THE BARTLETT
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Net zero emission energy scenarios and land use

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FIGURES

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Glossary

AD	Anaerobic Digestion
BECCS	Biomass Energy Carbon Capture and Storage
BEIS	Department of Business, Enterprise, Industrial Strategy (now Department for Energy Security & Net Zero)
BRE	Building Research Establishment
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
DACCS	Direct Air Carbon Capture and Storage
DLUHC	Department of Levelling Up, Housing and Communities
GGR	Greenhouse Gas Removal technology
GIS	Geographical Information System
HCA	Home and Communities Agency
LCOE	Levelised Cost of Energy
LED	Low Energy Demand
LUE	Land Use England
LULUCF	Land Use, Land Use Change and Forestry
MHCLG	Ministry for Housing, Communities and Local Government
NDB	Non-Domestic Buildings
NEED	National Energy Efficiency Data framework
NG	National Grid
NLUD	National Land Use Database
NZES	Net Zero Energy Scenario
PDL	Previously Developed Land (*i.e.* brownfield)
PV	Solar Photovoltaic
REPD	Renewable Energy Planning Database
RSPB	Royal Society for the Protection of Birds
V2G	Vehicle-to-Grid battery discharge
Units	
Prefixes	k kilo (thousand), M Mega million, G Giga (billion), T Tera (trillion)
kW, MW, GW	Power W Watts
kWh, MWh, TWh	Energy Wh Watt-hours
MJ, GJ	Energy J Joules
kg, t	Mass metric: k kilogramme, t tonne
ha	Area: hectare (1/100 of a km^2)
km^2	Square kilometre
odt	Oven dried tonne (biomass)
CO_2	Carbon dioxide
CO_{2e}	Global warming equivalent carbon dioxide
/a	Per annum

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Of course, the materials and views expressed here are the responsibility of the authors alone.

EXECUTIVE SUMMARY

This report reviews the land use and certain impacts of net zero energy scenarios (NZES) for the UK (and England) designed to achieve net zero emissions of greenhouse gases by 2050. The impacts are confined to those incurred in the UK only: the impacts of imported energy are not considered. The scope and timetable of the project were such that a limited number of technologies were considered, and comprehensive modelling of impacts could not be undertaken in terms of impacts, economics or policies. Rather there is some quantitative assessment using data and relatively simple analysis coupled with commentary.

NZES have been developed by several organisations including the former Government Department of Business Energy and Industrial Strategy (BEIS), the Climate Change Committee (CCC), and National Grid (NG). The Centre for Research into Energy Demand Solutions (CREDS) investigated low energy demand (LED) scenarios (Barrett *et al.*, 2022a; Barrett *et al.*, 2022b); however, details of the supply side of the LED system were not available at the time of writing.

The focus of the research is on land use of solar photovoltaics (PV), biomass, and onshore wind as these are extensively deployed in rural areas. The land use includes the physical surface areas taken up by PV and biomass, and the extent of visual impact of wind turbines. Commentary is made concerning other technologies including transmission and offshore wind. Some discussion is given on the direct technology costs of PV and wind systems, but there is uncertainty in generalising these and supporting components have not been costed at all, such as transmission, storage and land. Beyond these technology costs are the social costs of environmental impacts such air pollution from biomass or loss of visual amenity due to wind turbines. Further, the assessment of ecological impacts − and to somehow put these against the more easily identified cost elements to arrive at a balanced strategy – is out of scope.

The capacities (GW, $MtCO_2$) and energy production (TWh) of onshore wind, PV and biomass are taken from the NZES. An assessment of the land use per capacity − the specific land use − is made of each of the three renewables. The scenarios' minimum and maximum capacities are then multiplied by the specific land uses to arrive at total land use for production in the UK.

The maximum England PV capacity in the NZES is 83 GW and the urban technical potential of solar PV is estimated as 117 GW. Currently in England there is about 14 GW of operational PV comprising 4 GW on dwelling roofs, 1 GW on non-domestic roofs, and 9 GW of large systems in the BEIS Renewable Energy Planning Database (REPD) (BEIS, 2022f) comprising 8 GW operational and 1 GW under construction, assumed to be built. This gives a total existing capacity of 14 GW, so an additional 69 GW (83 – 14 GW) is required. The remaining urban potential of 111 GW can be ranked by increasing cost (£/kW), from lower cost systems located in existing and new car parks and on non-domestic roofs which will be comparable in cost to solar farms, to more costly systems retrofitted on existing dwellings. In general, as well as requiring less financing, the lower cost PV systems require less labour per capacity installed and may therefore be built more quickly. This leaves a potential urban surplus of 42 GW (111 – 69 GW).

An extended analysis would be needed to construct robust and balanced development pathways for solar PV capacity in different urban and rural situations. This would account for retrofit and new PV system installation costs for different sizes and mounting, and for ancillary costs such as transmission. The environmental impacts of systems in different locations need detailing. The pace at which capacity could be expanded to minimise cumulative emissions on the path to net zero would require assessment of the supply chain capacity in terms of labour and finance, and the different regulatory and financial mechanisms that might be applied. For example, regulation might be applied to require PV on car parks, as in France, and on new build.

There is currently little planned expansion of onshore wind in the BEIS REPD, but the national planning policy regarding onshore wind is currently uncertain. However, the costs of offshore wind are now becoming competitive with onshore and has a higher capacity factor requiring fewer balancing costs for storage.

Bioenergy is the hardest technology to assess because of the complexity of biomass itself, competition for land, and its impacts, the variation in productivity per hectare of different crops, and the energy losses in its processing and use for energy and for carbon sequestration. The scenarios in general assume a waste resource of 90-100 TWh, imports of 40-110 TWh and UK production of 30-95 TWh. The REPD indicates plans for an increase of 10-20% in biomass electricity production. Biomass production in England is estimated to require 6,000 to 12,000 km^2 or 5-9% of the area of England. The mass of biomass (excluding food) in the NZES is estimated at about 75 Mt which would be extracted from natural and agricultural ecosystems and then transported, processed and used. For comparison, the current UK cereal harvest is 23 Mt (DEFRA, 2022) and 56 Mt of vegetable biomass, mostly food, is transported by road (Table RFS0104, Department for Transport, 2023).

Wind and solar produce variable electricity whereas biomass produces chemically stored energy and carbon, so their outputs are of a different nature and it is not generally possible to directly substitute one for another. However, solar PV produces about 10 times as much energy per area of land (GWh/km^2) as biomass. Renewable electricity can be used to produce carbon with direct air capture and electrolytic hydrogen which may be used for fuels, carbon sequestration or energy storage thereby fulfilling the same roles as biomass. Direct air capture requires little, low quality land but does require chemical and water inputs. Perhaps the most difficult problem is how aviation will be fuelled – what is the best mix of biomass, atmospheric carbon and fossil-based fuels to produce a kerosene equivalent? The Royal Society (The Royal Society, 2023) estimated that 68% of the total agricultural land in the UK would be required to produce 12.3 Mt of aviation fuel from biomass.

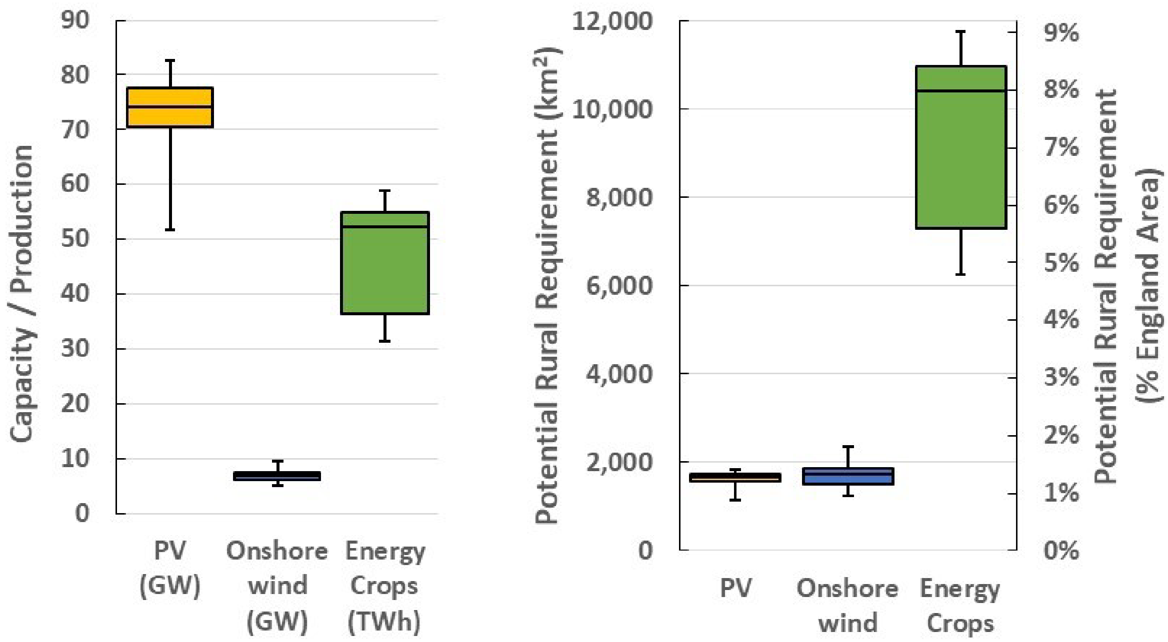
Table 1 and Figure 1 summarises the capacities and estimated land use of the renewables considered in the NZES.

Table 1 : Land use requirements in England for key technologies in 2050

		PV		Onshore wind		Offshore wind		Energy Crops (TWh)	
		Median	Range	Median	Range	Median	Range	Median	Range
Capacity	GW	74	52 - 83	7	5 – 9	88	52 – 112	52	31 - 59
Urban potential	GW	117	-	-	-	-	-	-	-
Rural Requirement*	GW	74	52 - 83	7	5 – 9	-	-	52	31 - 59
	km^2	1,650	1,150 - 1,800	1,700	1,250 - 2,300	-	-	10,500	6,250 - 11,750
% England Area*	%	1.3%	0.9 - 1.4%	1.3%	1.0 - 1.8%	-	-	8.0%	4.8 - 9.0%

** Values for PV if completely ground-mounted in rural areas. Values may not be additive e.g. the same land could be used for both onshore wind and PV or energy crops.*

Figure 1 : Land use requirements in England for key technologies in 2050



1. INTRODUCTION

This report makes estimates of the land use requirements of net zero greenhouse gas emission energy scenarios (NZES) for the UK, with a specific aim of assessing what can be accommodated in urban and rural areas in England. The impacts are confined to those incurred in the UK only: the impacts of imported energy in terms of land use or other effects are not considered. The focus is on solar photovoltaic (PV) systems, onshore wind turbines, and biomass. Some commentary is given on impacts other than land use. The limited scope of the project is such that most of the research is reviewing extant data, coupled with some simple analysis. There is no substantial collation of new data, detailed modelling or the use of Geographical Information System (GIS) analytic techniques which is an obvious route for further land use and built environment analysis.

The amount of land used by the renewable technologies assessed in this study is defined as the energy farm which is the entire area needed by the specific technology to function. For energy crops, it is assumed the majority of the land is solely used for crops. For solar farms, much of the land is covered by panels but there is potential for other uses such as grazing between or under panels. For windfarms, however, the "direct" exclusive land use (the area occupied by the tower foundations, access roads and substations *etc.*) can be around 1% of the windfarm area (Gaughan, 2018). This study focuses on the windfarm area which is the area of land needed to allow sufficient spacing between turbines such that the wind resource is not overly diminished; however most of this area can be used for other purposes such as growing crops or grazing. Wind farms and solar farms PV require transmission, generally overground, which takes little land but has visual impacts.

The visual impacts extend beyond the direct area used by energy farms. Energy crops and ground-mounted solar are low so their visual impact can be reduced through careful siting and shielding with hedges. Rooftop PV can be seen at a distance though it is integrated into the built environment. Wind turbines, however, are necessarily tall and wind resources are generally greater on higher ground, so their visual impacts can extend far. Quantifying visual impact is beyond the scope of this study as it varies substantially with the nature of the terrain, but should also be noted. A broad introduction – not intended to be comprehensive - is set out in the table below.

Table 2 : Land use categories

	Direct area	Beyond direct	Beyond direct	Beyond direct
Solar PV	Panels, supports, inverters, transformers, etc.		Access roads, transmission etc.	Visual
Biomass	Crops, processing facilities, etc.		Access roads etc.	Visual, noise, air/water pollution
Wind	Towers and foundations, transformers, etc.	Turbine spacing	Access roads, transmission etc.	Visual, noise

There is no attempt here to assess how current and future planning policies might bear on the development speed and magnitude of the different renewables and other energy sources such as nuclear, and supporting infrastructure such as transmission and storage. Information about planning for different assets is set out by BEIS (2021a).

There is often tension between the need to meet national objectives and local opposition due to local impacts.

Ideally all significant technologies should be consistently appraised and compared, including offshore wind and negative emission processes. In order to develop robust policy, research in phases such as these could be followed:

i. More detailing of NZES, such as waste streams, and the consideration of low demand scenarios and options for problematic sectors like aviation.
ii. The inclusion and detailing of all significant net zero technologies.
iii. A comprehensive environmental impact assessment, covering more than land use.
iv. A full technical appraisal, including how the technologies integrate into the energy system as a whole. One issue here is the pros and cons of urban versus rural in terms of transmission and storage: either way, it is certain more transmission capacity will be needed at high and low voltage.
v. An economic appraisal of the individual technologies as installed and connected in various contexts, and of the integrated energy system including costs such as for land.
vi. An appraisal of the social capacity required to implement net zero technologies sufficiently rapidly.
vii. A wider appraisal including social costs and benefits.
viii. Optimisation to find low cost, low impact solutions.
ix. Policy formulation based on the above.

Scenarios

The basic analytic flow is to collate a range of NZES, assess the land use per capacity (GW) or output (TWh) and thence estimate the land use implications of NZES.

NZES have been developed by bodies including National Grid, CCC and BEIS. The scenarios assume a range of energy demands, supply mixes and negative emissions. The NZES have assumptions about the energy demands and the power capacities (GW) and energy outputs (TWh) of key technologies (on and offshore wind, solar, biomass, interconnectors etc.) and these are specified with varying levels of detail. Most scenarios are for the UK. Renewable resources are not spread evenly across UK countries – the north is generally windier than the south (though some areas in the south such as coastal areas and Cornwall have high wind speeds) − and there is more solar radiation in the south than the north. The land types available and suitable for biomass and competing food production vary across the UK.

Perhaps the most problematic demand is aviation. For the foreseeable future this will require a kerosene equivalent fuel made from fossil oil, biomass or atmospheric carbon and electrolytic hydrogen. Aviation will also require negative emissions to balance the global warming it causes at high altitude, and negative emissions systems, where atmospheric CO_2 is removed from the atmosphere and stored, are not proven at scale.

Inventory

An inventory was made of the land use and some other environmental impacts of solar, wind and biomass energy technologies and processes. The focus is on land use per power capacity (GW) or annual energy output (TWh), but other impacts such as visual amenity, air pollution, and noise are considered in places. A literature search has been used to collate relevant data, and then some simple analysis has been used to compile technology impact databases in Excel.

There are good data on the annual solar radiation resource (kWh/m^2) on different angled surfaces and estimates of the efficiency of photovoltaic PV generation have a narrow range. The areas and suitability of urban surfaces on roofs and car parks are estimated from disparate data. Combining these features, the total technical potential PV urban capacity (GW) and generation (TWh) can be calculated. A commentary is given on the possible relative costs of urban and solar farm costs.

Biomass is complex in terms of its physically varying composition, the productivities of different crops as affected by land type and climate, and the variety of processes biomass is subject to prior to use. This leads to wide ranges of energy productivity per land area values (GWh/km^2/a).

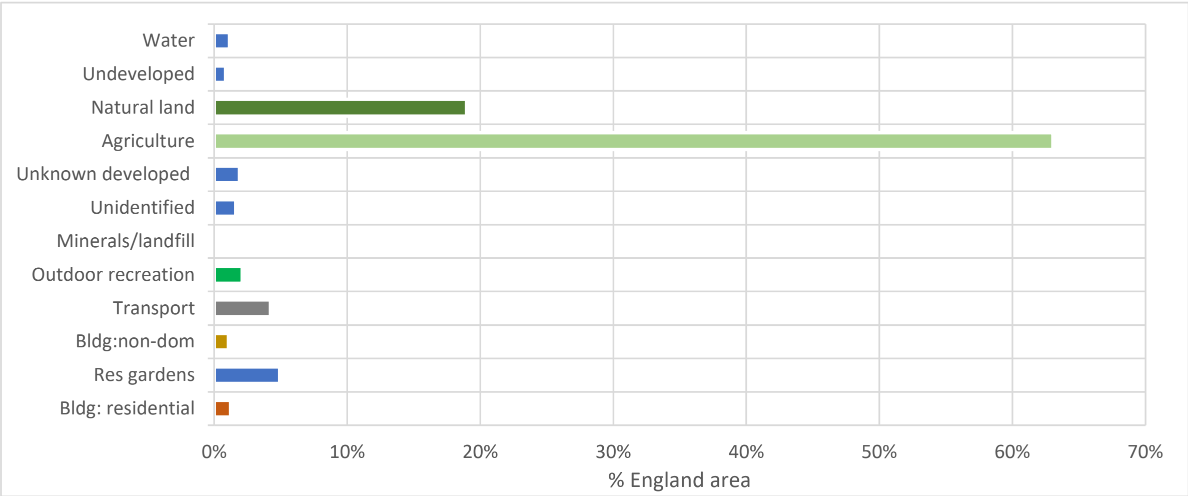
Onshore wind has a small land use footprint for its towers and access roadways, but its visual impact is extensive. The optimal siting of onshore wind requires a complex assessment of wind resources, environmental impact, and proximity to transmission.

Other mostly rural technologies are briefly discussed. These include nuclear stations and supporting energy infrastructure such as high voltage transmission, transformers, batteries, and hydrogen salt caverns. Predominantly urban or industrially sited technologies including district heating, electrolysers, etc are excluded.

1.1 Overview of land use in England

Land use statistics: England 2022 (LUSE; DLUHC, 2022c) gives the areas of buildings and different land use types as in Figure 2. About 19% of land area (including gardens) is developed, 63% is used for agriculture and 19% is forest, open land and water here labelled 'Natural land'. Approximately 90% of the land area is covered by vegetation.

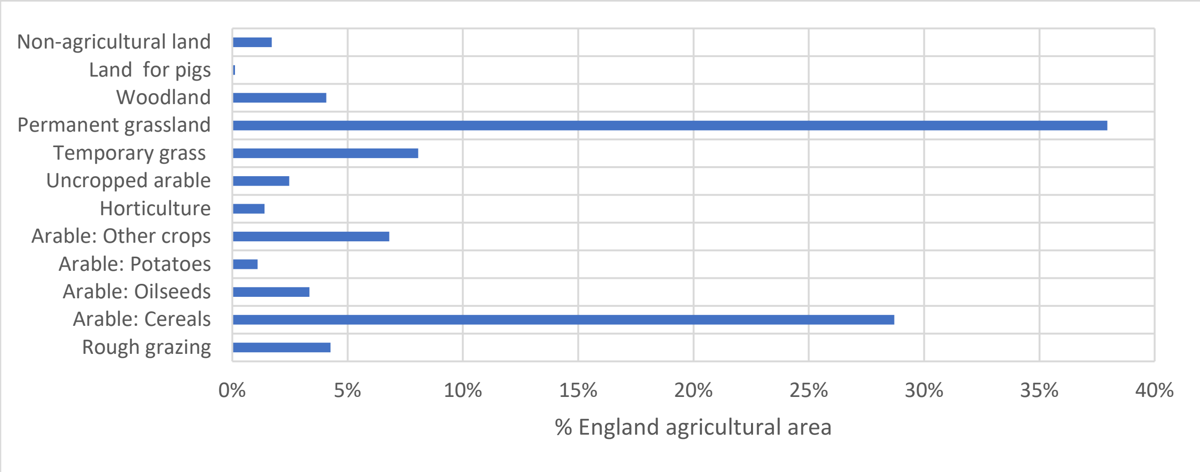
Figure 2 : Land use statistics England (LUSE) 2022



Source: Land use statistics England (LUSE) 2022 (DLUHC, 2022c)

Defra (Defra, 2022) give statistics on the *Structure of the agricultural industry in England and the UK at June* including land use as is shown in Figure 3: 42% of agricultural land is for arable crops and 46% is permanent and temporary grassland.

Figure 3 : Agricultural land use



Source: (Defra, 2022)

1.2 UK renewable energy planning database

A useful database of existing operational and planned renewable energy projects used throughout this report is the Renewable Energy Planning Database (REPD) (BEIS, 2022f). Note that the data are for electrical capacity only, so capacities for biofuels, biogas or BECCS, etc. are not included. The minimum threshold for installed capacity (MW) in the database was 1 MW until 2021, at which point it was lowered to 150 kW. This means that projects below 1 MW that were going through the planning system before 2021 may not be represented in the REPD. Note that the estimated energy production (GWh) of a plant depends on its capacity factor.

Table 3 and Figure 4 summarise the plant in England that are operational and at various stages of planning. If all proposed projects are permitted and built then large system solar capacity will increase by a multiple of 2.9, about threefold, and a significant fraction of this capacity will be non-urban, whereas the indices for onshore wind and biomass are about 1. The annual generation (GWh) by the plant are estimated using assumed capacity factors – the average capacity output divided by the installed capacity – suitable for wind and solar, with a 50% working assumption for facilities using stored biofuels. Of total operating and pipeline installations, offshore wind constitutes 65% of total annual output, onshore 5%, solar PV 9% and dedicated and co-fired biomass 11%. Other waste and biomass fuelled generation (energy from waste or EfW, anaerobic digestion, land fill gas, and sewage sludge) constitute 9%.

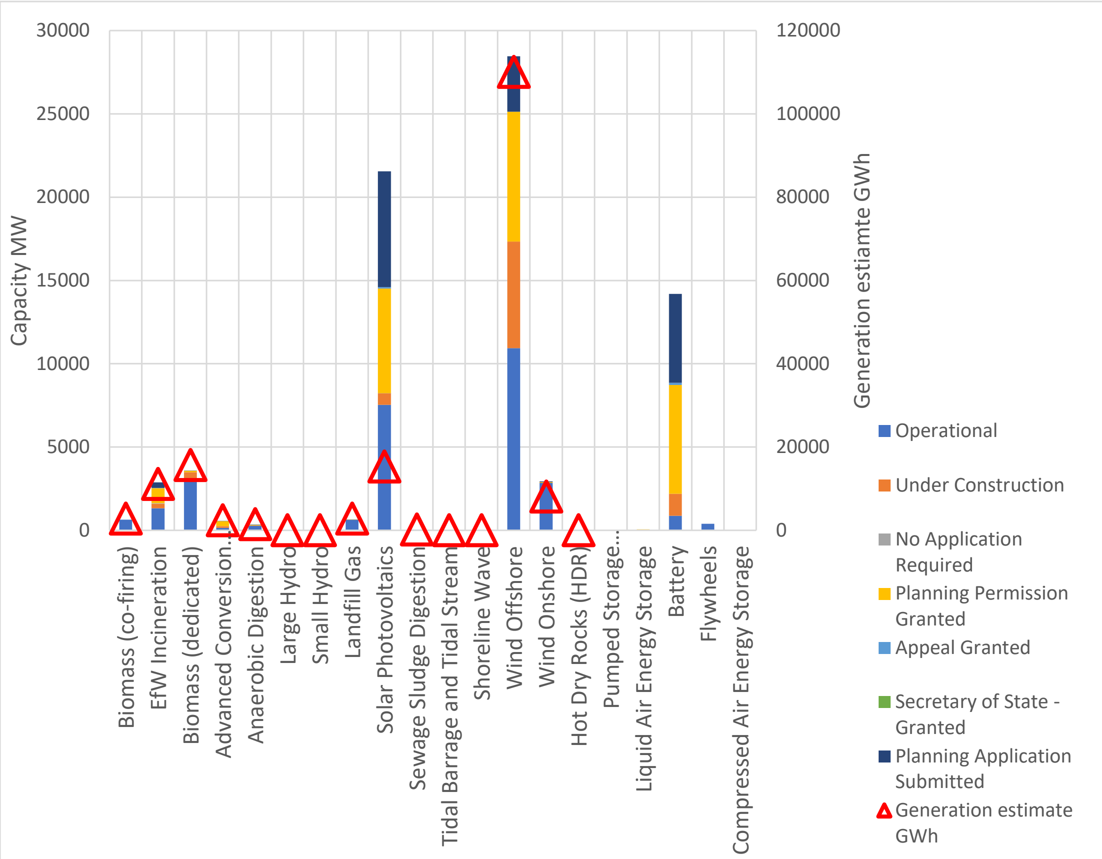
Table 3 : England renewable energy projects planning (REPD)

	MW Installed capacity									Estimate		
Technology	Operational	Under Construction	No Application Required	Planning Permission Granted	Appeal Granted	Secretary of State - Granted	Planning Application Submitted	TOTAL	Potential growth	Capacity factor	Generation estimate GWh	% Total REPD GWh
Biomass (co-firing)	**645**	**0**	**0**	**0**	**0**	**0**	**0**	**645**	**1.0**	50%	2825	2%
EfW Incineration	1323	277	28	903	21	0	332	**2883**	2.2	50%	11173	7%
Biomass (dedicated)	**3137**	**360**	**0**	**87**	**0**	**0**	**13**	**3598**	**1.1**	50%	15703	9%
Advanced Conversion Technologies	146	105	0	298	0	0	28	**577**	4.0	50%	2403	1%
Anaerobic Digestion	**287**	**12**	**0**	**42**	**1**	**0**	**9**	**351**	**1.2**	50%	1498	1%
Large Hydro	6	0	0	0	0	0	0	**6**	1.0	40%	21	0%
Small Hydro	2	0	0	4	0	0	0	**6**	3.5	40%	20	0%
Landfill Gas	621	0	0	29	0	0	8	**658**	1.1	50%	2847	2%
Solar Photovoltaics	**7529**	**709**	**0**	**6276**	**90**	**0**	**6940**	**21545**	**2.9**	12%	15353	9%
Sewage Sludge Digestion	45	0	0	0	0	0	0	**45**	1.0	50%	196	0%
Tidal Barrage and Tidal Stream	0	0	0	30	0	0	0	**30**	0.0	15%	39	0%
Shoreline Wave	23	0	0	0	0	0	0	**23**	1.0	20%	40	0%
Wind Offshore	10936	6400	0	7798	0	0	3319	**28453**	2.6	50%	110086	65%
Wind Onshore	**2859**	**1**	**0**	**42**	**0**	**0**	**39**	**2941**	**1.0**	32%	8134	5%
Hot Dry Rocks (HDR)	3	7	0	0	0	0	0	**10**	3.3	50%	44	0%
Pumped Storage Hydroelectricity	0	0	0	0	0	0	0	**0**	0.0			
Liquid Air Energy Storage	5	0	0	50	0	0	0	**55**	11.0			
Battery	869	1322	0	6530	140	0	5327	**14188**	16.3			
Flywheels	400	0	0	0	0	0	0	**400**	1.0			
Compressed Air Energy Storage	0	0	0	0	0	0	5	**5**	0.0			

Source: Renewable Energy Planning Database (REPD): (BEIS, 2022f)*, authors' estimates*

Figure 4 shows capacities (MW) and estimated annual energy production (GWh) from Table 3. This illustrates the importance of both capacity and capacity factor affecting annual energy output, particularly the low factor for solar and as compared to offshore wind.

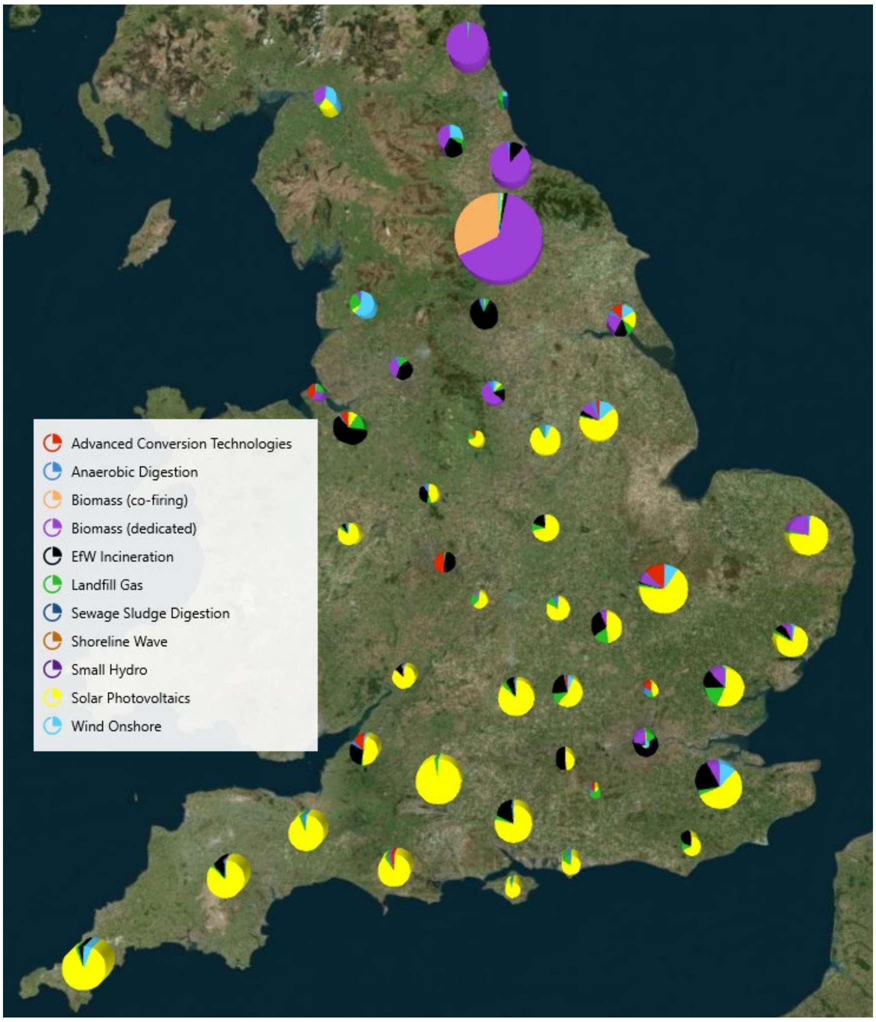
Figure 4 : England REPD renewable project capacities and energy



Source: Renewable Energy Planning Database (REPD): (BEIS, 2022f)*, authors' estimates*

Figure 5 shows a map of all facilities in England recorded in the REPD (October 2022), excluding offshore, where symbol size is proportional to capacity (MW). This shows the preponderance of PV in the south and the largest dedicated biomass plant Drax in the north east.

Figure 5 : Map England renewable energy projects



Source REPD – Operational, under construction, planning permission granted

2. ENERGY SCENARIOS

2.1 Energy scenarios for the UK, GB and England

Several recent energy scenarios from leading publications have been used for this study. The first is the set of five scenarios published by the Climate Change Committee for the Sixth Carbon Budget (CCC, 2020b). National Grid's Future Energy Scenarios 2022 have been also used (National Grid, 2022b). These have provided the main basis for this analysis. Note that although the Sixth Carbon Budget covers the period 2033-2037, the scenarios supporting the analysis extend to 2050. In addition some data from BEIS' Net Zero Strategy (BEIS, 2021b) have been used for biomass, but not for other technologies as the GW capacities needed to quantify land use requirements for these technologies were not reported for the BEIS scenarios.

The capacity, which is the maximum power output of a plant, is generally measured in GW (Giga/billion Watts) or MW (million Watts). The annual energy output or flow of biomass or electricity is generally measured in TWh (Tera/trillion Watt hours). The capacities for some of the main technologies in 2050 are shown in Table 4. The capacities reported by CCC are for the UK, and by National Grid for GB. As can be seen, all the scenarios achieve net zero emissions in 2050. Electricity generation across the scenarios is 610-898 TWh/a, though some of this is used for electrolysis to generate hydrogen, reducing electricity demand to 442 – 680 TWh/a. Although generated using different assumptions, some consistent ranges are apparent for the capacities of technologies of interest in this study. There is a clear indication that onshore wind capacities are expected to lie in the range 25-47 GW (compared to an existing capacity of ~14 GW, see Table 22), solar PV 57-92 GW, and offshore wind 65–40 GW. Table 4 also shows an ongoing role for nuclear, a falling role for unabated fossil fuels, and a growing role for hydrogen, carbon capture and storage (CCS) and bio-energy CCS (BECCS). Storage is expected to play a significant role, including vehicle-to-grid (V2G) storage. Additionally interconnector capacity is expected to grow, and in fact for the UK to become a significant exporter of electricity by 2050, with implications for increased capacity requirements of generating technologies and the potential for increased localised impacts of such technologies.

Table 4 : Energy capacity scenarios in 2050[1]

			CCC (2020) Sixth Carbon Budget (6CB)					National Grid (2022) Future Energy Scenarios (FES)		
		Unit	Balanced Pathway	Headwinds	Widespread Engagement	Widespread Innovation	Tailwinds	Consumer Transformation	System Transformation	Leading the Way
Emissions	Net 2050 Emissions	MtCO2e	-1	-12	-1	-44	-111	-0.4	-4	-30
Demand	Electricity Generation	TWh pa	730	610	727	898	793	710	716	672
	Electrolysis	TWh pa	120	60	117	218	173	117	147	154
	Electricity Demand	TWh pa	610	550	610	680	620	543	442	463
Capacity	Offshore wind	GW	95	65	100	140	125	111	116	108
	Onshore wind	GW	30	25	30	35	35	47	34	45
	Solar	GW	85	85	80	90	75	79	57	92
	(of which Domestic PV)	GW						41	21	41
	Other renewables	GW						11	13	6
	Fossil fuel	GW						0	0	0
	Fossil fuel CCUS	GW	15	15	5	15	5	3	14	4
	Nuclear	GW	10	10	5	5	5	15	13	8
	Hydrogen	GW	45	25	40	45	50	19	22	18
	Biomass	GW						0	1	0
	BECCS	GW	5	10	10	5	10	12	10	3
	Interconnectors	GW						22	16	27
	Electricity Storage	GW						46	32	51
	Total	GW						366	329	363
Other	V2G	GW						34	16	39
	Electrolysis	GW						28	45	44
	Electricity Storage	GWh						165	113	195
	V2G storage	GWh						123	57	140
	H2 storage	TWh						11	56	19
	IC imports	TWh pa						12	20	31
	IC Exports	TWh pa						-160	-82	-108

Source: (CCC, 2020b; National Grid, 2022b). *CCC data is for UK, National Grid for GB.*

Some additional scenario data are reported in Table 5, focussing on CCS, bioenergy and land use data. Care is needed when analysing the data for some of these technologies to clarify how they are defined, and likewise capacities can be reported on an emission (tCO_2), energy (TWh) or area (km^2) basis. The reader is reminded that land use and other impacts incurred by energy imports are out of scope. Again, however, some consistent trends can be observed. There is an expectation of 35 – 65 TWh/a of energy crops with total bioenergy usage of around 250 TWh/a, including imports, afforestation, wastes, etc. Note the energy crops data from Table 5 was supplemented for this study with three projections from BEIS' Net Zero Strategy (BEIS, 2021b); two of 58 TWh, and one of 62 TWh, which also lie in the same range. Significant GGR usage is expected, with typically 40 – 60 $MtCO_2$/a of BECCS, 0 – 30 MtCO2/a of DACCS, and 10 – 50 $MtCO_2$/a of other CCS.

[1] National Grid offshore wind capacity data includes non-networked offshore wind for floating electrolysis

Table 5 : CCS, bioenergy and land use scenario data

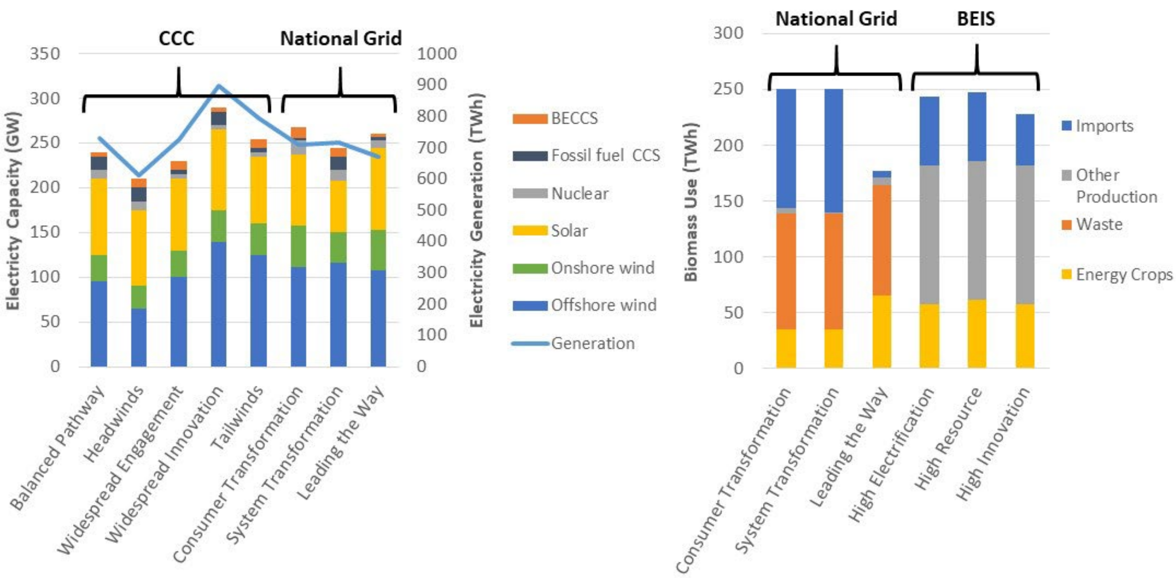
			CCC (2020) Sixth Carbon Budget (6CB)					National Grid (2022) Future Energy Scenarios (FES)		
			Balanced Pathway	Headwinds	Widespread Engagement	Widespread Innovation	Tailwinds	Consumer Transformation	System Transformation	Leading the Way
GGRs	CCS (Electricity generation)	MtCO2e	13	18	7	15	5			
	CCS (Industrial processes)	MtCO2e	8	13	8	9	6			
	CCS (Hydrogen production)	MtCO2e	16	52	6	3	1	0	12	3
	BECCS	MtCO2e	53	87	44	48	97	61	53	29
	DACS	MtCO2e	5	0	0	15	15	0	0	24
	Other	MtCO2e	10	11	6	9	9			
	Total CO2 captured	**MtCO2e**	**104**	**180**	**72**	**98**	**132**	**61**	**64**	**56**
Bioenergy	Afforestation	TWh pa								
	Biomass imports	TWh pa						102	106	0
	Biofuel imports	TWh pa						5	5	6
	Forest residues	TWh pa						47	47	45
	Energy crops	TWh pa						35	35	65
	Agri residues	TWh pa						14	14	9
	Waste wood	TWh pa						16	16	16
	Waste biodiesel, bioethanol	TWh pa						0	0	0
	Biogas	TWh pa						5	1	7
	MSW, C&I (biogenic)	TWh pa						27	27	28
	Landfill gas	TWh pa								
	Total	TWh pa						**250**	**251**	**177**
Land Use	LULUCF sources	*MtCO2e*	20	28	20	20	20			
	LULUCF sinks	*MtCO2e*	(39)	(35)	(39)	(53)	(58)			
	LULUCF total capture	MtCO2e	19	7	19	32	38	19	19	32
	Trees planted	Kha/yr	50	30	70	50	70			
	Energy crops planted	Kha/yr	30	30	10	61	61			
	Peatland restoration	Kha/yr	6	44	6	5	6			

Source: (CCC, 2020b; National Grid, 2022b). *CCC data is for UK, National Grid for GB.*

These ranges capture much of the current thinking about the future energy mix in 2050 and provide a good basis for the following analysis. However considerable uncertainties remain as with any future projections. Costs of offshore wind have fallen surprisingly quickly in recent years, one factor in a rapid switch from onshore to offshore wind build. Octopus Energy recently identified 2.3 GW of British onshore wind potential with local community support (Octopus Energy, 2022), which is enough to restart onshore wind deployment but still significantly below the additional capacity of onshore wind in the NZES, so unless significantly more onshore wind potential with community support is identified a reduction in onshore wind requirements could be consistent with the wishes of local communities. Marine technologies (excluding offshore wind) remain expensive, with expected deployment falling compared to previous analyses *e.g.* RSPB (2016). Deployment of greenhouse gas removal technologies (GGR) is particularly uncertain, and it is possible that a failure of these technologies to reach commercialisation would lead to a greater requirement for renewables than considered here.

The capacity data presented in Table 4 and Table 5 are summarised in Figure 6 for the UK and GB, not England. Reasonably consistent patterns for wind, solar and biomass can be observed and provides a good basis for the analysis in this study.

Figure 6 : Electricity capacity and biomass usage national scenario data



Source: (CCC, 2020b; BEIS, 2021b; National Grid, 2022b). *CCC and BEIS data is for UK, National Grid for GB.*

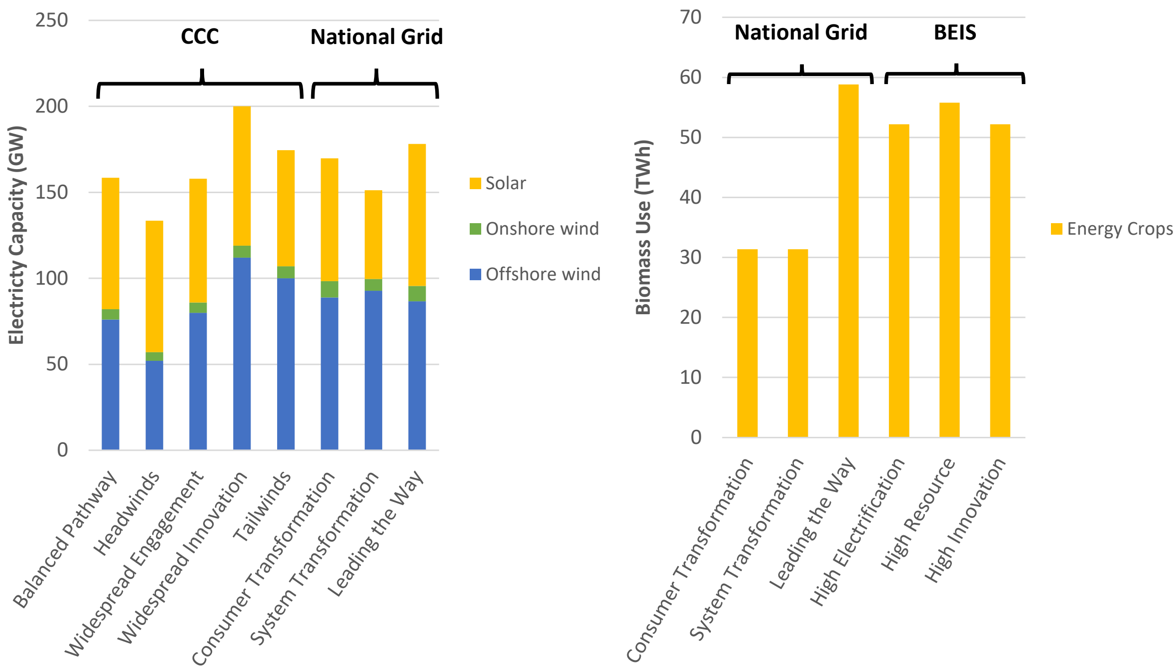
This data applies to the whole of the UK for the CCC and BEIS scenarios, and to GB for the National Grid scenarios. For this study, the fraction of these technology capacities expected to be placed in England needs to be estimated. These estimates are approximate, and it is beyond the scope of this study to estimate these allocations for all the technologies in Table 4 and Table 5. However, the allocations expected in England for certain key technologies (solar PV, onshore and offshore wind, and energy crops) have been estimated from operational and planned installations as reported in the Renewable Energy Planning Database and BEIS Energy Trends data as outlined in Appendix 1.

The results are shown in Table 6. It is assumed that 90% of the PV capacity and of energy crops is located in England due to its higher solar resource and area, but this is a working assumption requiring much deeper analysis. A slightly smaller amount (80%) of the offshore wind capacity is assumed adjacent to England, with growing deployment of offshore wind in Scotland and Wales. However only 20% of the onshore wind capacity is assumed in England, as historically a majority of onshore wind has been installed in Scotland, with higher onshore windspeeds generally in the north of the UK. The resulting capacity and usage data for England alone is shown in Figure 7.

Table 6 : England's share of 2050 UK scenario data

		UK Capacity		England Capacity		% in England
	Units	**Min**	**Max**	**Min**	**Max**	
PV	GW	57	92	52	83	90%
Onshore Wind	GW	25	47	5	9	20%
Offshore Wind	GW	65	140	52	112	80%
Energy Crops	TWh	35	65	31	59	90%

Figure 7 : Electricity capacity and biomass usage scenario data for England



Source: Author analysis. Published scenario data allocated to England.

2.2 Land use requirements in England

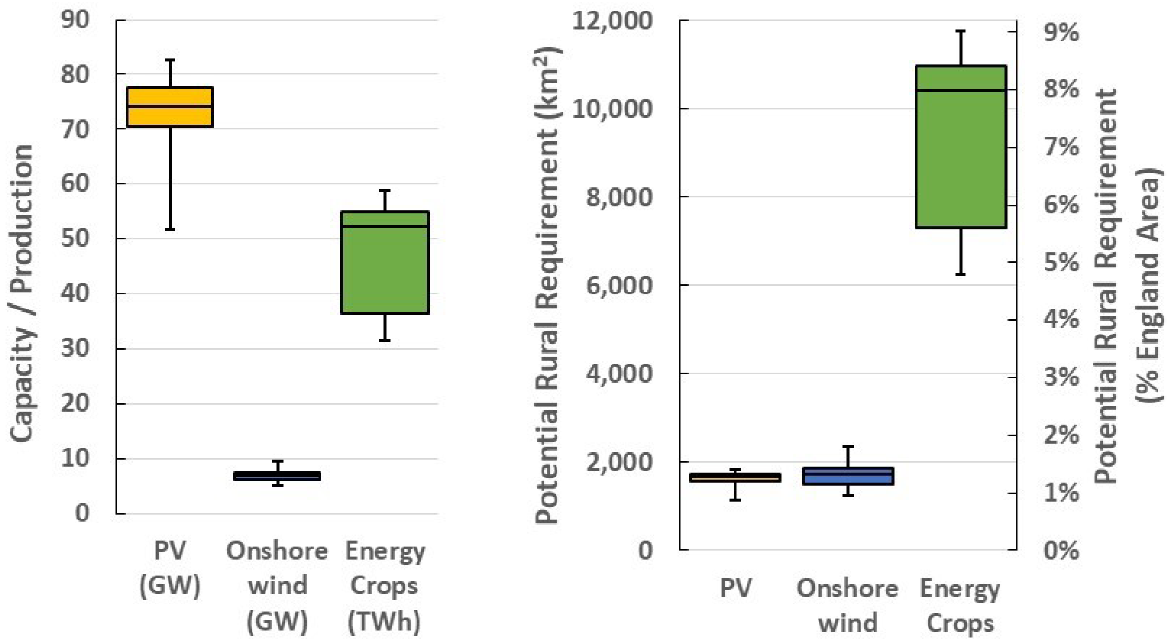
These capacity estimates have been combined with power (GW) and energy (TWh) density data (derived later in the report) to generate the land use requirements in England for key technologies to meet 2050 scenario requirements as shown in Table 7 and Figure 8. The power density assumptions here are 45 MW/km^2 for solar, 4 MW/km^2 for onshore wind, and an energy density of 5 GWh/km^2 for energy crops based on data from the Climate Change Committee and National Grid (CCC, 2020b; National Grid, 2022b), though it is emphasised there are wide variations in these densities for particular renewables and facilities. The median values for the scenarios used in this study are included, along with the range of values reported (maximum and minimum). For PV, as discussed later in section 0, the rooftop potential exceeds the total capacity of PV in NZES so ground-mounted systems in rural areas are not necessary though some may be lower cost. If this PV were installed in ground-mounted systems in rural areas, then 52 – 83 GW of PV would require 0.9 – 1.4% of England's land area of around 130,000 km^2. Onshore wind requirements for 5 – 9 GW are 1.0 – 1.8% of England's area. Energy crops could require around 5– 9% of England's land area to produce 31 – 59 TWh, indicating that energy crops could use substantially more land than PV and onshore wind. Offshore wind requirements are also shown for interest but have no rural land requirements other than for transmission.

Table 7 : Land use requirements in England for key technologies in 2050

		PV		Onshore wind		Offshore wind		Energy Crops (TWh)	
		Median	Range	Median	Range	Median	Range	Median	Range
Capacity	GW	74	52 - 83	7	5 – 9	88	52 – 112	52	31 - 59
Urban potential	GW	117	-	-	-	-	-	-	-
Rural Requirement*	GW	74	52 - 83	7	5 – 9	-	-	52	31 - 59
	km^2	1,650	1,150 - 1,800	1,700	1,250 - 2,300	-	-	10,500	6,250 - 11,750
% England Area*	%	1.3%	0.9 - 1.4%	1.3%	1.0 - 1.8%	-	-	8.0%	4.8 - 9.0%

** Values for PV if completely ground-mounted in rural areas. Values may not be additive e.g. the same land could be used for both onshore wind and PV or energy crops.*

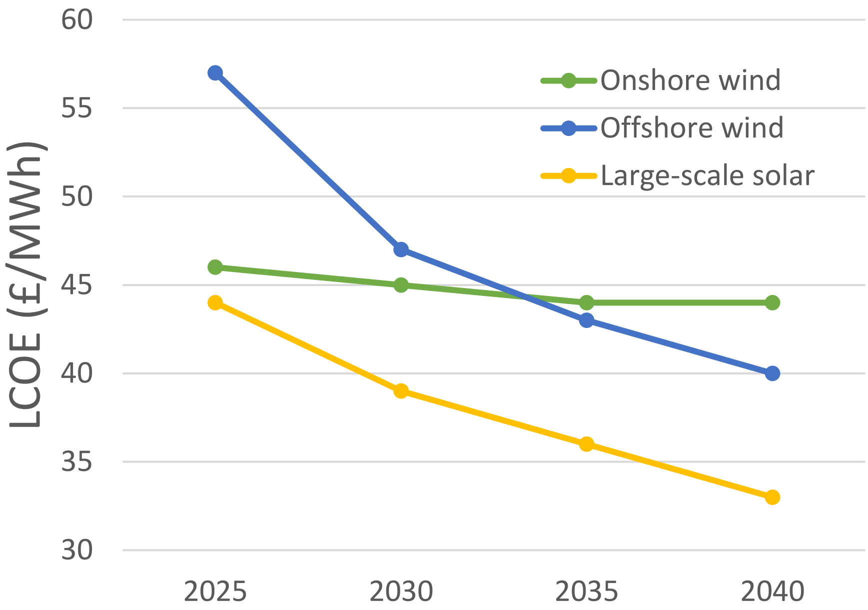
Figure 8 : Land use requirements in England for key technologies in 2050



2.3 Falling cost of offshore wind

Another factor driving the deployment of offshore wind in the UK is the falling cost of offshore wind. This can be viewed on a levelised cost of energy (LCOE) basis, which includes the effect of higher capacity factors of offshore wind (due to better wind conditions and larger turbines) which have been estimated by the UK government to reach 63% for offshore wind commissioned in 2040, compared to 34% for onshore wind (BEIS, 2020a). Note however LCOE estimates exclude connection and reinforcement costs, which may be higher for offshore than onshore wind. The resulting estimates for the UK are shown in Figure 9 and show the LCOE of offshore wind projected to fall faster than onshore wind, becoming lower by 2035. This probably reflects economies of scale resulting from both larger turbines and windfarms for offshore wind, in addition to higher capacity factors. Also a supportive policy environment for offshore wind including involvement in Contracts for Difference (CfD) auctions and a 50 GW target by 2030 (DESNZ, 2023) encouraging stable supply chains, whereas onshore wind has been excluded from CfD auctions and subject to an effective moratorium since 2015 (DECC, 2015). Higher capacity factors for offshore wind also mean the balancing costs for storage and back-up are lower than for onshore wind. There is also a substantial possibility that offshore wind costs will reduce faster than currently expected, with a recent analysis of industry experts showing substantial reductions in future cost estimates over the last five years (Wiser, Rand *et al.*, 2021).

Figure 9 : LCOE projections for solar (>5 MW), onshore wind and offshore wind



Source: (BEIS, 2020a). Central Nth of a kind (NOAK) estimates, real 2018 prices.

This falling cost of offshore wind has been observed in practice in the latest UK Contracts for Difference auction, which occurred in July 2022 (BEIS, 2022b), though it should be noted many variables affect auction outcomes. Here, nearly 7 GW of offshore wind was awarded strike prices of 37.35 £/MWh, lower than the 42.47 £/MWh awarded to onshore wind, indicating that strike prices for offshore wind can already be lower than for onshore wind. This trend is expected to continue in 2023, where administrative strike prices for the fifth allocation round (AR5) have been set at 53 £/MWh for onshore wind and 44 £/MWh for offshore wind *i.e*. offshore wind is still expected to have lower strike prices (BEIS, 2022c), though it should also be noted that some developers have signed offshore wind contracts for well below estimated LCOE values in anticipation of lower future turbine costs (BNEF, 2022).

Industry experts have indicated they expect that the LCOE of offshore wind will remain higher than onshore wind in 2050 on a global basis (Wiser, Rand *et al.*, 2021). Offshore wind can be cheaper in the UK than the global average due to its high windspeeds and shallow waters as well as supportive policies and established supply chains, suggesting the UK will remain a popular market for offshore wind in the coming decades. At the very least it appears offshore wind is reaching approximate cost parity with onshore wind, allowing the decision over which technology to deploy to be made on grounds other than cost alone, such as which technology has lower impacts or higher acceptability.

These costs do not include on and offshore transmission costs, for which there is great uncertainty. Note that Figure 9 also shows the LCOE of large-scale solar becoming substantially lower than for both onshore and offshore wind, potentially driving interest in large-scale solar. Also excluded are costs such as storage and back-up generation, which could be significantly higher for solar than wind due to the much lower capacity factor of solar power (about 11%) compared to offshore wind (about 50-60%) and that solar generation is much lower in winter when demand is higher.

2.4 Energy efficiency and demand reduction

A major option for accelerating GHG emission reduction and lowering the rural impact of low emission scenarios is to reduce the demand for energy. The scenarios outlined above used as a basis for this study all assume the implementation of at least some demand reduction measures. This section discusses one recent study by the Centre for Research into Energy Demand Solutions (CREDS) that specifically set out to investigate the potential impact that demand reduction could have by generating a series of low energy demand (LED) scenarios (Barrett *et al.*, 2022a; Barrett *et al.*, 2022b). The study found that energy demand can be significantly reduced firstly through a range of energy efficiency measures; electrification alone could triple the energy efficiency of two of the largest end use sectors (buildings and light vehicles) through replacing boilers with heat pumps and internal combustion engines with electric vehicles. Longer term, electrification could also improve efficiency in a number of industrial sectors including steel and ammonia. Increased insulation could substantially reduce energy demand in buildings, especially when taking a fabric first approach in newbuilds and retrofitting old buildings to high standards. Also, the energy efficiency of a range of appliances can be improved including the widespread adoption of light-emitting diode lighting, smart technologies can operate energy systems more efficiently, and transport demand can be reduced though increased home deliveries.

Secondly, demand can also be reduced through avoid and shift measures which could require some levels of lifestyle change, such as include increased home-working and hot-desking to reduce commuting and the need for office space. A reduction in car ownership and increased use of car-sharing, public transport and walking/cycling can reduce energy consumption and the use of raw materials. A range of products from clothing and furniture to appliances and electronics can be reused or recycled in the move towards a more circular economy, with the energy required to recycle materials much less in many cases than the energy required to extract them in the first place. Public awareness campaigns can reduce the amount of air travel and meat-eating. A co-benefit of these measures can be improved public health through reduced fuel poverty, cleaner air, improved diets and more active lifestyles. The study found that, although improved energy efficiency alone is sufficient to significantly reduce demand in some sectors (*e.g*. buildings and transport), the majority of demand reduction in sectors such as nutrition and materials and products came from broader societal changes and a reduced need for energy services, particularly for scenarios with deeper demand reduction. Hence it found that net zero is very difficult to achieve without considering broader shifts in consumption patterns.

The CREDS study found that implementing a range of these measures could reduce energy demand by up to 52% relative to 2020 levels by 2050. The CREDS generation requirements in 2050 range from 500 TWh in 2050 in the lowest demand scenario up to 800 TWh in other scenarios. This range is lower than the NG and CCC scenarios where generation spans 600 TWh to 900 TWh across the scenarios so the LED scenarios could lead to some reduction in the required capacities of renewable technologies, and hence to a reduction in the rural impacts these technologies have.

The exact consequences of demand reduction for primary energy and therefore renewables capacities depend on the reductions in the different categories of demand – e.g. building, transport – and the efficiencies of technologies (e.g. heat pumps) and types of delivered energy used (e.g. electricity, district heat). Although illustrating the kind of impact substantial demand reduction could have, these LED scenarios have not been included as core scenarios for this study as it is not clear at this stage the extent to which some of the proposed demand reduction measures are likely to be implemented in practice, and the implications for variable renewable supply and storage capacities.

3. SOLAR PHOTOVOLTAIC GENERATION

The main objective here is to estimate the technical potential of solar photovoltaic (PV) capacity and generation on rooftops and car parks in urban areas. Some data and commentary are given on mainly rural solar farms but the area for this is not constrained in the same way as for urban PV.

3.1 Solar radiation

Solar radiation is the primary energy driver of solar PV and biomass systems. Solar radiation consists of direct radiation from the sun's disk as on a clear day, and diffuse radiation coming from across the sky because of scattering by the atmosphere and clouds. Over the year, in the UK, about 60% of solar energy is diffuse and 40% direct. London is chosen as a location to be representative of England's solar resource and can be seen illustrated with MCS data (MCS, 2023) which show total annual solar energy is about 830 kWh/m^2 on a horizontal surface and a maximum of 985 kWh/m^2 on a surface facing due south (azimuthal angle of 180° from north) with an elevation of 40°. A less than optimal angle will reduce the radiation received. For a surface with 30-50° elevation (typical domestic roof pitch) the reduction in output is less than the south facing maximum by about 10% if the panel faces between southeast and southwest. The decision about how much loss is acceptable is largely an economic one; the lower the cost of the PV system and the higher the value of the electricity generated, the greater the loss due to poor orientation that is acceptable and the greater the fraction of roofs and other surfaces that can economically accommodate PV. Some tracking panels, usually in solar farms, can change their orientation dynamically to track the sun and increase the radiation intercepted.

3.2 Solar PV technology

The analysis focuses on the potential for electricity generating, grid connected solar photovoltaic systems (PV). The potential solar capacity is fundamentally determined by the solar resource, the size and orientation of suitable roof and land areas, and the coverage and efficiency of PV generation systems. The main operational impact of urban PV is on visual amenity, and this can be important for heritage buildings; guidance on this is given by Historic England (Cattini, 2018).

PV panels are usually mounted on top of the roof covering of tiles, slates, etc. Panels are generally about 1 m by 2 m. Smaller solar tiles are made: they look similar to conventional roofing and replace it in new build and can be used if visual amenity is critical, but they are less efficient and more expensive than standard panels[2].

PV system efficiency. This is determined by the panel design, maintenance (cleaning etc.), deterioration, and operating conditions – efficiency falls with high temperatures. Current commercial panels have efficiencies of 18-20% when new. Projections are made that efficiencies will rise to 25% by 2030 and more beyond that.[3] PV efficiency declines with age and an average lifetime loss of 5% loss is assumed. Additionally, the PV panel output is direct current and this is usually converted to alternating current with an efficiency of 93-98%. A projection is made that the future (2030 average year)

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[2] https://renewableenergyhub.co.uk/blog/is-it-worth-investing-in-solar-tiles/

[3] https://www.dnv.com/to2030/technology/solar-pv-powering-through-to-2030.html

solar PV system including inverter has an average efficiency of 23% (= 25% x 95% x 95%). A possibility, not included here, is bifacial panels where solar radiation reflected from the roof is collected on the underside of the panel, and this might increase output by 3-30%[4].

It is beyond scope to assess the transmission voltages, losses and costs of connecting PV to the grid. In general, systems less than 50 kW will be connected at 230 V (domestic) or 415 V (non-domestic), whereas larger systems may be at higher voltage.

Peak solar radiation and panel output. UK peak solar radiation may be taken as 900 W/m^2 (Renewables Ninja, Pfenninger and Staffell, 2016). If a 23% efficient PV panel is oriented to collect 90% of maximum solar then the PV installed or peak electrical capacity is 180 W/m^2.

3.3 Urban solar collection areas

Key to estimating urban solar PV potential are the urban areas that might be suitable. Here all that is considered are rooftops and car parks. Other land such as around motorways, service stations, railways or airports can be suitable, but this is not explored because of lack of data. The estimates are of technical potential, not of what might be economically optimal as compared to solar farms or indeed other renewables. Figure 10 shows an urban area in a town (Colchester, Essex) that includes non-domestic (hospital) buildings, car parks and a mix of dwellings. This illustrates the following:

- Non-domestic building roofs can be large, relatively uncluttered and have shallow slopes.
- Dwellings have small roofs with variable geometries which are fairly cluttered.
- About 50% of car park area is taken up with parking spaces and the remainder with access roadway.

[4] https://www.dnv.com/article/bifacial-pv-technology-technical-considerations-186095 https://www.nrel.gov/docs/fy19osti/74090.pdf https://ratedpower.com/blog/bifacial-modules/

Figure 10 : Colchester hospital, parking and residential areas

Source: Google Earth

New build and solar design

New dwellings or non-domestic buildings can be designed to maximise solar collection areas as far as possible within the constraints of site layout (e.g. road orientation) and built form (e.g. terrace). A mono-pitch roof could offer about double the south facing area of a conventional 'A' frame roof with opposed pitches. The roof dimensions could account for the standard PV panel sizes and clutter could be minimised. Solar panels can be integrated with the roof and replace some of the standard roofing thereby saving money; solar tiles are more costly and less efficient. Here it is assumed that all PV would be installed on roofs but PV can be applied to window shades or even vertical surfaces, though the solar radiation collected is reduced. Solar installation costs in new build are lower than in retrofit because of the large savings in installation costs.

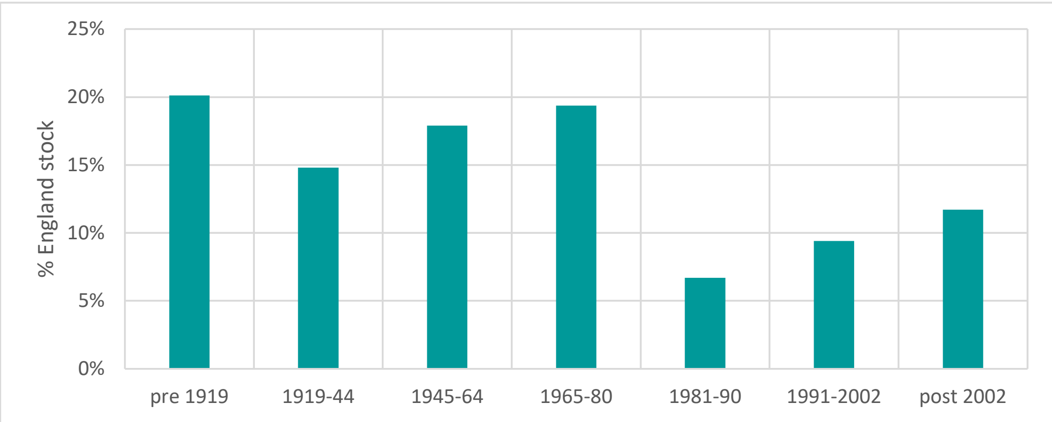
3.3.1 Domestic rooftop areas

NLUD (Harrison, 2006) gives a total area of 1634 km^2 (1.23% of England area) taken up by dwellings, with an additional 6423 km^2 (4.92%) for gardens, so about 20% of the total plot area of dwellings is the building. This basic statistic is used for the estimates of solar potential on existing dwellings. It would be possible to improve estimation by using data for different dwelling forms (detached, semi-detached, terrace, flats) and sizes, but this is beyond scope.

The population of England was 56.5 million (M) in 2021[5] and is projected to increase by 11% by 2050[6]. There were 23.8 M households[7] and 24.9 M dwellings[8]- a surplus of about 1 M dwellings. For England, the ONS (ONS, 2022) project a 14% increase in households between 2020 and 2043, because of population growth and smaller household size, which can be extrapolated to 18% or 4.3 M additional households by 2050, so about this number of extra dwellings will be required. Given a reducing household size, average dwelling floor area may decrease and there may be an increasing proportion of flats with less external roof area per dwelling; these trends may lead to an increase in rooftop area of less than 18% - to adjust for this 16% is assumed.

The lifetimes of buildings and their components (roofs, walls, windows, etc.) depend on the quality of materials and installation, and maintenance, and the needs for repurposing buildings for different household sizes or changing commercial uses. The future lifetimes of buildings are uncertain but historically has ranged from 20 to 200 years or more, with many dwellings over a century old. The average age of dwellings in England is estimated by the authors to be 67 years, with 20% over 100 years old (DLUHC, 2022a) as shown in Figure 11. If this average age were to persist then perhaps about 20% of the dwelling stock would be replaced between 2023 and 2050.

Figure 11 : Dwelling stock age distribution



Source: (DLUHC, 2022a)

Roofs may have a shorter life than the basic building structure; 20-50 years is one estimate found.[9] Altogether, a significant fraction of current buildings and roofs will be replaced or refurbished by 2050, and solar PV on these will in general be lower cost than retrofit.

Brownfield land

Brownfield land has previously been developed for building or other purposes. This land can be used for new development, including for buildings and parkland. Assuming

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[5] https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualmidyearpopulationestimates/mid2021
[6] National population projections - Office for National Statistics
[7] https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/datasets/householdsbyhouseholdsizeregionsofenglandandukconstituentcountries
[8] https://www.ons.gov.uk/peoplepopulationandcommunity/housing/datasets/subnationaldwellingstockbytenureestimates
[9] https://www.designingbuildings.co.uk/wiki/Average_life_spans_of_roofs

this land were used for housing then about 20% of the area would be taken up by the plan area of dwellings with the remainder being gardens, roads, etc. Alternatively, some brownfield area might be used for non-domestic buildings or ground mounted PV. One estimate of brownfield area by CPRE (2022) suggests 27,342 hectares (273 km^2) which might accommodate 1.233 M dwellings. The CPRE brownfield estimate is used here. Assuming 20% is dwelling area then the total dwelling plan area is 55 km^2. New buildings on brownfield land will have lower solar costs than retrofitting.

Assuming 4 M additional dwellings of the same size as current are required to accommodate growth in household numbers, then 1.2 M could be on brownfield areas and 2.8 M elsewhere, and this is accounted for. However, in the estimation of rooftop solar PV costs, no allowance is made for replacing dwellings or non-domestic buildings where costs will be lower.

3.3.2 Non-domestic rooftop areas

Non-domestic national energy efficiency data (ND-NEED) includes data on floor areas of buildings (BEIS, 2022e). ND-NEED is useful for giving the size distribution of all non-domestic buildings except for agricultural buildings. ND-NEED covers England and Wales so for England the areas are multiplied by 0.95, the proportion of England's population of the total of the two countries, though it is likely that England has a greater proportion of non-domestic commercial buildings than populations suggest. These floor areas may be divided by the assumed average number of floors to derive building plan areas as shown in Table 8. It might be expected that non-domestic building areas will increase with population and economic growth; an assumed 5% growth – lower than population growth – is assumed.

Table 8 : Non-domestic building plan areas

Average Floors		Building plan size m2 25	75	175	375	750	3000	6500	km2 Total
2.0	Leisure	0.0	0.2	1.4	1.8	1.6	1.8	0.5	**7.3**
2.0	Education	0.0	0.1	0.5	0.6	0.3	0.2	0.0	**1.8**
2.0	Emergency	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.1**
1.0	Factories	1.0	3.3	11.4	12.6	13.8	37.8	64.0	**143.9**
2.0	Health	0.0	0.2	0.5	0.3	0.1	0.0	0.0	**1.1**
3.0	Hospitality	0.1	0.3	1.2	1.4	0.9	0.4	0.0	**4.2**
3.0	Offices	1.1	1.6	3.5	3.2	3.2	6.0	5.6	**24.2**
1.5	Shops	2.9	7.9	11.2	7.1	6.6	15.2	12.4	**63.3**
1.0	Warehouses	0.7	2.0	8.1	12.7	18.8	61.5	95.4	**199.1**
2.0	Other	0.2	0.3	1.6	2.2	2.5	7.2	8.0	**22.0**
	Total	**5.9**	**15.9**	**39.2**	**41.9**	**47.9**	**130.2**	**186.1**	**467.1**

Sources: ND-NEED (BEIS, 2022e)*, authors' estimates*

3.3.3 Car parks

Most non-domestic buildings have associated car parking, and in addition there are public car parks and residential car parking (excluded here from the estimate of potential) and some of this area can be used for PV. France has approved legislation that will require all car parks with more than 80 spaces to be covered over by solar panels.[10] There are 17,000-20,000 car parks in the UK[11] which are presumably public, which would add to the 126.8 km^2 estimate but no public data on these is available so they are excluded. No comprehensive public UK data for car parking areas serving non-domestic buildings have been found so they are estimated.

Requirements for car parking spaces per floor area for different non-domestic building types are specified by Charnwood (Charnwood, 2004) and set out in Table 9. A standard space is specified by Charnwood as 5.0 by 2.4 metres with an area of 12 m^2, though another source (Rochford District Council, 2009) specifies 4.8 by 2.4 m with a lesser area of 10 m^2, which latter is assumed for the area of the actual parking spaces, excluding access roadways. Many modern cars have bloated to the extent they will not fit this area. An assumption, judged from aerial photography, is that the spaces take up 50% of the total car park area.

Table 9 : Parking spaces and areas per floor area

Class	m2 Building FA	m2 FA/car space	m2 CarSpace/FA	Floors	m2 ParkSpace/PlanArea	ParkSpace/FA	TotalParkArea/FA
Shops	5000	9	556	1.5	4267	85%	171%
Shops	2000	12	167	1.5	1280	64%	128%
Shops	1000	30	33	1.5	256	26%	51%
Shops	200	100	2	1.0	23	12%	23%
Financial: Offices	1000	35	29	4.0	82	8%	16%
Business: Offices	1000	25	40	2.0	230	23%	46%
Light industry	3000	50	60	1.5	461	15%	31%
General industry	3000	50	60	1.5	461	15%	31%
Warehouse	9000	125	72	1.0	829	9%	18%
Restaurants	500	40	13	1.0	144	29%	58%
Pubs	500	10	50	1.0	576	115%	230%

Sources: (Charnwood, 2004)*, authors' estimates*

These data are used to make assumptions about the total car park area as a ratio of building plan size which are multiplied by plan areas estimated from ND-NEED. The estimates are shown in Table 10, with a total of 126.8 km^2, similar in magnitude but smaller than Knight Frank's report (Knight Frank, 2023): *'In total, the study identified*

[10] https://theconversation.com/frances-plan-for-solar-panels-on-all-car-parks-is-just-the-start-of-an-urban-renewable-revolution-194572

[11] https://www.data.gov.uk/dataset/af896cab-79ee-43c2-a3cb-3a1198b97f52/car-parks

103,000 public and private surface car parks across the country, which comprise a land area of 20,000 hectares.' 20,000 ha is 200 km^2.

Table 10 : Non-domestic building parking areas

Car park %FA	Car park	Building plan size 25	m2 75	175	375	750	3000	6500	km2 Total
50%	Leisure:CPark	0.0	0.1	0.7	0.9	0.8	0.9	0.3	**3.6**
30%	Education:CPark	0.0	0.0	0.2	0.2	0.1	0.1	0.0	**0.5**
30%	Emergency:CPark	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
25%	Factories:CPark	0.2	0.8	2.8	3.1	3.4	9.5	16.0	**36.0**
50%	Health:CPark	0.0	0.1	0.2	0.1	0.1	0.0	0.0	**0.6**
50%	Hospitality:CPark	0.0	0.2	0.6	0.7	0.5	0.2	0.0	**2.1**
20%	Offices:CPark	0.2	0.3	0.7	0.6	0.6	1.2	1.1	**4.8**
90%	Shops:CPark	2.6	7.1	10.0	6.4	6.0	13.7	11.2	**57.0**
10%	Warehouses:CPark	0.1	0.2	0.8	1.3	1.9	6.2	9.5	**19.9**
10%	Other:CPark	0.0	0.0	0.2	0.2	0.3	0.7	0.8	**2.2**
	Total	**3.2**	**8.8**	**16.2**	**13.6**	**13.6**	**32.4**	**38.9**	**126.8**

Sources: ND-NEED (BEIS, 2022e)*, (Rochford District Council, 2009), authors' estimates*

An useful guide to solar car parks is by BRE (Coonick, 2018). There are several companies developing solar car parking. For example, Flexisolar claim to have built the largest commercial solar carport[12] in the UK at Bentley Motors, Crewe, with 1,378 bays and capacity 2.7 MW (Solar Power Portal, 2023b), see Figure 12. It illustrates that 50% PV covering 50% of car park area may be a reasonable assumption.

[12] https://www.solarpowerportal.co.uk/news/uks_largest_solar_carport_completes_at_bentley_motors_hq

Figure 12 : Bentley motors Flexisolar car park: 1,378 bays, capacity 2.7 MW

Source: Google Earth,
https://www.solarpowerportal.co.uk/news/uks_largest_solar_carport_completes_at_bentley_motors_hq

3.4 Calculating solar capacity and output

The electrical output of PV is determined by the panel area and orientation, the solar resource and the PV system efficiency.

Rooftops

- **Domestic**. The average pitch of UK house roofs is between 30° and 50° [13]. At an angle of 40° the total pitched roof area is 170% of the plan area, with two halves facing in opposite directions so 85% of plan area is one pitch. Monopitch maximises south facing area for a given plan area, but monopitch is rare in English houses.
- **Non-domestic.** Non-domestic buildings (NDB) have a mix of flat and sloped roofs where the sloped pitch is often quite low.
- **Panel fitting coverage**. Panels are of set dimensions and will only fit to cover a certain percentage of a roof. Dwelling roof areas can be small and of irregular shapes and orientations. The larger the roof the greater the percentage fitting can be.

[13] https://www.marley.co.uk/blog/specification-considerations-low-pitch-roofs

- **Roof clutter**. Some domestic roof area may be taken up with chimneys, windows and dormer windows, etc. Flat roofs such as on offices will often have equipment such as ventilation/aircon vents and fans.

Ground/flat roof spacing. Panels have to be spaced on a horizontal surface to avoid overshading. It is assumed that the spacing loss balances the increased area of elevated surface.

Car parks. It is assumed that 50%, just the car park spaces, of the total car park area is usable for solar. It may be that some of the roadways could be used which would increase this percentage. On the other hand, some car parks are multi-storey or underground.

Shading. A small fraction of roofs will have substantial shading due to trees etc.

Planning constraints. In some areas PV may be limited by visual amenity and heritage concerns. This may mainly apply to dwellings.

Usability indices. The above factors are summarised with indices in Table 11, the product of which gives an overall index to multiply the plan area by to obtain solar collection area. The values for the indices for different installation types (roofs, ground) are judgements (in italics) as set out in Table 12; no comprehensive source of data for these has been found.

Table 11 : Roof top usability indices

Usability indices	
Amenity	visual obtrusion
Roof:Plan ratio	allowance for pitched roof
Orientation	to collect >90% of solar
Coverage	account for clutter
Usable Of Plan	**product of indices**

Summary collated results for areas, indices, PV installed capacity and annual generation are shown in Table 12. The areas include existing areas for retrofit, and areas for buildings additions caused by population and household growth by 2050. The total potential is estimated as 117 GW generating 133 TWh. Of the total, 83% is retrofit to existing areas: 41% is dwellings, 33% nondomestic and 10% car parks. The remaining 17% is on new, additional buildings: dwellings for accommodating an increased number of households; and a 5% assumed addition in non-domestic building area. The rate of PV development on additional (or replacement) buildings obviously depends on how quickly these stocks are built.

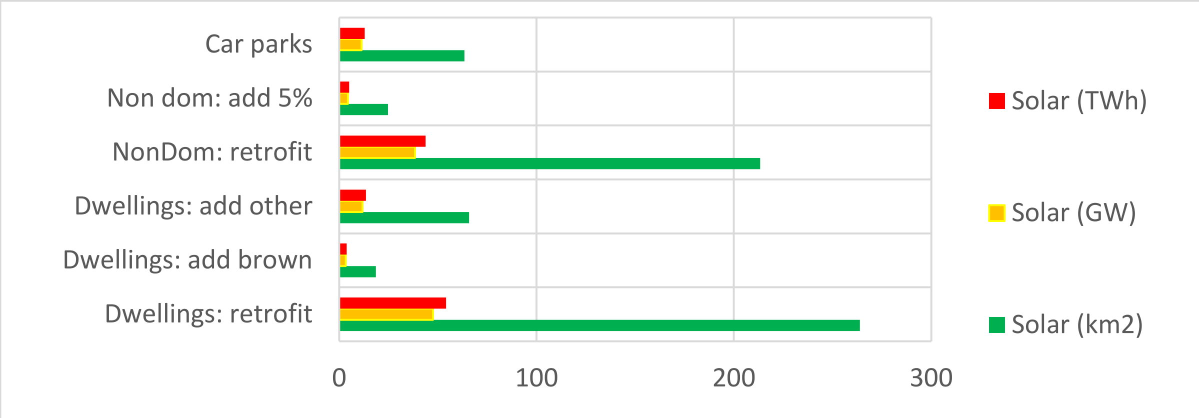
Table 12 : England urban solar potential

CATEGORY				INDICES					SOLAR		
	Area source	England_pc	Area_km2	Amenity	Roof:Plan ratio	Orientation	Coverage	Usable Of Plan	Solar_km2	Solar_GW	Solar_TWh
Dwellings: retrofit	LUE	1.232%	1634.0	*95%*	*170%*	*20%*	*50%*	*16%*	263.9	47.5	54.1
Agricultural	LUE	0.076%	101.2	*100%*	*110%*	*35%*	*90%*	*35%*	35.1	6.3	7.2
Leisure	ND-NEED	0.005%	7.3	*95%*	*110%*	*35%*	*80%*	*29%*	2.1	0.4	0.4
Education	ND-NEED	0.001%	1.8	*100%*	*110%*	*35%*	*80%*	*31%*	0.6	0.1	0.1
Emergency	ND-NEED	0.000%	0.1	*100%*	*110%*	*35%*	*80%*	*31%*	0.0	0.0	0.0
Factories	ND-NEED	0.109%	143.9	*100%*	*110%*	*35%*	*80%*	*31%*	44.3	8.0	9.1
Health	ND-NEED	0.001%	1.1	*100%*	*110%*	*35%*	*70%*	*27%*	0.3	0.1	0.1
Hospitality	ND-NEED	0.003%	4.2	*100%*	*110%*	*35%*	*70%*	*27%*	1.1	0.2	0.2
Offices	ND-NEED	0.018%	24.2	*100%*	*110%*	*35%*	*70%*	*27%*	6.5	1.2	1.3
Shops	ND-NEED	0.048%	63.3	*95%*	*110%*	*35%*	*80%*	*29%*	18.5	3.3	3.8
Warehouses	ND-NEED	0.150%	199.1	*100%*	*110%*	*48%*	*90%*	*47%*	94.2	17.0	19.3
Other	ND-NEED	0.017%	22.0	*100%*	*110%*	*48%*	*90%*	*48%*	10.5	1.9	2.1
CPark: Leisure	*Est*	0.003%	3.6	*100%*	*100%*	*100%*	*50%*	*50%*	1.8	0.3	0.4
CPark: Education	Est	0.000%	0.5	*100%*	*100%*	*100%*	*50%*	*50%*	0.3	0.0	0.1
CPark: Emergency	Est	0.000%	0.0	*100%*	*100%*	*100%*	*50%*	*50%*	0.0	0.0	0.0
CPark: Factories	Est	0.027%	36.0	*100%*	*100%*	*100%*	*50%*	*50%*	18.0	3.2	3.7
CPark: Health	Est	0.000%	0.6	*100%*	*100%*	*100%*	*50%*	*50%*	0.3	0.1	0.1
CPark: Hospitality	Est	0.002%	2.1	*100%*	*100%*	*100%*	*50%*	*50%*	1.1	0.2	0.2
CPark: Offices	Est	0.004%	4.8	*100%*	*100%*	*100%*	*50%*	*50%*	2.4	0.4	0.5
CPark: Shops	Est	0.043%	57.0	*100%*	*100%*	*100%*	*50%*	*50%*	28.5	5.1	5.8
CPark: Warehouse:	Est	0.015%	19.9	*100%*	*100%*	*100%*	*50%*	*50%*	10.0	1.8	2.0
CPark: Other	Est	0.002%	2.2	*100%*	*100%*	*100%*	*50%*	*50%*	1.1	0.2	0.2
Dwellings: brown a	CPRE	0.041%	54.7	*100%*	*170%*	*40%*	*50%*	*34%*	18.6	3.3	3.8
Dwellings: add oth	Est	0.097%	129.1	*100%*	*170%*	*50%*	*60%*	*51%*	65.9	11.9	13.5
Non dom: add 5%	Est	0.035%	46.7	*100%*	*110%*	*60%*	*80%*	*53%*	24.7	4.4	5.1
Dwellings: retrofit		1.232%	1634.0						263.9	47.5	54.1
Dwellings: add brown		0.041%	54.7						18.6	3.3	3.8
Dwellings: add other		0.097%	129.1						65.9	11.9	13.5
NonDom: retrofit		0.429%	568.3						213.3	38.4	43.7
Non dom: add 5%		0.035%	46.7						24.7	4.4	5.1
Car parks		0.096%	126.8						63.4	11.4	13.0
TOTAL		**1.931%**	**2559.5**						**649.7**	**116.9**	**133.2**
Add. buildings sub-total		0.174%	230.5						109.1	19.6	22.4

Sources : LUE, ND-NEED, CPRE, authors' estimates set out in text

The estimated urban solar potential is summarised in Figure 13.

Figure 13 : England urban solar potential



Source: Table 12

3.4.1 Other estimates

Other estimates of rooftop solar potential are very wide ranging, and some are inconsistent with the analysis here, though it is not clear why. McKenna *et al.* (2022) estimate a rooftop technical potential of 153 TWh for Great Britain, compared to 133 TWh estimated here for England. Defaix *et al.* (2012) estimate over 100 TWh, but this includes vertical surfaces. Bodis *et al.* (2019) estimates that the UK has an available rooftop solar area of 771 km^2, with a technical potential of 43.6 TWh, about one third of the estimate here, and an economic potential of 6.5 TWh, 5% of the technical potential estimated here. Joshi *et al*. (2021) estimate 238 TWh, twice the estimate here. Robinson (2022) says *'With only the largest 20% of warehouses there is enough roof space to double the UK's solar generation capacity from 14 to 28 GW.'* This 14 GW, on the largest roofs only, is to be compared to 17 GW estimated here for all sizes of warehouse roofs.

3.5 Solar costs

Solar installation costs per kW generally reduce as installation size grows because of economies of scale in panel purchase, installation costs, maintenance and so on. Note that transmission costs are not estimated here. The costs of a solar PV system itself comprise the equipment costs (panels, inverters, supports etc.) and installation (design, fitting, etc.), and for farms the cost of the land. Details of the cost breakdown for systems are sparse but, whereas the costs of panels and inverters are projected to fall significantly, the installation and transmission costs are likely to fall less. In general, installation costs will be highest on retrofit rooftop systems and lowest on ground mounted rural or car park systems and on new building rooftops. The installation capacity (kW) will range widely. Domestic installations are typically 3 to 5 kW. Non-domestic installations will generally be larger because about 90% of total roof area is large factories, warehouses and agricultural buildings. Current costs range from about 1500 £/kW for installations 0-10 kW, to 1100 £/kW for 10-50 kW installations[14]. These costs are predominantly for retrofit; solar PV costs on new build, such as on brownfield sites, will be significantly less.

There are few data on the cost of solar farms, but panel costs may in 2023 be about 200 £/kW[15] with a total installed cost of 700 £/kW[16]. About 41% of the total cost is for the panels and inverter[17]. If solar farm capacity were 0.2-0.4 MW/acre and land value 7500-10000 £/acre[18], then the land component would be 20-50 £/kW. Solar PV costs are likely to continue falling – for example BEIS (2020b) project large solar system costs as 350 £/kW in 2035, approximately a 50% reduction from current prices. The cost of the panels and inverter are about 30% for a retrofit domestic installation[19]. It may be expected that the costs of this equipment will fall faster than installation and other costs, increasing the relative cost of small retrofit PV compared to large ground or roof mounted systems. A minimum cost of 500 £/kW is assumed for a future large roof or ground mounted system.

There are few data on transmission costs. It is suggested in 6.3.1 that the urban distribution transmission may be reinforced for heat pump input and EV charging, and this might accommodate solar PV export which will in general peak at different times. The connection costs of solar farms will depend on the proximity to suitable transformers and transmission, and currently there is concern about the long lead times for connection[20].

The potential solar capacity by area type and illustrative unit cost £/kW are shown in Figure 14, but no allowance is made for lower costs on new buildings.

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[14] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1078223/Solar_Costs_2021-22.xlsx

[15] https://renewableenergyhub.co.uk/blog/everything-you-need-to-know-about-solar-farm-requirements/

[16] https://www.lancasterguardian.co.uk/health/lancaster-leisure-centre-solar-farm-would-save-council-ps130000-a-year-on-energy-bills-1573282

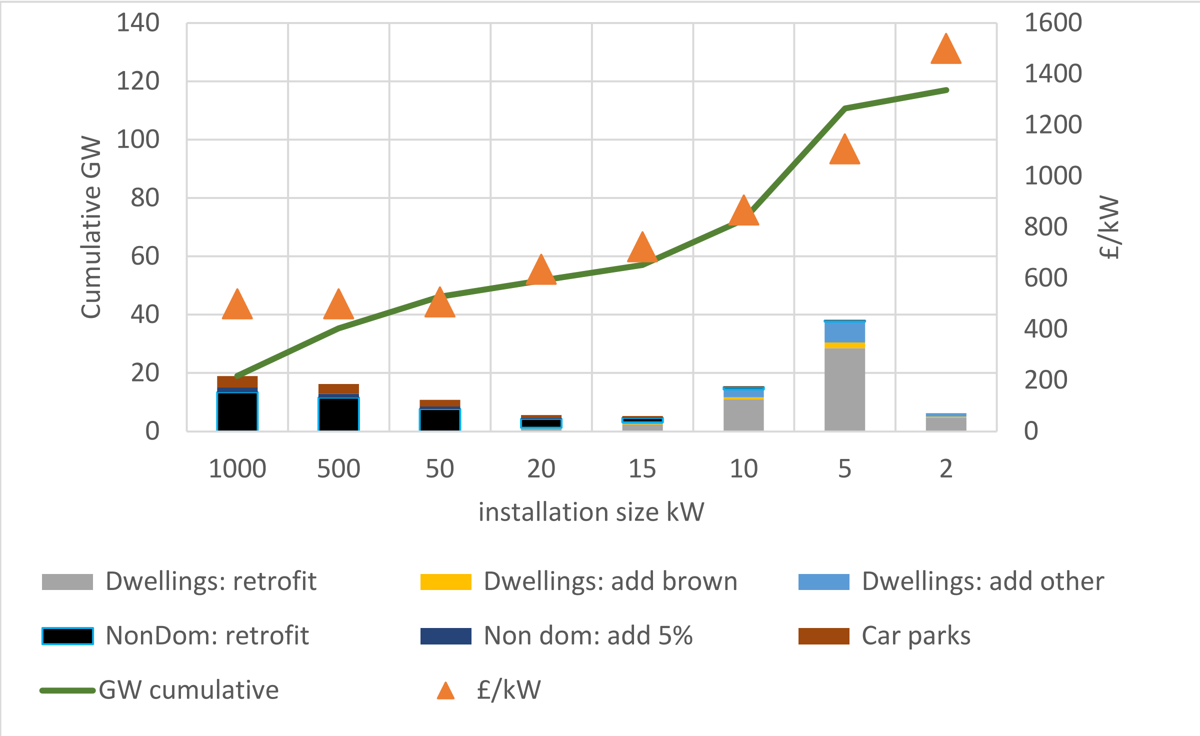
[17] https://ratedpower.com/blog/solar-farm-costs/

[18] https://addland.com/research/guides/solar-farms

[19] https://www.spiritenergy.co.uk/kb-solar-panel-installation-cost

[20] https://eandt.theiet.org/content/articles/2023/02/delays-threaten-net-zero-goals/

Figure 14 : Solar capacity and cost by area type



We may rank the solar capacity by increasing cost per kW. About 40 GW is at the lower cost of 500 £/kW, thereafter costs rise. Thus the first 40 GW of urban solar capacity may be similar in cost to solar farms. The average cost across all sizes is 800 £/kW. Again, it is noted that the different transmission costs and losses of rural or urban siting are not estimated.

About 83% of the total potential is retrofit for which the speed of implementation is flexible. The remaining 17% on new build is constrained by the rate at which new dwellings are built: in 2021/22, 171,000 dwellings were completed[21]. At that rate it would take about 25 years to build the additional 4 M dwellings that will be required by 2050.

3.6 Solar farms

Solar PV farms require near horizontal or south facing land. The panels are mounted on low frames 2 to 3 m high with spacing to minimise overshading and allow access for maintenance. Generally farm panels are south oriented, but the Cleve Hill (now Project Fortress) solar farm panels will be higher (up to 4 m) to avoid flooding and oriented east and west for closer installation which will impact on wildlife according to the Kent Wildlife Trust[22].

Solar farms have a range of impacts which it is beyond scope to thoroughly review, but some commentary is given. PV panels reduce the solar radiation received by the ground, reducing temperatures and variations in humidity, and thereby changing plant

[21] https://www.ons.gov.uk/peoplepopulationandcommunity/housing/articles/ukhousebuildingdata/financialyearendingmarch2022
[22] https://www.kentwildlifetrust.org.uk/campaigns/planning-and-development/cleve-hill-solar-park

photosynthesis and productivity; this is discussed by Armstrong *et al*. (2016). Taylor *et al.* (2019) review ecological impacts including on aquatic vertebrates, birds, bats and biodiversity. They opine that their original 2014 review was little changed: *'Our original review, published in 2014, concluded that the ecological impacts of ground-mounted solar panels in the UK were relatively limited and location-specific'.* Solar farms cause a loss of visual amenity which − to a degree – can be reduced by consideration of how hilly the landscape is and by hedging the solar farm.

Agrovoltaics

Agrovoltaics combine PV and agricultural production by growing crops or allowing grazing around or under the panels. The panels reduce the solar radiation reaching plants but with the loss fraction varying with solar farm design parameters such as panel angles, height and spacing. Panels will reduce direct solar radiation more than diffuse radiation. The loss or gain of biomass productivity this reduced radiation causes depends on the fraction of solar energy the plant uses, the fraction that is surplus to what it can use and indeed may stress the plant, and the impact of solar reduction on environmental factors such as ground and air temperatures and moisture, and the effects of these on crop pests and disease. These processes vary with time of day and year and the type of plant. A further issue is how biomass under and around panels is harvested; this may be by grazing animals, machines or by hand. This complexity and the effects of PV on yields is reviewed by Toledo and Scognamiglio (2021). Plants use radiation of particular wavelengths and there is the future possibility of having panels which are transparent to these wavelengths and absorb some of the remainder for generation, thereby minimising plant productivity loss and maintaining good PV output; this is reviewed by Stallknecht *et al.* (2023).

For England, the REPD (BEIS, 2022f) gives 7.5 GW of solar installations greater than 1 MW (reduced to 150 kW in 2021) currently operating, with 0.7 GW under construction, 6.3 GW with planning permission: if all these were to become operational apart from there would be 14.5 GW of large solar PV, most being rural and ground mounted. 6.9 GW are applying for permission which would add to this total if built. Some planned solar farms will have tracking bifacial panels[23]. Solar farm development takes one year or more for proposal development, grid connection and planning applications, contracts, and construction. Table 13 shows some of the larger operating and proposed solar farms for which there are area data, with capacity intensity ranging from 60 to 100 MW/km^2.

Table 13 : Larger solar farms

Farm	MW	MW/km2	km2	ha	acres
Botley (planned)	840	86.5	9.7	972	2400
Cleve Hill (planned)	350	97.2	3.6	360	890
Shotwick	72	71.4	1.0	101	250
Lyneham	70	80.9	0.9	86	213
Bradenstoke	70	69.2	1.0	101	250
Owl's Hatch	52	60.5	0.9	86	212

Sources: https://www.deegesolar.co.uk/uks_biggest_solar_farms/, https://www.fwi.co.uk/business/diversification/farm-energy/uks-largest-solar-farm-sparks-contrasting-views

[23] https://www.theengineer.co.uk/content/news/warrington-solar-project-hailed-as-uk-s-most-advanced

One interesting aspect is the proposals for solar farms, some with capacities of 500 MW, near to existing transformers and transmission previously built for now-decommissioned fossil generation[24].

An image of one of the largest operating solar farms, Bradenstoke, with a capacity of 70 MW, may be seen in Figure 15 (Solar Power Portal, 2023a) but as noted, much larger ones are proposed. Bradenstoke is located adjacent to a disused airfield.

Figure 15 : Bradenstoke solar farm

Source: Google Earth,

Figure 16 shows a map of large PV installations from the REPD, the majority of which are ground-mounted rural solar farms. The majority are in the south.

[24] https://www.solarpowerportal.co.uk/news/8710

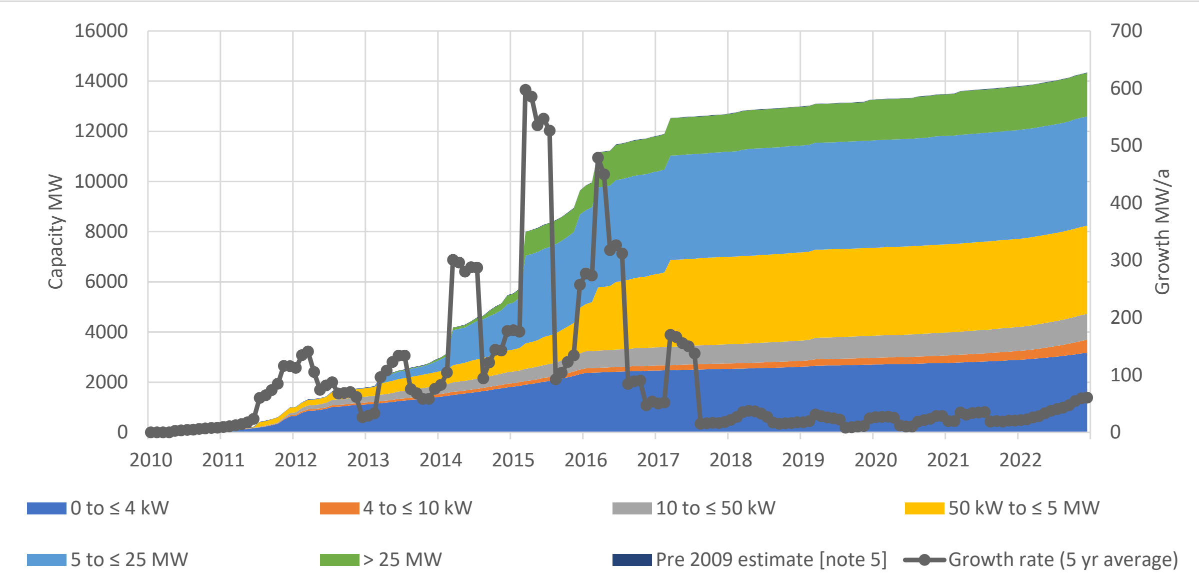
Figure 16 : Large solar PV (MW capacity)

Source : REPD – Operational, under construction, planning permission granted

3.7 Solar PV development

Early solar PV installation was dominated by small rooftop systems, but after 2014 the main growth was in larger systems. The growth rate was fast from 2014 to 2017 and thereafter diminished. This is shown in Figure 17.

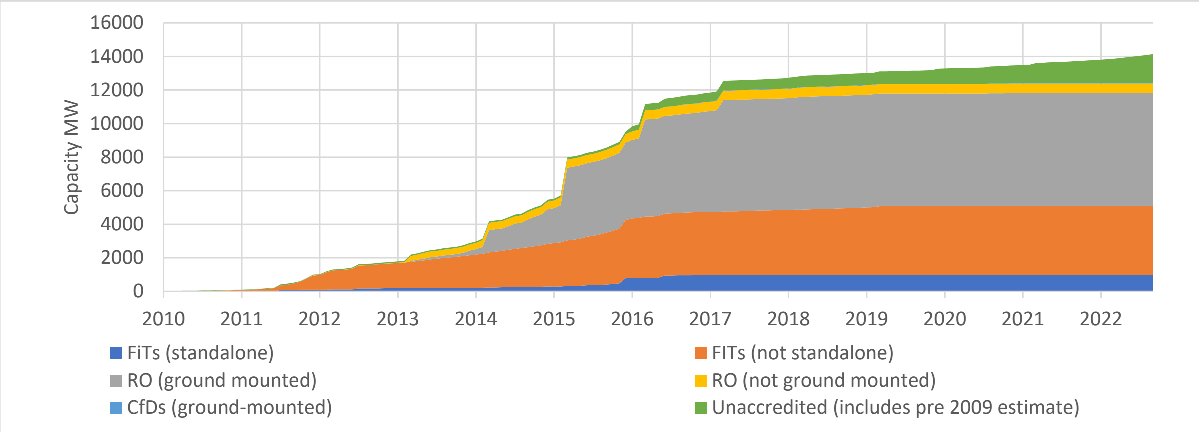
Figure 17 : UK Solar PV development by installation size



Source: https://www.gov.uk/government/statistics/solar-photovoltaics-deployment

Accompanying the larger installation size, is the trend for more ground mounting of systems (mainly solar farms) as shown in Figure 18.

Figure 18 : UK Solar PV development by accreditation and mounting



Source: https://www.gov.uk/government/statistics/solar-photovoltaics-deployment

The time taken to develop solar installation varies. For domestic installation, development time is less than a year. For large rooftop or car park installations, Beba suggest it takes about a year from conception to operation[25]. For solar farms, the duration may be longer and more variable because of planning issues. These periods may be constrained by obtaining grid connection.

Solar Power Portal[26] report strong activity in solar installation, *'the main reason for the new impetus in the commercial rooftop space is coming from environmental and sustainability targets set by corporates (aided by securitisation of energy supply)'* such that *'The commercial rooftop market in the UK is undergoing explosive growth, up more than 135% during the first half of 2022.'* Solar Power Portal says: *'for 2022 …we are now working off 800MW rooftop and 500MW on the ground.' And 'At this point, we are forecasting residential deployment in 2022 to reach about 400MW.'*

3.8 Conclusions and future development

This assessment has focused on urban PV which is constrained by available areas but has relatively little environmental impact. The estimate of the urban technical potential of solar PV In England is 117 GW. Currently in England there is about 13.7 GW of operational PV comprising 4.3 GW on dwelling roofs, 11 GW on nondomestic roofs, and large systems in the REPD (October 2022) totalling 7.5 GW operational and 0.7 GW under construction, which latter is assumed is built. This gives a total existing capacity of 13.7 GW. Given a maximum NZES target capacity for England of 83 GW, an additional 69.3 GW (83 – 13.7 GW) is required.

We may accumulate future 111 GW total additional remaining potential urban PV capacity in segments approximately ordered by increasing cost (£/kW) but note that the data do not allow an exact allocation of existing PV to the different categories. Some of the urban PV, such as that in car parks or on large non-domestic roofs, will be comparable in cost to solar farms. In general, as well as requiring less financing,

[25] https://www.beba-energy.co.uk/solar-panel-installation-timescale/

[26] https://www.solarpowerportal.co.uk/blogs/uk_installs_556mw_of_new_solar_capacity_in_first_six_months_of_2022

the lower cost PV systems require less labour per capacity installed, but larger ground mounted rural or urban systems may engender longer planning lead times.

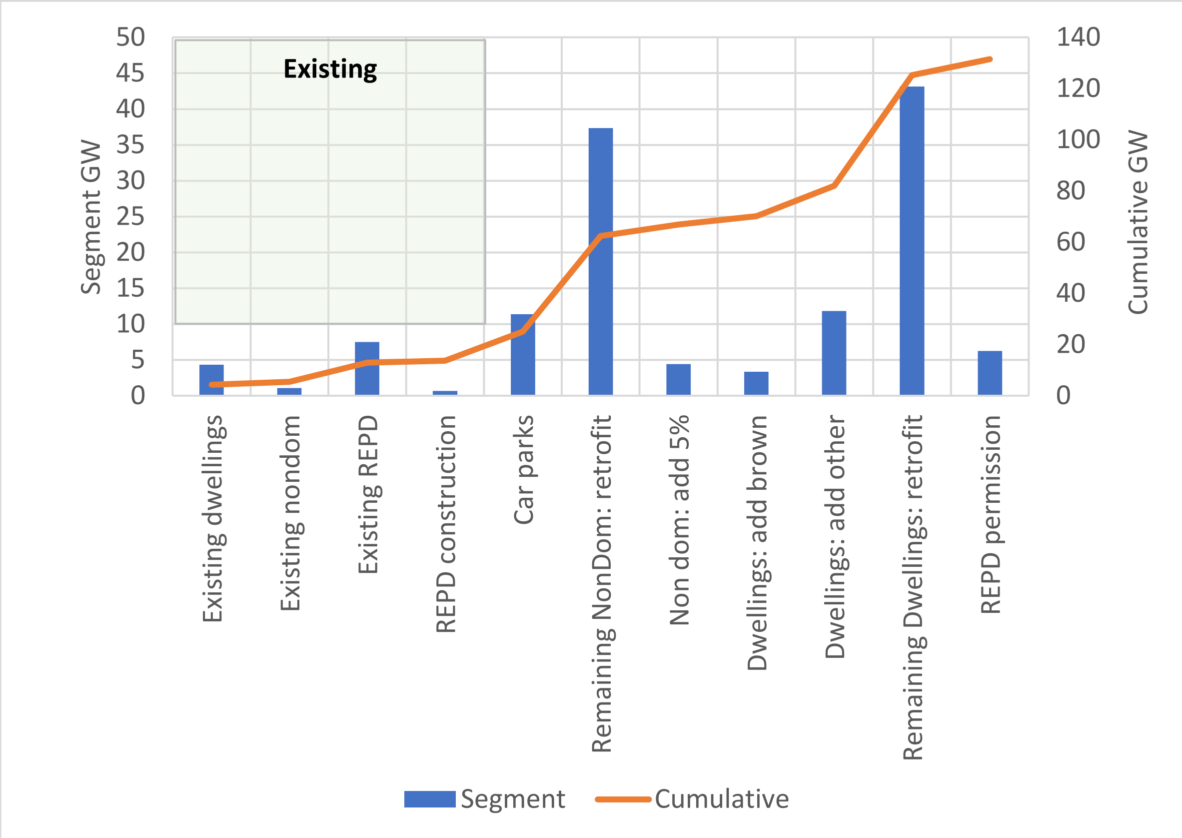
The remaining urban potential increases the cumulative total from 13.7 GW to a total 125.2 GW which is 42.2 GW more than the 83 GW required. If it is assumed that the 6.3 GW of REPD plant with permission is built, then the potential retrofit and new urban surplus is 48.5 GW. About 20 GW of the additional urban potential is on new dwellings and nondomestic buildings for which the rate of expansion depends on new build rates, so the retrofit urban potential surplus, which is not limited by new build rates, is 22.2 GW (42.2 – 20 GW). These data are set out in Table 14 and charted in Figure 19. Italicised entries are for projected new buildings which are uncertain.

Table 14 : Current and future potential solar PV

		GW Segment	GW Cumulative
Existing	Existing dwellings	4.3	4.3
	Existing nondom	1.1	5.4
	Existing REPD	7.5	13.0
	REPD construction	0.7	13.7
Future potential	Car parks	11.4	25.1
	Remaining NonDom: retrofit	37.3	62.4
	Non dom: add 5%	*4.4*	*66.8*
	Dwellings: add brown	*3.3*	*70.1*
	Dwellings: add other	*11.9*	*82.0*
	Remaining Dwellings: retrofit	43.2	125.2
	REPD permission	6.3	131.4

Source: Author's summary

Figure 19 : Current and future potential solar PV



Source: Author's summary

This assessment of solar PV is of technical potential with a discussion of unit costs for different rooftop and ground mounted systems. Further analysis would be needed to construct swift, robust and balanced development pathways for solar PV capacity in different urban and rural situations. This would account for retrofit and new PV system installation costs for different sizes and mounting, and for ancillary costs such as transmission. The environmental impacts of systems in different locations need detailing. The pace at which capacity could be accelerated to minimise cumulative emissions on the path to net zero would require appraisal of the supply chain capacity in terms of labour and the regulatory and financial mechanisms that might be applied. Regulation requiring PV on new buildings would be effective, but its pace is limited by new build rates. The Future Homes Standard and Part L may accelerate the application of PV[27]. The integration of PV into the wider energy system has not been addressed here. The capacity factor - the average output divided by the peak output - of PV is about 11%, whereas onshore wind is about 30% and offshore about 50% so they respectively generate three times and five times as much energy per year per GW installed compared to PV. Furthermore, solar's peak output is in the summer at noon whereas high demand is currently in the winter and the evenings. These features of solar energy mean it may require more storage and back-up generation along with their associated costs, as compared to wind, particularly offshore.

27 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/956094/Government_response_to_Future_Homes_Standard_consultation.pdf

4. BIOMASS

4.1 Introduction

Biomass is used for food, materials and energy. It is perhaps the most difficult primary energy source to assess because of the complexity of the biological, physical and chemical properties of different biomass types; and this is coupled with the variety of land types and local weather and water availability, the many environmental impacts, and the many agricultural inputs and processes to grow and use biomass.

The only common feature of biomass is that it is produced by plants. These plants range from grass to trees, with products ranging across solids, liquids and gases, and waste ranging from sewage to paper. It is varied in terms of plant types, physical and chemical composition, requirements for inputs, transport, processing, and use. Biomass is part of a complex ecosystem of flora and fauna. Essentially the land taken, the commercial plants grown, the agricultural inputs and the biomass extracted from agricultural or natural systems negatively impact as compared to natural ecosystems. The NZES have about 100 TWh of UK waste and 150 TWh of UK crops and imports which at an average 12 GJ/t results in about 30 Mt of waste and 45 Mt of crops and imports. Thus about 75 Mt of biomass would be removed from the land in the UK or other countries, transported, processed and used. For comparison, the current UK cereal harvest is 23 Mt from Table 7.1 of DEFRA agricultural statistics (DEFRA, 2022) and the total food crop output carried by road is 56 Mt (Table RFS0104, Department for Transport, 2023). This extraction of biomass from ecosystems means they will not attain a ‘natural’ equilibrium, but it may be that biomass for energy can reduce some of the ecological impacts of current agricultural and land use practices.

Biomass impacts will vary widely with many factors. The proposal is, of course, that the energy and emission benefits of biomass outweigh these impacts. It is not possible here to detail and assess its many attributes because of study scope and the authors’ expertise, but comments are made on some aspects. These are some of the questions that can be posed concerning UK or foreign originated biomass production and use.

i. What land types are needed for biomass, and what ecosystems or food production is it displacing?
ii. What are the risks and benefits of genetically modified biomass?
iii. What direct or indirect energy inputs are required for biomass planting, tending, harvesting, transporting and processing; and for agrochemicals etc.?
iv. What other inputs are needed such as fertilizers, pesticides, herbicides, water?
v. What impact does biomass production have on carbon flows in standing and soil biomass, and emissions? If biomass is extracted from perennials (trees), how quickly is it replaced with new growth?
vi. What greenhouse gases does biomass production, processing and use emit, including nitrous oxide and methane?
vii. What air pollutants does biomass production, processing and use emit, such as particulates and nitrogen oxides?

viii. What is the level and variability of biomass productivity, and how will these be altered by climate change, agricultural practice, and plant breeding and selection?
ix. What are the social and economic impacts of biomass, both negative in terms of food prices, visual amenity, wildlife degradation, land access, etc., and positive in terms of rural income and employment?
x. How will UK and international biomass demands and supplies evolve?
xi. How will the national/international price of biomass change in the future?

Wu *et al.* (2018) survey impacts, saying '*Although we recognize that the bioenergy production can indeed exert negative effects on the environment in terms of water quantity and quality, greenhouse gas emissions, biodiversity and soil organic carbon, and soil erosion, the adverse impacts varied greatly depending on biomass types, land locations, and management practices.*'

The net effect of biomass on global warming through land use change and greenhouse gas absorption and emission is complex. Plant growth removes atmospheric CO_2 and stores the carbon in biomass. The net changes to atmospheric CO_2 depend on the temporal profiles of biomass carbon oxidation, sequestration or regrowth; thus the net global warming has to be accounted for over some time horizon. For example, using wood from an existing forest will immediately add to atmospheric CO_2 and this will only be balanced assuming a profile for the future growth in forest carbon. Dead biomass might add to carbon sequestration in the soil which would not occur if the biomass were removed. Biomass can emit greenhouse gases such as nitrous oxide and methane during certain production, processing, storage and use processes. The use of fossil fuels for agrochemicals or the production, transport and processing of biomass will cause GHG emissions. The global warming from biomass due to these processes will change in the future because of decarbonisation (e.g., of transport), marginal land use, climate change and so forth. Thus, there is a complex interplay of many factors affecting biomass global warming over different time horizons. These issues are discussed by authors including Jeswani *et al*. (2020) and Sterman *et al*. (2018).

Care has to be taken to control air pollutants such as particulates and nitrogen oxides when using biomass. This is reviewed by the Air Quality Expert Group (AQEG, 2017). The emissions from Drax are summarised in 4.3.6.

4.2 Biomass uses and production

The importance of biomass energy is manifold: it contains reduced carbon which can be used for negative emissions and to produce hydrocarbon fuels such as for aviation; and it is stored energy unlike wind and solar. However, biomass energy production per area of land used is low compared to solar and wind, though some biomass, such as straw from wheat, is a by-product of food or other production.

Biomass can be processed and used for many purposes (apart from food):

- direct combustion for heat and power
- anaerobic digestion (for methane-rich gas)
- fermentation (of sugars for alcohols)
- oil extraction (for biodiesel)

- pyrolysis (for biochar, gas and oils)
- gasification (for carbon monoxide and hydrogen-rich syngas) to synthesise hydrocarbons
- to produce negative carbon emissions by sequestering biocarbon in the ground or other storage
- to produce materials for use in buildings, industry, etc.

Biomass can require a range of inputs and ancillary processes (e.g. fertilising, watering, drying, transport, stabilization, dewatering, upgrading, refining). The low productivity per area of biomass means that there is a complex balance between the costs and impacts of collecting and transporting biomass to a use or processing plant, and the size and scale economies of the plant. In general, the land use of biomass processing and utilising facilities will be small compared to crop areas, though there will be some visual amenity impact.

Biomass utilises solar energy via photosynthesis converting carbon dioxide and water into carbohydrates and other biochemicals, part of which the plant metabolism uses and part of which is stored in the plant which may be harvested. Biomass productivity varies widely with the season, the climate, the type of plant (e.g. deciduous, evergreen), the quality of the soil, and water and fertiliser inputs, and so on. The solar energy available may be taken as London's 830 kWh/m^2 per year for England but, with leaves oriented variously, plants intercept different fractions of this. The basic photosynthesis process has a theoretical efficiency of 11%, but overall it is much less than this because of various factors such as ground cover, reflection and self use. In practice, biomass has an overall efficiency to a harvestable resource of 0.1% to 1%, so plants have a harvested biomass yield of 8-80 kWh/m^2/a of stored biomass energy. In general, the production of stored energy in some types of plant matter (e.g., grass) is higher efficiency than producing high energy value constituents such as seeds which can be processed relatively efficiently into liquid biofuels. Thus, the basic plant efficiency and the downstream processing efficiencies need to be accounted for: for example, *Miscanthus* grass is highly efficient at producing gross energy but is not efficiently converted into transport biofuels, whereas maize produces less gross energy but is more efficiently converted into biofuels such as biodiesel. Compared to solar PV, biomass has the advantage that it produces stored carbon-based energy, but PV produces 10 or 20 times more energy (high grade electricity) per unit area.

4.3 Scenarios

4.3.1 Current status

Biomass supply comprises waste and biocrops. Table 15 shows the 2021 UK production, imports and consumption of biomass.

Waste biomass includes animal biomass (poultry litter, meat, bone), sewage gas, landfill gas, waste wood, part of municipal waste (e.g. paper) and by-products such as straw arising from wheat production. Some waste biomass will be used without processing (e.g. straw in boilers) and some as input to processes such as drying or anaerobic digestion. In addition, there are non-renewable waste streams containing energy and carbon; these include industrial waste, hospital waste and the non-biodegradable part of municipal solid waste and tyres. These wastes in general have a lower intensity of energy produced per unit area than biocrops and are transported over short distances to small facilities. Some wastes have physical and chemical constitutions which make it difficult to process them efficiently into high grade fuels such as kerosene, an exception to this is methane in sewage and landfill gas but even then the collection facilities are small. Currently UK produced renewable biowaste accounts for about 40% (53 TWh) of bioenergy production, with an additional 22 TWh of non-renewable waste, for a total 75 TWh. The future availability of waste biomass and non-renewable waste for energy depends on many factors such as diet and food demands and UK production, and waste reduction and recycling. It is notable that the BEIS and FES NZES assume 90-100 TWh of waste. In the NZES 48 TWh of plant biomass is imported – about 25% of biomass demand, the bulk of which is wood chips used by the Drax power station; a commentary on Drax is given in 4.3.6.

Table 15 : Biomass and waste production, imports, and demand - 2021

ktoe	Production	Imports	Demand
Animal biomass	242	0	242
Sewage gas	374	0	320
Landfill gas	805	0	805
Renewable waste	1773	0	1773
Anaerobic digestion	1391	0	887
Waste wood	232	120	307
Wood	889	35	920
Plant biomass	3413	4076	7488
Non-renewable waste	1849	0	1849
UK Waste	**4585**	**0**	**3140**
UK Total	**10969**	**4231**	**14592**

Source: DUKES 2021 Table 6.1

Excluding forestry, 961 km² of agricultural land was used for biocrops in 2019. The area is dominated by anaerobic digestion from maize (69%) and wheat bioethanol (11%). This is shown in Table 16.

Table 16 : Biocrop area 2019

Region	Crop	km2
UK	Wheat: bioethanol	107
UK	Barley: bioethanol	0
UK	Oil seed rape: biodiesel	0
UK	Sugar beet: bioethanol	84
England	Maize: anaerobic digestion	666
England	Coppice	22
England	Miscanthus	82
	TOTAL	**961**

Source: (DEFRA, 2019)

Figure 20 shows biomass facilities that produce electricity, most of which are small. This excludes biomass production and non-electricity facilities such as anaerobic digesters. The largest electrical facility by far is the Drax power station which is described in 4.3.6.

Figure 20 : Bioenergy electricity capacity (MW)

Source: REPD – Operational, under construction, planning permission granted

4.3.2 Production

Scenarios generally give assumptions about the future production and use of biowastes and biocrops in terms of primary energy though, in some cases, land areas are given. Where areas are not given, some estimates may be made about the land requirements by using assumed biomass productivity (GWh/km^2) but, as has been noted, a wide range of efficiencies applies. It is beyond the scope of this research to suggest an optimal mix of biocrops and land types or indeed an optimal share of bioenergy in primary energy.

Table 17 summarises some types of biomass, their physical characteristics and the productivity in energy per unit area (GJ/ha) where energy is measured as gross calorific value (GCV) or net calorific value (NCV). Where given, the efficiency is the percentage of incident solar energy converted to harvested biomass energy. There is a wide range of values due to variation in plant types, land type, moisture content and so on, and a coherent and comprehensive database of biomass types and UK productivities could not be found.

Table 17 does not include grass. As shown in 1.1, Defra (2022) give statistics that 46% of agricultural land is permanent and temporary grassland. This grassland is used for purposes including grazing, haymaking, flood control, and for wildlife. It might also be used for bioenergy. French (2019) has assessed the bioenergy potential of grassland biomass from conservation areas in England, and *says 'Grasslands managed for conservation yielded up to 160% more biogas per ton dry matter than cereals or crop waste and only slightly less than Miscanthus.'* Qi, Holland *et al*. (2018) also assess bioenergy from grassland including the balance between productivity and ecosystem services. The use of grassland for biomass might compete with its use for animal feed. This raises the wider issue of how changed diet might impact on land use requirement as considered by Smith *et al.* (2020).

Table 17 : Biomass characteristics and productivity

		Attributes				Productivity		
Biomass source	Biomass type	NCV MJ/kg	GCV MJ/kg	Carbon %mass	Eff -icency	Energy GJ/ha	GWh/km2	Land km2/TWh
Biomass	Biomass	19.0		47%				
Biomass	Wood (average)	15.6	16.3	52%		37		
Waste	Forestry residues	13.0				37		
Waste	Wheat straw	13.5	15.8			47		
Waste	Litter	7.6	12.8					
Waste	Municipal waste	6.8	10.0					
Waste	Tyres	30.4	32					
Waste from pulp	Blackliquor	11.8						
Waste	Landfill gas	50.4						
Waste	Sludge gas	50.4						
Primary	Hardwood	19.0						
Primary	Softwood	19.2						
Primary	SRC Willow	18.4			0.56%	167	4.6	216
Primary	Poplar		17.3		0.58%	216	4.8	208
Primary	Miscanthus	13.0			0.75%	225	6.3	160
Primary	Switchgrass		17.4		0.47%	139	3.9	259
Primary	Wheat		12.3		0.41%		3.4	293
Fuels	Wood chips (30% MC)	12.5						
Fuels	Wood (solid – oven dry)	19.0						
Fuels	Wood pellets (10% MC	17.0						
Fuels	Other biogas	50.4						
Fuels	Charcoal	29.5						
Fuels (from rapeseed oil)	Biodiesel	37.0			0.14%	41	1.1	878
Fuels (from sugar beet)	Bioethanol	27.0	29.7		0.40%	119	3.3	303
Fuels (from wheat)	Bioethanol	27.0	29.7		0.21%	62	1.7	581
Fuels (from cattle slurry)	Biogas @60% CH4	30.0			0.09%	26	0.7	1385
Fuels (from sugar beet)	Biogas @60% CH4	30.0			0.53%	159	4.4	226
Fuels	Bio gasoline	27.0						
Fuels	Biodiesels	37.0	38.7					
Fuels	Other liquid biofuels	27.4						

Main sources: (McKendry, 2002),(Forest Research, 2022), (BEIS, 2021c), (DEFRA, 2021a), authors' estimates

Table 18 gives data on biomass composition from McKendry (2002). Here the carbon (C) content is important as it determines the CO_2 equivalent per mass of biomass which may be used to estimate the potential for carbon sequestration with biomass.

Table 18 : Biomass composition

	Elements %wt			
Biomass	C	H	O	N
Cypress	55.00	6.5	38.1	
Ash	49.7	6.9	43.0	
Beech	51.6	6.3	41.4	
Wood (average)	51.6	6.3	41.5	0.0
Miscanthus	48.1	5.4	42.2	0.5
Wheat straw	48.5	5.5	39.9	0.3
Barley straw	45.7	6.1	38.3	0.4
Rice straw	41.4	5.0	39.9	0.7

Source: (McKendry, 2002)

4.3.3 Future productivity

Climate change will affect the productivity of biomass, both for food and for energy. Higher, but not excessive, UK temperatures and CO_2 atmospheric concentration will increase productivity. Countering that, extreme heat waves, changed precipitation patterns causing drought or flooding, high winds, sea level rise, and worse or new pests and crop diseases will reduce productivity. These factors will impact differently according to the crop type and land type, and location in the UK. Production may vary significantly from year to year. Plainly these factors will apply to foreign biomass production and the availability for UK import. If food productivity were to fall this would exacerbate the competition for land for bioenergy.

Improved agricultural practices and crop types and genetics may improve yields. For example, Thomson *et al.* (2020) consider a large increase in productivity: *'Innovative agronomy and improved plant breeding including genetic modification (GM) increases the yield of SRC* (short rotation coppice) *and Miscanthus from 12 t/ha to between 15 - 20 t/ha oven-dry material by 2050'.*

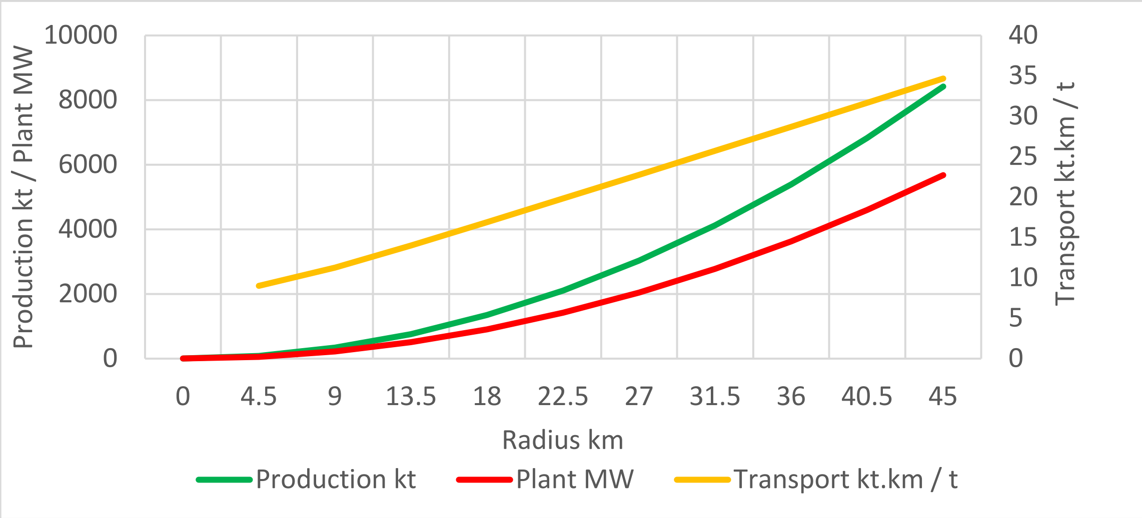
There is a range of assessments as to the possible effects of climate change on productivity, some suggesting productivity will increase, others the opposite. Poudel *et al.* (2011) made an assessment for forestry in Sweden: *'Our results show that an average regional temperature rise of 4 °C over the next 100 years may increase annual forest production by 33%.'* NERC (2016) say '*Changes in the UK's climate will, in the long term, have significant positive and negative impacts on agricultural and forestry production.';* and DEFRA (2021b) say '*Climate change and emissions pose significant risks to production and food security'.* Xu *et al.* (2022) say *'However, the detrimental effects of climate change on crop yields may reduce the capacity of BECCS and threaten food security'*. Beillouin *et al.* (2020) analyse the impact of extreme weather conditions on European crop production in 2018 and note *'Extreme weather increases the risk of large-scale crop failure.'*

This uncertainty in future productivity brings into question the reliability of biomass as an energy resource, whether from indigenous production or import.

4.3.4 Biomass transport

Biomass needs to be transported to a location where the biomass is processed to produce heat, electricity, biofuels, etc. and as noted above, the total NZES biomass might amount to 75 Mt. The larger the biomass catchment area for the processing facility, the greater the capacity (MW) of the facility and scale economies are better realised. However, the greater the catchment area, the greater the biomass transport demand in tonne kilometres (t.km) per tonne of biomass produced, and this transport demand increases faster than the area. The evolution of these factors assuming a circular catchment area of *Miscanthus* production with a productivity of 225 GJ/ha and an energy content of 17 GJ/t is shown in Figure 21. For a circle of radius 10 km, production is 400 kt and 2800 kt.km of transport is required and the plant size is 280 MW; for a radius 5 km, production is 100 kt, transport is 350 kt.km and plant size 70 MW. The transport per tonne (kt.km/t) is twice as high for the 10 km radius catchment as the 5 km. In addition will be transport required for agricultural inputs and residues. This transport demand requires energy and will have impacts in terms of air pollution, noise and traffic. *Miscanthus* is one of the highest yield crops in terms of mass and energy so transport per energy harvested will be less in mass than for wood, but its density is lower.

Figure 21 : Biomass production and transport



Source: Author's calculations

4.3.5 Bioenergy with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) is a negative emission process whereby biomass is used to produce useful energy (heat, electricity, biofuels, etc.) and a fraction of the waste CO_2 or carbon char is sequestered for long term storage. BECCS is described by a number of authors (Ricardo Energy & Environment, 2017; Fajardy and Mac Dowell, 2018; Daggash, Fajardy *et al.*, 2019). However, the processes to separate the CO_2 from the exhaust stream, process it and transport it to a sequestration site reduce the net useful energy output obtained from the biomass and therefore the amount of fossil fuel it can displace. Donnison *et al.* (2020) report an estimated Drax BECCS efficiency and therefore output loss of 24%. Collas and Benton (2023) estimate that BECCS can sequester 27-33 $MtCO_2$ using UK sourced waste. The diffuse and varied nature of UK waste sources may make it technically and economically problematic to capture CO_2 from some of these sources and transport it to sequestration sites.

This simple assessment assumes biocrops are grown on additional land area for BECCS, rather than the use of waste or imported biomass. The productivity of *Miscanthus* ranges 12-15 oven dried tonnes (odt) per hectare and short rotation coppicing (SRC) has a range of 8-15 odt/ha or 800-1500 odt/km^2 (Defra June Survey of Agriculture and Horticulture[28]). Assuming the carbon content of the biomass is 50% by weight, then the carbon productivity is 400-750 tC/km^2, equivalent to 1500-2800 tCO_2/km^2 if the biomass is burned in a power station producing electricity and possibly heat, and 80% of the flue CO2 is captured and sequestered, BECCS provides 1200-2200 tCO_2/km^2 negative emissions, or 450-830 $km^2/MtCO_2$. This ignores any GHG emissions incurred during biomass production, transport and processing.

[28] Section 2: Plant biomass: miscanthus, short rotation coppice and straw - GOV.UK (www.gov.uk)

4.3.6 Drax power station

The Drax power station was converted from coal to become the largest biomass generator in the UK and the world[29]. Drax serves as an example of some of the complex issues concerning energy from biomass. Concerns about Drax include the sourcing and carbon content of the biomass and therefore its non-renewable emissions incurred by changes to current and future standing biomass carbon; and also other impacts including air pollution.

Drax (or its equivalent) may be a key facility for the NZES in its possible multiple roles of zero emission generation and negative emission and energy storage. The scope of this report is UK located energy demand and supply only but of course environmental impacts outside the UK should be considered. If biomass imports are too high emission or too costly, then Drax biomass supply might be reduced or switched to UK sources.

Drax is located in the countryside with little local energy demand so that a small fraction of its heat output could be used in efficient district heating. Garcia-Freites *et al*. (2021) appraise the role of BECCS and comment that medium-scale biomass CHP has a higher efficiency than electricity only plant. Drax's chimney and biomass domes are large and its cooling towers are 114 m high and emit condensed water vapour, so Drax has a substantial visual impact as may be seen Figure 22 (Drax, 2023).

Figure 22 : Drax power station

Source: Google Earth

[29] https://www.drax.com/about-us/our-sites-and-businesses/drax-power-station/

The wood pellet supply system to Drax power station includes 320 kt (1.6 TWh) of pellet storage at the power station (DraxBiomass, 2020b) and 200 kt (1.0 TWh) at the Immingham dock (DraxBiomass, 2020a), to give a total 2.5 TWh of storage. This can provide about 1 TWh of electricity which can be used when variable wind and solar generation is low; however, the large size of Drax's generators limits its flexibility in output over short time periods so its role will be constrained.

Table 19 below summarises some data for Drax. The data shown in italics are approximate and vary year to year. The station has a capacity of 3,906 MW, of which 2595 MW uses wood pellets, and coal may be used in the remainder though this is being phased out. Drax generates about 14 TWh of electricity per year from around 8 Mt of wood pellets which are made from about 16 Mt of green wood. We see that amongst Drax emissions are nitrous oxide and other air pollutants.

According to Biofuelwatch (2022):*'During 2021, Drax power station in Yorkshire burned 8.3 million tonnes of pellets…60% of the pellets burned by Drax that year were imported from the Southeastern US, 22% from Canada and 11% from the Baltic States. The remainder came mostly from Brazil, Portugal and Belarus. No UK wood was burned.'*

There is fierce debate about the degree to which these pellets are carbon neutral. It is certain that some emissions are incurred because of fossil fuels used during harvesting, transport and processing. What is more problematic is estimating the effect of the wood supply on the carbon flows, greenhouse gas emissions and stocks in the forests or other biomass sources over different time periods. For example, Brack *et al.* (2021) assess these issues and remark *'A fundamental reason why biomass is treated by policy frameworks as zero-carbon at the point of combustion is because emissions from biomass consumption for energy are reported not in the energy sector of national reports under the UN Framework Convention on Climate Change (UNFCCC), but rather in the land-use sector of the country in which the biomass is harvested (in order to avoid double-counting).'* They also say: *'The UK's adoption of a ceiling on feedstock supply chain emissions of 29 kg CO_2eq/MWh is welcome in limiting the types of feedstock that can be used.'*

Table 19 : Drax power station data

	Item	Units	
Electricity	Biomass capacity	MW	*2595*
	Generation	TWh	*14*
	Capacity factor	%	*62%*
	Efficiency	%	*42%*
Biomass	Pellets	Mt	*8*
	Green wood equivalent	Mt	*16*
	Pellets	GJ/t	*15*
		PJ	*120*
		TWh	*33*
Emissions 2021			
Greenhouse gas	Carbon dioxide (CO2)	kt	14800
	Carbon dioxide (CO2) excluding biomass	kt	507
	Carbon dioxide biomass	kt	14293
	Nitrous oxide (N2O)	kt	0.2
Air pollution	Nitrogen oxides (NOx/NO2)	kt	8.0
	Particulate matter (PM10)	kt	0.4
	Sulphur oxides (SOx/SO2)	kt	1.5
	Carbon monoxide (CO)	kt	13.2

Sources: Emission 2021 https://www.gov.uk/guidance/uk-pollutant-release-and-transfer-register-prtr-data-sets

The 29 kg CO_2eq/MWh feedstock limit (BEIS, 2019), other concerns about Drax biomass supply chain and import costs may mean that Drax's current biomass supply chain becomes unviable. Dwivedi *et al.* (2019) developed the Forest Bioenergy Carbon Accounting Model to model carbon flows in wood pellet supply and conclude; *'the total (biogenic and direct life-cycle) carbon intensity of wood pellets per unit energy at the time of harvesting is 307.02 g C/kWh, of which 80.2% is biogenic carbon emission, and the rest is life-cycle carbon emission.'* This is much greater than the 29 kgCO_{2e}/MWh feedstock limit. There have been complaints[30] about *'misleading or inaccurate statements about their business' carbon emissions, and the environmental impact of their business activities'* about Drax to the national contact point (NCP); with the NCP saying, *'The UK NCP has decided that five paragraphs under two chapters cited in the complaint merit further consideration.'* All this underlines the great uncertainties about biomass.

The possibility is being explored to use Drax for BECCS (Drax, 2021; Harris, 2021), with one option where biomass is gasified and flue gas CO_2 is captured and either sequestered or used to make fuels. If Drax were used for BECCS then its efficiency would fall significantly so requiring more biomass per unit of electrical output and providing less energy to displace fossil fuels. We can estimate the implications of switching Drax fuelling to domestic production. If it is assumed that UK short rotation coppice (SRC) willow produces 10 t of dry wood per hectare per annum, and losses and energy overheads for harvesting, transport and pellet processing are negligible,

[30] Initial Assessment: Group of NGOs complaint to the UK NCP about Drax Group PLC - GOV.UK (www.gov.uk)

then 8 Mt of wood supply to Drax would require 8000 km^2 of land, about 3% of UK land area.

Using the simple assessment procedure above, 8 Mt of wood supply requires transport of the order of 300 Mt.km with the transport per energy (t.km/GWh) higher than for a number of smaller facilities. The transport would have an attendant energy consumption and environmental impact – Drax fuel is currently imported and moved from port to Drax by rail and so has relatively little impact in the UK but this would not apply if the biomass were of UK origin. Biomass transport in other countries and import by ship or rail is not discussed here.

4.3.7 Biomass scenarios

Table 20 summarises the biomass and waste assumptions in the National Grid and BEIS scenarios, with some estimation in italics. The assumed waste biomass energy is similar across scenarios, but BEIS assume more UK production than imports, whereas National Grid assume the opposite. Between 10-54% of biomass is used for BECCS in the scenarios.

Table 20 : Biomass scenarios

			National Grid (2022) Future Energy Scenarios			BEIS (2021) Net Zero Strategy (NZS)		
			Consumer Transformation	**System Transformation**	**Leading the Way**	**High electrification**	**High resource**	**High innovation**
Waste	Forest residues	TWh	47	47	45			
	Agri residues	TWh	14	14	9			
	Waste wood	TWh	16	16	16			
	Waste biodiesel, bioethanol	TWh	0	0	0			
	MSW, C&I (biogenic)	TWh	27	27	28			
	Landfill gas	TWh	0	0	0			
Imports	Biomass imports	TWh	102	106	0	62	62	46
	Biofuel imports	TWh	5	5	6			
Production	Energy crops	TWh	35	35	65	58	62	58
	Biogas	TWh	5	1	7			
Summary	Waste	TWh	104	104	99			
	Imports	TWh	106	111	6	62	62	46
	Production	**TWh**	40	36	72	58	62	58
	Other biomass	TWh				124	124	124
	Total	**TWh**	**250**	**251**	**177**	**244**	**248**	**228**
BECCS	BECCS	MtCO2e	61	53	29	*55*	*55*	*55*
	BECCS biomass	TWh	*37*	*32*	*18*	*131*	*133*	*57*
	BECCS and H2	TWh				72	74	
	BECCS and power	TWh				59	59	57
	BECCS % biomass		15%	13%	10%	54%	54%	25%
	Assuming England 90% of UK biomass							
	Production area (England)	**km2**	6269	6269	11762	10440	11160	10440
	% England area		5%	5%	9%	8%	9%	8%

Average *Miscanthus*/SRC productivity is 180 GJ/ha, 5 GWh/km^2 or inversely 200 km^2/TWh. Assuming *Miscanthus* is 13 GJ/t and 50% carbon then its energy carbon ratio is 6.5 GJ/tC, 1806 kWh/tC or 492 kWh/tCO_2. If it is assumed that 80% of the CO_2 is captured then the energy requirement is 0.6 TWh/MtCO_2 or in terms of area 123 km^2/MtCO_2.

To estimate England biocrops area, it is assumed that 90% of the biomass is produced in England. Altogether, biomass production (i.e. not waste or imported) takes 5-9% of England's total area, though a higher fraction of agricultural land which is about 63% of the total area as shown in 1.1.

The use of biomass for BECCS is separately estimated assuming 0.49 TWh of biomass is used to sequester 1 MtCO_2, but no assumption is made whether this uses waste, UK or imported biomass.

4.4 Hydrocarbon synthesis

Some energy and products will require carbon-based materials for the foreseeable future. The largest hydrocarbon demand with no near-term substitute is for aviation kerosene, and this is perhaps the hardest energy problem to solve. Net zero carbon fuels require a renewable source, or negative emissions to balance carbon emissions. Kerosene can be synthesised from biomass supplemented with renewably generated hydrogen, using Fischer-Tropsch and other processes. Current aviation fuel demand is about 15 Mt[31] containing 13 Mt of carbon. It is unlikely that all wastes would be used for hydrocarbon fuel production (or indeed CCS) because of their physical and chemical characteristics and diffuse geographical distribution. If all the UK waste biomass and non-renewable carbon (~10 Mt) and energy (~263 PJ) were used for aviation, a maximum 76% of current aviation kerosene could be produced but, taking into account biomass suitability and Fischer-Tropsch product mix, perhaps 24% is practicable using the simple estimation as set out in Table 21.

Beyond wastes, additional carbon and energy is required for net zero kerosene. This carbon might come from biocrops or imported biomass. Assuming *Miscanthus* produces 8 tC/ha p.a. then a minimum of about 1200 km2 or 5% of the UK land area would be required to provide carbon for 75% of kerosene demand. However, The Royal Society (The Royal Society, 2023) estimated that 68% of the total agricultural land in the UK would be required to produce 12.3 Mt of aviation fuel from biomass.

Alternatively direct air capture (DAC) could supply carbon, and electrolytic hydrogen as inputs to Fischer-Tropsch plant producing hydrocarbons, of which a fraction will be kerosene. DAC requires small amounts of low quality land. Fossil kerosene might be used, but for net zero that would have to be balanced with negative emissions from DACCS or biomass: this option might be environmental and economically competitive. In any case, even with zero carbon kerosene, high altitude emissions from aircraft cause global warming which requires negative emissions for balancing.

[31] ONS, Energy use of carbon based fuels by fuel type in the United Kingdom, 1990 to 2020 https://www.ons.gov.uk/economy/environmentalaccounts/datasets/ukenvironmentalaccountsfuelusebytype

Table 21 : Simple estimation of kerosene production from biowastes

	Energy			Mass	Carbon		Max Ker	Suitable		Bio	Ker	
	PJ	TWh	GJ/t	Mt	%	MtC	Mt	%	MtC	PJ	FT prod	Mt
W:Animal biomass	10	3	13	0.8	30%	0.2	0.3	30%	0.1	3	60%	**0.0**
W:Sewage gas	16	4	50	0.3	75%	0.2	0.3	70%	0.2	11	60%	**0.1**
W:Landfill gas	34	9	50	0.7	75%	0.5	0.6	50%	0.3	17	60%	**0.2**
W:Renewable waste	74	21	10	7.4	50%	3.7	4.4	70%	2.6	52	60%	**1.8**
W:Anaerobic digestion	58	16	14	4.2	75%	3.1	3.7	50%	1.6	29	60%	**1.1**
W:Waste wood	10	3	13	0.8	50%	0.4	0.4	50%	0.2	5	60%	**0.1**
Wood	37	10	13	2.9	50%	1.4	1.7	50%	0.7	19	60%	**0.5**
Plant biomass	143	40	12	11.9	50%	6.0	7.0	50%	3.0	72	60%	**2.1**
Non-renewable waste	78	22	10	7.8	30%	2.3	2.7	30%	0.7	23	60%	**0.5**
UK Waste	**263**	**73**	**150**	**21**	**3**	**10**	**11**	**3**	**5**	**132**	**4**	**4**
					Mt CO2	**36**						
UK Total	**461**	**128**		**37**		**18**	**21.1**		**9.3**	**231**		**6.5**
					Mt CO2	**66**						
UK Waste: % UK aviation fuel							**76%**		**34%**			**24%**
UK Total: % UK aviation fuel							**141%**		**62%**			**44%**

Source: biowastes DUKES Table 6.1, authors' estimates

4.5 Discussion and conclusions

Overall, biomass can be characterised by complexity and uncertainty in the production and import of biomass, and in the optimum use of biomass for energy, BECCS or biofuels within the overall context of NZES. Biomass is inefficient in terms of its energy production per unit area as compared to wind or solar. Waste biomass uses no extra land, but its varied properties and low geographical density pose technical and economic problems for its utilisation. Unlike wind and solar, biomass does contain carbon which may be use for renewable hydrocarbon production or negative emissions, and biomass constitutes stored energy which may be used to balance variable renewables. The productivity of biomass depends on environmental factors which may alter substantially with climate change. Biomass has impacts on ecosystems through its land cover, species narrowness and agricultural practices including inputs such as fertiliser and water.

The pressure of biomass on land will depend on many factors. Particularly important is the degree to which biomass production will compete with domestic food production, which will be affected, *inter alia*, by the future UK diet and food import policy, and the objective of expanding natural ecosystem cover. For example, Smith *et al*. (2020b) look at the implications for land use of diet: *'Our Sustainable High Ambition Pathway represents a future in which… we assume that this future would lead to much higher rates of tree planting, higher agricultural productivity, a higher protected area of natural habitats, lower rates of urban expansion, lower food waste and lower consumption of meat and dairy produce.'*

It is beyond scope to suggest an optimal pattern of biomass energy production in terms of land classification use and plant types. It is also beyond scope to optimise the balance between biomass and energy produced from atmospheric carbon and hydrogen, nor between negative emissions with BECCS or DACCS, nor the best mix of biomass and other renewable energy and carbon sources. It also needs to be highlighted that UK biomass imports will have impacts in the exporting countries.

5. ONSHORE WIND

Offshore wind is projected to be at a similar or lower cost than onshore wind in the UK in the near future. Constraining onshore wind capacity is therefore unlikely to increase wind costs overall. The offshore resource is very large and floating wind turbines have also now entered into government auctions; offshore capacities up to 140 GW have been explored (ARUP, 2022).

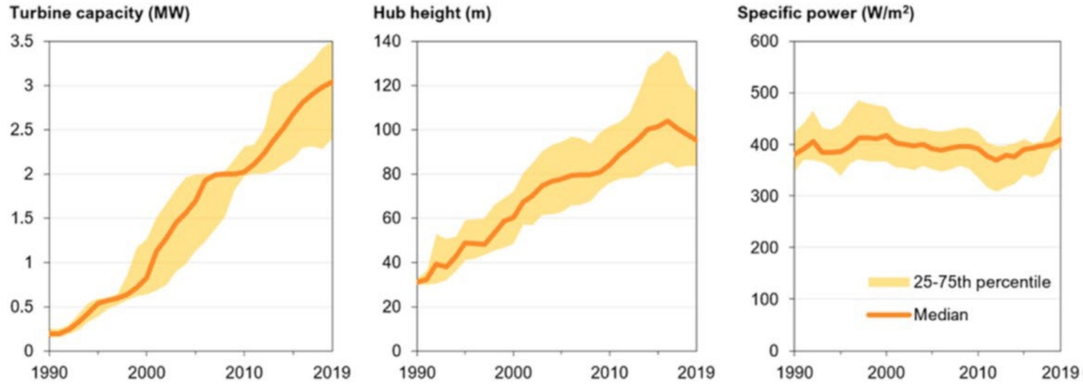
5.1 Onshore wind impacts

Onshore wind can have a range of impacts, including visual, noise, economic and wildlife impacts. A previous CPRE study highlighted concerns through public preference surveys about the impact of onshore wind turbines on people's experience of tranquillity (CPRE, 2005). A comprehensive analysis of these impacts is beyond the scope of this study, but a short discussion is included here along with brief considerations of how they could be addressed. Several references to council planning documents are included as examples of how planning policy can be applied. Likewise, some international studies are included as overseas experience could be relevant to the UK, though it should be noted different ecological or cultural attitudes and regulatory controls can affect this.

5.1.1 Visual impacts

A number of factors affect the visual impact of onshore wind turbines. The size and height of turbines have been steadily growing to improve energy yield and reduce costs (Figure 23), increasing their prominence over the surrounding landscape (though Figure 23 indicates hub height has reduced slightly in recent years), but conversely this can reduce the number of turbines required, and fewer turbines can improve acceptance (Molnarova *et al.*, 2012). Following the shape of the terrain can also be less visually invasive, in preference to straight rows of turbines, and visual effects can be reduced by appropriate siting, design and landscaping (North Somerset Council, 2014).

Figure 23: Changing characteristics of onshore wind turbines



Source: (McKenna, Pfenninger et al., 2022). Reproduced under a Creative Commons Licence.

Turbine blades are moving features of the landscape, in contrast to pylons and other stationary structures (North Somerset Council, 2014), and blade rotation and movement has been identified as a potential distraction for sport and recreation users (North East Lincolnshire Council, 2019). There are also concerns the moving blades can be a distraction to car drivers, though there are now a large number of windfarms located close to road networks without having a noticeable impact on accidents (Aylesbury Vale District Council, 2013).

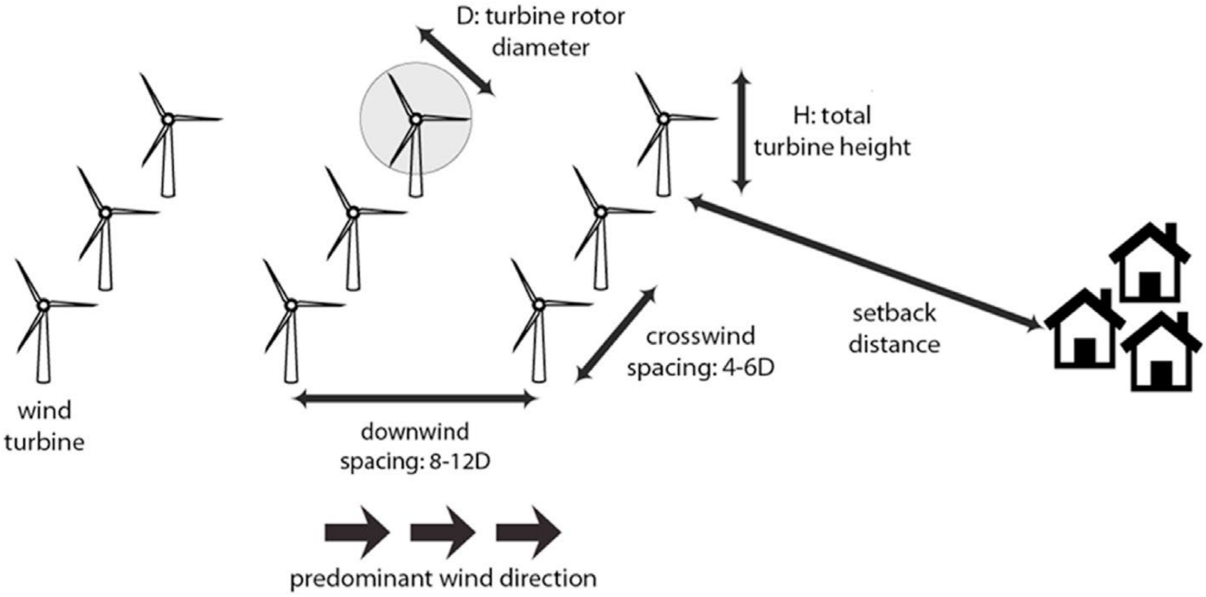
Onshore turbines have flashing red lights to warn aircraft of their presence. These have dark sky impacts, especially in large numbers, and affect night sky perception and its value to rural character and tranquillity.

The physical attributes of the landscape is also important, with more acceptance in unattractive landscapes than scenic ones (Molnarova *et al.*, 2012). One recent attempt to quantify this used crowd-sourced "scenicness" data from the website Scenic-or-Not.com, where users rated geotagged photographs taken at 1 km^2 resolution for the whole of Great Britain on an integer scale of 1 - 10, where 10 indicates "very scenic" and 1 indicates "not scenic", generating 1.5 million ratings for over 200,000 images (McKenna, Mulalic *et al.*, 2022). Although subject to a range of subjective influences such as photograph quality and orientation, weather and scorer demographic, the study nevertheless found a strong correlation between scenicness rating and the likelihood of a windfarm planning application in the area being rejected. However, this did not hold for ground-mounted solar panels, suggesting a much lower impact of PV on landscape aesthetics. A related study found that accounting for scenicness could increase system costs by up to 14.2%, highlighting the need to find mechanisms to reduce visual impact (Price *et al.*, 2022). The need to avoid scenic areas is reflected in regulations restricting onshore wind deployment in National Parks, Areas of Outstanding Natural Beauty *etc.*

5.1.2 Noise impacts

The movement of the turbine blades through the air inevitably creates noise, which can increase with larger turbines (Wang and Wang, 2015; CSE, 2017). These are typically addressed though minimum setback distances (Figure 24) which vary nationally and by settlement type (single houses or groups of houses) and can be defined in terms of noise level (dB), horizontal distance, or multiples of turbine height or rotor diameter. For England these vary with local regulations, and can be 700 m (in some cases 2,000 m) to 10x total height (McKenna, Pfenninger *et al.*, 2022). The quieter design of modern turbines means noise levels can be comparable to outdoor background noise (CSE, 2017). The effects of topography or changing wind patterns at night can be addressed through adequate planning (CSE, 2017). Health effects reported due to noise are likely a result of already being in an annoyed or stressed state (Knopper and Ollson, 2011). Negative perceptions of noise can be reduced by engaging communities in the planning process and giving them direct financial benefit from wind farms (CSE, 2017; Pohl, Gabriel *et al.*, 2018). Likewise concerns about 'infrasound' (inaudible low-frequency noise) are stated to lack empirical evidence (CSE, 2017).

Figure 24: Typical windfarm spacing and setback distances



Source: (McKenna, Pfenninger et al., 2022). Reproduced under a [Creative Commons Licence]

5.1.3 Economic impacts

Concerns about economic impacts can depend on user type; one study in Iceland found that, although both residents and tourists prefer landscapes without power plant infrastructure, residents can be more tolerant to landscape change for economic reasons, but that windfarms can pose a threat to the tourism industry (Sæþórsdóttir and Ólafsdóttir, 2020). A study for the Welsh Government found no evidence of significant impacts on tourism for long-established windfarms, though windfarms have generally been kept away from key visitor areas (Regeneris, 2014). It also found that attitudes could vary by user-type, whether tipping points have been reached, and that more familiarity could increase tolerance. Windfarm location can help, e.g. away from scenic areas and observation points such as settlements, transportation infrastructure and viewpoints (Molnarova *et al.*, 2012).

Attitude to wind power is also important (Molnarova *et al.*, 2012). One study on the Upper Rhine region found that co-ownership of local plants had a positive effect on public acceptance, as did former experiences with renewable energy plants in the local vicinity as actual impacts tend to be overestimated (Schumacher *et al.*, 2019) (though acceptance can vary by technology and does not guarantee that a majority are supportive). Residents may also be more supportive in remote areas where turbines can contribute to energy security.

There are also concerns about the effect of windfarms on property prices. Detailed analyses have shown that prices can drop temporarily in areas close to proposed windfarms due to an "anticipation stigma", but that prices quickly recover once operation commences, and may even outperform regional averages (CSE, 2017).

The tower, nacelle and blades of a wind turbine are all able to reflect the radio waves used by radar systems, potentially disrupting defence and air traffic control systems (CSE, 2017). This effect diminishes with distance, so exclusion zones are one solution (Aylesbury Vale District Council, 2013). Upgrading obsolete radar systems is another, and in fact additional UK wind capacity has been unlocked through implementation of mitigation measures (CSE, 2017).

5.1.4 Wildlife impacts

Data on turbine impacts on wildlife is variable and uncertain. One of the main wildlife impacts of onshore wind turbines is on birds. It has been estimated that wind turbines kill between 10,000 and 100,000 birds each year in the UK, but this is dwarfed by the 55 million birds killed each year by domestic cats (Bassi *et al.*, 2012; Asher, 2022). In the US wind turbines have been estimated to kill only 0.007% of birds, with the biggest killers of birds being cats, windows and cars (U.S. Fish & Wildlife Service, 2017).

However the type of birds killed may be a concern, with endangered birds of prey particularly vulnerable to blade strikes as they tend to fly at the same height as turbine blades while looking at the ground for prey (Millar, 2022). One small-scale study in Norway found that painting one of the wind turbine blades black reduced bird deaths by 70 per cent, perhaps because the black blade reduces motion smear (May *et al.*, 2020; Gessel, 2022). Another project is using cameras to spot when eagles are in the vicinity, and slow the turbine blades (Oltermann, 2022).

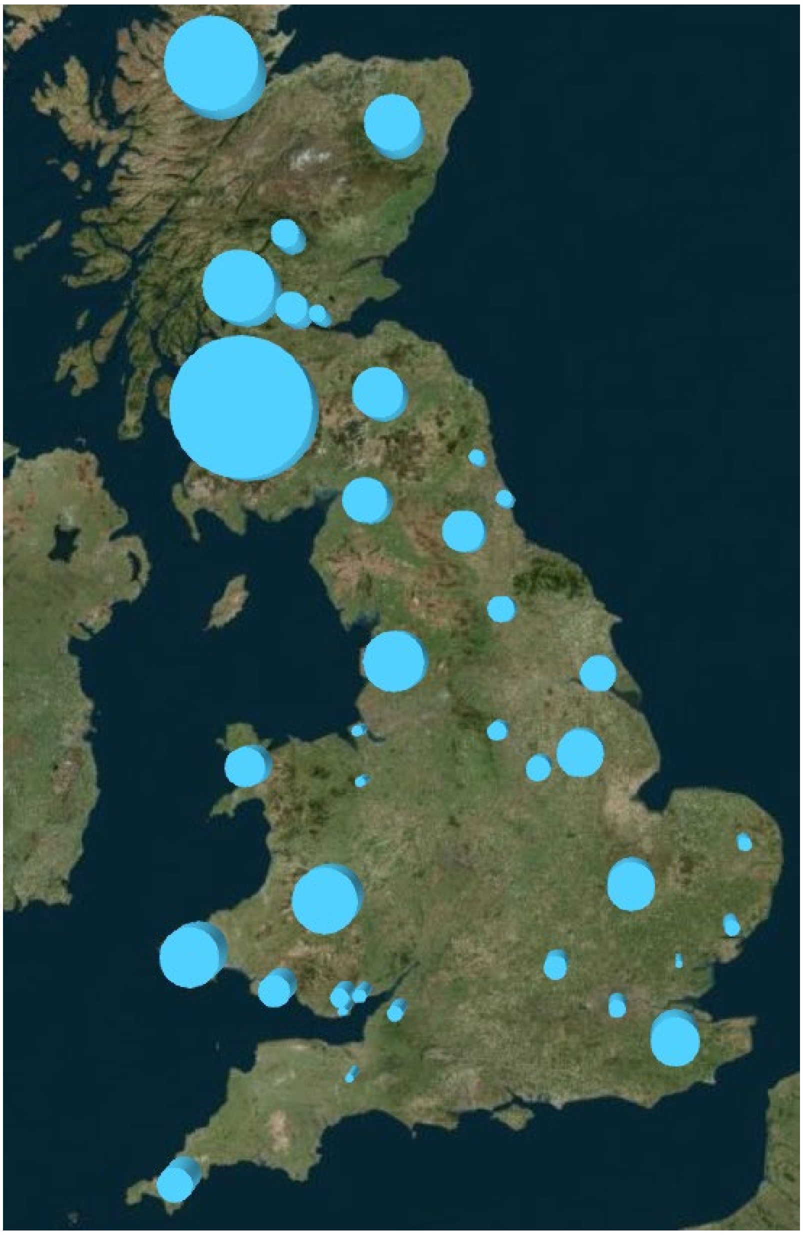
The RPSB recognises the threat climate change poses to nature and the essential role of renewable energy plays in addressing this, and that the impacts of windfarms can be minimised through siting in the least sensitive areas e.g. away from major migration routes and important feeding, breeding and roosting areas (FOE, 2012; RSPB, 2022).

Wind turbines may not just affect birds: one recent study found that some mammals as well as birds avoided wind turbine-dominated areas, with implications for their distribution patterns (Kumara *et al.*, 2022). Wind turbines are estimated to kill hundreds of thousands of bats globally every year (Arnett *et al.*, 2016), and guidance to minimise risks to bats has been published by the Bat Conservation Trust and partners (NatureScot *et al.*, 2021). For example, bats appear to be drawn to turbines' red lights; only switching on the lights when aircraft are in the area could reduce this (Voigt *et al.*, 2018).

5.2 Land use requirements

Two recent studies have reported the power densities of onshore wind as 3–5 MW/km^2 (CCC, 2020b; Price, Mainzer *et al.*, 2022). Note this is the total land covered by windfarms; the actual amount of land used by the masts, access roads, and substations *etc.* themselves is much less than this, allowing multifunctional land use. In contrast, the same studies report higher power densities for solar PV of 40-45 MW/km^2 and some solar farms have densities 60-85 MW/km^2. This is partially offset by the higher capacity factors of onshore wind, and the fact more of the land can also be used for other purposes such as crops (though windfarms also require land for access roads), whereas the use of the land under solar farm panels is more constrained, such as for grazing. The lower projected LCOE of ground-mounted solar in the future compared to onshore wind (Figure 9) may indicate that solar could become increasingly competitive to onshore wind. Figure 25 shows UK onshore wind farms (>150 kW) with status operational, under construction, or with planning permission. Topography and wind resources mean generally more, larger farms in Scotland and Wales.

Figure 25 : Onshore wind map



Source: REPD – operational, under construction, planning permission

5.3 Offshore wind

The focus of this report is land use impacts, but offshore wind will also have impacts, mainly at sea, but also for the land-based components and transmission it requires. For a given annual energy production from a given turbine size, offshore wind will require about half the number of turbines because its capacity factor is about double that of onshore wind. 100 GW of offshore capacity would require 10,000 10 MW wind turbines. Offshore power density is reported at around 5 MW/km^2 depending on how wind conditions and turbine size and design affect optimal spacing; *e.g.* see Borman *et al*. (2018). 100 GW would require 28000 km^2: for comparison, the UK land area is 244,000 km^2 and the North Sea has an area of 575,000 km^2.

Offshore wind will have impacts during construction, operation and decommissioning with these differing according to turbine type (floating, fixed) and location. These impacts occur above the sea, affecting birds, bats and insects, and below, affecting marine animals and plants. As for all ecological impacts, complexity is great and knowledge partial, and both negative and positive impacts are listed. Galparsoro *et al.* (2022) review impacts from 158 publications and summarise *'Among the 867 findings extracted from the analysed publications, 72% reported negative impacts, while 13% were positive.'* They highlight the need for better assessment to reduce the uncertainties and better plan development. Bennun *et al.* (2021) conclude *'The available scientific literature agrees on the key impacts of offshore wind: i) risk of collision mortality; ii) displacement due to disturbance (including noise impacts); iii) barrier effects (also including noise impacts); iv habitat loss; and v) indirect ecosystem-level effects.'* Offshore turbines also affect people's visual amenity and leisure activities, and commercial fishing and shipping.

This underlines the generality that all energy supply options have impacts.

6. OTHER LAND USE IMPACTS

Brief consideration is given below to other technologies included in NZES: carbon capture and storage (CCS), nuclear power, electricity transmission infrastructure and storage. No attempt has been made to comprehensively quantify the land use or other impacts of these technologies. There are many technologies not included here, for example: anaerobic digesters, waste incinerators, biomass CHP/boilers, sewage farms, hydrogen electrolysers and pipelines, ammonia plant, and ACDC converters. Some of these will be sited in rural areas, some in industrial or urban areas.

6.1 Atmospheric carbon capture and storage

Most scenarios include negative emission through atmospheric CO_2 capture and storage (ACCS). The reason is that some energy and industrial processes cause global warming through the emissions of a GHG such as the CO_2 from aviation fuel or cement production for which it is technically and economically difficult to entirely prevent with energy or material substitution, or process change. There are other global warming processes such as that caused by aviation's high altitude emissions of water and NOx which cannot be prevented without radical change to demand, technology or operations. To balance these, negative emissions are included in the NZES. However, all negative emission options are subject to limitations and uncertainties because of environmental impacts or because the technologies and processes are not commercialised, and therefore the optimal mix of ACCS cannot yet be determined.

There are many negative emissions processes; these are reviewed by the Royal Society (2018). Three leading basic processes are proposed for ACCS in the NZES:

- Biomass absorbs CO_2 followed by carbon storage in trees or soils, or possibly in materials such as wood in buildings. This option is not explored because the biomass is not used for energy. Also, some of this sequestration is required to balance agricultural (not energy) emissions. Estimates of this potential are made by the CCC (CCC, 2020a), who say *'In 2017, emissions from agriculture, land use and peatlands were 58 MtCO2e. With ambitious steps, emissions in these sectors can be reduced by 64% to 21 MtCO2e by 2050…There are also additional annual savings (25 MtCO2e) from using the harvested materials from trees and energy crops for use elsewhere in the economy.'*
- Biomass absorbing CO_2 followed by biomass processing (*e.g.* combustion) and CO_2 storage, BECCS. This is described in 4.3.5.
- Machines driven by electricity and heat using alkalis to absorb CO_2 and then store it, called direct air capture with carbon sequestration (DACCS), see Depellegrin *et al.* (2014) for a description.

CO_2 can be transported and sequestered geologically in depleted gas or oil fields, in aquifers or in rock formations. BECCS requires about 1000 times the land area of DACCS per tCO_2 sequestered, and it requires agricultural land, though this may be unsuitable for food production.

6.1.1 Direct air capture and carbon sequestration (DACCS)

DACCS does not require a particular land type but it needs to be sited where electricity and consumables such as chemicals and water can be supplied, and these consumables themselves have impacts. The CO_2 extracted needs to be transported to geological storage so proximity of storage is one criterion. Electricity and low temperature heat can be used for some DACCS systems. Excluding energy supply, DACCS has a low land use requirement per $MtCO_2/a$ capacity, reported to be less than 1 $km^2/MtCO_2/a$; for example (Viebahn, Scholz *et al.*, 2019). It is to be noted that the actual CO_2 captured depends on the capacity factor of the plant – the fraction of the maximum captured if operating at full capacity all year.

There is investigation by the Offshore Wind and CCUS Co-location Forum (Crown Estate, 2023) of the possibility that DACCS and carbon utilisation processes can be co-located with offshore wind. *'Offshore wind and carbon capture, usage and storage (CCUS) have a significant role to play in helping the UK achieve its net zero targets, including ambitions to: deliver four CCUS clusters, capturing 20-30 MtCO2 across the economy per year by 2030, and deliver 50GW of offshore wind, including 5GW of innovative floating offshore wind by 2030.'*

6.2 Nuclear power

Nuclear stations and nuclear waste sites are small in area per capacity (km^2/GW). However, stations are sited on the coast where they can impact visually over long distances. The British Energy Security Strategy (BEIS, 2022a) mentions plans for deployment of civil nuclear to up to 24 GW by 2050. The firmest projection is for the only operating nuclear plants after 2030 to be Hinkley C (3.3 GW) which is under construction and Sizewell B (1.2 GW) which may close in 2035 but possibly have a 20 year extension. These two stations might have a capacity of 4.5 GW operating in 2050 leaving a possible 20 GW needed to total 24 GW. The UK has eight designated nuclear sites in the Strategy (BEIS, 2022a) which have or had nuclear stations: Hinkley, Sizewell, Heysham, Hartlepool, Bradwell, Wylfa, Oldbury and Moorside. Of these, Sizewell C (3.2 GW) has been granted development consent (Planning inspectorate, 2022).

6.3 Electricity grid

The electrification of demand with electric renewables is a central policy of NZES. This will require an expanded electricity grid with higher transmission and transformer capacities, and storage to absorb high capacities of renewables.

6.3.1 Transmission

Currently the peak demand on the UK electricity system is about 55 GW. The peak demand will increase, perhaps two or threefold to 100-150 GW as demands are electrified, such as heating with consumer and district heat heat pumps and electric vehicles, and industrial demands using electrolytic hydrogen. Most of this demand will be connected at lower voltages - 230 V, 415 V and up to 11 kV for some industrial users - to the distribution system, which is mostly underground in urban areas but with significant lengths overground in more rural areas. It is likely that some uses of electricity such as for hydrogen electrolysis and storage would be located coastally near where offshore wind power is landed. The low voltage distribution system will need an increase in capacity (GW) as a consequence of electrification factors: for example, a domestic heat pump is about 5 kWe and in cold weather many heat pumps will be operating at peak, and an EV charger is perhaps 3-7 kWe, so houses will require low voltage distribution capacity of the order of 5 kWe. This might be enough to export 5 kW of solar power given that its peak will generally occur at different times from heat pump and EV charging peaks. Thus, urban PV capacity may not require further substantial transmission increase.

The installed capacities (GW) of generators in all NZES are much greater than today, partly because of general electrification but also because of the lower capacity factors of renewables compared to fossil and nuclear stations. The total wind, solar and nuclear generation capacity in the NZES ranges from 200-320 GW which is the potential maximum non-dispatchable generation. Some fraction of this maximum will be sent to demand or storage, but some may be spilled. Thus the total capacity of high voltage transmission will need to expand by a factor of three or four.

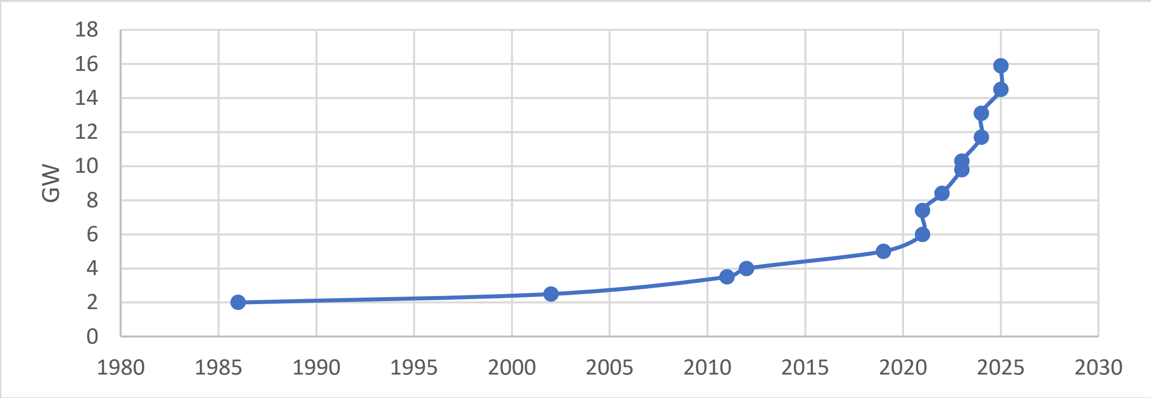
The capacities and locations of renewable generators will be different and diffuse as compared to fossil and nuclear generators, requiring extensions to capacity and routes for transmission. The cost of underground transmission is about five times higher (Parsons Brinckerhoff, 2004) than overground and the direct impact on land is greater; therefore onshore high voltage transmission is mostly overground except in cities. Onshore high voltage overground transmission is similar to onshore wind in that the actual land used by pylons is small, but pylons can be seen at a distance and so impact on visual amenity. A large fraction of new generation capacity will be offshore wind and this is transmitted by undersea cables to shore where it has to be connected to demand centres. In order to reduce onshore transmission some of this transmission can be around the coast, for example from the North Sea to the Thames and to London. An example of a major transmission onshore project is the East Anglia Green Energy Enablement (GREEN) project proposed by National Grid (National Grid, 2022a) which is mostly overground but underground in designated landscapes – this project incurs considerable local protest.

A composite map of on and offshore wind farms, transmission, substations and other information has been developed by The Crown Estate[32] (The Crown Estate, 2021). This particularly shows that much development is driven wind farms off the east coast.

The UK has interconnectors that connect with other countries and that capacity is expanding. These are mostly high voltage direct current (HVDC) systems. The conversion between HVDC and alternating HVAC power is done with inverter/rectifier plant at coastal sites. Current projects will increase interconnector capacity to 16 GW by 2025. BEIS Research Paper number 2020/056 (Aurora Energy Research, 2020) reports a possible additional 8 to 23 GW by 2050. Figure 26 shows current near term interconnector expansion.

[32] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1035655/otnr-generation-map.pdf

Figure 26 : Possible interconnector expansion



Source: (Ofgem, 2022)

The concentration of interconnector landing points in the east and south may be seen in a map by the Crown Estate[33] (The Crown Estate, 2019).

6.3.2 Transformers

Apart from the cables, the transmission system includes transformers which increase or decrease voltages. Some are called grid supply points (GSP), which decrease the 400 kV voltage to a lower transmission and distribution voltage. There are some 380 GSPs in the UK and they are usually outside urban areas. There are many more lower voltage transformers, but most of these are in or near demand centres.

Figure 27 : GB grid supply points

Source: https://data.nationalgrideso.com/future-energy-scenarios/regional-breakdown-of-fes-data-electricity/r/fes_2022_grid_supply_point_info

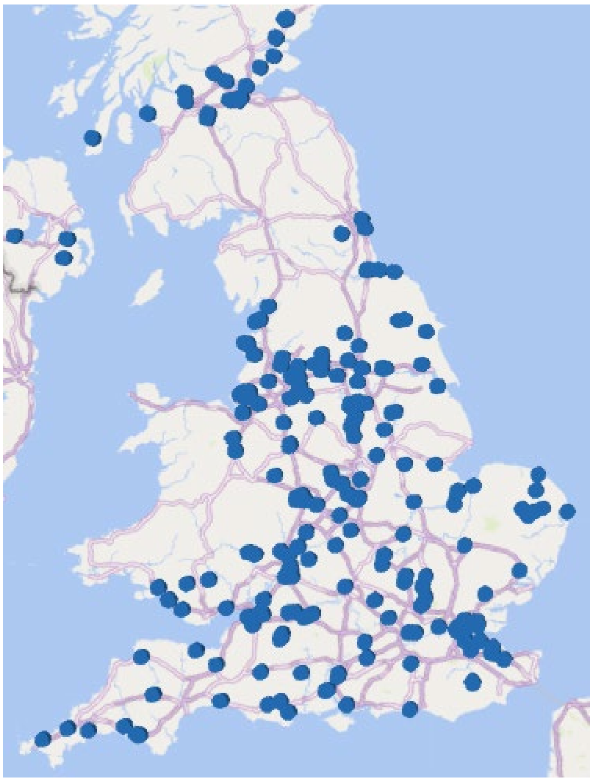
[33] https://www.thecrownestate.co.uk/en-gb/media-and-insights/stories/2018-electricity-interconnectors/

6.3.3 Storage

Electrification using variable renewable electricity will require storage to provide a secure supply across the hours of the year. Most current storage is pumped hydro but a rapidly expanding option is batteries with other technologies such as compressed air, flywheels and liquid air in development at a minor scale. National Grid project electricity storage need for 2050 of up to 50 GW (National Grid, 2022b), but not all of this would be batteries. There is flexibility in battery siting but it will often be integrated with renewable generation, and transmission and grid supply points. An example is the 98MW/196MWh Pillswood battery farm project that is coordinated with the development of the Dogger Bank wind farm; this may be seen here[34] (EDIE, 2023).

The REPD gives data for battery grid storage co-located with fossil and renewable generators, and stand alone. There are 0.9 GW operational, 1.3 GW under construction, 6.5 GW with planning permission and 5.3 GW with planning applications. If all these are built, then the total operational would be 14.2 GW in 336 battery farms. Figure 28 maps these.

Figure 28 : UK grid battery storage map



Source: REPD

6.4 Gas and hydrogen

In net zero systems the use of natural gas directly or for making hydrogen has to be limited because of CO_2 and methane emissions, but some consumption will likely remain for uses such as organic chemicals production and back-up generation. Many scenarios include electrolytic hydrogen that is used for heating or power generation,

[34] Europe's biggest battery storage facility comes online near Hull - edie

industrial processes, or as input to the production of ammonia or other fuels. Electrolysis may be located in industrial areas or near hydrogen storage facilities. Hydrogen transmission will be required; it is not clear what are the technical and cost implications of repurposing natural gas transmission system (pipes, valves, compressors etc.) for hydrogen.

6.4.1 Salt caverns

It is suggested that large scale hydrogen storage will be required and salt caverns are proposed for this, with depleted gas fields also considered. There is relatively little experience with the impacts of salt cavern hydrogen storage. There is literature on factors including safety and geology that are important to hydrogen storage; see for example, (Stone, Veldhuis *et al.*, 2009; Portarapillo and Di Benedetto, 2021; Epelle, Obande *et al.*, 2022; Valle-Falcones, Grima-Olmedo *et al.*, 2022).

The above ground infrastructure of the Aldbrough storage system may be seen here[35] (Aldbrough hydrogen storage, 2023). The locations for hydrogen storage will be determined by many factors including the geological suitability and the proximity to hydrogen demands, production and transmission system.

The British Geological Survey[36] (British Geological Survey, 2001) shows a map of current and possible storage siting. A substantial fraction of storage potential is along the north east coast, with further large potential in the Wessex and Cheshire basins.

[35] https://www.aldbroughhydrogen.com/

[36] mpf_storage.pdf (bgs.ac.uk)

7. CONCLUSIONS

7.1 Scope

The study has assessed the NZES land use impacts in England of onshore wind, solar and biomass as this is a central issue for CPRE. Commentary is given on some other technologies, and some other impacts. This study has generally been of physical and technical aspects. Some commentary is given on the direct technology costs of PV and wind systems, but there is uncertainty in generalising these, and supporting components, such as transmission and storage and land have not been costed here. Beyond these technology costs are the social costs of environmental impacts such air pollution from biomass or loss of visual amenity due to wind turbines, and perhaps most important, ecological impacts.

It has been beyond the scope of this study to conduct complex analysis with data and modelling to evaluate land use. It has also been beyond scope to quantify all environmental impacts, wider energy system issues, costs, and to assess planning and development policies. These wider costs have to be compared with the more easily identified technology cost elements to arrive at a balanced strategy. Nonetheless, the findings of this report will aid thinking in a number of policy areas and highlight where deeper analysis is needed.

7.2 Conclusions on renewables

The conclusions regarding the three specific renewables are:

- There is enough urban rooftop area to accommodate NZES solar PV capacities, but some will be higher cost than for solar farms. Urban PV has relatively little impact.
- Onshore wind uses little physical land for the towers and access roads but has a wider visual impact. Offshore wind is reaching a comparable cost and is becoming a viable alternative.
- Biomass has low productivity (GWh/km^2/a) compared to wind and solar and uses large land areas, but it produces fixed carbon which can be used for making hydrocarbon fuels and for negative emissions.

These renewables produce different energy forms with different temporal profiles and so are not generally comparable. PV and wind cause little material flows when operational whereas biomass in the NZES engenders some 75 Mt of plants extracted, transported and consumed. PV produces about 10 times as much energy (electricity) per area (GWh/km^2 p.a.) as biomass, but it is not in stored form or directly suitable for negative emissions. Offshore wind produces about five times as much energy per GW as solar PV, and onshore about three times. This means they are generating for more of the time, including at night unlike solar, and so they require less storage.

7.3 Further research

Further research could build on work such as by CCC (2020a), McKenna *et al.* (2022), and the House of Lords (Land Use in England Committee, 2022), and might include some of the following elements:

i. Identify where current understanding points to significant uncertainties, problems and conflicts.
ii. Expand detailed coverage to include all technologies in the Renewable Energy Planning Database (BEIS, 2022f), and other generation such as nuclear, and other supply such as biogas and hydrogen, and supporting infrastructure such as transmission and storage.
iii. Develop coherent detailed GIS datasets of population, buildings, developed land, natural land, and agricultural land classes, and energy assets.
iv. Extend the quantification of environmental impacts to ecology, visual amenity, access, noise, air pollution, traffic, etc.
v. Refine estimates of the direct market costs for the construction and operation of renewables and supporting technologies in different urban and rural contexts.
vi. Build an integrated energy and environment model to facilitate energy system designs and assess the competition between land use for food, bioenergy and material products such as wood.
vii. Assess the energy and food security implications of different plans.
viii. Construct coherent policies balancing the costs and benefits.
ix. Use analysis to appraise current planning policies and suggest extensions or improvements.

8. APPENDIX 1: ALLOCATION OF UK SCENARIOS TO ENGLAND

The scenarios reported in Section 0 specify technology capacities for the UK for the CCC and BEIS scenarios, and GB for the National Grid scenarios. These capacities for key technologies need to be allocated to England for the purposes of this study. However, these allocations are not necessarily likely to follow population or land area trends. For example, technologies dependent on solar irradiation (PV and biomass) are more likely to be located in southern regions, while onshore wind is generally more likely in the north. Energy crops are also more likely in regions with higher quantities of fertile arable land. Some regions also have stricter planning laws than others, and more local acceptance or resistance to different technologies. A detailed analysis of these issues is outside the scope of this study but an indication of the likely future allocation of energy technologies can be obtained from the location of previous energy systems, which will have taken at least some account of these issues.

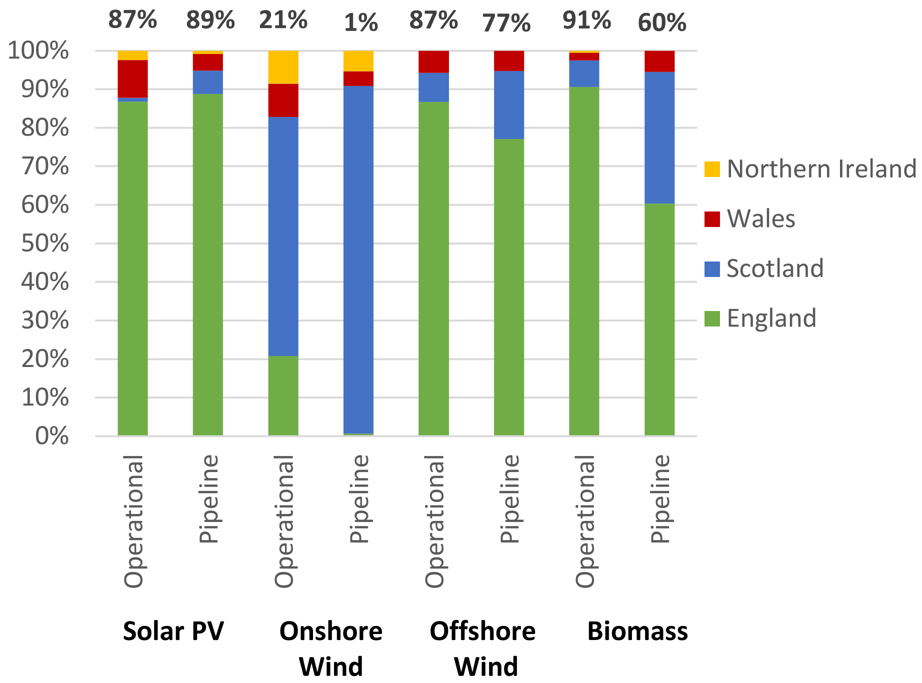
Two data sources were consulted for this analysis; firstly the Renewable Energy Planning Database (REPD), which records the size and planning status of renewable energy technologies above 150 kW for each of the four UK nations (BEIS, 2022f); and secondly BEIS's Energy Trends report, which also publishes data for the four UK nations (BEIS, 2022d). The REPD also gives an indication of how this allocation could change in the future through its project pipeline, which for this study included submitted, granted and under construction systems. It is possible the REPD pipeline includes dormant applications and projects that will not be approved or built, but it was assumed here this would not affect the distribution between the four UK nations. The results are shown in Table 22 and Figure 29. Note that fractions of these technologies in England have been generated for both UK and GB totals (*i.e.* excluding Northern Ireland).

Table 22: Operational and pipeline renewable energy capacities (MWe) for the four UK nations

			England	Scotland	Wales	Northern Ireland	Total	% in England of UK	% in England of GB
REPD	PV	Operational	7,523	80	853	209	8,665	86.8%	89.0%
		Pipeline	14,016	960	682	133	15,791	88.8%	89.5%
		Total	21,539	1,040	1,535	342	24,456	88.1%	89.3%
	Onshore wind	Operational	2,859	8,535	1,191	1,178	13,764	20.8%	22.7%
		Pipeline	82	11,242	466	671	12,460	0.7%	0.7%
		Total	2,941	19,777	1,657	1,849	26,224	11.2%	12.1%
	Offshore wind	Operational	10,936	952	726	0	12,614	86.7%	86.7%
		Pipeline	17,517	4,017	1,200	0	22,734	77.1%	77.1%
		Total	28,453	4,969	1,926	0	35,348	80.5%	80.5%
	Biomass (dedicated)	Operational	3,137	238	69	20	3,464	90.6%	91.1%
		Pipeline	461	261	42	0	764	60.3%	60.3%
		Total	3,598	499	111	20	4,228	85.1%	85.5%
Energy Trends	PV	Operational	12,001	405	1,221	339	13,965	85.9%	88.1%
	Onshore wind	Operational	3,087	8,691	1,286	1,430	14,492	21.3%	23.6%
	Offshore wind	Operational	9,586	946	724	0	11,255	85.2%	85.2%

Sources: Renewable Energy Planning Database (REPD) and Energy Trends (BEIS, 2022f, 2022d)

Figure 29 : Operational and pipeline renewable energy capacities (MWe) for the four UK nations



Source: Renewable Energy Planning Database (REPD) (BEIS, 2022f)

The data from the two datasets are broadly in agreement. REPD capacities are smaller in some cases due to its exclusion of systems below 150 kW (or 1 MW for systems going through the planning system before 2021); this is particularly noticeable for PV systems. The Energy Trends data is also smaller in some cases (*e.g*. offshore wind) as this data reports capacities at the end of 2021, while the REPD was last updated in October 2022.

Nevertheless some trends can be observed. Firstly, 86-87% of PV systems have been installed in England, reflecting the higher demand and solar resource in England. This rises to 89% for pipeline systems as, although Scotland is now significantly increasing its planned PV capacity, this is outweighed by smaller rises in Wales and Northern Ireland. For the purposes of this study the pipeline value seems appropriate, and a value of 90% has been used.

Biomass productivity will generally, assuming adequate water and so on, be higher in the south than the north because of higher solar radiation and arable land percentage, however food may take higher priority there for the same reasons. Hence a value of 90% from Table 22 has also been used. The large majority of onshore wind to date has been built in Scotland, with only around 21% of the UK's onshore wind capacity built in England. This has been exacerbated by the effective moratorium on new onshore wind imposed in 2015 (BEIS, 2015; MHCLG, 2015), as in 2015 the fraction of onshore wind built in England reached a peak of 26.5% and has been falling since (BEIS, 2022d). Proposed changes to the planning system could see onshore wind deployment continue in communities that want them (DLUHC, 2022b) and a value of 20% has been used for this analysis. For offshore wind (which can determine the amount of transmission lines needed in some regions), 85-87% of historical capacity has been installed in England. The pipeline data indicates this is expected to fall to

77% due to the growing pipeline in Scotland,[37] so an average value for both existing and planned systems of 80% has been used. These fractions have been used to calculate England's share of UK scenario data as reported earlier in Table 6.

[37] *e.g.* nearly 25 GW of offshore wind announced in a 2022 leasing round (Crown Estate Scotland, 2022)

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