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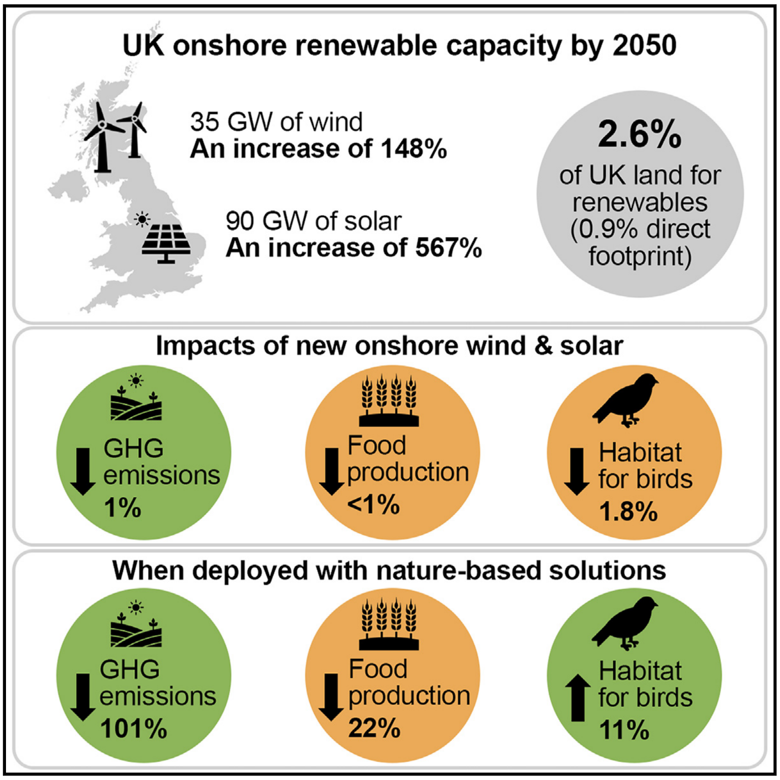
Ambitious onshore renewable energy deployment does not exacerbate future UK land-use challenges

Graphical abstract



Highlights

- We explore the capability of UK land to accommodate future onshore renewables
- High renewable energy ambition requires only a small fraction of suitable land
- Renewable energy targets can be met with minor impact on food production
- High renewable ambition could accompany ambitious nature-based solution deployment

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In brief

Transitioning to renewable energy can help address climate change. The UK is relying on wind and solar power deployment, raising questions around land-use competition, for instance, with food production. Copping et al. show that high renewable deployment levels require a small fraction of the suitable land, with negligible impact on food production or breeding birds, even after accounting for widescale nature-based solution deployment. This suggests that integrated land-use decisions could deliver net-zero greenhouse gas emissions from UK land.

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Ambitious onshore renewable energy deployment does not exacerbate future UK land-use challenges

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SCIENCE FOR SOCIETY A transition to renewable energy can help mitigate global climate change. However, the widespread deployment of wind and solar technologies raises concerns about their impacts, from visual amenity to food production. Further, the renewable transition alone is insufficient to reach net-zero greenhouse gas emissions. We need active removal of greenhouse gases from the atmosphere as well as emissions reductions. Such removals can be enabled by nature-based solutions, such as habitat creation and restoration, which concurrently help biodiversity. In a UK case study, we show that ambitious renewable deployment targets require little land, in addition to what is needed for nature-based solutions, and can avoid the most productive farmland to minimize the impact on food production. Even in such a densely populated country with many competing land-use interests, integrated land-use decisions could help to simultaneously achieve net-zero targets, nature recovery, and maintenance of food production.

SUMMARY

Transitioning to renewable energy is crucial for meeting net-zero targets to tackle the climate crisis. Although wind and solar are the main generation methods being pursued, they risk exacerbating future land-use challenges. Here, we explore the UK's land capacity to accommodate two levels of increased future onshore wind and solar energy capacity. We quantify the impact on breeding bird habitat, food production, and net greenhouse gas flux in the presence and absence of a range of nature-based climate change mitigation measures. We find that even the highest onshore renewable energy ambitions require only a small fraction of the suitable land area, with little cost to food production, greenhouse gas sequestration, or breeding birds, even under pessimistic modeling assumptions. Therefore, the UK could boost onshore renewables without contributing substantially to future land competition, especially if potential synergies between multiple land uses, such as cropping and solar, are realized.

INTRODUCTION

The transition of energy production to a sustainable, renewable, and fossil fuel-independent mix is a major societal challenge that will play a key role in determining the ultimate scale of human-induced climate change. In 2021, the energy sector emitted 44% of total global greenhouse gas (GHG) emissions, making it the largest emitter by sector.[1] The United Nations Framework Convention on Climate Change (UNFCCC) 2015 Paris Agreement aims to limit global warming to "well below" 2°C[2] by focusing on the reduction of GHG emissions, particularly through the transition to the generation of renewable energy. Some progress has been made, with a rise in the use of renewable energy over the past decade, from 19.6% of all electricity generation in 2010 to 29% in 2020,[3] and this is projected to increase further in the next 10 years, reaching 48.5% by 2030.[3] These figures are made possible by the diverse mix of renewable energy sources available,[4,5] enabling generation in most situations and locations. This not only provides the benefit of no GHG emissions from electricity generation but also reduces the reliance upon imported fossil fuels, enabling domestic energy production in the current time of heightened concern surrounding energy security.

Of all renewable energy sources, wind and solar are the fastest growing, with respective global increases in capacity of 12.9% and 32.2% in 2023 alone.[4] Both sources combined accounted for 13.2% of the 2023 total global electricity production,[6] a share that had already doubled since the Paris Climate Agreement.[7] However, despite the benefits of wind and solar energy, there is often strong local opposition to their installation.[8–10] There is also a growing library of evidence highlighting the direct impact turbines have on wildlife. Displacement and mortality of birds through collision with turbines, both onshore and offshore, are well documented,[11–14] and more recently, studies have shown similar impacts on bats[15,16] and insects.[17] Similarly, collision with photovoltaic panels at solar farms has been recorded.[18,19] Research suggests this could be due to aquatic birds confusing large arrays of solar panels with lakes[19,20] although to date there has been no detailed analysis of this hypothesis. The long-term cumulative impacts on populations and ecosystem dynamics are still relatively unknown.[21]

Another issue, which garners less attention, is the direct land-take associated with wind and solar energy generation. Studies have investigated the impacts of new renewable energy facilities on land; for example, Diffendorfer et al.[22] highlight an increase in developed land due to wind turbine deployment, and Hernandez et al.[23] and Rehbein et al.[24] show a high proportion of renewable energy facilities are sited within protected areas, which may threaten biodiversity. Furthermore, there is much debate surrounding the use of productive agricultural land for renewable energy generation,[25,26] and the GHG emissions associated with production of renewable infrastructure and land-use change through its deployment.[27,28]

Land is a finite resource subject to competing interests, many of which are now the subject of their own regional, national, and international targets. Any deployment of new renewable energy therefore needs to consider the implications of land-use change for the delivery of other competing requirements from land,[29] including food production,[26] nature restoration,[30] and climate change mitigation.[28] Of the suite of negative emission technologies (NETs) proposed to enable the carbon dioxide removal that are explicitly included in most general circulation models, the most immediately available option is nature-based solutions (NbSs), which use the natural process of photosynthesis to remove legacy CO_2. NbSs include the creation or restoration of peatlands, saltmarshes, woodlands, and other habitats.[31,32] Although both renewable energy and NETs/NbSs are needed to address the climate crisis, alongside demand reduction and increased efficiency,[33] finding the balance between these competing land uses may be difficult, raising the prospect that food and energy security may compete with climate and nature goals or with each other.

Here, we investigate this question using the UK as a test case of a country with a high population density and a large economy. The UK Government has committed to achieving net-zero GHG emissions by 2050, with renewable energy playing a pivotal role in the UK Government's ambition.[34] In 2021, UK renewable energy capacity was 49 GW, up from 15 GW in 2012,[35] and produced 39.3% of the total electricity generated in 2021.[36] Several organizations have suggested that the UK can achieve greater than 90% generation by renewable methods by 2050,[37–39] with the most detailed pathways illustrated by the Climate Change Committee (CCC).[40] The CCC's cross-sector pathways entail a more than 6-fold increase in solar capacity alongside an 80%–150% increase in onshore wind capacity, alongside bioenergy with carbon capture and storage (BECCS) and NbSs such as peatland restoration and woodland creation. The contribution of NbSs to climate change mitigation is relatively well understood,[41,42] and recent modeling reveals the likely consequences of such land-use change for food production and bird populations.[43] However, the extent to which new renewables will compete for land with NbSs and further exacerbate impacts on food production and nature remains unquantified. We therefore develop exploratory, spatially explicit land-use scenarios for the UK to determine:

- Whether the future capacity in renewable energy ambitions outlined by the CCC is compatible with biophysical and ecological constraints.
- The impact of installing the CCC-recommended capacity of new onshore wind and solar energy on food production, GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU), and bird populations.
- How choices about combined deployment of NbSs for carbon drawdown and onshore renewable energy installations can impact achievement of the UK Government's 2050 net-zero target.

RESULTS

Methods summary

Our land-use scenarios are designed to be indicative rather than prescriptive or predictive and build on two of the exploratory scenarios developed by Finch et al.[43] (Table 1) by incorporating onshore renewable energy (wind and solar) at two levels of ambition based on CCC pathways (Table 2). One of the underlying scenarios, *baseline*, reflects 2015 land cover (from the CEH Land Cover Map 2015) and includes future urban expansion, whereas the ambitious *NBS extra* scenario also includes additional high levels of (mainly nature-based) climate change mitigation measure deployment (Table 1). Mitigation measures were deployed between 2020 and 2050 and involved modification of land cover (e.g., conversion to woodland, semi-natural grassland, and fen), the addition of trees to existing farmland (agroforestry and hedge creation), low-carbon farming practices, and improved condition of degraded peatlands.

For onshore wind and solar, we created opportunity maps using a range of criteria (e.g., minimum wind speed, land cover, designated sites, and infrastructure) and prioritized deployment based on agricultural land classification (ALC) to avoid the most productive farmland.

We consider *baseline* and *NBS extra* both without renewables ("no renewables") and at two ambition levels of new renewables deployment (low, corresponding to the CCC's "headwinds" pathway, and high, correspond to the CCC's "widespread innovation" pathway; Table 2). We also consider a further exploratory "maximum wind" scenario, where we supplemented the *NBS extra* scenario with as much onshore wind as possible, therefore reducing the required expansion of offshore wind. We then estimate the consequences of each scenario for (1) annual net GHG emissions from the land sector (Agriculture, Forestry, and Other Land Use); (2) potential habitat availability for breeding birds, modeled as a function of future land use using data from the Breeding Bird Survey; and (3) food production. We report results for the year 2050 (in line with the UK net-zero policy target).

Table 1. Scenario details

Measure	Baseline	NBS extra
Urban expansion	13 kha/year	13 kha/year
Intertidal habitat creation	–	0.48 kha/year
Peatland restoration	–	all upland peat restored by 2045; all extraction halted by 2035; 75% of lowland grassland restored and 25% to paludiculture by 2040; 50% of lowland cropland restored and 50% to paludiculture by 2040; 100% of forestry on peat removed by 2050
Woodland creation	–	30 ka/h by 2025, rising to 50 kha/year by 2030, then 70 kha/year 2035–2050; 66% broadleaved
Agroforestry	–	11 kha/year silvoarable, 25 kha/year silvopasture
Wood pasture	–	25 kha/year on current grassland
Semi-natural grassland creation	–	15 kha/year on current grassland/cropland
Hedge creation	–	50% increase in hedge length by 2050
Low-carbon farming	–	crops, grass leys, grass-legume mixtures, covering slurry tanks, high sugar content grasses, precision feeding, feed additives, improved livestock breeding, electrification, improved nitrogen use efficiency, legumes in crop rotations, and loosening compacted soils

Ambition of measures deployed under the *baseline* and *NBS extra* scenarios.

Land and energy generation potential

The indicative opportunity area for renewables varied slightly between the two underlying land-use scenarios (Figure S1), with 4.9% of the UK's total land area available for solar under *baseline* and 4% under *NBS extra*. 24.3% was available for wind under *baseline* and 20.7% under *NBS extra* (Figure 1). The ambitious *NBS extra* scenario had a smaller opportunity area for energy installations due to conversion of areas that would otherwise have been suitable for renewable generation to new semi-natural habitats and other uses, such as broadleaved woodland. There was ample space within the mapped opportunity areas to achieve both low- and high-ambition renewable energy capacity targets for solar and wind under both land-use scenarios. Depending on the underlying land-use scenario and the renewable ambition target, wind occupied 3.7%–8.3% of the opportunity area, and solar 13%–17.3% (Figure 1).

The relatively small portion of the indicative opportunity area used by each technology allowed installation to be focused on the areas with lower ALC values, avoiding the best and most versatile land (having already excluding areas deemed unsuitable based on ecological criteria, Figures 2 and S1). As a fraction of total UK land, the overall site footprint of onshore wind was between 0.9% (low ambition) and 1.7% (high ambition; only 2% of this area is directly impacted by infrastructure), and solar occupied between 0.6% (low) and 0.9% (high).

Net AFOLU GHG emissions

The addition of renewable energy to the existing land-use scenarios, whether at low or high ambition, had little impact on net GHG emissions from the AFOLU sector. The changes in emissions due to new renewable deployment were ∼2% compared with when new renewables were not deployed (“none,” Figure 3). The combined effect of new solar and wind energy deployment and the other changes to land cover in the underlying *NBS extra* scenario caused large reductions in emissions. *NBS extra* experienced a reduction in net emissions of 102.3% and 100.7% from 2015 levels for low and high ambition, respectively, surpassing net zero by 2050. The *baseline* scenario saw an increase in net emissions compared with 2015.

Table 2. Onshore wind and solar capacity in gigawatts, currently and projected for 2050 under two CCC energy scenarios (widespread innovation: high ambition; headwinds: low ambition)

	Capacity (GW)				
Renewable	Current	2050	Difference	Capacity density (MW/km^2)	Area (kha)
Widespread innovation (high scenario)					
Solar	13.5	90	76.5	45	170
Wind	14.1	35	20.9	5	418
Headwinds (low scenario)					
Solar	13.5	85	71.5	45	159
Wind	14.1	25	10.9	5	218

The difference in capacity is given between current and 2050, with capacity density used to calculate the required land area in kha to reach the new capacity target.

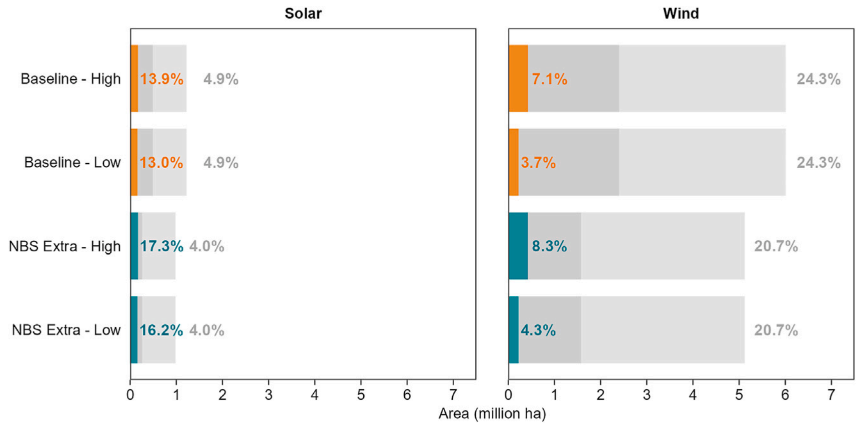

Figure 1. Area of land (million ha) occupied by new onshore solar and wind in 2050
Gray bars represent total opportunity area, with light gray representing the best and most versatile land according to ALC and darker gray representing less productive land. Percentage values in gray text indicate the opportunity area as a percentage of total UK land area. Percentage values in colored text indicate the percentage of the opportunity area occupied.

Food production

The addition of renewable energy had little impact on food production, which declined by between 0.6% and 0.9% relative to the scenarios without new renewables (Figure 4), with only minor differences between our high and low energy ambition levels (typically ∼0.1%). The combined impact of new renewables and the other changes to land cover in the underlying scenarios caused greater reductions in food output. Compared with 2015, *baseline* experienced the smallest reduction in food production (−3.5% and −3.4% for high and low energy ambition, respectively) due to urban expansion. *NBS extra* had a greater decrease, with 21.7% for high ambition and 21.6% for low ambition. The small reduction in food production due to new renewables can be attributed to the decrease in farmable area due to the footprint of wind turbines and the conversion of arable land to improved grassland for solar. Allowing grazing on all solar farms made no material difference to food production at the national scale (Table S3).

Breeding birds

The predicted aggregate effect of new wind and solar on breeding bird habitat availability was small at the national scale. For the 109 breeding bird species in 2050, our pessimistic estimates (no birds present in areas of land converted to renewable energy production) were 1.8% lower than our optimistic estimate (no impact of renewables; represented by none in Figure 5). Under high energy ambition, our pessimistic estimates were around 0.6% lower than under low ambition. The relative differences between renewable ambition levels are mirrored across scenarios and bird groupings (Figure S2). The all-species indicator increased compared with 2015 under the *NBS extra* scenario but declined under *baseline*. Similar results were observed for Birds of Conservation Concern (Figure S2). Generally, woodland birds saw the greatest increases in population, up to 40.9% for *NBS extra* with low energy ambition; however, farmland birds experienced declines of up to 21.4% under *NBS extra* with high energy ambition (Figure S2).

Maximizing onshore wind

Under the maximum wind scenario, 89% of the new offshore wind capacity recommended by the CCC's widespread innovation pathway could be moved onshore. With conversion factors, this equated to an additional 254.1 GW on top of the 20.9 GW of onshore capacity used in the high-ambition scenarios (275 GW in total). Food, climate, and bird results largely followed the trends seen for high and low ambition (Figure S3). By 2050, food production was only reduced by 0.2%, 0.3%, and 1.1% compared with high, low, and no energy ambition, respectively. GHG emissions decreased due to the NbS measures implemented and experienced a 95.5% reduction to 1.9 Mt CO_2e from 2015 levels, compared with a 100.7% reduction under high energy ambition. Breeding bird habitat availability varied considerably between optimistic and pessimistic estimations. Our optimistic estimate was in line with high and low energy ambition; however, under our pessimistic estimate, there were considerable reductions in habitat availability. The all-species group experienced a 7.7% reduction in habitat availability in 2050 compared with 2015, where under high ambition there was an increase of 11%. The large, predicted change under the pessimistic estimation was due to the exclusion of breeding birds from areas of land converted to wind and solar, which under maximum wind was 5.25 million ha, compared with 0.59 and 0.38 million ha under high and low, respectively.

DISCUSSION

Renewable energy deployment

Our key finding is that ambitious levels of onshore renewable energy deployment require relatively little additional land compared with the land-use change involved in bringing AFOLU emissions toward net zero. In turn, there is little further impact on food production, GHG emissions, or bird populations above those likely to occur if the UK's land-based climate change mitigation ambitions are realized (see Finch et al.[43]). Differences in food production, net emissions from AFOLU, and bird habitat availability are much more strongly driven by differences in NbSs and other land-based mitigation measures than by renewable energy deployment.

Our indicative opportunity mapping suggests there is sufficient space to deploy all of the additional onshore wind and solar capacity (20.9 and 76.5 GW in 2050, respectively) outlined in the CCC's highest ambition renewable energy scenario.[40] With such a small portion of opportunity area used, this indicates that ambitious deployment may still be possible even if important social and political constraints are taken into account. Furthermore,

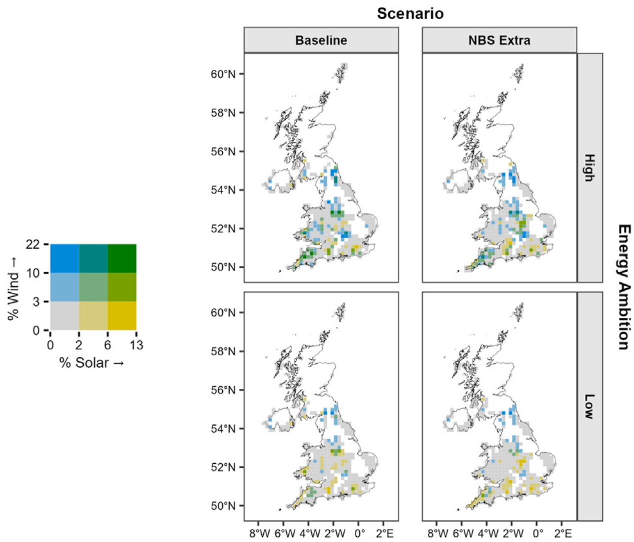

Figure 2. Fractional maps showing the percentage of 20 km squares occupied by solar and wind farms under low and high energy ambition for both the *baseline* and *NBS extra* scenarios

Blue squares indicate wind farms, yellow indicates solar farms, and green indicates both. The deeper the color, the greater the percentage of land occupied by renewable energy infrastructure. Colorless areas indicate no renewable deployment. These maps do not represent RSPB policy on where developments should be located, and a full environmental impact assessment process should take place as part of any application.

deployment goals were achieved even while avoiding sensitive wildlife areas and the best and most versatile agricultural land. However, the maximum capacity of new solar and wind that we found we could deploy differed greatly from previous studies. Under our scenarios, we could have sited 445 GW of solar under *NBS extra* and 549 GW under *baseline*, whereas Palmer et al.[44] state that the UK can support up to 3,500 GW, and Gove et al.[45] suggest the ability to site 1,250 GW. By contrast, for wind, our mapping suggests the potential to site 256 GW under *NBS extra* and 300 GW under *baseline*, whereas Gove et al.[45] demonstrate the potential for 53 GW. The disparity in maximum capacity comes from the variation in capacity density and the use of different siting constraints. For example, Palmer et al.[44] did not consider sensitive wildlife areas in their opportunity mapping, and Gove et al.[45] set no minimum threshold for solar irradiance and set policy, planning, and regulatory constraints for siting wind. Although we use conservative opportunity mapping to minimize impacts on food and nature, we did not implement policy constraints due to their fluidity and likelihood of change within our study period (e.g., changes between DECC[46] and HM Government[47]).

Under our high energy ambition scenario, only 17.3% and 8.3% of our indicative opportunity area were used under *NBS extra* for solar and wind, respectively, and there was space to shift 85% of the 2050 offshore wind capacity onshore, under our maximum wind ambition, with little impact on food production. Although this is purely an illustrative scenario, it does highlight the potential for the UK to increase the onshore renewable energy ambition, particularly when public support for onshore wind and solar is high,[48,49] the per MW cost is considerably cheaper than other generation methods,[50] and the main factor in restricting future wind development is national policy.[51] Additionally, of the renewable energy sources outlined in the CCC[40] scenarios, onshore wind has the lowest land-use intensity and highest energy density (due to the footprint of turbines), followed by solar.[52,53] This indicates an efficient use of land with small spatial footprint and high energy output, unlike biomass energy, which has a land-use intensity three orders of magnitude greater. However, an increased deployment of wind turbines would potentially amplify the impact to birds, as displayed by our maximum wind scenario.

In all CCC scenarios, bioenergy plays a key part in electricity generation (5 or 10 GW), with land dedicated to growing energy crops (e.g., miscanthus), occupying up to 705,000 ha according to the CCC.[54] The area of land is 315% greater than that of new solar and 8,200% greater than new wind, yet it delivers 87% and 52% less capacity than solar and wind, respectively, highlighting the relative inefficiency of biological compared with physical energy sources.[55] On the other hand, bioenergy does serve a different function to wind and solar energy, being dispatchable and providing the opportunity for carbon capture and storage (CCS), which other renewables cannot provide. Despite this important contribution, BECCS does not yet function efficiently at commercial scale,[56] which will cause a delay in the deployment of this technology and a reduction in the cumulative negative emissions delivered. This risks increasing the already high land-use intensity of BECCS and lowering its carbon dioxide removal potential, which will impact the ability to meet net zero.[57]

Food production

Our results find that the impact of new onshore renewables on food production was minor compared with the large reductions incurred by the climate change mitigation measures realized by Finch et al.[43] The reduction in food production due to new renewables was under 1%, but when combined with NbS measures, a decrease of 21.6% and 21.7% was observed, with low and high energy ambition, respectively. Our method for siting new wind and solar followed suit, prioritizing lower-quality farmland first, and appears to have been successful, with all new renewables sited on low agricultural classification land. As demonstrated by Leirpoll et al.,[58] prioritizing unproductive or abandoned arable land may aid in minimizing competition between renewables and food security. The impact of wind infrastructure on food production was minimal, with only a small area of land removed from production to account for the turbine's footprint (1,279 ha under *NBS extra* and high energy), compared with 57,838 ha for solar through the conversion of arable and horticultural land to grassland. As land is a limited resource and food security is a major concern, maximizing land-use efficiency and minimizing impacts of the water, energy, and food nexus should be a priority.[59] Here, we did not consider the indirect impacts of arable and horticultural land contraction, such as carbon leakage through offshoring food production (see de Ruiter et al.[60] and Grubb et al.[61]). Though, through modeling, Finch et al.[43] explore how to mitigate reductions in domestic food production to avoid leakage and suggest that a combination of measures such as dietary change (which would allow

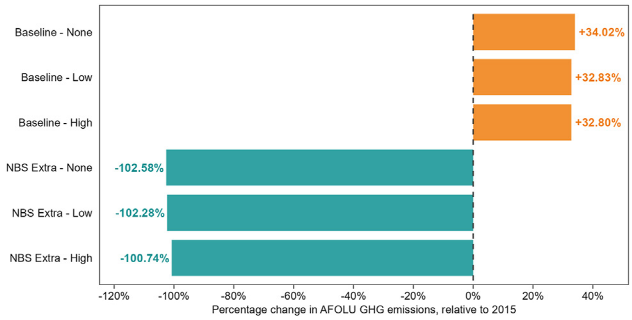

Figure 3. Annual net AFOLU GHG emissions in 2050, expressed as percentage change from 2015 (59.4 Mt CO_2e)

Each scenario (*baseline* and *NBS extra*) has three nested energy scenarios, none (no new renewables), and low and high ambition. Dashed line represents 0% change.

for a reduction in the area used for animal feed production), food waste reduction, and increases in productivity can be used to maintain food security.

One method by which we sought to increase land-use efficiency was the implementation of pastoral grazing on the land converted for solar energy production, as outlined by BRE.[62] However, this produced a negligible reduction in food production of 0.0024% (171.3 million kcal, equating to the average annual consumption of 1,317 people) under *baseline* with high energy ambition. This therefore reduced the land-use efficiency rather than providing an increase. These results were due to the assumption that grazing livestock would be supplemented with feed diverted from monogastric livestock, thus reducing overall output. Even if fed on waste products or a 100% grass-based diet, the additional food production from grazing solar farms is likely to be small, though this practice could supplement farm incomes and facilitate the re-integration of livestock into arable farming systems. The most efficient use of agricultural land will ensue when solar farms can be combined with highly productive arable crops. Research into this practice is ongoing but has produced promising results so far: Valle et al.[63] and Chae et al.[64] show agrivoltaic systems do not appear to negatively impact crop yield, and Amaducci et al.[65] suggest that yields can be higher than in the full light of an open field due to more favorable microclimatic conditions. However, such studies have been experimental, so how this translates into large-scale commercial agriculture remains to be seen.

One further step in reducing the impact of new solar infrastructure on food production is to increase the use of rooftop solar, leaving agricultural land for food production. Modeling by Bódis et al.[66] shows the UK has the potential to produce 43.5 TWh/year from rooftop solar, based on a panel efficiency of 14%. Comparable results were found by Joshi et al.,[67] again using an efficiency factor of 14% to show a range of 67 to 267 TWh/year based on a 20% and 80% rooftop availability, respectively. Under our high energy ambition (CCC widespread innovation scenario), there is a total demand of 680 TWh in 2050[40]; therefore, using the 80% coverage figure, rooftop solar would be able to deliver up to 39% of total electricity demand. Under our high energy ambition, the 76.6 GW of new solar capacity equates to 69 TWh/year, indicating there is the potential to shift the majority, if not all new solar from farmland onto rooftops, almost removing the impact of new renewables on food production, save for the 2% of farmland lost to wind farms. As solar panel technology advances, energy conversion is likely to become more efficient, requiring less space for the same output.[68,69] Though Joshi et al.[67] estimate that the UK is among the costliest countries ($251/MWh) in terms of ability to attain the potential rooftop solar production, the per MW levelized cost of electricity produced by large-scale field solar is considerably cheaper than other technologies in the UK.[50,70]

Impacts on the climate and nature

Addressing the twin climate and nature crises is one of the greatest challenges facing humanity.[71] NbSs have a role to play in addressing both,[72] and the national-scale deployment of NbSs in addition to low-carbon farming practices has the potential to achieve UK AFOLU net zero at the same time as delivering a net increase in bird habitat availability.[43] Although such scenarios do use a considerable area of land, negatively impacting food production, the addition of new onshore renewables has little further impact. Though under *baseline*, the opposite was observed, and emissions were reduced through the addition of onshore renewables compared with the scenario with none. This can be attributed to greater soil carbon sequestration potential[73] following conversion of arable to solar farms. Although this is still the case under the high energy ambition, the increased soil disturbance from wind turbine foundation construction reduces soil sequestration potential, partially negating the benefits provided through land conversion from installing solar panels. Finally, it is unlikely that net-negative and comparatively low emissions from AFOLU will be sustained past ca. 2060 without further GHG mitigation measures, requiring additional land-use change or other GHG reduction technologies.

The NbS measures implemented by Finch et al.[43] resulted in an estimated increased breeding bird habitat availability. The additional impact of new wind and solar alone was minor at this national scale. Even when we made the pessimistic assumption that breeding birds would be totally absent from areas of new wind or solar energy infrastructure, mean change in habitat availability only declined by 1.8% under our high energy ambition compared with the scenario with no new renewables. In reality, solar and wind farms can and do support breeding birds,[74,75] and our opportunity mapping aimed to avoid the most sensitive sites and species. Therefore, at the national scale, population change may be closer to our optimistic estimate (i.e., no impact from new renewables). Montag et al.,[75] Gazdag and Parker[76] and Copping et al.[77] describe how well-designed and managed solar farms, particularly those with hedgerows and wildflower margins, can increase farmland bird, bat, and pollinator abundance. Additionally, Blaydes et al.[78] illustrate that the number of bees a solar farm can support is doubled if managed as wildflower meadow, as opposed to only wildflower margins. Our modeling and designation of solar land as improved grassland reflects the currently widespread practice of solar farms establishing species-poor grassland under solar panels.[62] However, in light of recent evidence,[78–80] perhaps this practice should change, and where possible, semi-natural grassland should be

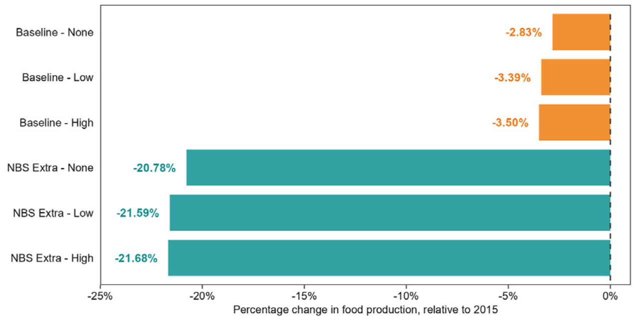

Figure 4. Food production in 2050 expressed as percentage change from 2015 (70.7 trillion kcal)

Each scenario (*baseline* and *NBS extra*) has three nested energy scenarios, none (no new renewables), and low and high ambition. Dashed line represents 0% change.

restored, providing wildlife-rich habitats. In our scenarios, this could provide an additional 170,000 ha of land for nature under *NBS extra* with high energy ambition.

The effects of wind turbines on birds have been widely studied, in particular collision risk (see Thaxter et al.[12] and Perold et al.[13]), and action can be taken to reduce this. May et al.[81] show that fatality rate in some bird species through collision with turbines can be reduced by over 70% by painting blades black to increase visibility and reduce motion smear. Similarly, the use of an automated curtailment camera can substantially reduce the collision and fatality risk in eagles.[82] Our conservative selection of opportunity areas avoided the most important and high-risk areas for birds, potentially resulting in lower risk of collision events. However, May et al.[83] argue that displacement and habitat loss have a greater impact on population than collision. The results of our pessimistic estimate, effectively reflecting habitat loss, showed a 1.8% reduction in habitat availability under high energy ambition. Previous modeling shows the impact of habitat loss results in lower bird densities at wind farms, with greater impacts closer to turbines and magnified effects in wooded habitats compared with open areas.[84] Furthermore, wind turbines can also act as barriers, reducing habitat.[85,86] This highlights the importance of site selection in avoiding sensitive species and habitats. Nevertheless, by far the biggest driver of population change here, whether positive or negative, were the changes to the underlying land cover through NbS measures, implemented by Finch et al.,[43] largely mirroring the findings of Lamb et al.[87]

Planned increases in the UK's offshore wind capacity to 50 GW by 2030[47] and the potential for up to 140 GW by 2050[40] are considerably more than the suggested future onshore wind capacity and may have a large impact on the UK's internationally important seabird populations. Northern gannets (*Morus bassanus*), for which the UK holds 55.6% of the world breeding population,[88] are among the most at-risk species from offshore wind farms.[89] Studies at Bass Rock have quantified the impact of wind turbines on the northern gannet population; Cleasby et al.[90] suggest around 1% of the colony's population of breeding gannets could be killed by collision with turbines per annum; and Lane et al.[91] outline that the added mortality could cause a reduction in annual population growth by 3%. Furthermore, Kooten et al.[92] predict the median population of North Sea gannet colonies will be 17% lower with the deployment of future wind farms, compared with in their absence, over a 30-year period. Such impacts are not only restricted to northern gannets,[93,94] although they are perhaps the most studied species.

The predicted changes in seabird populations caused by offshore wind turbines, though relatively wide ranging, are greater than our estimates of change for terrestrial breeding birds caused by habitat loss through onshore renewable deployment. Moreover, the severe strain of highly pathogenic avian influenza (HPAI) that has been circulating in wild birds in Northern Europe since winter 2021 disproportionally impacts seabird species and has caused considerable mortality.[95,96] The cumulative effects of HPAI and increasing offshore wind farm capacity in addition to stressors such as climate change and changing prey bases are unknown, but the outlook does not look positive. Therefore, to reduce the risk to the UK's internationally important populations of several seabird species and given the lower price[50] and increasing public acceptance of onshore wind,[49] perhaps there is scope to displace some of the future offshore capacity with greater ambition for onshore wind farms. This, we have demonstrated, would have relatively little negative impact at the national scale if sensitively sited, and when NbSs are implemented to a positive effect.

Conclusions

The UK has a large and relatively untapped resource of wind and solar energy available. We have demonstrated that the CCC's highest onshore wind and solar energy ambitions use only a fraction of the potential opportunity area even after accounting for a range of realistic deployment constraints. Whether new onshore renewable energy comes at the expense of food production, the climate, and nature is a complex and rather nuanced question, as these four factors are inextricably linked. Although our results have shown that new onshore renewables have little impact on food production, a small impact on climate change mitigation, and a slightly more modest impact on breeding bird habitat availability at the national scale, the magnitude of these impacts is small compared with the potential changes due to other land-use changes such as for NbSs. To achieve net zero, climate change mitigation measures need to be paired with renewable energy, but the combined impacts on food and breeding birds can be sizable. Therefore, where possible, land should be used more efficiently and its capacity maximized through synergies to combine multiple land uses per unit area. Ultimately, shifting our ambition for wind energy onshore would have little further impact on food production and the climate, but further research is needed to understand the net impact to birds of moving our offshore energy production onshore. Despite using a densely populated country as our test case, with the majority of land devoted to agriculture, we found there was still sufficient potential for widescale deployment of onshore wind and solar. Although conditions will vary between countries, our results suggest that decarbonization of the energy sector at the global scale need not come at the cost of food production, and if sited appropriately, there could be minimal impact to biodiversity.

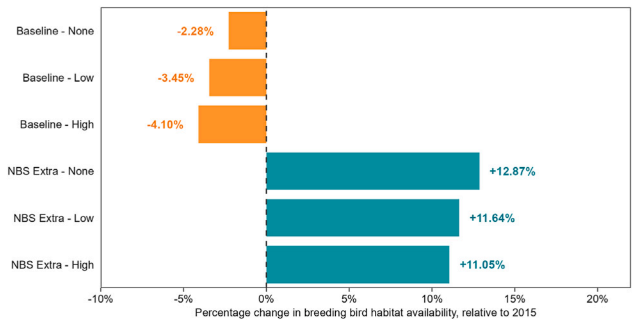

Figure 5. Geometric mean change in breeding bird habitat index in 2050, expressed as percentage change from 2015, across all species (*n* = 109) for our pessimistic estimate (no breeding birds in areas of new wind or solar installations)

Each scenario (*baseline* and *NBS extra*) has three nested energy scenarios, none (no new renewables, which also reflects the optimistic estimate for low and high scenarios), and low and high ambition. Dashed line represents 0% change.

See also Figure S2.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Joshua Copping (joshua.copping@rspb.org.uk).

Materials availability

This study did not generate new, unique materials.

Data and code availability

Where permitted by external licensing agreements, all data will be shared by the lead contact upon request after publication. Original code has been deposited in a Zenodo repository (Zenodo: https://doi.org/10.5281/zenodo.10999603).

Land-use scenarios

We explore two contrasting CCC scenarios (widespread innovation and headwinds), which have high and low levels of onshore renewable energy ambition, respectively[97] (Table 2). We combine each energy scenario with two future land-use scenarios developed by Finch et al.[43]: *baseline*, reflects 2015 land cover but contains future urban expansion; *NBS extra* includes ambitious levels of climate change mitigation measure deployment (Table 2).

Energy opportunity mapping

The siting of renewable energy infrastructure is not only determined by the available resource, i.e., wind speed or solar irradiance, but also by other physical and policy-based constraints. In the UK, there is little guidance outlining the suitable physical conditions for siting wind farms and solar arrays, and the literature shows a large range in the criteria and thresholds used in planning studies to select suitable areas Table S1. Although there have been studies using current governmental policy to constrain siting locations of wind and solar, we did not implement policy constraints because we wanted to explore the best technical option for siting onshore renewables. Data from the literature included in Table S1 was used to inform subsequent decisions as to which constraints and thresholds should be selected when mapping the opportunity area for wind and solar in the UK.

The first criterion we used to select suitable areas for renewable development was the available energy resource. For wind farms, average wind speed data for the UK were downloaded from the NOABL (Numerical Objective Analysis Boundary Layer) wind speed database at a resolution of 1 km^2.[98] All areas with an average wind speed of at least 5 m/s at 45 m above ground level were considered suitable. For solar, data for long-term average irradiation at optimum tilt were downloaded at a resolution of 250 m^2.[99] Little guidance exists for the minimum viable irradiance needed for commercial solar developments in the UK. Therefore, we calculated our own minimum limit by extracting irradiance values at all operational or approved-for-construction solar farms with a 1 to 50 MW capacity.[100] We used the third percentile of solar irradiance across these solar installations (1,075.2 kWh/m^2 per year) as a minimum threshold for identifying suitable areas for solar deployment.

Next, we constrained according to land cover, assuming that solar developments were restricted to enclosed farmland (arable and horticultural land or improved grassland) and wind farms to enclosed farmland plus coniferous woodland (excluding Caledonian pinewood in Scotland). We recognize that in the UK, wind farms exist outside of these parameters; however, we chose these constraints to protect sensitive upland land covers and peat soils. We used 25 m resolution rasters representing land cover in 2050 under the two scenarios produced by Finch et al.[43] to ensure suitable areas retained the required land cover classes throughout the 2020 to 2050 period of interest. Following Bradfer-Lawrence et al.,[42] we excluded peatlands (buffered by 100 m), mapped priority habitats (buffered by 50 m). We also buffered the built environment by a 100 m and transport infrastructure by up to 20 m, though due to the energy density used in deployment and siting rules, the distance from excluded area to a wind turbine or solar panel will be greater than the buffer.

Then we generated aspect and slope variables using a 90 m resolution digital elevation model.[101] Based on the modal value from the studies in Table S1, areas with slope no greater than 5% or 18% were considered suitable for solar and wind, respectively. Solar opportunity areas were also constrained using aspect, selecting only southeast-, south-, and southwest-facing slopes as suitable. Finally, a further criterion for wind developments was the exclusion of areas within 5 km of all operating UK civilian and military airports.[102]

The final group of criteria was based on ecological sensitivity of protected sites and species. We used the maps produced by Gove et al.,[45] where areas of the UK were classified according to the sensitivity of their bird species to wind and solar energy infrastructure. We excluded wind and solar development from all areas classed as medium or high risk, using their respective sensitivity map. Designated protected areas (SACs, SPAs, NNRs, SSSIs, and ASSIs in Northern Ireland) were considered unsuitable for renewable development and excluded. They were also given a 300 m buffer, unless designated for waders, when a 700 m buffer was used, to reflect edge effects on species.[103] Additionally, SPAs designated for geese or swan species were given a buffer (for wind opportunity area only) based on the maximum dispersal distance of the species for which the sites were designated. The geese and swan buffer distances were chosen based on those outlined by SNH,[104] Bright et al.,[105] Table S2. Protected landscapes (National Parks, Areas of Outstanding Natural Beauty [recently renamed as Natural Landscapes], and National Scenic Areas) were also excluded due to the low likelihood that government policy would allow for wind and solar farm development within these areas. To combine the selected criteria into solar and wind opportunity raster layers per scenario (Figure S1), a Boolean process was used. This method was chosen rather than weighting variables because of the subjectivity associated with designating weights and producing an unbiased score.

Deployment of onshore wind and solar

Areas of land indicated as suitable in solar and wind opportunity rasters for each scenario were ranked in 25 ha blocks. Ranking was performed in a descending order based on the UK agricultural land classification (ALC), where values 1, 2, and 3a/3.1 indicate the best and most versatile land for agricultural use, grades 3b/3.2 and above indicate less productive land. For each scenario, we then updated the underlying land cover rasters to include new onshore wind and solar in 5-year periods, between 2020 and 2050, using the ranked opportunity rasters to determine where and in which order the land cover was changed. The area of land converted to either a solar or wind electricity generating area in each 5-year period was determined by the energy ambition taken from the CCC energy scenarios, as outlined in Table 1. Knowing the capacity in gigawatts needed by 2050 and the difference to current capacity, we calculated the build rate per 5-year period. We then converted the build rate to area using the capacity densities outlined by the CCC (45 MW/km^2 for solar; 5 MW km^2 for wind, representing the project site area, of which 2% is occupied by directly occupied by turbines and associated infrastructure[40]), which informed us of the area of land needed for conversion per 5-years.

In addition, one further level of energy ambition was tested, in which we converted as much future UK offshore wind capacity (129 GW capacity under the CCC's widespread innovation) as possible to onshore wind (*maximum wind*). We took into account the difference in load factor (26.5% for onshore, 58.4% for offshore[106]), which equated to a requirement of 254.1 GW, giving an additional 275 GW when combined with the 20.9 GW of onshore capacity under widespread innovation. Here, we used the underlying land cover raster from the *NBS extra* scenario of Finch et al.[43] and excluded protected landscapes from the relevant opportunity raster. Solar capacity remained the same as under the widespread innovation energy ambition.

Finally, to estimate annual food supply and GHG emissions as outlined below, we used linear interpolation to convert 5-yearly land cover rasters into tabular data representing annual land cover (and land cover change) areas.

Impacts on food production

Our food production evaluation model estimated total agricultural production (in kcal) from UK land for each scenario-year (see Finch et al.[43] for a full description of the food production evaluation model). All UK crop and livestock production, including livestock that is fed imported fodder crops, was included, and we did not distinguish between products grown for export versus domestic consumption. Per-hectare rates of food production were derived by allocating national-scale government-reported production of crop and livestock products from 2015 to 25 m pixels according to 2015 land cover, ALC, and NUTS1 region (Nomenclature of Territorial Units for Statistics). Crop, pork, poultry, and egg production was limited to arable and horticulture pixels, and beef, lamb, and dairy production limited to improved grassland and grazed semi-natural habitats, with land cover-specific relative grass yield. ALC was used to determine relative crop yields and crop composition, and NUTS1 was used to determine crop and grazing livestock composition. We then calculated domestic feed production according to the reported fraction of each crop type used for feed and extracted livestock dietary rations from Lamb et al.,[107] which allowed us to calculate the quantity of imported feed needed to satisfy remaining demand from UK livestock. Finally, we converted total food production into consumable kcal according to product-specific nutritional information.[108,109]

To evaluate the future scenarios, we applied per-hectare rates of food production to the new land cover areas in each scenario-year. The models accounted for the loss of land associated with solar and wind farm infrastructure. For solar, land was considered improved grassland and had a 5% reduction in size to account for the footprint of solar panels and associated infrastructure.[62] Results were generated for when solar land was both grazed and not grazed. For wind energy, the underlying land cover was kept the same, with 2% of the total area removed from production to account for turbine footprints and associated infrastructure (derived from EWEA,[110] East Ayrshire Council[111]).

Impacts on greenhouse gas emissions

Our greenhouse gas model estimated the total net flux of GHGs from Agriculture, Forestry, and Other Land Use (AFOLU) in each scenario-year.[43] All scenarios are essentially concomitant with a zero-carbon electricity sector, so we chose not to include GHG emissions from electricity generation. We estimated changes in emissions from AFOLU, including agriculture, new and existing woodland, agroforestry, wood pasture, and new and existing hedges. In addition, we estimated the loss or gain of soil carbon following land-use change between woodland, cropland, grassland, and urban according to expected changes in soil carbon density equilibrium using the UK Greenhouse Gas Inventory.[112] The 2% of the area converted to wind farm was considered urban land due to the footprint of wind infrastructure, over which we estimated soil disturbance from the turbine's foundations. Where turbines were deployed in coniferous woodland, loss of above-ground carbon was also accounted for. For solar, the whole area was re-classified as improved grassland (resulting in soil carbon sequestration when transitioning from cropland), without accounting for foundations due to the comparatively shallow depth of panel foundations. We express emissions in terms of CO_2 equivalents (CO_2e), using IPCC AR4 100-year global warming potential values (GWP_{100} = 25 for methane, 295 for nitrous oxide; IPCC[113]).

Impact on breeding birds

Our bird habitat evaluation model used data from the UK Breeding Bird Survey[114] to fit habitat-abundance models for each of 109 native terrestrial species, estimating the habitat availability as a function of changes in land cover for each scenario (see Finch et al.[43]). The models predicted expected abundance in each 1 km square based on local (1 km square) and landscape-scale (2 km buffer around square centroid) land cover composition, hedge length, latitude, longitude, and elevation. We produced two total population estimates (optimistic and pessimistic) for each scenario based on 2050 land cover and hedge length. The optimistic estimate assumed no impact of wind and solar infrastructure on bird habitat availability (except a change to grassland where solar is deployed on cropland), whereas the pessimistic estimate assumed no birds were present in the areas of land designated for wind and solar. The true population size is likely to fall between these two values, but due to lack of detailed data regarding the impact of wind and solar energy infrastructure on each of our 109 focal bird species, this approach was chosen to indicate the potential range in population. Finally, we calculated the geometric mean change in population size from 2015 across all species (n = 109), as well as for subsets of species (farmland and woodland birds,[115] and species of conservation concern[116]). Our modeling approach ignores other known limiting factors such as non-breeding habitat, climate, disease, and persecution. Furthermore, the results presented here are at the national scale, and as such, our findings do not apply at the local/landscape scale where the impact of renewable energy installations is likely to be greater. As such, the predicted changes presented in this study should be interpreted as changes in national breeding habitat carrying capacity.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100122.

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AUTHOR CONTRIBUTIONS

Conceptualization, J.P.C., R.H.F., R.B.B., L.J.W., and T.F.; methodology, J.P.C., R.H.F., and T.F.; formal analysis, J.P.C. and T.F.; writing—original draft, J.P.C., R.H.F., R.B.B., and T.F.; writing—review and editing, J.P.C., R.H.F., R.B.B., L.J.W., and T.F.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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