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Quantifying impacts of onshore wind farms on ecosystem services at local and global scales

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ABSTRACT

Energy technologies have both local and global impacts on ecosystem services, with local impacts occurring where the energy is generated, and global impacts occurring where energy feedstock or raw materials for energy infrastructure are sourced. Assessing these impacts in both local and remote locations is important but challenging. In this paper we present a first attempt to quantify the impacts of onshore wind farms on ecosystem services for the UK at local and global scales, building on approaches used for life cycle analyses of energy technologies, that consider the provenance of materials used for energy infrastructure. We first identify the lifecycle processes of onshore wind farms, and then use a systematic literature review of local impacts of onshore wind farms on ecosystem services and a 'Broadbrush' approach for global impacts. Results show that onshore wind farms tend to have significant positive local impacts on primary production and air quality, and tend to have negative local impacts on soil, water and livestock which are mostly associated with the operational and decommissioning stages of wind turbines in the UK. At global scale, onshore wind farms tend to have negative impacts on a number of ecosystem services, due to the processes associated with the mining of steel and concrete in other parts of the world, but this is common to all energy infrastructures. These should help wind farm developers and researchers identify and avoid adverse impacts of onshore wind farms on ecosystem services.

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Contents

1. Introduction

Ecosystem services refer to the outputs of ecosystems from which people derive benefits [1]. They are critical to the functioning of Earth's life-support system, and contribute to human well-being, both directly and indirectly [2]. It is important to account for the direct and indirect role of ecosystem services in supporting human activities since i) they are the basis of sustainability, and many are deteriorating rapidly [3], and ii) the public's ecological knowledge is fading as the role of ecosystems becomes indirect and less apparent [3,4]. Given our reliance on energy for modern life, it is necessary that we assess the impacts of the energy technologies we use, not just locally where the energy is generated or used, but also remotely, accounting for the impacts on ecosystem services elsewhere in the world, where energy feedstocks and raw materials for energy technology infrastructure are sourced.

Accounting for the impacts of energy provision on ecosystem services has merited much attention recently. Wiedmann et al. [5]

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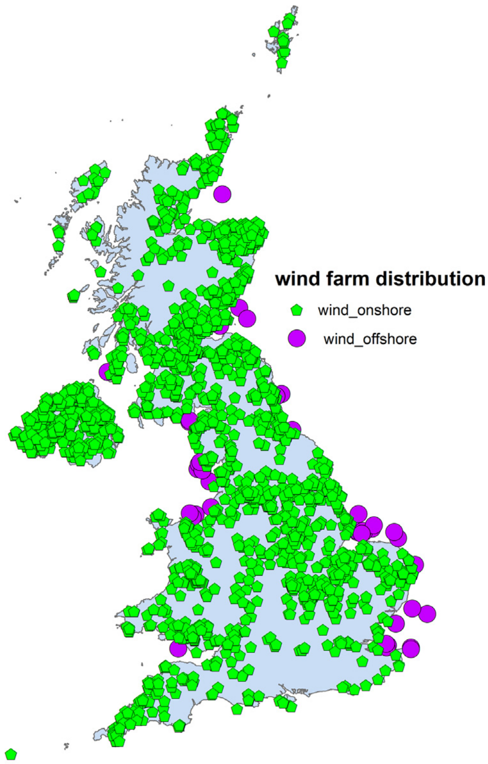

Fig. 1. Wind farm distribution [13].

accounted for the indirect greenhouse gas emissions of wind power generation in the UK. White et al. [6] assessed potential conflicts among offshore wind energy, commercial fishing, and whale-watching sectors in Massachusetts, and identified and quantified the value of choosing optimal wind farm designs that minimised conflicts among these sectors. In addition, many studies have investigated the local impact of bioenergy crop provision on ecosystem services [7–9]. The latter studies used land-use as a proxy to examine the impacts on the carbon cycle, biodiversity and the hydrological cycle. Most of studies are limited to only one or a few ecosystem services. However, little effort has been devoted to frameworks to assess impacts on a wider range of ecosystem services, due to methodological [3] and/or data/knowledge gaps.

Due to growing concerns about the influence of emissions from fossil fuel use on climate change and concerns about the national energy security, spurred by the decline in North Sea oil and gas production and aging nuclear and coal fired power stations, wind energy has been recognised as an important energy source in the UK [10,11] and has grown rapidly recently. Onshore wind energy capacity increased by 1.6 GW between July 2012 and June 2013, making the total installed capacity 7.0 GW by the end of June 2013 [12]. Fig. 1 shows the distribution of wind farms in the UK. Since wind farms are promoted to ultimately improve the natural environment, their growth should be not at the expense of natural environment; rather, it should be achieved in harmony with the natural environment [14,15], addressing the challenge of quantifying the impacts of onshore wind farms on ecosystem services at local and global scales. In this paper, for the first time, we attempt to quantify the impacts of onshore wind farms on ecosystem services for the UK at local and global scales, building on the Life Cycle Analysis (LCA) approach used for UK wind technology by Wiedmann et al. [5]. The resultant ecosystem service impact

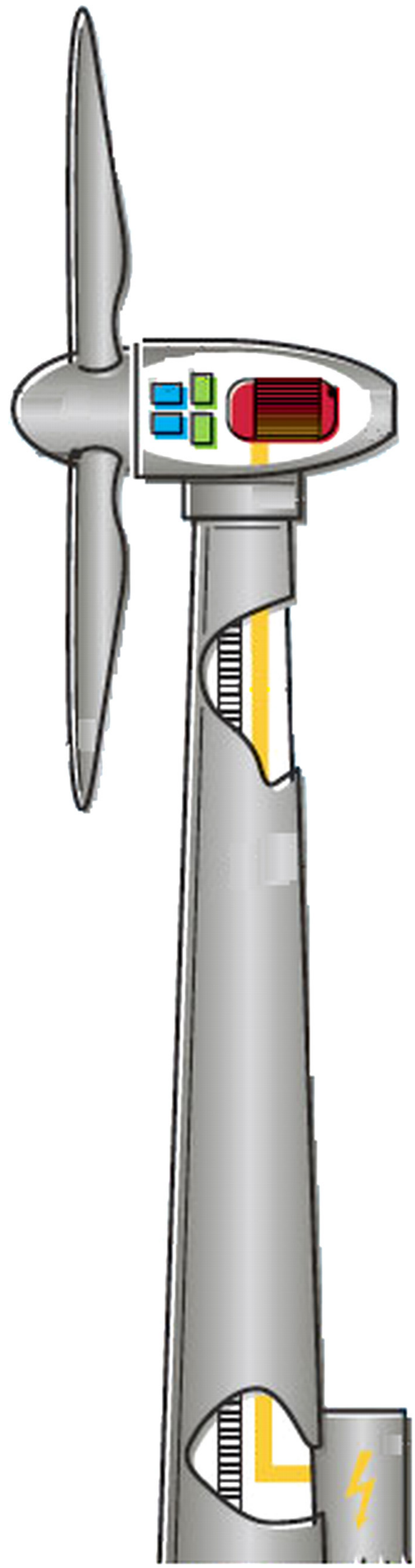

Fig. 2. Wind turbine structure. Adapted from ⟨http://www.rwe.com/web/cms/en/87226/rwe-innogy/technologies/wind/wind-power/⟩.

Table 1
Lifecycle processes of onshore wind farms (Y for yes and N for no).

Level 1-lifecycle stage	Level 2-process	Level 3-process-detail	Subject (i.e. land, air, and water)	Local and/or global impact	
				Local (UK)	Global
Upstream (i.e. construction of wind turbines)	Resource extraction	Concrete – quarrying sand and gravel + transport	Land	Y [18]	N [19]
		Concrete – quarrying limestone + transport	Land/air	Y [20]	N [19]
		Steel – mining of iron ore, coal, flux materials (e.g. limestone) and alloys (e.g. manganese) + transport	Land/air/water	N [21]	Y [21]
		Aluminium-mining from bauxite	Land/air/water	N	Y [22]
	Material manufacturing	Concrete – cement production+transport	Land/air/water	Y [20]	N [19]
		Concrete – concrete production+transport	Land/air/water	Y	N
		Steel – steel production (70% new steel/blast furnace+30% recycled steel/electric arc furnace)+transport	Land/air	Y [21,23]	Y [21]
		Aluminium—Aluminium production+transport	Land/air/water	Y	Y
	Component manufacturing	Concrete – component production+transport	Land/air	Y	Y (Assume some import of concrete components)
		Steel – component production (e.g. girders, reinforcing rods, cables, nuts & bolts etc.)+transport	Land/air/water	Y [23]	Y (bound to be component imports)
		Aluminium-component production + transport	Land/air	Y	Y
	Construction	Tower	Land	Y	N
		Nacelle	air	N	N
		Hub	Land/air	N	N
		Blades	air	Y	N
		Foundations	Land/air	Y	N
		Grid Connection cables	Land/air	N	N
		On-site erection and assembling	Land/air	N	N
		Transport of turbine component	Land/air	Y	N
Operation	Maintenance	Maintenance of turbines			
		Oil changes	Land/air/water	Y	Y
		Lubrication	air	Y	N
		Transport	Land/air/water	Y	Y
Downstream (i.e. decommissioning of wind turbines in the UK and reversion of land to previous use)	Dismantling	Dismantling turbines	Land/air/water	Y	N
		Transporting turbine to disposal sites	Land/air/water	Y	Y
	Decommissioning				
	Disposal and recycling	Recycling some components	Land/air/water	Y	N
		Depositing inert components in landfills	Land/air/water	Y	N
		Recovering other material such as lubricant oil	Land/air/water	Y	N

matrix at local and global scales can be used to guide the development and deployment of onshore wind farms. The focus of this paper is to examine the impacts of one energy technology (i.e. onshore wind farms) on ecosystem services, rather than the energy generation potential, which can be found in, e.g. IPCC [16] and the UK Department of Energy and Climate Change Renewables Roadmaps [11,12].

2. Materials and methods

We use a method, which is built on the LCA approach used for UK wind technology by Wiedmann et al. [5], to quantify the impacts of onshore wind farms on ecosystem services at local and global scales. The method can be described as two parts: the lifecycle process identification of onshore wind farms and the quantification of impacts on ecosystem services. The lifecycle process allows each stage of development to be identified, for which ecosystem service impacts need to be assessed. We use the LCA to identify the processes involved for each component of the development of onshore wind farms. Fig. 2 shows the typical onshore wind turbine structure, which basically contains 89.1% steel, 5.8% fibreglass, 1.6% copper, 1.3% concrete (primarily cement, water, aggregates, and steel reinforcement), 1.1% adhesives, 0.8% aluminium, and 0.4% core materials (primarily foam, plastic, and wood) by weight [17]. The processes of onshore wind farms are divided into three hierarchic levels (Table 1), with Level 3 having the most detail. Level 1 is the lifecycle stage which includes upstream, operation and downstream of wind turbines. Level 2 describes the corresponding processes such as resource extraction, and Level 3 is the detailed processes involved at Level 2. These processes may have impacts on ecosystem services at local and global scales. The tracking of energy sources and materials for onshore wind farms in the LCA is conducted separately within the UK and outside the UK. Within the UK, we track these to the locations where energy feedstocks and the infrastructure materials of onshore wind farms originate, whereas outside the UK we track these materials only to the level of the countries which have transactions with the UK (i.e. the countries from which the UK directly imports the volume of materials and products). We do this for simplicity, and due to the availability of data for transactions outside the UK [5].

We use a systematic literature review for local impacts of onshore wind farms on ecosystem services and a ‘Broadbrush’ approach for global impacts on ecosystem services. The systematic literature review was based on a search of ISI Web of Science using the term ‘wind energy’, ‘wind farm’, or ‘wind turbine’ together with keywords relating to commonly examined ecosystem services which we described later. The returned references for each search were coarsely filtered using the title and abstract to exclude those of no relevance. The full text for each of the remaining references was then obtained, and where possible, the relevant information was extracted and summarised. In total, 178 papers were used. We classify the impacts into five classes: large positive (++), positive (+), no impact (0), negative (−), large negative (− −). The rules for scoring the impacts to each class are as follows: (1) if articles had clearly indicated the level of impact, such as 'significant' (i.e. ++ or − −) or 'slight' (i.e. + or −), then the impact was allocated to the corresponding class; (2) if articles did not have a clear definition on the level of impact, but the data contained in articles showed the temporal pattern of the impact, the temporal pattern of the impact was used to determine the class of impact. If the variation in temporal pattern of impact was within 5%, then it was classified as no impact. If the variation ranged from 5% to 75%, then the impact was classified as positive or negative, depending on the direction of impact. Otherwise the impact was classified as large positive or negative; (3) if articles had different views on the level of impact on a single ecosystem service, for example, some articles indicated the impact as 'significant' but others showed it as 'slight', then the ambiguous classes were assigned. The intention of future work is to validate the resultant impact matrix through academic and industry expert consultation. The ecosystem services follow the Millennium Ecosystem Assessment (MEA) classification system [1], in which the ecosystem services are divided into provisioning, supporting, regulating and cultural services, in order to collate the information for the impacts of onshore wind farms on ecosystems. The broad categories can be further divided into subcategories, with the 23 used in the MEA and as keywords of systematic literature review.

3. Results

Many processes of onshore wind farms have impacts on ecosystem services at local and global scales (Table 1). Almost all lifecycle processes of onshore wind farms will generate local impacts on ecosystem services. The steel, aluminium and concrete have no local impacts on ecosystem services, since the impacts occur where these materials are mined and processed. They are imported to the UK mainly from Germany, Spain, Belgium, France, and China. In 2013, the UK imported 942 thousand tonnes steel from Germany (14.7%), 750 thousand tonnes steel from Spain (11.7%), and 361 thousand tonnes steel from China (5.6%). Consequently, the impacts of mining of iron ore, coal, and flux materials for steel will generate global impacts, rather than local impacts. This again confirms the necessity of quantifying the impacts of onshore wind farms on ecosystem services at local and global scales. In contrast, the global impacts of onshore wind farms on ecosystem services are mainly due to the mining and disposal of steel and concrete as well as the global effect of atmospheric change such as greenhouse gas emissions.

Table 2
Aggregate local and global impacts of onshore wind farms on ecosystem services from the systematic literature review (n.d. denotes no data).

Ecosystem service		Local impact	Global impact
Supporting	Soil formation	–	− −
	Nutrient cycling	n.d.	−
	Water cycling	−/0	−
	Primary production	++	+/−
Provision	Crops	n.d.	−
	Livestock	−	−
	Wild fish(aquaculture)	n.d.	−
	Timber	n.d.	−
	Water	−/0	−
	Peat	n.d.	n.d.
	Wild game	−	−
	Honey	n.d.	0
	Ornamentals	−	−
	Genetic resources	−	−
Regulating	Climate	−/+	−
	Hazard	n.d.	−
	Disease and pests	0	n.d.
	Pollination	0	0
	Noise	−/0	−/0
	Water quality	−	−
	Soil quality	−	−
	Air quality	++	−
Cultural	Environmental setting	−	−

Onshore wind farms tend to have significant positive local impacts on primary production and air quality, and tend to have negative local impacts on soil, water, and livestock (Table 2). These negative impacts are mostly associated with the operational and decommissioning stages of wind turbines in the UK. At global scale, onshore wind farms tend to have negative life-cycle impacts on a number of ecosystem services, including air quality (Table 2). These negative impacts are mainly due to the mining of steel and concrete in other parts of the world.

There are uncertainties among the results. First, when searching literature for the estimation of impacts on ecosystem services, some studies used different terms to describe, or use different classification systems for, ecosystem services, resulting in some omission or ambiguity of impacts on ecosystem services. Second, although the resultant ecosystem service impact matrix is based on literature, and will be validated by experts, some uncertainties remain when two or more literature present different impacts on ecosystem services. In this case, ambiguous findings need to be noted.

4. Discussion

Ecosystem service frameworks have been developed to illustrate how changes at the ecosystem level can affect the health and wellbeing of humans [1]. Studies to date have focused on one or multiple ecosystem services (see discussion in Zhang et al. [3] and Bennett et al. [24]), but no studies have attempted to consider all ecosystem services holistically. Accounting for provisioning services is the easiest, due to the greater availability of data, while accounting for other ecosystem services is more challenging [3]. In addition, to the best of our knowledge, this research is the first in suggesting to quantify the impacts of onshore wind farm on ecosystems at both local and global scales, and the idea can be extended to other energy technologies.

The global impacts of onshore wind farms on ecosystem services are mainly due to the mining of steel and concrete in other places in the world. The mining of steel and concrete has already been shown to have negative impacts on ecosystem services [25]. If the mining of steel and concrete is conducted in developing countries, the negative impacts could be worse, due to low technology levels used and often lower environmental standards. Sourcing materials from regions with the strongest environmental protection standards would minimise these impacts.

LCA has recently been used to account for ecosystem services. Zhang et al. [3] conducted a critical review for LCA methods. The methods, however, are limited by data. For some ecosystem services such as cultural ecosystem services, little/no information is available. The availability of data impacts the boundary of a LCA. On the other hand, the understanding of the relationship between ecosystem services and its environmental impacts may also impact the boundary of LCA. Some studies have suggested that greater effort should be dedicated to understanding how ecosystem services function and how they are linked to production and consumption of marketed goods and services [2,3,26–28]; that is, understanding the interaction among industrial ecology, ecosystems and system ecology, decision and policy making, and economics. Such understanding will enrich the assessment of energy provision impacts on ecosystem services.

There are numerous classification systems for ecosystem services: the MEA classification [1]; The Economics of Ecosystems and Biodiversity classification (TEEB) [29]; the UK's National Ecosystem Assessment classification [30]; and others. Each classification system has its own advantages and disadvantages. For example, the MEA classification distinguishes the functional groups, but could be regarded as confusing services (means) and benefits (ends) [31–33] which could lead to double counting when used to support ecosystem service valuation [31,33]. The MEA classification is used here, because it is the most commonly-used approach, and thus the evaluations can be compared with other global studies.

In this paper, we did not further disaggregate the direct and indirect impact of energy provision on ecosystem services. Rather, we aggregated them. This was because for some ecosystem services like pollination, only qualitative information is available, which is hard to implement using a mathematical operation, although other ecosystem services such as carbon cycling have quantifiable information. Expert judgement is necessarily involved where quantification is not yet possible.

We only identify the countries having direct transactions with the UK in terms of materials of onshore wind farms. These countries can in fact also import materials from other countries from which the materials might be sourced. Therefore, further tracing of the supply chain to identify countries of origin of raw materials is necessary to assess all impacts accurately. This paper presents a first attempt to quantify the impacts of onshore wind farms on ecosystem service locally and globally. Further research will focus on the understanding of interaction of these ecosystem services for onshore wind farms at local and global scales and also the quantitative estimation of the impacts on ecosystem services.

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