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Research paper

Scotland's onshore wind energy generation, impact on natural capital & satisfying no-nuclear energy policy

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ABSTRACT

Onshore wind electricity generation is key to mitigating greenhouse gas emissions. Poorly sited wind farms degrade high carbon soils and habitats, diminishing overall emission reductions. We explore the viability of the Scottish Government's renewable energy plan with respect to land use, natural capital and low carbon storage. With avoidance of sensitive peatlands a main consideration, six constraining factors were combined to determine areas of least habitat and soil sensitivity to onshore wind development in Scotland. Currently, 14 out of 21 terrestrial habitats have been impacted by installation of 389 onshore wind sites. Accounting for 73% of the total area, Coniferous Woodland, Acid Grassland, Bog, and Heather Grassland have been the largest habitats impacted. The most common soils of the least sensitive areas available for installation are brown earth and podzols, and construction of new wind farms on environmentally sensitive areas can be minimised by targeting relatively disturbed habitats such as improved grasslands. Scotland has a potential of 2.75 Mha of relatively low sensitive land, the largest areas sited in the Highlands, Dumfries and Galloway and Aberdeenshire. Additional to current installed capacity (13.9 GW), Scotland would require 6.6 GW of installed onshore wind capacity to function without nuclear energy generation and 464 GWh additional storage capacity (provided by 8.2 GW wind capacity). This equates to an installed and additional total of 346.676 ha required for wind electricity generation, potentially satisfied by shared land use with 23% of Scottish improved grasslands. Scotland has the available land area to achieve the Scottish Government's policy to move towards carbon-neutral, nuclear-free electricity generation through the use of renewables alone. Questions remain on which source of low carbon dispatchable (immediately accessible) energy to use in the case of a several day wind lull.

1. Introduction

In 2010 the global energy and heat production sector produced 14.4 Gt CO_2e, making it the largest greenhouse gas emitter responsible for 35% of global GHG emissions for the year (IPCC, 2014). As the electricity generation industry is consistently the highest emitter of greenhouse gases across all regions in the United Kingdom (Salisbury et al., 2016), it is critical that the UK develops a low-carbon energy system. This will allow for a substantial reduction in GHG emissions, thus enabling the UK to start mitigating climate change and meet internationally agreed, legally binding, emission targets (UNFCCC, 1997, 2015; European Commission, 2014) In light of this there has been a political impetus within the UK to increase the share of low-carbon energy generation in the market, with policies put in place to support its deployment.

For low-carbon electricity generation, two current commercially viable technologies for Scotland are nuclear and renewables. Scotland and Germany are set to phase out nuclear generation over the next decade, whilst many European countries, including England, have disclosed plans to construct new nuclear power plants (NPP) (World Nuclear Association, 2021). Since the 2008 UK Climate Change Act (UK Govt, 2008), total installed renewable capacity in the UK has grown by a multiplier of seven from 6.79 GW to 47.16 GW in 2019, increasing overall supply from 21,846 GWh to 120.5 TWh (National Statistics, 2018; BEIS, 2020). This increase in generation capacity has allowed renewables to become the second largest supplier of electricity, generating 37.1% of the UK's total electricity in 2019 and not far behind 40.6% for gas (BEIS, 2020). Within the UK, Scotland has seen the largest gains in renewable generation accounting

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for 61.1% of gross electricity consumption in 2019 (BEIS, 2020), which allowed the Scottish energy sector to reduce emissions by 13.4 Mt CO_2 year^{-1} and growing (BEIS, 2016). By 2015, 96% of all newly installed electrical generation capacity in Scotland used renewable technologies (Scottish Govt, 2017). Having more than doubled in size since 2008, current renewable capacity installed in Scotland stood at 11.9 GW in 2019 (BEIS, 2019) and installed onshore wind at 8.4 GW, (we have not taken into account data beyond 2019 due to effects of Covid restrictions altering consumption and production trends). Accounting for 74% of the installed renewable capacity, onshore wind is the largest single provider of renewable electricity in Scotland. The introduction of renewables has led to power balancing challenges for the national grid as these sources of electricity can be intermittent leading to peaks and troughs in electricity generation which do not follow the demand curve.

Traditionally, energy demand has been balanced through the use of base-loading and dispatchable generation (instant on-demand energy). Nuclear power is currently relied upon for the majority of the Scottish grid base load. Providing 35% of generated electricity in 2015, nuclear power is the second largest source of electricity in Scotland. Together Torness and Hunterston B power stations continuously provide a combined base load output of 2.2 GW to the Scottish grid. An increase in electrical interconnectivity alongside increasing bulk storage, the introduction of 'smart-grids' and improving load-management also help provide solutions to the effects of intermittency on the grid (Bassi et al., 2012).

With the two nuclear power plants in Scotland set to close by 2030, the Scottish Government is faced with a 2.2 GW generation deficit in the energy sector. With a popular pro-renewables sentiment (Nelson, 2019) and in order to meet a target of net-zero emissions by 2045 (Scottish Govt, 2020a,b) the Scottish Government has set out to completely decarbonise the energy system through the use of renewable generation technologies alone. It is clear that onshore technologies will make up the bulk of the supply (as they do already). Of these technologies, wind farms are set to take centre stage as wind is arguably the most convenient method to generate electricity, especially in remote locations (Wang and Sun, 2012). In Scotland, these 'remote' locations tend towards the uplands as they are windy, of low agricultural value, and are away from major residential centres (Cowell, 2010; Smith et al., 2014). With the combination of an estimated further 11.5 GW of onshore wind potential (RSPB-WWF-FoE, 2006) and ample upland area, the renewable mix in Scotland is set to remain heavily weighted towards onshore wind production.

A decrease in the cost of onshore renewable generation technologies has increased their economic viability by bringing them in line with or below the cost of fossil fuel and nuclear generation, of which the least expensive are onshore wind and large-scale solar (BEIS, 2020b). As of March 2020, Scotland's wind generation had an operational capacity of 9.1 GW. With a further 8.4 GW of onshore wind generation under construction or planning consented and an additional 4.2 GW of offshore wind with planning consent (Scottish Govt, 2020a,b). However, as wind generation becomes more prevalent in our landscape concerns have been raised over land-use change and the impact on Scotland's natural capital; especially the degradation of peatland, and the loss of "wildness" (Scottish Natural Heritage, 2010; SEPA, 2015).

The ability of peatlands to sequester carbon has seen their importance rapidly rise in the political and public eye in recent years. In 2011 the IUCN Peatlands Inquiry (Bain et al., 2011) found that most of the UK peatlands have been severely damaged or modified and a loss of 5% of the UK's peatlands would lead to the equivalent release of the UK's annual GHG emissions. The Scottish Government developed a methodology to calculate carbon emission savings when siting windfarms on Scottish peatlands (Scottish Govt, 2011). More recent studies (Smith et al., 2021, 2014, 2012) have highlighted the need for regulation in the Scotland. In Scotland, peatlands are particularly important as 60% of the UK total peatland (4% of European peatland) is found here (Marsden and Ebmeier, 2012). Indeed, concerns about carbon loss from the siting of windfarms on peatland were reportedly a contributing factor in the rejection of the 181-turbine Lewis Wind Farm (BBC News, 2008). Following this decision, multiple authorities have issued good practice guidelines on how to manage peatland disturbed by building activities (SEPA, 2015; Scottish Natural Heritage, 2015) and how to suitably site windfarms to minimise environmental damage (RSPB, 2010).

However, these measures to reduce the impact of siting renewables in rural areas of low development (such as peatlands, forests, and moors) still involve a trade-off between the decarbonisation of the energy sector and the loss of other land functions, biodiversity, ecosystem services and visual amenity (van der Horst, 2007; Tilman et al., 2009; Jackson, 2011; Hastik et al., 2015). All habitats which do not have strict conservation designations (such as NNR, SAC, SPA or SSSI status) may be at risk if they occur in an area that is deemed suitable for renewable development. Amongst a multitude of services, Scotland's natural landscapes are essential for carbon storage, biodiversity, and the regulation of water runoff (RSPB, 2010). They also provide recreation, food, fuel and timber as well as being integral to the human psyche by providing a sense of place.

Scotland's onshore wind electricity sector continues to grow but sources of electricity can be intermittent leading to peaks and troughs in electricity generation. Does Scotland have sufficient land area to allow minimal disturbance of natural capital while adding sufficient onshore wind generation to attain net zero, plus carbon neutral storage and backup dispatchable energy.

Scotland is not alone in this type of dilemma, Fuso Nerini et al. (2019) and Thornton and Comberti (2017) describe environmental trade-offs with sustainable development internationally. Kati et al. (2021) writing about wind electricity generation in Greece and other countries suggest locating windfarms in fragmented land outside protected areas to protect against further fragmentation. Jewell et al. (2016) state that there is a history of countries having to consider the ramifications of trying to become energy independent with climate policies and the impacts of land use change on natural capital. In 2019, Scotland met 90.1% of its equivalent electricity consumption from renewables, but only by relying on external fossil based generation when renewables and current nuclear fleet did not meet demand. Scotland's Climate Change Bill sets a legally binding target of reaching net-zero emissions by 2045 (Scottish Govt, 2020a,b) and electrification of heat and transport will require a substantial increase in electricity generation. Meanwhile, it also sets to restore a significant amount of the natural environment by 2032 with a sustainable land use system that prioritises nature and biodiversity. It targets that by 2032, 21% of land will be forest cover and 250,000 hectares of peatland will be restored. Gardner et al. (2020) emphasise the need for a greater convergence of biodiversity with climate policies, meanwhile this year the UK government published a guidance document for enabling a natural capital approach (ENCA) into policy (Defra, 2021).

With the potential for renewables to ameliorate greenhouse gas emissions in the electricity sector, an analysis of the current information of their impacts on land-use change needs to be undertaken. By providing an assessment of Scotland's technical wind potential and impact, this paper will help to define the potentially available land for onshore wind generation across Scotland. Specifically, this study's objective is to determine the area of land required for onshore windfarms, if carbon neutral energy is attainable through renewables only, the habitats affected by turbine installation and the locations for potential new sites.

2. Methodology

An extensive literature search was undertaken using Scopus, Google Scholar, Springer and Science Direct databases as well as on internet search engines. Highly cited articles were identified as well as papers, documents and publications from reputable organisations. Based on this literature, a series of mapped data layers for Scotland were compiled using ArcGIS software (ESRI, 2020). A brief description of the data contained in the layers used and the sources from which they were obtained can be found in Table 1.

Mapping was carried out with the intention to answer three main questions:

(1) What is the area of land needed for onshore Scottish wind generation and is carbon neutral energy attainable through renewables only?
(2) Within these calculated areas, which habitats have been affected by the installation of turbines?
(3) Where in Scotland could new onshore wind turbines be installed?
To answer question 1, the 'Scotland Renewables' and 'Wind Speed UK' layers were used. First of all, every onshore wind site within the 'Scotland Renewables' layer was extracted to a new point data layer based on the following selection criteria:

(i) Technology_type = 'Wind Onshore'
(ii) Development_Status_short_ = 'Awaiting Construction' or Development_Status_short_ = 'operational' or Development_Status_short_ = 'Under Construction'

The 'under construction' and 'awaiting construction' sites were included as they are assumed to become operational in the near future. Following this, the weighted average of installed and to be installed wind farms produced a load factor of 0.337 or 33.7% (BEIS, 2016b) and was applied to the installed capacity (MW) enabling an estimation of the power output in W at each site. The mean annual wind speed ($m\ s^{-1}$) for kilometre square grid cells 45 m above ground level (reanalysis of measured data 1975–1984) in the 'Wind Speed UK' raster was then extracted to each point to allow for the calculation of the wind power density (WPD) (Eq. (1); MacKay, 2008). The area (ha) needed by each site to produce the estimated output could then be calculated by using Eq. (2).

$$\text{WPD}\,(\text{W m}^{-2}) = \frac{1}{2}.\ \text{air density}\ .\ \text{wind speed}\,(\text{m s}^{-1})^3 \tag{1}$$

$$\text{area (ha)} = \frac{\text{Power (W)} \times 10\,000}{\text{WPD}\,(\text{W m}^{-2})} \tag{2}$$

These data were then collated enabling the calculation of the average Wind Power Density across the existing sites in Scotland. Using Eqs. (3) and (4), this average value was then used to estimate the potential power available (GW) from installed onshore wind generation in Scotland

$$\text{area}\ \left(\text{m}^2\right) \times \text{WPD}\ \left(\text{W m}^{-2}\right) = \text{Power (W)} \tag{3}$$

$$\frac{\text{Power}}{1{,}000{,}000{,}000} = \text{Power in Gigawatts (GW)} \tag{4}$$

To answer question 2, a layer displaying the active onshore wind turbines in Scotland and the 'Land Cover Map 2007' layer were used. The study is related to land use change so the older land use cover shows the land use prior to wind farm development over which the recent (up to 2019) onshore wind generation data is laid for comparison. Having calculated the area needed by each site, a buffer based on the radius of the area if it were a circle (radius $= \sqrt{\text{area}/\pi}$) was applied around each location. This was followed by intersecting the buffer layer with the 'Land Cover Map 2007' layer to extract land cover type(s) at each turbine location. This data was collated with data of existing turbine sites to determine their underlying habitat.

The layers 'Scotland's Peatlands' and 'Zones of Natural Sensitivity' were used to answer question 3. These, and previously created layers helped to form a new 'Wind Turbine Potential' mask (Fig. 1a) with the following criteria:

(i) Wind speed $\geq$ 4.7 $m\ s^{-1}$ and $\leq$ 11 $m\ s^{-1}$
(ii) Zone of Natural Heritage Sensitivity 1 or 2
(iii) Peatland class not 1 or 2

The wind speed criteria were chosen as this is the range in which the current turbines in Scotland are found. There is a window of operation for each turbine which depends on location and average wind speed, the lower threshold is determined by average wind speed to make the turbine work economically. Zones 1 and 2 of Natural Heritage Sensitivity have been identified by the Scottish Natural Heritage (SNH) through an assessment of land designations and natural heritage interest as the areas of land with the lowest and lowest-medium areas of sensitivity to wind farms (Scottish Natural Heritage, 2016). Thus, these are areas with the greatest potential for wind farm development in terms of natural heritage. Class 1 and 2 peatlands have been identified by the SNH through a consolidation of existing soil and vegetation data from the James Hutton Institute 1:25,000 and 1:250,000 scale soil data and Land Cover Map Scotland 1998 as "Nationally important carbon-rich soils, deep peats and priority peatland habitat" (Scottish Natural Heritage, 2002) They are therefore areas that require high protection from development and were therefore excluded from the turbine potential mask.

The potential turbine development mask was then used to interrogate the area and types of habitat and soils that may be affected by new onshore wind installations to help answer the main aims of the study. This was done through the use of the Extract by Mask tool for the raster datasets: 'Land Cover Map 2007', 'Scotland Soils', and 'Zones of Natural Heritage Sensitivity', and the Clip tool for the vector layers: 'Local Authorities', 'Lowland Areas', and 'Upland Areas'. Following this, the attribute tables from the outputs of these operations were extracted to Microsoft Excel, allowing for easier data manipulation through Pivot tables. The examination of the area, habitat type, soil type and total MW attributes, allowed comparisons to be made between existing turbine sites and the potential areas for new installations (creation of Tables 2 and 3), as well as between local authorities (creation of Table 4).

To recap, we have been using four criteria: Existing/planned infrastructure, current operational wind speed, low natural heritage sensitivity, exclusion of peatlands. A fifth and sixth criteria will be added, the exclusion of sensitive/unsuitable habitats and sensitive soils, respectively.

The term wind power is also known wind electricity generation or wind energy as per the Wind Energy journal which covers wind power (https://en.wikipedia.org/wiki/Wind_Energy_(journal)). The habitat data contained within the 'Land Cover Map 2007' and the wind turbine potential mask were used to calculate the land area and wind power available after the exclusion of sensitive/unsuitable habitats. To do so, a new selection criteria based on the following broad habitat categories: Bog, Broadleaf, Mixed or Yew Woodland, Fen, Marsh, Swamp, Freshwater, Littoral Rock, Littoral Sediment, Montane Habitats, Saltwater, Saltmarsh

Table 1
Data sources used in GIS analysis.

Layer names	Definitions and data sources
Local Authorities	Electoral wards of local authorities in Scotland based on 2014 boundaries to produce an accurate basemap depicting Scotland. *Data from,* https://www.arcgis.com/home/item.html?id=568baa3547094e14843daf6b8d2557d0
Scotland Basemap	Basemap of Great Britain based on 2014 boundaries to produce an accurate basemap depicting Scotland. *Data from,* https://www.arcgis.com/home/item.html?id=19d70336c226486bacb45c1e49d3cdb6
Lowland Areas	Scottish lowlands vector dataset created from the SNH Land Character Assessment (LCA) shapefile (based on selection of the records in the 'Context' field that do not contain the words "Highland" or "Upland"). *Data from,* https://gateway.snh.gov.uk/natural-spaces/index.jsp *(Landscape, Open Space and Access).*
Upland Areas	Scottish uplands vector dataset created from the SNH Land Character Assessment shapefile (based on selection of the records in the 'Context' field that contain the words "Highland" or "Upland"). *Data from,* https://gateway.snh.gov.uk/natural-spaces/index.jsp *(Landscape, Open Space and Access).*
Wind Speed UK	Raster dataset displaying the mean annual wind speed (m s^{-1}) estimate at kilometre square scale for mast 45m above ground level; an air flow modelled reanalysis of measured data for the effect of topography on wind speed. *Data originally from the Department Of Trade And Industry Wind Speed Database,* http://webarchive.nationalarchives.gov.uk/20121217154048/http://www.decc.gov.uk/en/content/cms/meeting_energy/wind/onshore/deploy_data/windsp_databas/windsp_databas.aspx
Land Cover Map 2007	Land cover map (LCM) 2007 of the UK Broad Habitat Types derived from satellite data with land parcels derived from national cartography (OS Master Map and OS Northern Ireland) supplemented with agricultural census data boundaries and image segments. (Morton et al., 2011). https://www.ceh.ac.uk/services/land-cover-map-2007
Wilderness Perceived Naturalness	Perceived naturalness of Scotland's landscape based on a 1–256 scale indication relative levels of naturalness. Land classes were assigned a 'naturalness score' from 1 (low perceived naturalness) to 5 (high perceived naturalness). A 250m focal statistics window was then passed over the dataset which averaged the naturalness values across this and the surrounding area. *Data from,* https://gateway.snh.gov.uk/natural-spaces/index.jsp *(Landscape, Open Space and Access).*
Scotland Peatlands	Scotland's Carbon and Peatland 2016 map. A Spatial dataset of 'carbon rich soil, deep peat and priority peatland habitats' in Scotland derived from existing soil and vegetation data (James Hutton Institute 1:25,000 and 1:250,000 scale soil data and Land Cover Scotland 1988). *Data from, https://gateway.snh.gov.uk/natural-spaces/index.jsp (Renewables).*
Natural Heritage	"Scotland's Zones of Natural Heritage Sensitivity to wind farms. This dataset provides an overview of the natural heritage sensitivity to wind farms. It identifies land with the greatest opportunity for wind farm development in natural heritage terms, and areas where natural heritage sensitivities indicate a medium or high level of constraint." *Data from,* https://gateway.snh.gov.uk/natural-spaces/index.jsp *(Protected Areas).*
Scotland Renewables	Government data on all renewable technologies in Scotland based on clipping the UK database to the 'Scotland Basemap' layer. *Data from,* https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract
Power Lines	National Grid locations network routemap in Scotland. *Original shapefile* (DECC, 2012).
Scotland Soils	1:250,000 National Soil Map of Scotland. *Data from,* http://www.hutton.ac.uk/learning/natural-resource-datasets/soilshutton/soils-maps-scotland/download

Suburban, Supra-littoral Rock, Supra-littoral Sediment, and Urban within the potential area mask was created. This allowed for the exclusion of these habitats from the potential mask (creation of mask, Fig. 2a). The attribute table was then extracted to Excel to allow for the conversion of the mask land area to energy potential in electrical generation power availability in Gigawatts.

The soil data contained within the 1:250,000 National Soil Map of Scotland and the potential area mask were then used to calculate the land area and energy available after the exclusion of sensitive/unsuitable soils (those that are important for carbon sequestration i.e. peats, or are unsuitable for building on i.e. gleys and screes). To do so, a new selection criteria based on the following soils: Ground-water gleys, Peats, Scree and Surface-water gleys within the potential area mask was created. This allowed for the exclusion of these soil types from the potential mask (creation of mask, Fig. 2b). The attribute table was then extracted to Excel to allow for the conversion of the mask land area to wind electricity generation availability (GW).

Following this, a composite least-sensitive mask was created (Fig. 3) through intercepting the Least Sensitive Habitats and Soils masks to display the least sensitive land area to turbine development based on the six selection criteria used throughout answering question 3. Again, the attribute table of this new mask was extracted to Excel to allow for the calculation of generation availability (GW) within the area displayed.

3. Results

3.1. Land area availability and energy potential

The area of land available in Scotland for onshore wind turbine amounts to 4.38 M ha (Fig. 1a) providing a potential 118 GW of wind electricity generation (based on an average of 2.7 W m^{-2} wind power density). The area identified is well suited for development as it is already well provisioned with high voltage power infrastructure and, in general, encompasses Scotland's existing turbine sites (Fig. 1b). However, when perceived naturalness (Fig. 1c) is taken into consideration there are vast areas (such as those in the southern, central, and northern Highlands) of the mask that become unsuitable for development. A substantial amount of current or planned power stations (Fig. 1d) are in upland areas which encompass areas in Fig. 1c.

When constraints such as the suitability of certain habitats (Table 2) or soil types (Table 3) for onshore wind development are considered, the area available is reduced to 3.83 M ha (103 GW; initial four criteria plus habitat sensitivity) (Fig. 2a) or 3.19 M ha (86 GW) (Fig. 2b; initial four criteria plus soils sensitivity), respectively.

With all six criteria are accounted for, the land area available for turbine development is greatly reduced to 2.75 M ha, providing a potential 74 GW of electricity generation (Fig. 3).

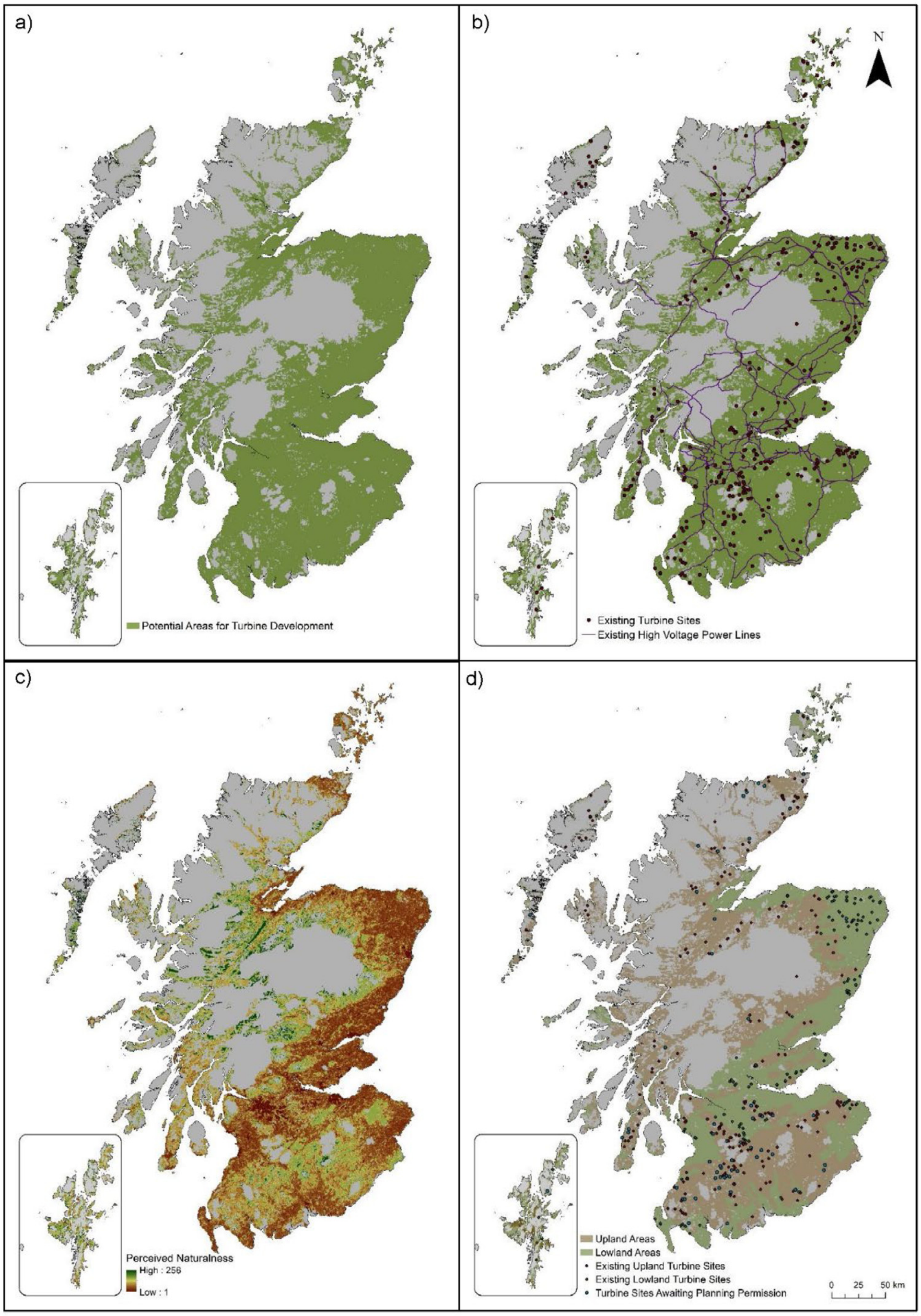

Fig. 1. Masks developed through GIS work. (a) Technical Potential areas for turbine development, (b) Existing Turbine sites and Power infrastructure in relation to the potential areas for turbine development, (c) Perceived naturalness (derived from SNH 'Wilderness Perceived Naturalness' layer), (d) Potential area for turbine development and existing turbine sites displayed by either lowland or upland characteristics (derived from SNH LCA shapefile) and turbine sites awaiting planning permission.

3.2. Habitat sensitivity

Table 2 summarises the total area of each broad habitat type affected by existing turbine sites, the four criteria mask (Fig. 1a) and the five criteria mask (four criteria plus habitat exclusion) (Fig. 2a). Of the 21 terrestrial habitats listed in the CEH 2007 Land cover map it was found that 14 have been affected by the installation of 389 onshore wind sites. Accounting for 73% of the total area, Coniferous Woodland, Acid Grassland, Bog, and Heather Grassland have been the most affected by the installation of wind turbines (Table 2). With 62% of Scotland's existing turbine sites situated in upland areas (Fig. 1d) it is perhaps unsurprising that habitats characterised by this topography are those most affected.

By overlaying the four criteria mask over the CEH 2007 Land Cover Map it was found that whilst Acid Grassland, Heather Grassland, and Coniferous Woodland still accounted for 37.6% of potentially affected habitat, Bog only made up 1.2% of the total area (Table 2).

The highly disturbed farmland habitats such as: Improved Grassland, and Arable & Horticulture accounted for 40.1% of the

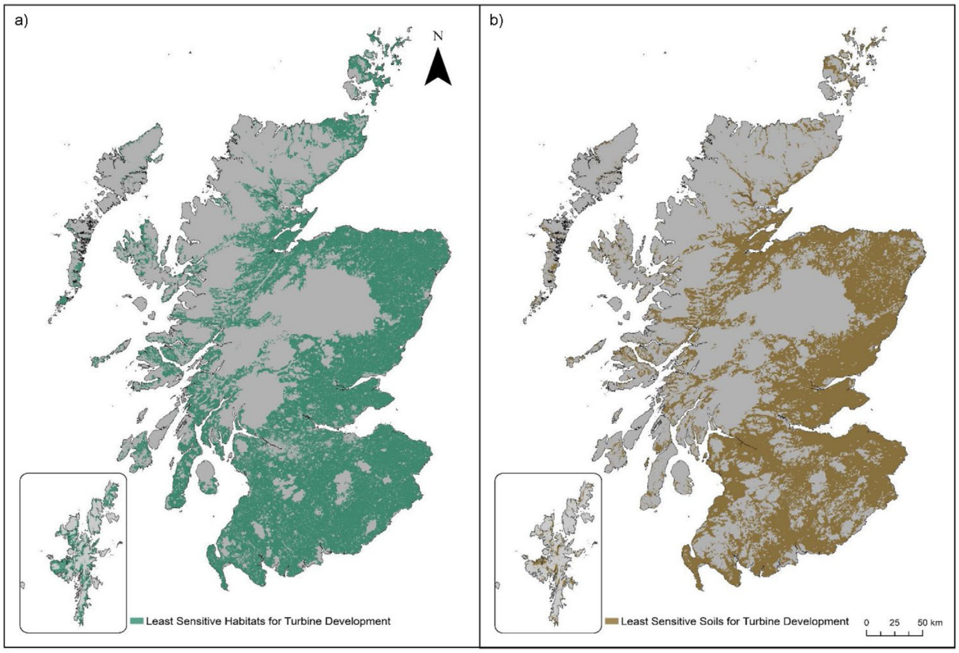

Fig. 2. (a) Least sensitive habitats for turbine development mask, developed by excluding the potentially unsuitable habitats identified in Table 2 from the Potential areas for turbine development mask in Fig. 1(a), (b) Least sensitive soils for turbine development, develop by excluding the potentially unsuitable soils identified in Table 3 from the Potential areas for turbine development mask in Fig. 1a.

Table 2
Distribution of area and installed capacity by habitat (based on LCM 2007) for existing turbine sites according to the potential area for turbine development in Fig. 1a and the least sensitive habitats to turbine development shown in Fig. 2a.

Habitat	Existing installed capacity (MW)	Existing total area (ha)	Potential total area (ha)	Least sensitive total area (ha)
Acid Grassland	2839	34,620	445,483	317,291
Arable and Horticulture	488	6345	683,599	611,489
Bog[a]	2203	24,867	52,960	–
Broadleaf, Mixed or Yew Woodland[a]	89	1203	190,547	–
Calcareous Grassland	–	–	557	549
Coniferous Woodland	2883	37,202	785,838	435,837
Fen, Marsh, Swamp[a]	–	–	1414	–
Heather	968	10,902	65,929	148,018
Heather Grassland	2225	27,164	212,576	205,689
Improved Grassland	1154	15,775	351,675	806,084
Inland Rock	78	1361	1,004,114	13,424
Littoral Rock[a]	–	–	19,043	–
Littoral Sediment[a]	–	–	2484	–
Montane Habitats[a]	206	2283	1478	–
Neutral Grassland	–	–	60,085	3297
Rough Grassland	329	4430	6642	204,953
Suburban[a]	336	4580	324,754	–
Supra-littoral Rock[a]	–	–	778	–
Supra-littoral Sediment[a]	-	-	679	–
Unclassified	20	241	32,865	4413
Urban[a]	130	1824	859	–

[a]Potentially unsuitable for turbine development.

mask area. The potentially unsuitable habitats identified in Table 2 account for 10.4% of total area identified in Fig. 1a. When all five criteria are accounted for, the % share for Acid Grassland, Coniferous Woodland and Heather Grassland remains similar at 35% but the farmland habitats now account for 51.5% of the total land area covered by the mask (Fig. 3).

3.3. Soil sensitivity

The total area of each soil type affected by existing turbine sites, and the six criteria mask (Fig. 2b) are summarised in Table 3. Of the 14 soil types listed in the JHI National Soil Map of Scotland, half have been affected so far by wind turbine development. As with habitats, the soil types related to upland topography are those which have been most affected by previous turbine development.

When the four criteria mask were considered it is the soils that lay under farmland, coniferous forests and acid grassland (brown earths and podzols) that may be most affected. However, peaty soils and gleys also featured prominently with a 27% share of the potential total area. With the addition of soil unsuitability to habitat unsuitability (six criteria), brown earths and podzols now account for 94.5% of the total area available for turbine development.

Table 3
Distribution of area and installed capacity by soil type (based on Scotland soils layer) for existing turbine sites the potential area for turbine development in Fig. 1a and the least sensitive areas to turbine development shown in Fig. 2b.

Soil type	Existing installed capacity (MW)	Existing total area (ha)	Potential total area (ha)	Least sensitive total area (ha)
Unclassified	528	7142	179,739	34,195
Alluvial soils	293	4856	106,713	92,994
Brown earths	1680	22,386	1,523,572	1,383,887
Calcareous soils	–	–	8141	5098
Ground-water gleys[a]	2801	34,837	501,146	–
Lithosols	–	–	337	27
Magnesian soils	–	–	967	893
Peats[a]	3829	44,384	236,313	–
Podzols	4010	48,940	1,348,877	1,216,797
Rankers	–	–	14,070	11,041
Regosols	–	–	7399	5701
Rendzinas	–	–	424	411
Scree[a]	–	–	2319	–
Surface-water gleys[a]	808	10,251	448,704	–

[a]Potentially unsuitable for turbine development.

Table 4
Proportion of local authority area covered by development potential and least sensitive area masks.

Local authority	Potential mask land available (ha)	Potential mask % of local authority	Least sensitive mask land available (ha)	Least sensitive mask % of local authority
Highland	778,002	30	430,239	16
Dumfries and Galloway	554,367	86	371,276	58
Aberdeenshire	465,265	74	367,750	58
Scottish Borders	419,815	89	319,233	67
Argyll and Bute	328,345	47	103,355	15
Perth and Kinross	316,841	59	238,873	44
Angus	172,549	79	151,357	69
South Lanarkshire	162,214	91	107,581	61
Moray	160,987	72	119,781	54
Fife	128,385	97	105,809	80
South Ayrshire	109,597	90	60,275	49
East Ayrshire	102,402	81	47,494	37
Stirling	87,619	39	46,437	21
East Lothian	65,219	96	57,313	84
Shetland Islands	60,729	41	14,364	10
Orkney Islands	59,374	59	25,884	26
North Ayrshire	48,523	55	22,299	25
North Lanarkshire	44,412	94	13,327	28
Eilean Siar	40,934	13	10,696	3
West Lothian	40,880	95	17,961	42
Midlothian	33,831	95	24,875	70
Falkirk	27,707	93	11,769	40
City of Edinburgh	26,057	99	12,529	48
Renfrewshire	23,873	91	13,412	51
Aberdeen City	17,850	96	11,023	59
Glasgow City	17,345	99	3382	19
East Dunbartonshire	16,630	95	8951	51
East Renfrewshire	15,857	91	9106	52
Clackmannanshire	14,015	88	8881	56
Inverclyde	11,548	71	5694	35
West Dunbartonshire	11,180	63	4770	27
Dundee City	5792	97	2174	36

3.4. Development potential distribution across local authorities

The distribution of Figs. 1a and 3 by local authority are examined in Table 4. According to the four criteria mask over 80% of Scotland's local authorities have >50% of their area as suitable for the development of wind generation. Even with only 30% of the land area as suitable for the generation of wind electricity generation, the area available in the Highlands is still 40% larger than the next local authority, Dumfries and Galloway, and is equivalent to the area available in the bottom 21 local authorities. With the addition of the habitat and soil suitability (six criteria) only 43% of Scotland's local authorities have >50% of their area as suitable for the development of wind generation. The Highland local authority remains the largest holder of available land, equivalent in size to the areas available for the bottom 21 local authorities.

3.5. Future energy requirements

During the exploration of the 'Scotland renewables' data, summing all the onshore wind installed generating capacity, under construction or having approved planning permission, Scotland's generation capacity will be 13.95 GW, enough to cover current peak demand. Extra capacity will be required to replace Scotland's two nuclear power plants and replenish storage capacity in times of a persistent drop in wind which involves replacing the Peterhead CCGT (Eqs. (5) to (8)).

- Power generation of the two Scottish nuclear power stations:

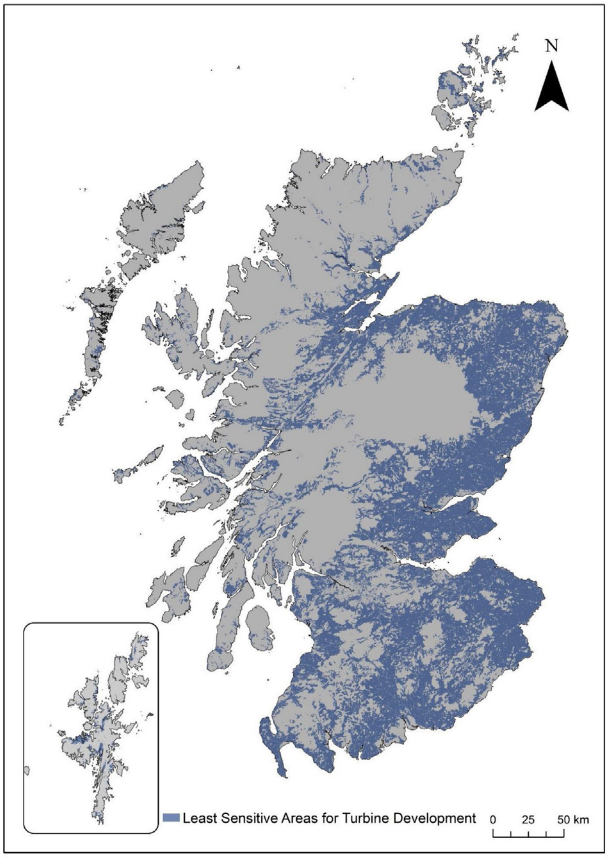

Fig. 3. Least sensitive areas for turbine development according to the six criteria identified in the methodology: Wind speed $\geq$4.7 m s^{-1} and $\leq$11 m s^{-1}, Zone of Natural Heritage Sensitivity 1 or 2, Peatland class not 1 or 2, suitable habitat (Table 2), and suitable soil type (Table 3).

$$1.36\ \text{GW (Torness)} + 1.28\ \text{GW (Hunterston B)} \times \text{power station load factor of } 84\% = 2.23\ \text{GW} \quad (5)$$

To replace by wind electricity generation:

$$\frac{2.23}{\text{land wind load factor } 33.7\%} = 6.62\ \text{GW wind power} \quad (6)$$

- Storage capacity for seven days when no wind: Total consumption of electricity in Scotland = 24,194 GWh/365 = 66.3 GWh day^{-1} (based on average electricity consumption in 2018; Scottish Govt, 2018–19)

$$7\ \text{days} \times 66.3\ \text{GWh} = 464\ \text{GWh in storage} \quad (7)$$

Wind energy generation required for storage:

$$\frac{66.3\ \text{GWh day}^{-1}}{24 \times \text{load factor for wind } 33.7\%} = 8.20\ \text{GW} \quad (8)$$

We calculated that a total of 14.82 GW of extra installed onshore wind capacity would be needed to replace both current nuclear (6.62 GW) and run an excess (8.2 GW) to store energy in case of a 7-day wind lull. This would provide an additional 129,823 GWh $year^{-1}$ (14.82 × 365 × 24). Without nuclear and imported power, this is the extra capacity required to cover lulls in wind generation to supply the 464 GWh of storage capacity required for self-sufficiency.

Replacing the 0.75 GW CCGT (combined cycle gas turbine) gas-fired power plant used for dispatchable energy at Peterhead with wind electricity generation would mitigate a total of 2,325,780 tonnes of CO_2 $year^{-1}$ (Eq. (9)):

$$750\ \text{MW} \times 365 \times 24 \times 0.354^{*} = 2{,}325{,}780\ \text{tonnes CO}_2 \quad (9)$$

*0.354 tonne CO_2 MWh^{-1} electricity generated by a CCGT (UK Parliament, 2015).

4. Discussion

4.1. Is onshore wind generation possible?

This study aimed to explore the impact of replacing nuclear power with primarily onshore wind electricity generation on Scottish land use and ecosystem services. The initial four constraints showed that 55.6% of Scotland may be suited for the development of wind turbines, but when habitat and soil suitability (six criteria) were included the land area available decreased to 2.75 M ha (34.9% of Scotland). With an estimated technical potential to provide at least 74 GW of onshore wind generated electricity, Scotland has 6.4 times the amount stated by the RSPB (RSPB, 2006). This amount of available energy would allow Scotland to future proof its energy production with onshore wind generation alone, but would also require the development of significant storage capacity.

Based on the existing onshore wind capacity and area, it currently takes 12,387 ha to generate 1 GW, 2.7 times less than stated by Denholm et al. (2009). It is 354 times the area needed for 1 GW of Nuclear Generation in Scotland (Denholm et al., 2009). However, as not all of the land under wind turbines is utilised for production, the area directly impacted by development would be much smaller than that of the area disturbed. Not included in this is the 464 GWh worth of land area needed by the backup storage required to compensate for the intermittency of wind. To support carbon neutral electricity generation in Scotland, our study calculated that 14.82 GW of additional installed onshore wind capacity, covering at least 4.5% of the potential total land area (12,387 ha × 14.82 GW = 183,575 ha), would be needed to replace current nuclear and run an excess to store energy in case of a 7-day wind lull.

Wind electricity generation has limitations in its inability to function without a dedicated dispatchable power system, in case of a sustained decrease in windspeed. The Coire Glas PS hydro storage scheme has 25.9 million m^3 of water stored in a 63 ha reservoir to provide Scotland with an additional 0.171 GW during a 7-day lull. For 464 GWh of stored energy, the equivalent of 16 Coire Glas PS hydro storage schemes (464/(0.171 × 7 × 24)), requiring a potential 1008 ha of upland area, would need to be constructed. At the cost of £14.4 billion (BEIS, 2016), pumped storage remains cheaper than Flat Land large scale Electricity Storage (FLES) (£109 billion; Huynen et al., 2012) or 14 KWh Tesla batteries (£225.5 billion; Tesla, 2017). However, the building of another 15 large scale PS schemes across Scotland may be unfeasible due to a lack of potential sites as well as public resistance to wild land development.

As technology develops, large scale energy storage could or may become more feasible as efficiencies increase and prices decrease. Another option would be to utilise biomass or CCGT natural gas with carbon capture and storage as emergency backup power sources. Costing £49.3 million and £63.8 million (BEIS, 2016c) respectively, they are 292 to 225 times cheaper than 16 pumped storage schemes and would utilise far less land area for generation. Biomass production requires either arable or wooded land for fuel production as well as needing enough stored material to be used during lulls. Neither are completely carbon neutral and therefore would not help the Scottish Government achieve a carbon neutral generation network (Scottish Renewables, 2010; Brack, 2017; Foley et al., 2011).

A promising alternative is the 'NorthConnect' or 'North Sea link', more than half-way through construction by June 2020, this is a 1.4 GW Scotland–Norway power link enabling electricity to be transmitted both ways between the UK and Scandinavia and maximising renewables in Scotland (wind power) and Norway (hydropower) (Energy Live News, 2020).

Consideration must also be given to offshore wind. Offshore wind generation cost has fallen by 32% since 2012 (Offshore Renewable Energy Catapult, 2016) and is now only 24% higher than onshore wind per MWh (BEIS, 2020). Tidal generation still remains relatively high, and is set to be 137% to 269% higher than the cost of onshore wind in 2025 (BEIS, 2020). There is a large investment in green hydrogen from offshore wind, with falling wind electricity generation and electrolyser costs reducing costs. Strategic investment in hydrogen transportation and storage is key, Scotland has extensive port and pipeline infrastructure that can be repurposed and there is considerable hydrogen supply chain overlap with different sectors, most notably, oil and gas, offshore wind and subsea engineering (Scottish Govt, 2020a,b). Offshore generation advantages include the ability to erect much larger turbines, away from population, with no obstructions to the wind, the only physical limiting factor is depth to the sea floor. However, their impact on natural capital and marine ecosystem services must be considered and factored into all planning.

Onshore turbines have become taller and larger and as they do, so the load factor will increase and continually modify these calculations. However, the important point is that excess generation of electricity must be put into a dispatchable form, hence with recent developments (Widera, 2020; Thomas et al., 2020; Valverde-Isorna et al., 2016), hydrogen generation seems the most practical method since banks of batteries require a huge chemical resource and stored hydro would be a controversial development in many of Scotland's valleys.

So to answer our question, Scotland does have sufficient land area with relatively low sensitivity required to generate sufficient onshore wind electricity generation, but it is not that simple because generation by itself is not sufficient, it requires storage for backup energy. There are multiple options for storage capacity, the most likely of these being new developments in hydrogen.

4.2. Implications for Scotland's natural capital

It is impossible to ignore the impact that an extra 112,079 ha of wind turbines and their associated infrastructure development will have on Scotland's natural capital, given that 389 installed onshore wind farms have impacted 14 out of 21 terrestrial habitats listed in the CEH 2007 Land Cover Map, and that Coniferous Woodland, Acid Grassland, Bog, and Heather Grassland account for 73% of the total area. As the UK becomes increasingly populated, areas that are perceived as wild are becoming rarer. Much of the appeal of Scotland's uplands is that they have remained relatively wild and the installation of highly visible structures such as wind turbines can ruin that (Roddis et al., 2018; Wen et al., 2018). Thus, there are fears that the scenic beauty of Scotland will be jeopardised in favour of energy production. The figures presented in this study aim to reduce the possibility of that happening by accounting for perceived naturalness and zones of natural heritage sensitivity. In terms of storage however, it may be impossible to avoid damage to peatland if hydro power storage is used. Coire Glas PS alone is predicted to affect 84,000 m^3 of peat holding at least 2520 tonnes of carbon (Highland Council, 2012; Agus et al., 2011), with 16 of these sites needed, a potential 40,320 tonnes of stored carbon could be disrupted.

As seen in Fig. 4b, vast swathes of Scotland's wildest areas are excluded, keeping the suggested areas for turbine develop in areas of low perceived naturalness. Existing turbine sites and power infrastructure overlaid on the least sensitive area for turbine development shows turbine development is away from these areas (Fig. 4a) and the mask agrees with the low perceived naturalness mask (Fig. 4b). However, controversy will still arise as areas of low perceived naturalness cover much of Scotland's farmable land, bringing the food versus energy debate back into the foreground. By targeting pastoral land, the loss of crop area is negated and the risk of damage to turbine infrastructure by farm machinery is limited. As livestock can still graze underneath the turbines, the loss of farmable area will be limited to the footprint of the turbines and sub-stations as well as the infrastructure built for access. With the third largest area of availability, the coniferous woodland habitat is also at major risk. As this paper has only used broad habitat categories, no distinction between plantation and native pinewood can be made. With the Scottish government aiming to achieve 25% woodland cover by 2050 (Forestry Commission Scotland, 2006) it is imperative that turbine development is kept out of wooded areas, not only to achieve governmental goals, but also as they are a key resource for biodiversity and tourism as well as providing a multitude of ecosystem services.

Through the mask produced by the final six criteria, this study hopes to demonstrate that we do not have to sacrifice important habitat, scenic areas and peatlands for energy production. Scotland has an abundance of land where wind production can take place in less-environmentally damaging and more urbanised areas. Thus, consideration must be made of micro vs macro generation. Of the 13.9 GW of installed onshore wind capacity in Scotland, 8.2 GW is macro generation (>50 MW; Scottish Government, 2017b), and the other 5.3 GW is micro generation. If this trend were to continue Scotland could see further micro generation, helping to reduce consumer bills (through feed in tariffs) and relieve the some of the pressure from large wind farms on Scotland.

4.3. Limitations and further research

Further research could refine the area of the masks presented in this study. The use of predetermined criteria (in particular the zone of natural heritage sensitivity) does not allow for the flexibility of developing one's own criteria. By looking at technical potential no consideration was made to the practicalities of building wind turbines, MOD low fly zones, opposed parties, land ownership, field sports or the effect turbines will have on the urban fringe. Undoubtedly, if these were taken in to consideration, the land area available for development would reduce, but further study is needed to show where and by how much.

A further examination of different renewable generation and storage mixes also needs to be undertaken. In light of new developments (North Connect) and recent years' cost reductions and investment in hydrogen and offshore wind, their share of the energy mix needs further consideration.

5. Conclusion

Scotland has the available land area to achieve the Scottish Government's policy to move towards carbon neutral, nuclear-free electricity generation through the use of renewable technologies alone. Already, there is adequate installed renewable capacity to meet peak demand. However, to future proof the electricity network and provide backup power in case of a lull this study estimates that an extra 8.2 GW of generation and 464 GWh of storage is needed. Doing so will increase Scotland's onshore wind capacity by 14.8 GW, energy which could be diverted to

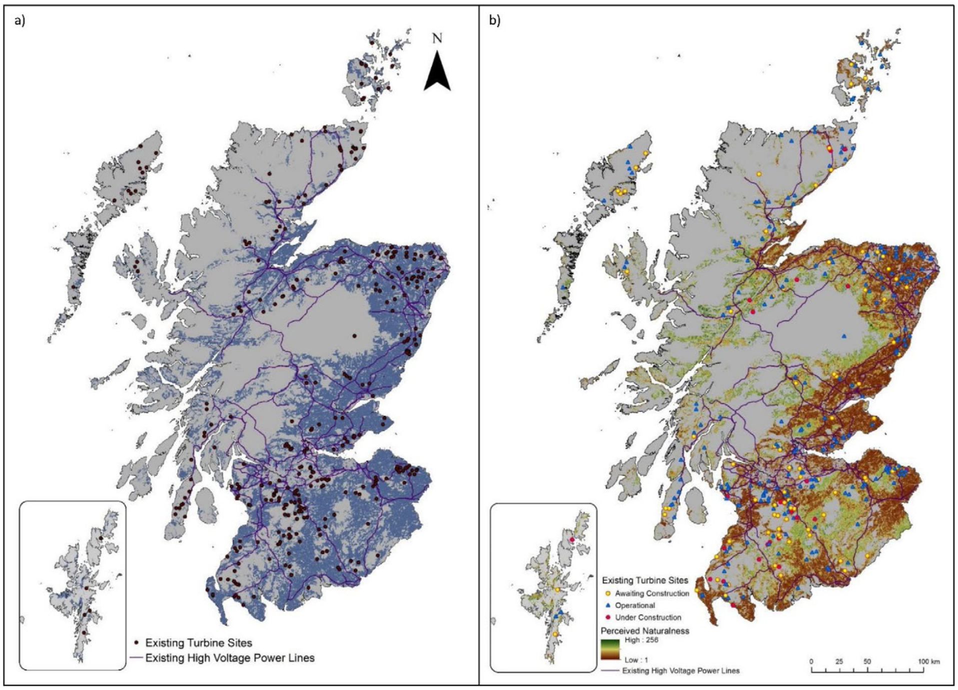

Fig. 4. (a) Existing turbine sites and power infrastructure in relation to the least sensitive area for turbine development mask, (b) Perceived naturalness (derived from the SNH 'Wilderness Perceived Naturalness' layer of the least sensitive area to turbine development, existing power infrastructure and turbine sites displayed by their planning application status (as of December 2016).

heating or transport helping to further reduce Scotland's carbon emissions as both sectors are responsible for 78% of total final energy consumption combined (Scottish Govt, 2017). Another option would be to increase exports to the rest of GB, allowing other areas of the country to reduce their reliance on fossil fuels.

Our study determines that after accounting for natural heritage, habitat and soil sensitivity, there is 74 GW across 2.75 M ha of technical potential. Increasing Scotland's 13.9 GW onshore wind capacity by an additional 14.8 GW means the land area in Scotland covered by turbines would equate to 346,676 ha. On top of the land area needed, an extra 1008 ha of upland area and £14.4 billion would be needed to for the installation of 464 GWh of pumped storage. The construction of new wind farms on environmentally sensitive areas can be minimised by targeting relatively disturbed habitat types such as intensive pasture, 23% of the least sensitive improved grassland area in Table 2 would be needed to for new turbine installation.

Innovation and investment in wind development is continuous and proceeding rapidly, research on these developments is continually being updated and there will be knowledge gaps as new development outpaces publication. However it is clear to see that Scotland is not far from achieving an entirely carbon and nuclear free electricity. It is possible for the Scottish electricity sector to achieve carbon neutrality and mitigate a total of 2,325,780 tonnes of CO_2 year^{-1}. However, to do so requires zero imported electricity from the rest of GB and adequate backup generation through carbon neutral sources, alternatively, Scotland may have to rely on close to neutral dispatchable power.

Scotland's Climate Change Bill (Scottish Govt, 2020a,b) states that the Scottish government plans to review electricity generation policy in 2022 with respect to its contribution to achieve net zero and calling for evidence on smart storage and technology to ensure secure storage of supply, and also technology to ensure a stable supply and the ability to re-start after a power outage based on renewables. It is evident that storage is a known problem and stability of supply using renewables involves developing new technologies. At the time of writing, we see a new SNP-Scottish Green Party government alliance who want a large increase in wind for electrification and hydrogen production in the economy. Their draft (Scottish Government, 2021) policy sets out a green industrial strategy supported by regulations to create zero emission domestic heating, zero carbon local and district heat networks, decarbonise rail transport, and support the transition of an oil and gas sector to net-zero energy and chemicals industries, supported by plan to deliver 8–12 GW of additional onshore wind and 11 GW of offshore wind by 2030 (Scottish Government, 2018-2019). They will undertake a programme of research to better understand energy requirements for transition to net zero and how this aligns with a climate change target to limit global warming to below 2 degrees C, compared to pre-industrial levels.

This study aims to make up a part of the evidence showing that near net zero is achievable but whether energy infrastructure and dispatchable energy will be sustainable and renewable are key issues. As Scotland develops solutions to these dilemmas, what it is gaining is an expertise in technologies leading to net zero.

CRediT authorship contribution statement

A. Shepherd: Editing, formatting, updates & recalculation, corresponding author. **S. Roberts:** Conceptualization, Methodology, Writing – original draft, Review response. **G. Sünnenberg:** Conceptualization, Data provision. **A. Lovett:** Conceptualization, Method, Data provision. **A.F.S. Hastings:** Funding, Conceptualization, Methodology, Supervision, Data curation, Review response.

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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The data that support the findings of this study are available from the corresponding authors, upon reasonable request.

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