity of the seascape for at least some sections of the general public, and this is viewed by many as the primary negative environmental impact of OWF developments [50-52]. However, the visual impacts of OWFs are rarely considered in any wider context, such as being compared against other factors that reduce visual amenity. When this was attempted through an open-ended question asking respondents which factors currently disturbed coastal views, the most common responses were pollution, the bustle of tourism and harbour activities, while only three people mentioned existing OWFs [53]. Attitudes to visual impact are not homogeneous across the population. Older people are most affected by potential changes to the aesthetic quality of the seascape [48], while respondents under 30 years of age appear largely unconcerned about the distance offshore (and hence visibility) of OWFs [54,55]. There is evidence that size of OWFs may effect aesthetic impacts, as even those with a favourable attitude to OWFs perceive them more negatively as the density of turbines increases [50,53].

3.3.4. Existence

The potential change in existence values primarily relates to possible harm to marine mammals and seabirds, as highly valued charismatic species [56,57]. The focus of research effort has been on the impacts of construction noise on marine mammals (particularly harbour porpoise) and the flight patterns (and hence collision risk) of seabirds and waterfowl within OWFs.

Marine Mammals

The studies reviewed provide some evidence that marine mammals may be disturbed during OWF construction: seals may reduce the frequency with which they haul out [58,59] and both seals and harbour porpoise have been shown to avoid OWF areas during pile driving [59-64]. There has been one attempt to link noise disturbance to physiological effects, in which the breathing rate and breaching behaviour of a porpoise increased in response to the playback of noise resembling that of OWF construction [65], but as this study involved a single captive animal within an aquarium, its results should be interpreted with caution. Disturbance effects on porpoise have been detected 20km from the construction site [60,66], and it can take three to six days for activity levels in OWF areas to return to normal following pile driving [60,62]. However, the disturbance period may be as short as six hours [64], and over time porpoise may become habituated to the noise levels [67,68].

It should be noted that developers have a mandatory obligation to reduce the exposure of marine mammals to potentially harmful noise levels [69], and therefore deploy techniques such as acoustic deterrents and 'soft start' approaches to reduce the presence of marine mammals in the area, and hence minimise harm. It is not clear whether mammals leave the area in response to these actions or as a direct result of pile driving noise [60,62]. Observed changes in abundance may also be caused by other factors such as boat activity or changes in prey behaviour [67].

The noise created by the installation of gravity base turbines (which do not require pile driving) did not appear to have a significant effect on porpoise abundance [70]. In addition, there is no evidence of significant negative effects on porpoise or seals during OWF operation [59,61,64,71-73], although increased boat traffic and periods of intense maintenance activity may be a source of disturbance during this phase [64,74]. Increasing porpoise activity within OWF areas has also been reported [75], with additional evidence that seals repeatedly forage at OWF foundations [76].

This body of evidence suggests that OWF development may lead to some changes in marine mammal behaviour, particularly during construction, but this cannot be unequivocally attributed to corresponding changes in existence value as the studies reviewed did not consider these wider impacts. It remains unknown whether the small scale, short term or temporary displacement of individuals even has a significant effect on cultural services, compared, for example, to the mortality of individuals or changes in the size of mammal populations. Population effects were rarely assessed, but have been considered for seals: no overall changes in population size have been observed [59], although the techniques used often lack the statistical power to detect OWF effects [61,77]. A poor breeding season coincident with OWF construction was observed for one seal population, from which it took two years to recover, but this could not be conclusively attributed to the OWF [74].

Seabirds

As with marine mammals, the outcomes of studies on behavioural change in birds cannot be interpreted with confidence in terms of impacts on cultural services. There is growing evidence that most birds avoid OWFs, altering the orientation and height of flight paths in response to turbine presence [78-83], although there can be significant interannual variation in migration orientation [84] and there is some evidence that gulls and cormorants may be attracted to OWFs [78]. The likely energy costs of avoidance behaviour have been calculated and shown to be negligible for species such as eider, which migrate long distances, but is potentially more significant for other species that must negotiate OWFs on a daily basis as they move between roosting and feeding grounds [79]. It has also been shown that OWF construction represents a loss of habitat for lesser black-backed gull, divers, and northern gannet [85], but, again, this has not been connected to wider consequences for population status.

There is a larger body of studies that consider individual mortality and population level effects for birds than is the case for marine mammals, and changes in these parameters may have a more significant effects on cultural services. In terms of mortality, the rates at which individuals are likely to collide with turbine blades or towers has been calculated (usually through modelling) at 10 to 15 strikes per year for passerines and waterbirds [81,82], reducing to less than three strikes per turbine per year for gulls [86], and less than two strikes per turbine during an autumn season for common eider [80]. An alternative approach suggested that strikes from an OWF with nine turbines were responsible for 3% of local bird deaths (approximately 11 per year), the vast majority of which were seabirds [87]. The design of an OWF can have implications for collision risk, with higher bird mortality likely where turbines are lower [88].

At the population level, there is growing evidence of a decline in gannet populations at OWF sites [44, 80, 86], and it has also been reported that common guillemot, razorbill and long-tailed ducks avoid OWF areas [80,86]. However, there has been no change in abundance for eider [89,90] and the abundance of large gulls and cormorants has been shown to increase, with these species showing little avoidance behaviour [71,80,86,89]. The abundance of common and sandwich terns has also been reported to increase following OWF development [44,89], although the construction process itself has been shown to negatively affect the foraging success of little terns [91].

There remains some uncertainty in the population level effects on seabirds, as evidence of trends is rarely unequivocal and suggests that location- or development-specific factors may affect bird populations. For example, while most studies suggest that the abundance of cormorants increases at OWF sites, Rothery et al. [89] report a decline in cormorant numbers. Similarly, diver abundance was unaffected in one study [71], but the species disappeared from another site despite having been present in average densities prior to OWF construction [80]. OWF development has had similarly variable effects on the abundance of common scoter [71,80,89].

3.4 Supporting Services

Many of the environmental parameters considered in evaluations of OWF impacts concern species or processes which, while having a key role in ecosystem functioning, do not link directly to a final ecosystem service and are thus considered as supporting services under the Millennium Ecosystem Assessment [6] classification. This is a wide category, and shows mixed results, with positive, negative, insignificant and uncertain impacts reported from OWF development. There is some evidence that impacts are greatest during OWF construction, but that communities are sufficiently resilient for characteristic biotopes to become re-established during the operation phase [71].

3.4.1 Species Habitats and Genetic Diversity

In terms of negative impacts, while an increase in mussels can be considered positive for certain provisioning and regulating services (as reported above), the changes in water chemistry resulting from their increased abundance can have negative effects on local plankton communities [92]. A decrease in the coverage of red algae has also been reported [22] and a significantly lower number and diversity of benthic species has been found on OWF turbine foundations compared to the surrounding area, due primarily to the absence of algae and sand dwelling species [23]. It has also been reported that the diversity and species richness of fish communities is significantly lower on the turbines than the surrounding seabed [23].

Conversely, other studies have shown positive effects for fish and benthic species and communities, including an increase in the number of fish species around turbine foundations compared to control sites, and enhanced abundance of certain species, particularly black and two-spot gobies and eelpout [22,23,28]. The development of the benthic community on turbine foundations has shown an increasing number of species and total biomass over time [24,25,44,93-95], and an increase in biomass within surrounding habitats has also been observed, although not consistently [33]. Potential impacts on species of conservation importance cause particular concern, and targeted research on *Sabellaria spinulosa* (Ross worm) reefs was undertaken at the Thanet OWF, which showed an increase in the extent of the reefs at the site following construction, perhaps as a result of natural variability or changes in trawling pressure due to the OWF development [96].

A number studies have not detected any significant changes in the abundance, biomass, diversity or community composition of fish [22,28,43,44,71] or benthic species [41,44,97], while others have reported uncertain or mixed effects on benthic communities [28,33,41]. It is possible that the high natural variability of marine systems disguises any impacts resulting from OWF construction or operation [22,33,41,44], and the limitations of current monitoring programmes in this respect have already been highlighted [17,18].

3.4.2 Hydrodynamic Impacts

The focus of research has been on species and habitats, but a limited number of studies have considered the impacts of OWFs on oceanographic parameters. These have shown that the presence of OWFs can decrease local current speeds considerably, with effects detectable 1km or more from the turbines [38]. Seabed topography is also affected by the development of scour pits around the base of turbine foundations [39,40]. These oceanographic changes have consequences for sediment transport (as described in Regulating Services, above), but also affect the ecosystem more widely, for example currents are a mechanism for nutrient and gamete transport, and scour affects the development of benthic communities. The consequences for the wider ecosystem of hydrodynamic changes may be varied and potentially act in different directions. Therefore, while the parameters evaluated show clear changes, the likely effect on supporting services is reported as uncertain.

4. Discussion

4.1 Impacts of OWFs on Ecosystem Services

This work demonstrates that the implications of OWFs for ecosystem services are mixed: negative impacts do not dominate and the presence of OWFs may be beneficial to the supply of certain services, particularly in terms of supporting commercial fisheries and providing nursery habitat for key species, as well as the waste remediation and carbon sequestration provided by the mussels that colonise turbine foundations. The findings suggest that minimising aesthetic impacts is potentially important in gaining public support for OWF development. Context is an important consideration however; local community characteristics and people’s sense of place, as well as existing levels of industrial development or other disturbance in the area are key factors in public perceptions of OWFs [51,53]. The potential role of OWFs in the transport of non-native and nuisance species could also be a significant negative impact. In most cases, however, the number of studies was limited and more empirical research would increase confidence in the conclusions drawn.

There is also a need to understand better the wider context of any environmental change brought about by OWF developments. Behavioural responses by marine mammals and birds have been observed (e.g. marine mammals temporarily leaving the area during construction, or birds slightly altering their migration path to avoid turbines), potentially reducing the delivery of cultural services. However, such short-term, reversible or minor displacement without clear links to mortality or population level effects may be less likely to have any substantial effect on cultural services compared to significant long-term impacts. At present, the observed behavioural responses are rarely linked to health or survival consequences for the affected individuals, and assessment of the implications at the population level or in the context of other pressures such as climate change or the implications of fisheries on food web dynamics is also lacking.

4.2 Using the ecosystem service approach for impact assessment: limitations and recommendations

This paper provides evidence that broadly supports the practical application of the ecosystem service approach as a tool for impact assessment. It enhances the outcome of Papathanasopoulou et al.'s [10] research as the inclusion of a larger number of studies allowed the impacts of OWFs to be considered in greater detail, particularly for regulating services for which Papathanasopoulou et al.'s [10] search strategy had generated no evidence. Also, the study demonstrated that a wide range of biophysical variables can be consistently mapped onto the most detailed levels of the CICES hierarchy. It also shows that where a large number of variables or studies exist, subdivision of results into detailed ecosystem service classes is more useful than aggregation at section level. This is illustrated by the consideration of supporting services as a single category: the studies included showed mixed outcomes and hence reduced the potential for drawing useful conclusions about impacts across that category of services.

There are some limitations to the method of interpreting existing environmental data in ecosystem service terms, particularly that the relationship between the variables evaluated and ecosystem service demand was not considered. For example, an increase in the abundance of mussels is likely to increase services such as filtration (and hence contribute to waste mediation), but the provision of this service depends on the context in terms of the level of waste or toxin input, the extent to which other species or habitats already remediate waste/toxins, and whether any beneficiaries are present to utilise the service provided. Without this context, potential positive impacts may be overstated.

More focussed assessments of the implications of energy systems for ecosystem services are therefore required to increase confidence in outputs, although there remain challenges to achieving this aim. The characterisation of indicators that can be used to directly measure ecosystem services, or to provide more robust proxies, is an emerging field. There is not yet consensus on how such indicators should be selected [98], and effort in the development of indicators for services and the benefits they provide has been unequal across the provisioning, cultural and regulating categories [99].

A further limitation of using existing ecological data for the purposes of ecosystem service assessment is that our understanding of links between ecological outcomes and ecosystem services remains very limited [100], requiring assumptions to be made that may not fully reflect the complexity within the social and ecological systems involved. For example, the increased presence of commercially important species at turbine foundations may not actually translate into increased nutrition biomass that is available for fishers to exploit. There is not yet equivocal evidence as to whether OWFs support any increase in fisheries production, as opposed to simply attracting individuals from elsewhere (e.g. [101-103]. Also, fishers may be unable or unwilling to access enhanced stocks due to formal exclusion zones or to concerns about safety, insurance or liability issues [104]. However, if fishers do not exploit the area, then OWF development may become a *de facto* marine protected area with potential spillover benefits to commercial fish stocks in the wider region [105], again supporting the assumption that exploitable biomass, overall, could increase.

Given the complexity of the marine environment, it is unlikely that the connections between ecological functions, processes, services and benefits will ever be fully understood, or that comprehensive data on all these factors will ever be available, and so expert judgement will continue to be a necessary component of any evaluation. The robustness and comparability of future assessments would be enhanced by consistency in the assumptions used to link ecological and cultural change to ecosystem service impacts. To this end, the development of a series of formalised principles (based on consensus between a large group of recognised experts) to facilitate linking the outcome of environmental change to the CICES hierarchy would be highly beneficial to future application of that classification and its development as a tool to standardise ecosystem service assessment. The foundation for this already exists in the Ecological Principles Approach [106], which connects a selection of ecosystem services with a series of ecological principals that describe the key elements of the underlying ecosystem functioning.

Qualitative studies based on expert judgement have an important role in drawing attention to key issues. They are widely used in existing Environmental Impact Assessments [107] as well as in other decision support mechanisms such as scenario analysis [108]. However, quantification of ecosystem service impacts would support more detailed evaluation (such as through modelling) and would aid interpretation of the results by permitting the magnitude of impacts to be communicated. For example, most of the research reviewed concerned the local impacts of OWFs, and it would be useful to understand if these impacts were of sufficient magnitude to affect ecosystem services over a wider area. The development of appropriate indicators (as discussed above) is a vital precursor to quantification, but the nature of the service is also key: certain cultural services in particular are difficult to quantify in a meaningful way [109].

Quantification in monetary terms of the impacts of OWFs on the benefits received from ecosystem services was rare, and primarily concerned changing recreational and aesthetic values [55,48,110]. Therefore, considerably more empirical research is needed if the concept of monetising impacts in order to incorporate enhanced cost-benefit analysis into impact assessment is to be realised. However, this step may be unnecessary: previously, attempts to encourage the adoption of monetary valuation within the planning process were not well received (as reviewed in [5]).

5. Conclusions

The ecosystem services approach is a useful tool to support impact assessment, as it can highlight how environmental change brought about by the development of energy systems may impact (positively or negatively) upon the goods and services people receive from nature. This research has demonstrated how ecological and social data can be mapped onto detailed levels of the CICES hierarchy, supporting the potential for comparative assessment using this standardised framework.

However, to fully realise the potential of the ecosystem service approach, direct (and ideally quantified) evaluation of ecosystem service changes should be a priority within future assessment of the impacts of energy systems. A better understanding of the relationship between ecological change and ecosystem service delivery is also required. The absence of such comprehensive empirical evidence necessitates the continuing role of expert judgment in interpreting impacts in ecosystem service terms. The further development and application of standardised frameworks such as CICES therefore requires a formalised process to clearly define the key assumptions made in linking ecological and cultural change to ecosystem service impacts.

In the specific context of OWFs, the approach taken provided a generalised overview of impacts on ecosystem services, providing a clear indication of how ecological change resulting from OWF development has consequences of societal importance. This process showed that the outcomes of OWF development are mixed across different ecosystem services. Potentially of most relevance to future expansion of the industry are the negative effects on the seascape and pest control as well as the possible positive effects on commercial fish and shellfish. Such a generalised approach can highlight key areas of concern or requirements for further research, but may have limited relevance to individual developments as the services provided and the impacts upon them are likely to vary on a case by case basis. However, the methodology remains applicable at a local scale and so can be used as part of the impact assessment process for an individual OWFs.

The principal lessons learned from this process are that more robust results would be generated if the ecosystem service demand was considered as part of the evaluation process. This would be challenging for a generic assessment as presented in this review, but becomes more realistic (and necessary) at the level of a specific development. The ability to quantify impacts is hampered by an absence of standard indicators for ecosystem services, although frameworks must also have sufficient flexibility to incorporate those services that are not amenable to quantification. The work also highlighted the need for a better understanding of long term and population level effects on species and habitats, and how these are placed in the context of other pressures on the marine environment.

Acknowledgements

The initial review of the ecological and social impacts of offshore wind farms was funded by The Crown Estate. Further analysis and development of the ecosystem service assessment method formed part of the programme of the UK Energy Research Centre supported by the UK Research Councils Award EP/L024756/1.

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