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Original article

Winds of change – modelling the onshore wind energy landscape of Great Britain for Net Zero targets

Rebecca von Hellfeld [a,*], Jon Reid [a], Arkan Eddine-Lomas [a,b], Heloise Robinson [c], Emma Hubbert [d], Carly Whittaker [e], Mark Pogson [f], Pete Smith [a], Astley Hastings [a]

[a] University of Aberdeen, School of Biological Sciences, St Machar Drive, Aberdeen AB24 3UU, UK
[b] Queen's University Belfast, School of Biological Sciences, 19 Chlorine Gardens, Belfast BT9 4DL, UK
[c] University of Bristol, School of Computer Science, 75 Woodland Road, Bristol BS8 1UB, UK
[d] Forest Research, 620 Bristol Business Park, Coldharbour Lane, Bristol BS16 1EJ, UK
[e] Forest Research, Alice Holt Lodge, Wrecclesham, Farnham GU10 4LH, UK
[f] University of Liverpool, School of the Arts, 19 Abercromby Square, Liverpool L69 3BX, UK

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ABSTRACT

Society needs to reduce its consumption of greenhouse gas (GHG) emissions-heavy resources to reduce its impact on the planet and climate. Thus, the United Kingdom Net Zero targets aim to reduce net GHG emissions by at least 100% by 2050, compared to 1990. Net Zero strategies aim to reduce emissions from all sectors of the economy and to actively contribute towards GHG removal. Major technological advancements have made wind energy the second largest contributor of renewable energy to the market. However, current research on the GHG emissions associated with wind turbines provides highly variable results linked to differences in the boundaries of the life cycle assessment (LCA), for example. Here, we demonstrate the sensitivity of wind turbine GHG-LCAs not only to wind speed but also to site initial soil organic carbon (SOC) and substitution credits (or grid decarbonisation). Moreover, our novel spatial model for onshore wind energy in Great Britain (WindFor) highlights nation-wide spatiotemporal trends in SOC change, GHG emissions, energy produced, and the emissions avoided when compared to the rest of the national grid. While the roll-out of UK wind energy has shown promise, significant challenges must be addressed to site turbines in locations that minimise emissions.

Introduction

The global population is continuing to grow by 1.1% annually, leading to a population of <8 billion in 2024 [1]. This has profound implications on the demand for housing, land, resources, and energy – in short: land use requirements – and demonstrates that society is no longer a variable with unchanging or linear impact [2]. The influence of societies on the environment must consider lifestyle, and technologies, institutions, and cultural/individual values/attitudes/behaviours that determine how those lifestyles are achieved [3]. The planetary boundaries framework (PBF) focussed on 9 biophysical boundaries within which a sustainable planetary future can be realised [4–6]. However, the PBF only indicates the maximum sustainable impact, a 'ceiling' below which society should remain. By including an adaptation of 'doughnut economics' [7], a 'floor' of minimum resource requirements can be integrated into the PBF. The resultant zone between conceptual floor and ceiling defines a safe and just space for humanity in the planetary context – a space we have exceeded far beyond: 6 PBF boundaries have been surpassed, with the 7th (ocean acidification) being dangerously close to the threshold [4].

Abbreviations: BEIS, Department for Business, Energy & Industrial Strategy; CCC, Climate Change Committee; CH_4, Methane; CO_2(−eq), Carbon dioxide (equivalent); CSV, Comma-Separated Values; DESNZ, Department for Energy Security and Net Zero; EPSG, European Petroleum Survey Group; GB, Great Britain; GHG, Greenhouse Gas(es); GJ, Gigajoule; h, Hour; ha, Hectare; HGV, Heavy Goods Vehicle; HWSD, Harmonised World Soil Database; IPCC, Intergovernmental Panel on Climate Change; kg, Kilogram; l, Litre; LC(A), Life Cycle (Assessment); LUC, Land Use Change; MW(h), Megawatt(−hour); N_2O, Nitrous oxide; PBF, Planetary Boundaries Framework; PNG, Portable Network Graphics; RCP, Representative Concentration Pathway; SI, Supp Information; SOC, Soil Organic Carbon; t, Tonne; t-km, Tonne-kilometre; UK, United Kingdom; UNEP, United Nations Environment Programme; yr, Year.

* Corresponding author.
E-mail address: rebecca.vonhellfeld@abdn.ac.uk (R. von Hellfeld).

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At its conception, climate change was one of three PBF boundaries (biodiversity loss and interference with the nitrogen cycle being the others) that had already been exceeded [5]. To reverse this and the resulting environmental consequences, decreased dependence on fossil fuels is necessary. The United Kingdom (UK) gains 80% of its energy from fossil fuels, a reduction of only 10% since the 1970s [8]. To further decarbonise the economy, the UK government passed the 2008 Climate Change Act [9], setting the unilateral target of reducing territorial net carbon emissions by 100% by 2050 since 1990 (herein referred to as the Net Zero target). Moreover, the UK government provided strategies and targets for existing and emerging technologies [10], including offshore wind, nuclear power, hydrogen, and carbon capture and storage.

In 1989, the UK energy sector became subject to a 'Non-Fossil Fuel Obligation', supporting the development of alternative energy sources [11]. The implementation of onshore wind has grown steadily since [12], but reduced governmental support in 2015 affected the development of new sites and slowed research and development [13]. Currently, wind and solar energy together account for little more than 1% of the total global primary energy supply [12], while the global energy demand is only predicted to increase [14]. Challenges around onshore wind energy deployment include local/national restrictions, site access, and ecological impacts [15,16]. Spatial modelling to determine the most suitable sites can consider e.g., distance from buildings, grid connectivity, and quality of land [17]; and areas of exclusion, such as protected peatlands [18], or Sites of Special Scientific Interest [19]. Such models have successfully been implemented, for example, for the growth of the bioenergy crop *Miscanthus* through the modelling tool MISCANFOR [20], or when assessing wind energy spatially for windfarm development [21,22].

The legal framework for ensuring environmental protection in energy autonomy means that we must quantify the impact of any process on the environment. This can be done through a consequential life cycle assessment, or LCA [8]. Successful quantification of the life cycle (LC) begins with accurate goals and boundary setting, followed by an inventory analysis of all processes, material and energy requirements, site alterations, and environmental interactions. Further, associated emissions with the acquisition, processing, and use of materials are sought, as well as those associated with the final decommissioning stage. Lastly, the generated data must be reviewed critically, data sensitivity determined, and the findings presented coherently [9]. An LCA developed to determine the impact of windfarms on carbon-rich Scottish peatlands provided vital insight into management practices and environmental implications of windfarms and highlighted the need for continued attention on environmental impacts and emissions for future projects [23].

LCAs have been widely applied to wind energy to quantify greenhouse gas (GHG) emissions across all stages of a turbine's life, including material extraction, manufacturing, transportation, construction, operation, maintenance, and decommissioning [10–13]. While operational emissions are often shown as negligible [14,15], the embodied energy and associated emissions of turbine components and infrastructure contribute measurably to the total carbon footprint [16–18]. Moreover, these are strongly influenced by land type and soil carbon content [19], particularly for carbon-rich soils such as peatlands [23]. In the present study, we conducted a streamlined, GHG-focused LCA of onshore windfarms sited on different land types (arable land, grassland, and peatland) in Great Britain (GB), accounting for soil organic carbon (SOC) changes and the energy generated. LC emissions are reported as absolute values per turbine and per unit of electricity generated and are contextualized against the UK electricity grid to illustrate potential avoided emissions from wind energy deployment, without assessing other environmental impact categories such as toxicity or eutrophication. We then integrated these insights into the novel spatial model 'WindFor', providing high resolution insights into the GHG impacts and energy gains across GB. As the aim of this work was to support GB-wide energy sector decision making, this only included large-scale windfarms and does not account for smaller scale or farm/business level turbine placements.

Materials and Methods

Windfarm LCA

The LCA for windfarms in GB was adapted from the Windfarm Carbon Calculator [24]. It should be noted that we did not conduct a full LCA (e.g., under ISO standards 14040 or 14044 [20,21]), wherein the environmental impact of the windfarm across all LC stages (i.e., cradle-to-grave) is assessed for climate and atmospheric impacts (i.e., GHG emissions, ozone depletion, smog and particulate matter formation), ecosystem impacts (i.e., terrestrial, freshwater, and marine ecotoxicity, acidification, eutrophication, land use and land use change, and biodiversity impacts), human health impacts (i.e., toxicity and respiratory effects), and resource depletion (i.e., fossil resource scarcity, mineral and metal use, and water consumption). Instead, this study has opted to focus only on the GHG emissions aspect of the LCA, as well as including energy generation and SOC changes (i.e., a steam-lined LCA). Throughout this publication, the approach will be referred to as an "LCA" to facilitate readability. Here, our LCA was separated into four main phases: 1.) Turbine production; 2.) Site establishment; 3.) Operation and maintenance (and site re-energising); and 4) Decommissioning. For each phase, the GHG emissions were derived, as well as the SOC change, and the resulting energy generation. The system boundaries include the material extraction for turbine production and end with the decommissioning solutions for different turbine parts (Fig. 1). Where possible, the associated GHG emissions were recorded for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) however, for decommissioning only CO_2-equivalent (eq.) emissions were available.

GHG emissions associated with production, operation, and decommissioning

The GHG emissions associated with each item/process were determined (Table 1) for all materials listed in Vestas reports for the different turbine sizes [25–27]. To derive the kg CO_2-eq. emission, conversion factors of 29.8 (CH_4) and 273 (N_2O) were used [28].

Turbine production. The turbine production assumed the development of UK standard turbines (such as the V110-2 MW, V150-4.2 MW, or V150-6 MW turbines [32–34], herein referred to as 2, 4, and 6 MW turbines), summarised in Table 2. Relying on the reports for the LCA development meant that the reported transport distances of materials to site were used, which differed between the reports. The material emissions for each turbine were obtained from the literature and through the SimaPro version 8.3.0.0 [28] Ecoinvent database, including the raw material production. The emissions provided here account for the manufactured components from a given material [35].

For fibreglass, a 1:1 ratio with epoxy was assumed, while for glass fibre reinforced polymers a 3:1 ratio was assumed [22]. Information regarding specific electronic components were limited and substituted here with 'Electronics for control unit' emissions [28]. Diesel was used as the assumed fuel source throughout, with the associated emissions calculated based on the litre consumption for various equipment [31]. From the same report, emissions per tonne-kilometre (t-km^{-1}) for transport with an articulated heavy goods vehicle (HGV) or cargo ship were obtained, thus eliminating the need to account for return trips or transport of bulk objects (Supplementary Information (SI) 1). A distance of 600 km to site for all materials was assumed, other than cement for which a distance of 50 km [33].

Site establishment. This includes emissions associated with the transport of turbine parts to the site; the excavation of foundation, borrow pits, and tracks (assuming that the roads are built using hard core fill); turbine installation; and hard standing construction (SI 1). The foundation

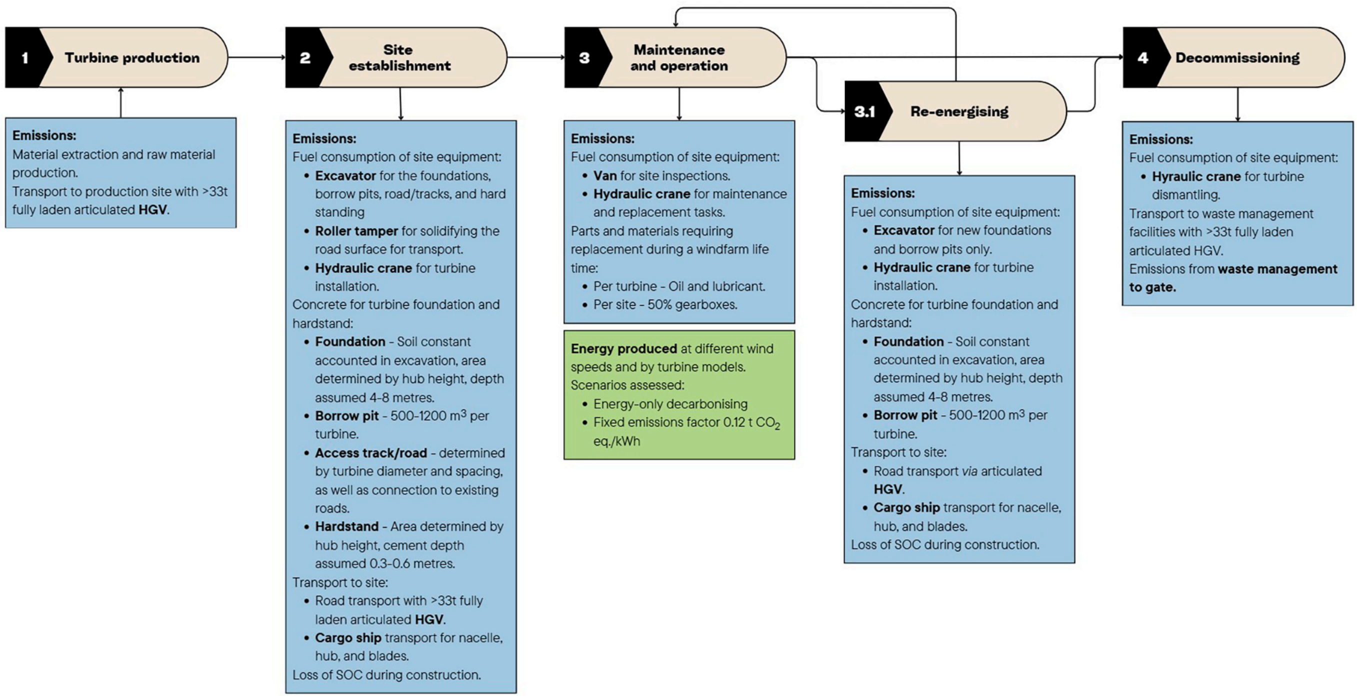

Fig. 1. Windfarm LCA entailing emissions generated between material extraction and windfarm decommissioning. Blue boxes: Emissions associated with each stage; Green box: Energy production.

area (*Af*; m^2) was determined through an adaptation of the simplified load-bearing equation [25], multiplying the soil constant (*k*) by the squared hub height (m) *H*. The access tracks (*AT*) were derived from the turbine diameter (Ø) and the turbine spacing [26], as well as the length (m) given in the report for a 10 m wide road, and the number of turbines:

$$\mathrm{AT} = \mathrm{Turbine}_{\varnothing} \times \mathrm{Turbine}_{\mathrm{spacing}} + \left(\mathrm{Track}_{\mathrm{length}} / \mathrm{Turbine}_{\mathrm{number}}\right) \times 10 \tag{1}$$

The hardstanding area (*HS*) was calculated by multiplying H by H and diving the result by 2 [27].

Operation and maintenance. A bi-annual inspection of the site is conducted [37], with previously stated transport-associated emissions [31]. Further, 8 h of hydraulic crane work are required per turbine in its lifetime [37], and we assumed that the crane type was the same as for site establishment. For parts replacement, 320 l oil per turbine are needed every 5 years, as well as 16 kg yr^{-1} lubricant per turbine [37]. Lastly, 50% of all gear boxes are replaced (90% steel and 10% electronics) [38].

Re-energising. For sites that can be re-energised, it will first be decommissioned, removing the wind turbines and constructing new foundations and borrow pits (see below). New turbines must be produced and established. However, the access roads are re-used, therefore these emissions are not included in re-energising processes.

Decommissioning. This includes the site deconstruction and emissions associated with waste management. Hydraulic cranes dismantle the turbines [37], followed by road transport to a recycling centre/landfill site/incinerator. Approximately 92% of metals will be recycled and 8% of metals landfilled (Supplementary Information (SI) 1) [32]. The emissions for landfilled material include collection, transport, and landfill emissions. For combustion/recycling, the emissions only consider transport to facility, with subsequent emissions from electricity generation or material production respectively included in the LCA of the new product, not the waste material [31].

SOC loss from site establishment

To assess SOC change, the area of soil removed for foundations, hard standings, borrow pits, and roads was determined, considering only the top 1 m of soil to contain organic carbon [39]. A 'per turbine loss' was determined by dividing the area of soil removed by the number of turbines. For re-energised sites, the SOC loss for the second lifetime only included foundation and borrow pit area.

Energy generation and emissions offset

The energy generated was calculated for different wind speeds (at hub height), considering the energy density and efficiency, before converting it into generated energy. The wind speed at hub height (m s^{-1}) was calculated by:

$$\text{Wind speed at hub} = \text{Wind speed}_{10\mathrm{m}} \times \left(\frac{\text{hub height}}{10}\right)^{0.143} \tag{2}$$

where 0.143 is the power law exponent [40]. To determine the wind power density:

$$\text{Wind power density}\left(\mathrm{W/m^2}\right) = \mathrm{EF} \times 1.3 \times \text{Wind speed at hub}^3 \tag{3}$$

where EF is the efficiency factor (0.57, based on the Betz limit [41]). The turbine power in MW is calculated from the sweep area and the wind power density (Equation (4):

$$\text{Power (MW)} = \frac{\text{Wind power density}_{\mathrm{W/m^2}} \times \text{Sweep}}{1000000} \tag{4}$$

The sweep area is computed as:

$$\text{Sweep area}\left(\mathrm{m^2}\right) = \pi \times \left(\frac{\text{Sweep diameter (m)}}{2}\right)^2 \tag{5}$$

The efficiency of the energy density (MW ha^{-1}) is then computed as the product of the turbine-specific capacity factor and the energy density (MW ha^{-1}), which itself is the quotient of the power and ha area per turbine.

The annual generation per turbine (MWh) is the product of the wind

Table 1
CO_2, CH_4, N_2O, and CO_2-eq. emissions of each item/process of the LCA obtained from the literature (right-hand column 'Ref.', see SI 1 for assumptions).

Item/process	Unit	kg CO_2-eq./unit	kg CO_2/unit	kg CH_4/unit	kg N_2O/unit	Ref.
Steel	kg	2.33	2.31	0.00	0.00	[22]
Aluminium	kg	3.46	3.43	0.00	0.00	[22]
Copper	kg	6.59	6.54	0.00	0.00	[22]
Iron	kg	3.14	3.11	0.00	0.00	[22]
Concrete	kg	0.70	0.70	0.00	0.00	[22]
Reinforced concrete	t	80.90				[29]
Fibreglass [a]	kg	2.01	2.00	0.00	0.00	[22]
Plastic	kg	3.14	3.11	0.00	0.00	[22]
Epoxy	kg	3.98	3.94	0.00	0.00	[22]
SF_6 gas	kg	22800.00				[30]
Magnets [b]	kg	91.90				[24]
Electronics	kg	47.70				[28]
Insulation	kg	1.02	1.01	0.00	0.00	[22]
Glass fibre reinforced polymers [c]	kg	1.76	1.74	0.00	0.00	[22]
Diesel (average biofuel blend)	l	2.55	2.52	0.00	0.00	[31]
Large van/car emissions (Class I, up to 1.3 t)	km	0.14	0.14	0.00	0.00	[31]
>33 t articulated HGV, 100% laden	t-km	0.06	0.06	0.00	0.00	[31]
General cargo ship (Average)	t-km	0.01	0.01	0.00	0.00	[31]
Oil	litre	2.75	2.71	0.00	0.00	[31]
Lubricant	litre	2.75	2.74	0.00	0.00	[31]
Metal recycling [d]	t	0.99				[31]
Metal landfill	t	1.26				[31]
Plastic landfill	t	8.88				[31]
Plastic incineration [d]	t	21.28				[31]
Concrete landfill	t	1.23				[31]
Electronics landfill	t	8.88				[31]
Mineral oil landfill	t	21.28				[31]

[a]A 1:1 ratio of glass fibre and epoxy is assumed; b: Value derived for the average of all provided magnets; c: A 1:3 ratio of glass fibre and epoxy is assumed; d: Includes the transport to site and processing. Emissions/credit for recycling \incineration are not included in the decommissioned product listed here [31].

Table 2
Material requirements per turbine currently produced for the UK market [32–34].

	Tonnes per turbine		
	2 MW	4 MW	6 MW
Manufacture location	North America	Germany	Germany
Steel, iron	234.40	683.68	532.36
Aluminium, alloys	10.20	13.24	12.14
Copper, zinc, nonferrous metals, alloys	3.48	5.6	4.80
Polymer materials	27.24	31.80	32.90
Ceramic, glass, other materials	15.52	39.16	28.79
Concrete foundation	913.44	1934.36	1478.64
SF_6 gas	9.72	9.40	0.01
Magnets	0.12	0.12	0.32
Electronics	1.84	3.64	4.74
Oil, coolant [a]	1.48 (1329.50 l)	1.96 (1760.69 l)	2.46 (2209.85 l)
Non-specified materials	1.00	0.32	3.28

[a]Density of ethylene glycol of 1.1132 g/cm^3 [36].

power density and the cap factor over the 365 days. The resultant data informs the per turbine and per site energy generation, the carbon intensity of the electricity produced, and the electricity produced ha^{-1}. Finally, the emissions avoided (kg CO_2-eq. kWh^{-1}) were calculated by multiplying the energy generated by the difference between the windfarm carbon intensity and one of two scenarios of annual grid-average generation-based electricity emissions factors. The emissions factor to represent a non-decarbonised grid was 0.12 kg CO_2-eq. kWh^{-1}, the value used by the UK government for the year 2025 for the average grid. For the decarbonisation case we used the respective future annual projected emissions factor from the HM Treasury Green Book for each year [42]. Unlike full LCAs, this study has generated negative values for this LCA, which arise from a post hoc comparison between the LC-GHG of wind-generated electricity and those of the electricity grid and, therefore, represent potential avoided emissions rather than negative life cycle impacts.

LCA parameters across different wind speeds and initial SOC conditions

The LCA input was adjusted to represent the GHG emissions and SOC changes for windfarms sited on three different land options: arable land (60 t C ha^{-1}), grassland (120 t C ha^{-1}), and peatland (600 t C ha^{-1}) [43,44]. The number of turbines per site stated in the 2 MW, 4 MW, and 6 MW turbine reports were utilised here [32–34]. The Global Wind Atlas 3.0 suggests average wind speeds between 3.5 and 7 m s^{-1} at 10 m height for the UK [45], so low, medium, and high windspeed scenarios here represent 3.5, 5, and 7 m s^{-1}, respectively. No additional scenario was considered for increased extreme wind events due to climate change, as these are unlikely to cause a continuous increase in wind speed and the LCA does not consider variable wind speed.

Spatial model: WindFor

The spatial model WindFor was derived from MiscanFor [46], developed for the spatial estimation of energy yield from bioenergy crops, which included wind and solar energy generation for comparison [47]. Along with general updates and the implementation of daily and monthly meteorological data [46,48], more recent adaptations include, e.g., updating the IPCC climate change scenarios, the input of wind speed, adding the Penman-Monteith method, and a more fine-scale representation of the UK [49].

The WindFor model builds on the wind energy calculation analysis of MiscanFor on a finer spatial resolution and increased parameter options and combines it with site construction parameters from the LCA to produce outputs for total energy generated, total CO_2 mitigated, total CO_2 emissions of the windfarm, and SOC loss due to installation. It spatially models GB across a user-defined period in a km^2 grid. Results are output in Comma-Separated Values (CSV) format for processing in ArcGIS software (Environmental Systems Research Institute). For the model code, see SI 2.

WindFor datasets

WindFor uses surface wind speed and SOC data for the UK. The surface wind speed is taken from the CHESS-SCAPE dataset [50] and contains wind speed projections for 1980–2080 at a 1 km^2 resolution with the British National Grid (European Petroleum Survey Group (EPSG):27700) coordinate system for 16 representations each of future climate scenarios Representative Concentration Pathway (RCP) 2.6, 4.5, 6.0, and 8.5. The SOC data is from the Harmonised World Soil Database (HWSD) [51] and was transformed to a 1 km^2 UK National Grid projection using ArcGIS. All data points are pre-combined into a single dataset in CSV format.

User inputs

The model user inputs are separated into four categories: turbine manufacturing values, site information, LCA variables, and operational parameters (SI 3). As default, each parameter is pre-populated with a value representing typical Vestas 2–6 MW turbines (SI 4). There are also two options for running WindFor where either (1) the model is run with all parameters accounted for, simulating a new site development of a windfarm over its defined lifespan; or (2) road construction is omitted, representing site re-energising. This process is in line with the LCA process outlined in section 2.1, following the assumptions (see SI 1).

WindFor operation

The WindFor user interface (written in the Java programming language) writes the input parameter values to a text file when run (see SI 5 for details of all input variables). This triggers a Fortran script that reads it and produces CSV file outputs, suitable for input into a GIS system. The Fortran script also calls a Python script to plot sample maps. All output data are saved to a numbered folder containing the input values, CSV files, and Portable Network Graphics (PNG) maps.

Here, the first LC is modelled for 25 years, assuming a start year of 2025 and including emissions associated with the construction of roads. The following LC represents a re-energising of the site, thus not including the development of the road network but accounting for all other emissions associated with site establishment. The same 0.12 kg CO_2-eq. kWh^{-1} average grid emissions factor was utilised here, as previously used for the LCA. Grid decarbonisation was not modelled in WindFor.

Results

Windfarm LCA

Annual emissions

The annual emissions associated with turbine sizes, initial site SOC, and wind speeds over the first and following LCs were determined for non-decarbonised and decarbonised grid energy (Fig. 2). Up to 85% of emissions in all scenarios was turbine production (see SI 6 and SI 7). In the non-decarbonised scenarios, 2 MW turbines achieved negative annual emissions (i.e., mitigation compared to the rest of the national grid) in the first and following LCs in all scenarios other than at sites with low winds (Fig. 2A). Emissions of 1.6 and 0.6 t C ha^{-1} yr^{-1} in the first LC and following LC were observed in the low wind-high SOC scenario, with the most mitigating scenario being high wind-low SOC (−13.6 and −13.7 t C ha^{-1} yr^{-1} in the first and following LC). With grid decarbonisation, the 2 MW turbine only achieved negative annual emissions in the low and medium SOC sites at the highest wind speed scenario in the first LC (Fig. 2B; −0.7 and −0.6 t C ha^{-1} yr^{-1}, respectively). Without grid decarbonisation, 4 MW turbines achieved negative annual emissions in all scenarios other than low wind-high SOC, with negative annual emissions of −20 t C ha^{-1} yr^{-1} in the first and second LCs of the high wind-low SOC scenario (Fig. 2C). With grid decarbonisation, 4 MW turbines only achieved negative annual emissions at high wind speeds in the first LC (low SOC: −2.9 t C ha $^{-1}$ yr^{-1}, medium SOC: −2.7 t C ha $^{-1}$ yr^{-1}, high SOC: −1.7 t C ha $^{-1}$ yr^{-1}, Fig. 2D). Finally, 6 MW turbines without grid decarbonisation showed mitigations spanning −19.8 to −18.4 t C ha^{-1} yr^{-1} with increasing SOC in the first LC at high wind speeds (Fig. 2E). With grid decarbonisation, only 6 MW turbines under the high wind speeds and the two lowest SOC scenarios achieved negative annual emissions of −2.2 and −1.7 t C ha $^{-1}$ yr^{-1} in the first LC, with increasing SOC, respectively (Fig. 2F).

Cumulative emissions

Under non-decarbonised conditions (Fig. 3), the 2 MW turbine with low wind speed did not achieve negative emissions in any SOC scenario (19.8–40.6 t C ha^{-1} and 37.8–63.5 t C ha^{-1} at the end of the first and following LC, respectively). At higher wind speeds, the 2 MW turbine achieved negative emissions with increasing wind speed and decreasing SOC (−58 to −340 t C ha^{-1} and −133 to −682 t C ha^{-1} at the end of the first and following LCs, respectively). The 4 MW turbine achieved negative emissions in almost all assessed conditions, apart from the first LC of the high SOC-low wind speed scenario (6 t C ha^{-1}). The cumulative emissions at the end of the first LC ranged from −20 to −501t C ha^{-1}, with increasing wind speed and decreasing SOC, as well as −11 and −1005 t C ha^{-1} for the second LC. For the 6 MW turbine, the high SOC-low wind speed scenario did not lead to negative cumulative emissions at any point in the LCs (105 t C ha^{-1} and 123 t C ha^{-1} at the end of the first and second LC, respectively). At higher wind speeds, all SOC scenarios reached negative emissions in both LCs, ranging from −8 to −485 t C ha^{-1} at the end of the first, and −8 to −980 t C ha^{-1} at the end of the second LC. When grid decarbonisation was introduced, fewer scenarios led to negative emissions. 2 MW turbines only achieved this at the end of the first LC in the high wind speed scenario, with −14 and −16 t C ha^{-1} for the medium and low initial SOC sites, respectively. Similarly, the 4 MW turbine only achieved negative emissions in the high wind speed scenario at all initial SOC conditions after the first LC (−42 to −71 t C ha^{-1} and −26.1 to −64.5 t C ha^{-1}) And at the lower initial SOC scenarios in the second LC (−31 and −38 t C ha^{-1}). The 6 MW turbine only led to negative emissions in the high wind speed scenarios at low and medium SOC scenarios in the first LC (−43 and −55 t C ha^{-1}), and in low SOC in the second LC (−13 t C ha^{-1}).

WindFor results

For visualisation purposes, the figures represent the difference in measured parameter compared with the 4 MW turbine windfarm in the first LC. The maps showing actual outputs for each turbine and LC can be found in SI 9.

SOC changes

The change in SOC in the first LC of the 4 MW turbine scenario indicated that regions with higher initial SOC lost more SOC (Fig. 4, boxed map). Here, substantial SOC losses of almost −500 t C ha^{-1} were observed in east Kent, Lincolnshire, Norfolk, Fens, the Midlands, the Scottish Boarders and Southwest, East Anglia, and Devon and Cornwall. Compared with the 4 MW first LC scenario, the 2 MW turbine scenario led to a smaller loss of SOC (top left map), while the 6 MW turbine scenario led to a greater loss of SOC (bottom left map). Due to the reduced area of soil being removed for re-energising, the loss in a following LC was lower than for the first LC for each turbine scenario (as shown by the blue colour of the maps to the left). In all cases, the geographical pattern of highest losses remained the same throughout the scenarios.

Annual emissions changes

Similar observations were made for annual emissions (kg CO_2 MWh^{-1}) associated with the different wind turbines (Fig. 5). For the first LC of the 4 MW turbine scenario, regions with high SOC showed increased emissions even when considering the higher wind energy generation in, e.g., hill tops compared with other regions. Here, the emissions produced were between 5 and 33,600 kg CO_2 MWh^{-1}, with the highest emissions in the Scottish Highlands and the lowest in the Western Isles. In the 4 MW second LC scenario, almost all regions indicated lower annual emissions than in the first LC, apart from parts of the Lake District and various locations in Wales. In comparison, both LCs of the 2 MW windfarms indicated higher emissions than the first LC of a 4 MW windfarm in all regions other than the North, Northwest and Northeast of Scotland. Compared with the 4 MW turbine scenario first LC scenario, these regions were also the ones where the 6 MW scenario showed increased emissions. The re-energised 6 MW scenario, however, showed emissions less than for the first LC 4 MW windfarm scenario.

Energy generation changes

Accounting only for the energy generated, no substantial trends were noted, although slightly more energy was produced in coastal regions and more exposed sites (Fig. 6). Highest generation was recorded on the Western Isles (3,900 MWh ha^{-1} yr^{-1} in the first LC of the 4 MW turbine scenario), whilst lowest generation recorded for the same scenario was in Perth and Kinross (3 MWh ha^{-1} yr^{-1}). The energy generated in the

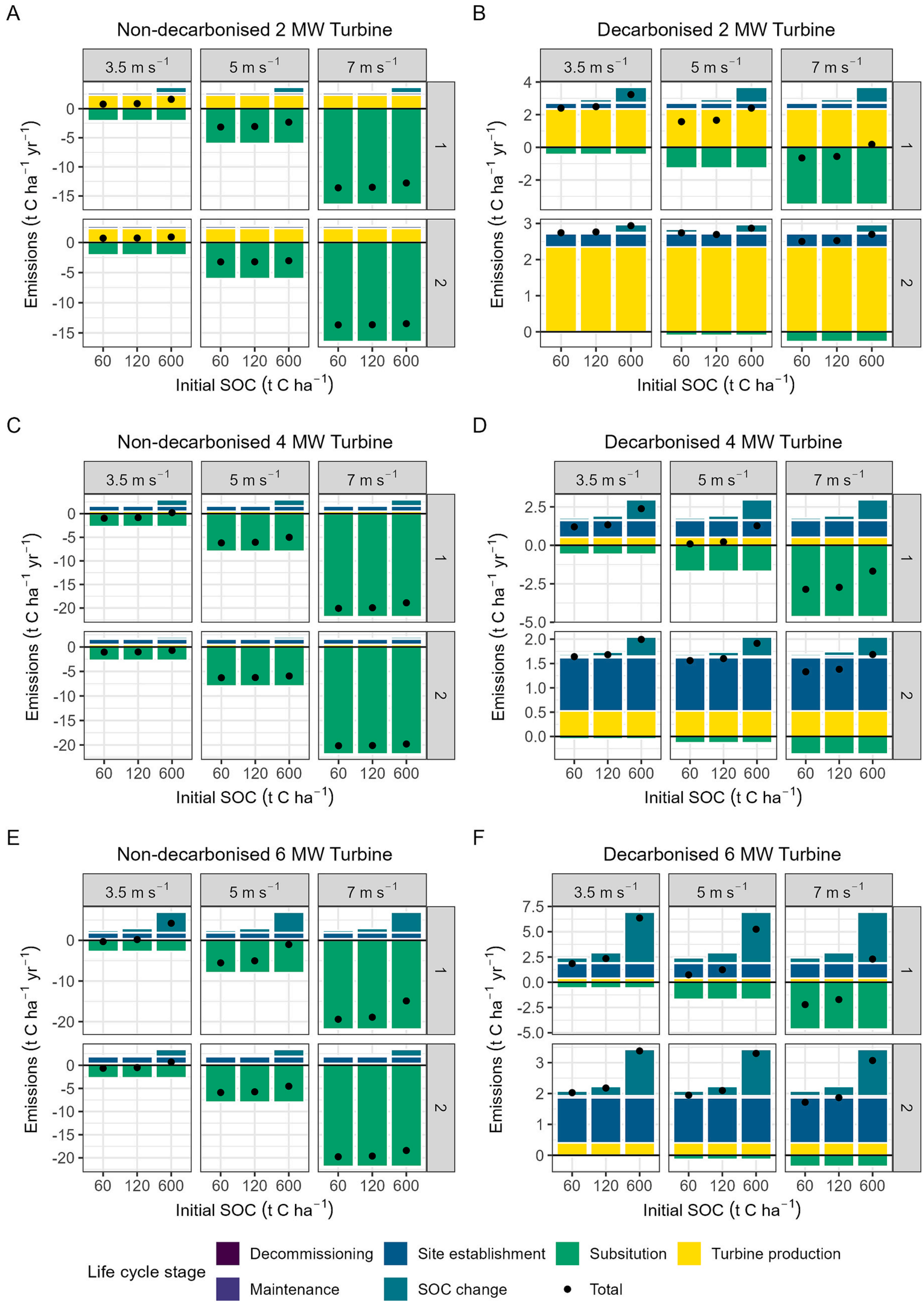

Fig. 2. Annual emissions (t C ha^{-1} yr^{-1}) during first (1) and following (2) LC of 2, 4, and 6 MW wind turbines, sited on 60, 120, and 600 t C ha^{-1} initial SOC, and wind speeds of 3.5, 5, and 7 m s^{-1}. A, C, E: No grid energy decarbonisation. B, D, F: Grid decarbonisation. Colour: LC stage; Dot: Total annual emission (t C ha^{-1} yr^{-1}).

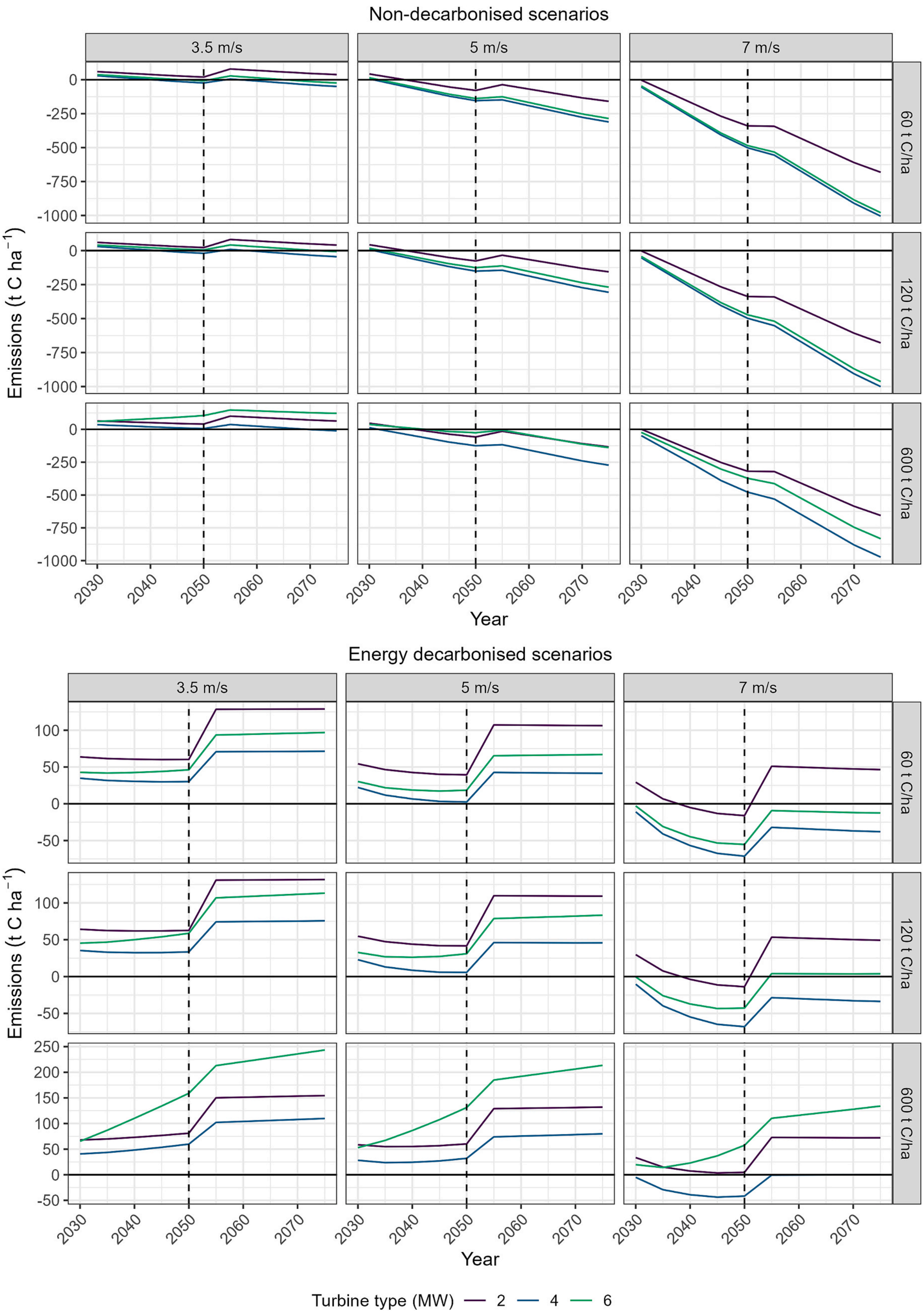

Fig. 3. Cumulative annual emissions (t C ha-1) associated with 2, 4, and 6 MW wind turbines, installed on sites with changing initial SOC and wind speeds for non-decarbonised (top) and grid decarbonised (bottom) scenarios. Timeline based on decarbonised emission factors provided by DESNZ [49]. Vertical dashed line: End of first LC.

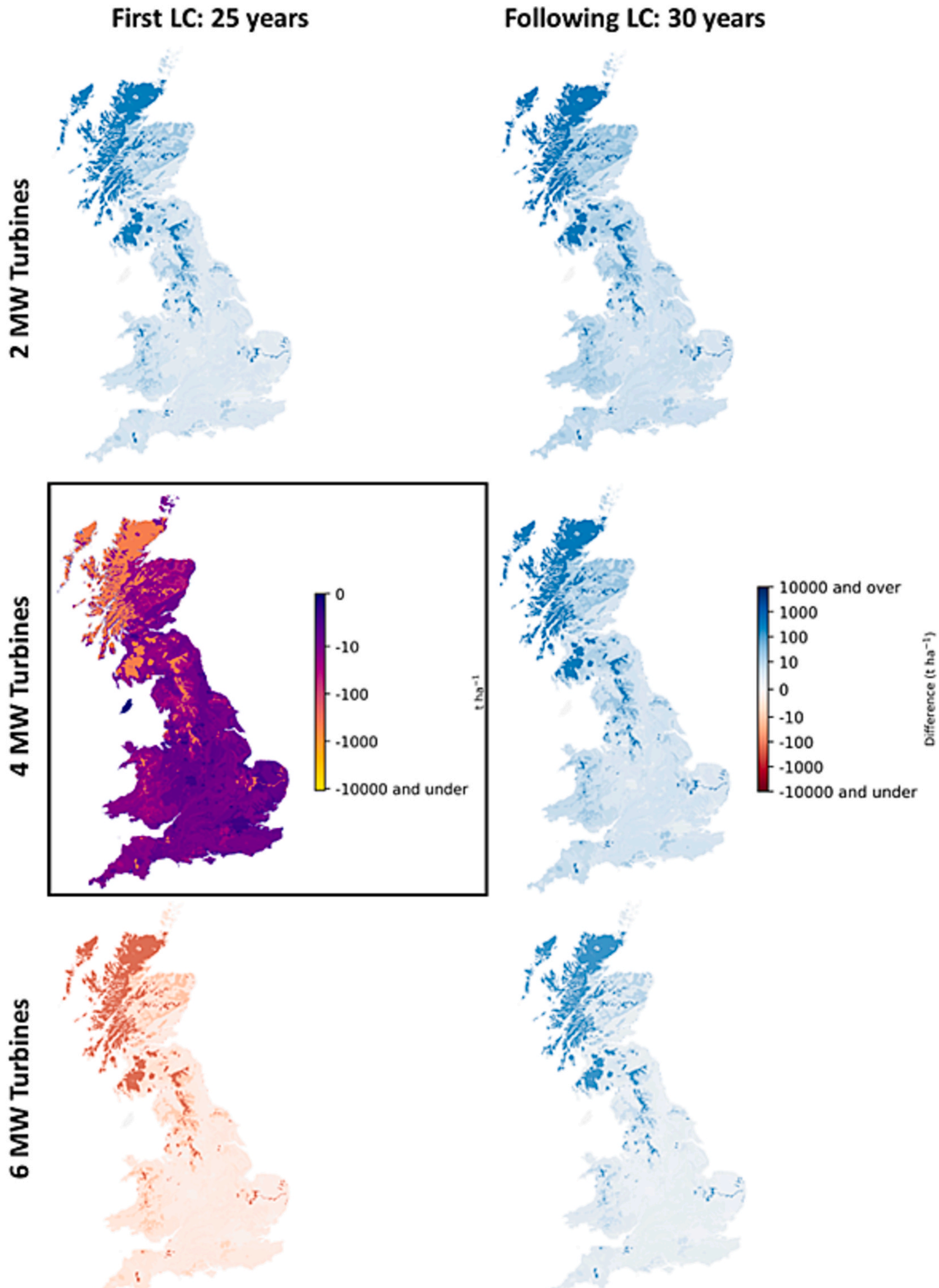

Fig. 4. SOC change (t C ha^{-1}) after the first or following LC for the different scenarios across GB. Box: 4 MW windfarm SOC change at the end of the first LC. All other maps: Representation of the difference between the 4 MW windfarm first LC, and the respective alternative. 4 MW LC 1 colour scale: Yellow indicates an SOC change of -1000 t C ha^{-1}, while dark blue indicates a change of 0 t C ha^{-1}. Comparative maps colour scale: Blue indicates a positive change in SOC compared to the first LC of a 4 MW windfarm; red indicates the opposite. See SI 6 for underlying data, and SI 7 for maps of the actual SOC change (t C ha^{-1}) for each case.

second LC of the 4 MW turbine scenario was lower than in the first, and similar to the first LC of the 2 MW turbine scenario (the second LC of which was also lower than the first). The same trend between the first and second LC was observed in the 6 MW turbine scenarios, although the energy generated here was higher than that of the first LC of the 4 MW turbine scenario in both LCs.

Avoided emissions changes

More exposed regions (coastal and elevated lands, excluding sites with high initial SOC such as the Scottish Highlands) contributed most to a reduction in emissions compared to the grid average (areas coloured shades of brown in Fig. 7, boxed map). In the first LC of the 4 MW turbine scenario, approximately 68% of GB was found to mitigate emissions when compared to the national grid, with areas mitigating

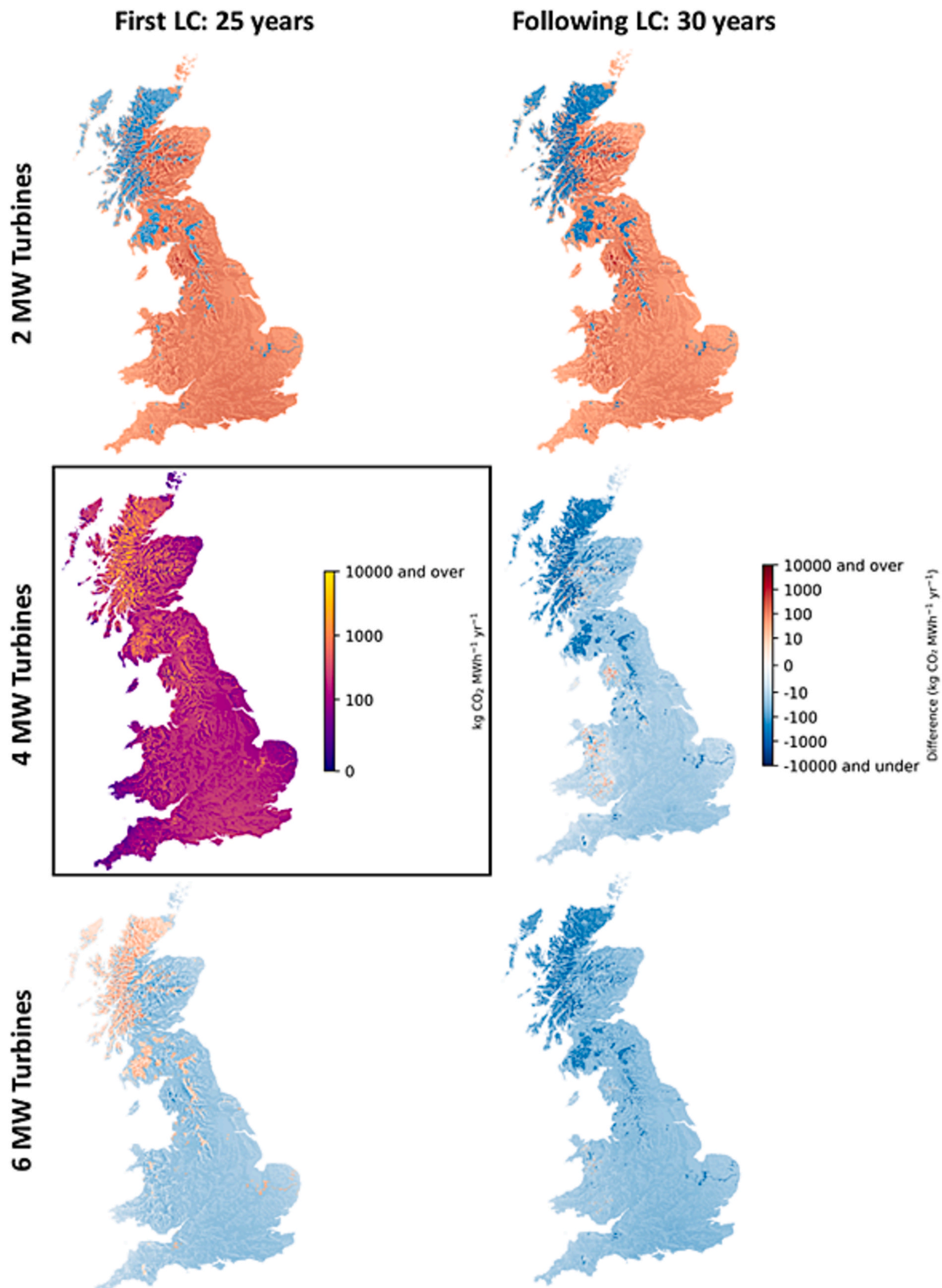

Fig. 5. Annual emissions (kg CO_2 MWh^{-1}) after the first or following LC for the different scenarios across GB. Box: 4 MW windfarm annual emissions at the end of the first LC. All other maps: Representation of the difference between the 4 MW windfarm first LC, and the respective alternative. 4 MW LC 1 colour scale: Yellow indicates annual emissions of $\geq$ 1000 kg CO_2 MWh^{-1} yr^{-1}, while dark blue indicates a change of 0 kg CO_2 MWh^{-1} yr^{-1}. Comparative maps colour scale: Blue indicates a negative change in annual emissions compared to the first LC of a 4 MW windfarm; red indicate the opposite. See I 6for underlying data, and SI 7 for maps of the actual annual emissions (kg CO_2 MWh^{-1}) for each case.

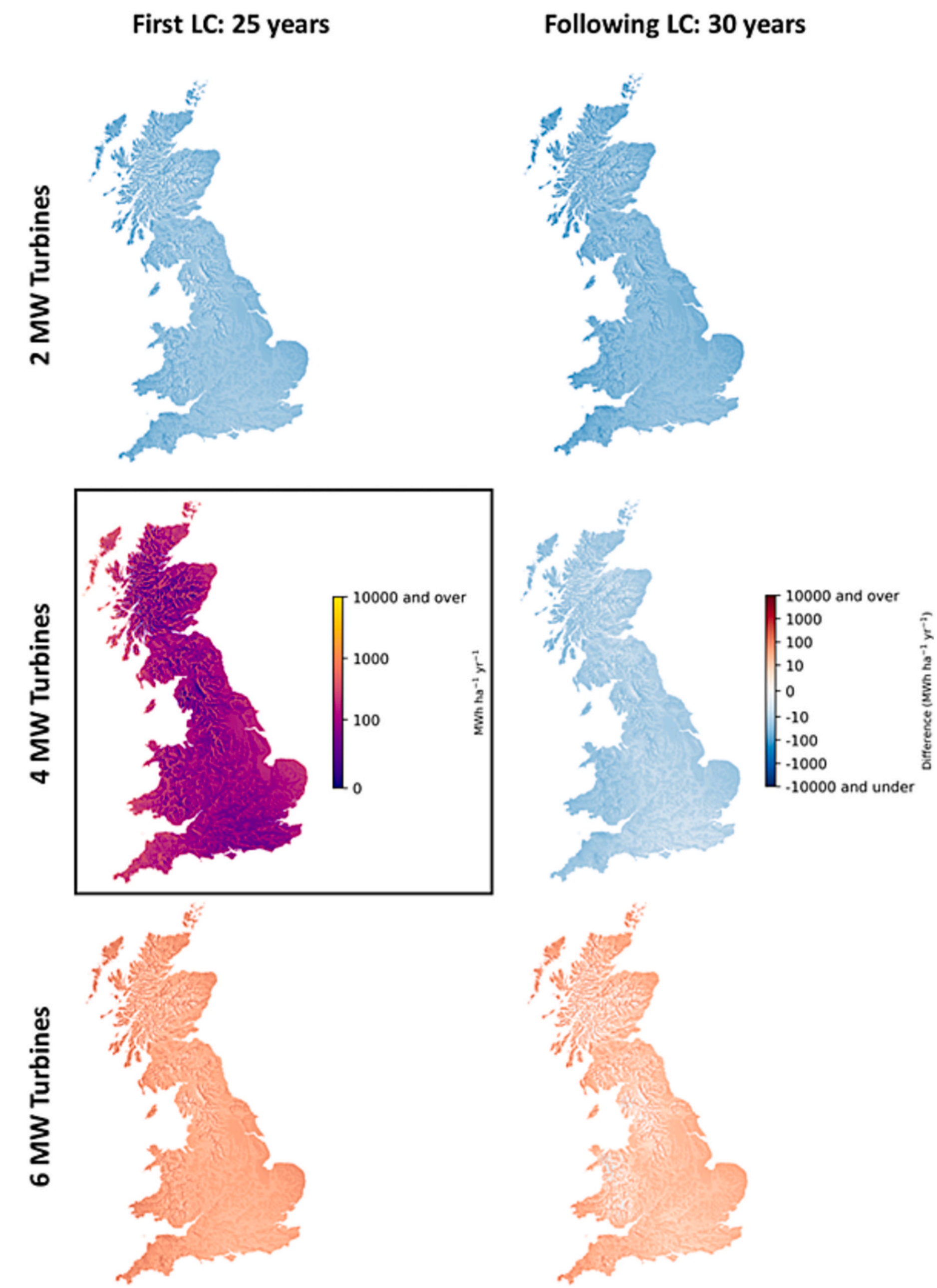

Fig. 6. Annual energy generated (MWh ha^{-1} yr^{-1}) after the first or following LC for the different scenarios across GB. Box: 4 MW windfarm annual energy generation at the end of the first LC. All other maps: Representation of the difference between the 4 MW windfarm first LC, and the respective alternative. 4 MW LC 1 colour scale: Yellow indicates annual energy generation of $\geq$ 1000 MWh ha^{-1} yr^{-1}, while dark blue indicates a change of 0 MWh ha^{-1} yr^{-1}. Comparative maps colour scale: Blue indicates a negative change in annual energy generation compared to the first LC of a 4 MW windfarm; red indicates the opposite. See SI 6 for underlying data, and SI 7 for maps of the actual annual energy generated (MWh ha^{-1}) for each case.

over 1,900 t CO_2 ha^{-1} yr^{-1} along the Welsch border. In the second LC of the 4 MW turbine scenario, areas with previously emitting high emissions (up to 11,300 t CO_2 ha^{-1} yr^{-1}) were mitigating in comparison to the first LC. No sites were determined to emit more in the second LC than in the first. The regional trend of emissions in high initial SOC areas was also observed in the 2 and 6 MW turbine scenarios. Here, compared with the 4 MW turbine first LC scenario, both LCs of the 2 MW turbine showed mitigated emissions in high SOC regions in comparison, but also showed increased emissions in the rest of the country. For the first LC of the 6 MW turbine scenario, emissions increased in the high SOC regions in comparison with the first LC of the 4 MW scenario but decreased in other regions of the country. In the second LC, most regions were mitigating in comparison to the 4 MW turbine scenario, apart from a few regions in the Highlands, Midlands, and Wales. While in the 2 MW turbine scenarios, a reduction in the emissions from most sites in Scotland is observed, these sites are, nonetheless, emitting in each scenario (see SI 9 for details).

Discussion

Our LCA highlights a sensitivity to wind speed, with a reduction from 7 to 5 m s^{-1} leading to a reduction in energy generation of 319 MWh ha^{-1} yr^{-1} for 2 MW turbines and over 400 MWh ha^{-1} yr^{-1} for 4 and 6 MW turbines. Overall, most emissions are associated with turbine production and site establishment (Fig. 2). The GHG intensiveness of site establishment was previously noted, linked to the global transportation

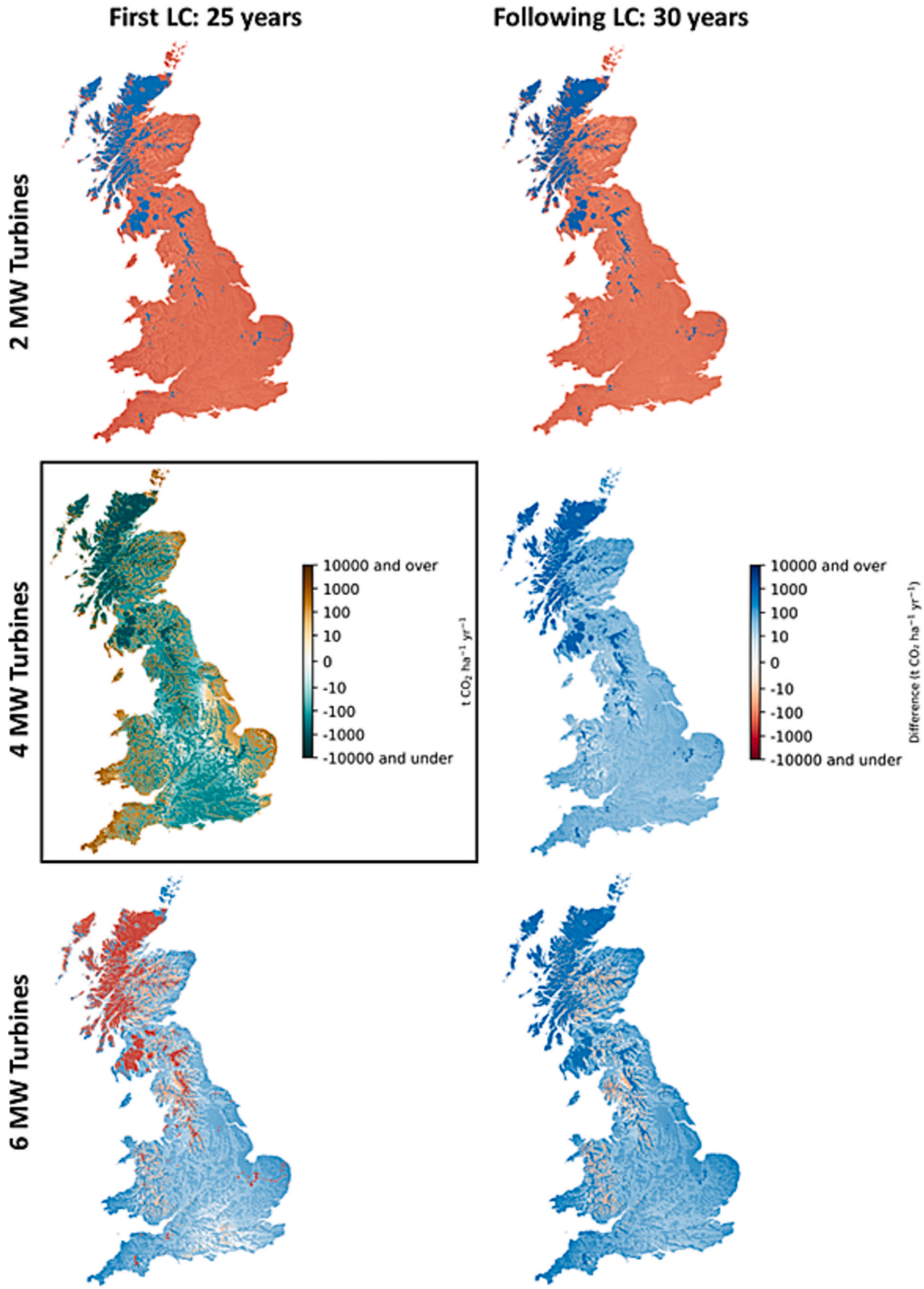

Fig. 7. Annual emissions mitigated (t CO_2 ha^{-1} yr^{-1}) after the first or following LC for the different scenarios across GB. Box: 4 MW windfarm annual emissions mitigated at the end of the first LC. All other maps: Representation of the difference between the 4 MW windfarm first LC, and the respective alternative. 4 MW LC 1 colour scale: Brown indicates annual emissions mitigated of ≥ 1000 t CO_2 ha^{-1} yr^{-1}, while dark green indicates a change ≤ -1000 t CO_2 ha^{-1} yr^{-1}. Comparative maps c olour scale: Blue indicates a positive change in annual emissions mitigated compared to the first LC of a 4 MW windfarm; red indicates the opposite. See SI 6 for underlying data, and SI 7 for maps of the actual annual emissions mitigated (t CO_2 ha^{-1} yr^{-1}) for each case.

of extremely heavy parts [35,52]. Emissions published for turbine manufacturing are more variable, based on the different material needs with turbine size [32–34], integration of manufacturing emissions into different LCA phases [13], and uncertainty around material production emissions data [35]. Our results suggest that windfarms on high-carbon soils will struggle to 'break even' in a decarbonised grid scenario over 55 years. However, it does not account for, e.g., increased emissions with distance from grid, longer transport distances for material delivery, and supply chain complexity. Further, the presented LCA is not adapted to specific requirements of peatland sites, not accounting for the removal of native plants, or the creation of floating roads. For this, we refer to the 'Carbon calculator for wind farms on Scottish peatlands' [23]. However, the best method to reduce GHG emissions on peatland is through peatland function restoration [53], which is aligned with current policy goals.

The WindFor model outputs show SOC losses increasing uniformly with turbine power rating, mostly due to increasing soil displacement as turbine foundation size increases. A much stronger geographic indicator is clear, however: in high-carbon soils, SOC loss reached almost 500 t C ha^{-1}, whereas low-carbon soils lose two orders of magnitude less (Fig. 4). This pattern supports existing advice that carbon-saturated peatlands should remain off-limits to new turbine construction, irrespective of turbine power [23,54,55]. Further, WindFor's outputs show that annual LC emissions scale with rated turbine power, as does electric power generation. Fig. 7 reveals that the mid-sized turbine mitigated CO_2 in 68% of GB, compared to grid electricity. In comparison, in their first LC, 2 and 6 MW turbines mitigated 87% and 60% CO_2 emissions when comparted to the grid average, respectively. The highest amounts mitigated in the first LC were approximately 1,200, 2,000 and 2,500 t CO_2 ha^{-1} yr^{-1}, for the 2, 4, and 6 MW turbine scenarios, respectively. This finding suggests that onshore windfarm plans should be optimised for turbine selection based on factors such as initial SOC and soil displacement volume as well as total energy generated.

However, the WindFor results thus far should be considered under the following considerations: (1) Only one CHESS-SCAPE climate scenario has been included; and (2) the total energy generation and CO_2 mitigation calculations use turbine blade diameters as a parameter (Equation (4). To mitigate potential limitations from point 1, future model iterations could incorporate scenario switching options, providing a deeper insight into the impact of changing climates on wind energy generation potential. Regarding the second point, the Vestas V150-4.2 MW and Vestas V150-6.0 MW turbines chosen here have the same blade diameter [33,34]. While the model inputs allow for modulation of all turbine-related values (SI 1), future iterations could assess the sensitivity of energy generated to changes in turbine parameters.

Uncertainties of the LCA and WindFor include the need to develop the grid to connect more remote sites and integrate wind power into the current systems [56–58], methodological and technological limitations of wind turbine blade recycling [37,59] and potential changes to substitution credits in the future. A plethora of additional limitations for the advancement of onshore wind are highlighted in a recent review, extending beyond the scope of this work [60].

Here, we assumed a static displacement of grid power with wind energy, which is not an accurate representation of current conditions. Two big challenges for integrating wind-generated energy into the grid are wind intermittency and grid reliability, with other challenges affecting the large-scale integration of wind energy [56]. Some solutions to address issues stemming from wind intermittency at the connection to the grid include new state-of-the-art wind generators and variable-pitch turbines [61]. Further developments include wind forecasting to improve the scheduling of wind energy capture [62,63], to address the seasonality of wind. Further, advancements are needed to avoid curtailment for energy networks operating at their limits with no/inadequate storage capacities [56]. Beyond the technical aspects, many nations globally face the limitation that the most suitable locations for highly productive sites are located at a great distance from load centres, requiring significant developments of the transmission networks. Moreover, the de-centralised generation of energy from windfarm sites requires additional investment, as current transmission networks are not designed for energy not fed directly to high-voltage levels [57]. In addition to these challenges, many also face issues such as the social acceptance (or lack thereof) of windfarm site establishment and grid connection [64,65]. Such challenges must be addressed to take sufficient steps towards current Net Zero aims.

Another major source of uncertainty when determining the GHG emissions associated with wind turbines is the decommissioning, disposal, and recycling of parts such as the turbine blades [66]. It is estimated that onshore wind blade material will account for 76% of the total waste material related to wind turbines, requiring 25% of the total generated energy in 2050 [67,68]. The material complexity of these blades is governed by the structural and aerodynamic requirements, with less focus being placed on the end-of-life processes [69]. The composite materials used for blades are notoriously challenging to process effectively, and novel techniques – such as adhesive bonding [70] – mean that we require extensive technological advances to facilitate their recycling [71,72]. Lastly, the sheer size and weight of the blades hampers the development of more sustainable practices as they require heavy machinery to manipulate or transport them [69]. To provide an incentive for advancements in the field of blade recycling, some countries have implemented a tax for land filling composite materials (e.g., £90 per t in the UK) or banned the practice altogether [68]. While the incineration of decommissioned blades may allow for the recovery of (some of the) energy required in the process, challenges include the non-flammable nature of glass fibres, leading to the accumulation of large amounts of residue [73]. Further uses of decommissioning products include the integration of mechanically recycled fibres into concrete (although this reduces its value compared to that of calcium carbonate) and the use in thermal or noise insulation [68,74,75]. There is also research into reusing decommissioned turbine blades for other purposes such as floats for marine solar farms [76]. It is evident that sustainable value chains for the end-of-life of windfarms are needed to tackle this issue [77], with a clear roadmap guiding the processes.

The 2050 Net Zero decarbonisation plan of the national grid means that the power dispatched today, primarily produced from petroleum (33.3 mil t oil equivalent in 2024 [78]) and natural gas (29.6 mil t oil equivalent in 2024 [78]), will have to be delivered by less carbon-intensive options such as battery storage, hydrogen, and natural gas with carbon capture and storage [79]. It should be noted that the viability of these options will not form part of this manuscript and are merely provided to highlight the current landscape of approaches. As highlighted in the present work, under grid decarbonisation, the carbon savings from substitution credits diminish over time (Figs. 2 and 3). While it is likely that new approaches to assessing substitution credits will be developed to account for the benefits of renewable energy as part of delivering Net Zero [80], current methods most likely underestimate future saving in highly conservative approaches, or overestimate them where, e.g., the scalability of novel methods is not fully determined.

In the present work, a 'single land use' approach was applied, wherein the conversion of land for wind energy purposes was assumed to exclude all additional land uses in and around the turbines. An analysis of the economic and GHG impacts of LUC of existing windfarms in Scotland estimated the loss of agricultural production and forestry in economic terms from only the area disturbed by the construction of the turbines and associated infrastructure. They concluded that the loss was significant especially in the case of grade 1-3a land and forest [54]. In addition, many of the existing windfarm sites in Scotland were found to generate electricity with a carbon intensity equivalent to that of fossil fuel thermal plants as they were developed on peaty soils. The present work has extended that methodology to estimate the GHG intensity of windfarm electricity to the rest of GB. In future, when developing new windfarms, the impact on current land use should be minimised so that dual use of land, itself a limited resource, should be part of the planning criteria where suitable. Hybrid land use approaches or dual land use options could be adopted that combine the benefits of different systems, with associated implications for GHG emissions. For example, in northern European countries, most windfarms are located on farms; this allows agriculture to be carried out beneath the turbines, and land disturbance is smaller as existing farm roads can be used. Most importantly, development of high carbon or peaty soils should be avoided if wind energy is to contribute to achieving Net Zero.

Implications

It has become increasingly evident that change is necessary in the way that we consume planetary resources, impact ecosystems, and change large-scale processes. One aspect of this is the reduction in GHG emissions generated from anthropogenic processes (through, e.g., Net Zero goals and other national and international initiatives), which exacerbate climate change and, in turn, the triple planetary crisis [81]. Renewable energy technologies will contribute to these goals substantially. As highlighted through the windfarm LCA, however, the modelled GHG mitigation of such technologies is highly dependent on substitution credits, with most emissions generated during the site establishment and turbine production phases, as well as changes in SOC which vary based on the initial soil conditions. Should grid decarbonisation be applied to all energy sources, only very limited regions would be suitable for the establishment of windfarms, as suggested by the LCA outcomes of this work. This is further supported by the WindFor outputs where clear regional trends are visible. This work lends itself as a basis for further research to assess the multi-purpose use of land to maximise the generation of clean energy whilst minimising the negative impacts on the planet.

In the context of climate change mitigation and energy systems transformation, sustainability constraints arise from the planet's finite capacity to absorb emissions without triggering irreversible environmental change. While renewable energy technologies, such as wind or solar power, are effectively limitless when considered on a human timescale, the continued reliance on fossil fuels is limited both by their declining availability and the environmental consequences associated with their extraction and consumption. Discussions of energy transitions must therefore be situated within the broader framework, such as the PBF, as well as considering competing land-use demands. Finally, it must be recognised that climate change mitigation, ecosystem/environmental protection, and energy security are tightly coupled challenges requiring integrated solutions.

CRediT authorship contribution statement

Rebecca von Hellfeld: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jon Reid:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Arkan Eddine-Lomas:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Heloise Robinson:** Writing – review & editing, Validation, Methodology, Investigation. **Emma Hubbert:** Writing – review & editing, Validation, Investigation. **Carly Whittaker:** Writing – review & editing, Project administration, Investigation, Funding acquisition. **Mark Pogson:** Writing – review & editing, Software, Resources, Investigation. **Pete Smith:** Writing – review & editing, Software, Resources, Investigation. **Astley Hastings:** Writing – review & editing, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2026.104962.

Data availability

All data is included in the Supplementary materials. Alternatively contact the corresponding author.

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