Could Britain’s energy demand be met entirely by wind and solar?

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Could Britain's energy demand be met entirely by wind and solar?

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ABSTRACT The UK government aims to decarbonise the domestic electricity system by 2035 and reach net-zero emissions by 2050. This paper estimates the practical contributions that wind and solar electricity generation could make, incorporating recent advances in technology and significant declines in cost. Using established literature and bottom-up technical assessments, we build on the methodology of MacKay (2008), and find that the time-bound assumptions therein resulted in a large underestimate of the practical resources available. We conservatively estimate that the practical potential for electricity generation in Great Britain is around 544 TWh/year for utility-scale solar photovoltaic farms, 25 TWh/year for rooftop solar, 206 TWh/year for onshore wind farms, and 2,121 TWh/year for fixed and floating offshore wind farms. The combined, conservatively estimated, potential generation from solar and wind (2,896 TWh) is almost double the maximum estimated final energy consumption of Great Britain in 2050 (1,500 TWh), and almost ten times current electricity needs (299 TWh/year). Furthermore, since wind and solar are the cheapest forms of new-build electricity generation in the UK, and are expected to remain so, electricity generation costs are not a barrier to a very high wind and solar future. Though variable renewable generation currently brings additional integration costs, with well-planned investment and proactive policy, alongside rapidly falling storage costs, these costs appear manageable for a high renewable energy future. An economy powered entirely by wind and solar may or may not be politically feasible, or publicly acceptable, but this paper demonstrates that Great Britain's practical wind and solar resources are more than sufficient to economically meet total net domestic energy needs.

Table 0. Summary of estimates for total practical energy supply and demand in Great Britain. Totals may not align due to rounding.

	Energy supply (TWh/year)	Key conservative assumptions
Utility-scale solar	544	• 2% of GB land
Rooftop solar	25	• 8.3% of GB rooftops
Onshore wind	206	• 5% of GB's land area • 7 MW turbines • Spacing of 6 x turbine diameter between turbines • Average 38% capacity factor
Offshore wind	Fixed: 563 Floating: 1,557	• **Fixed turbines:** 2% of UK's exclusive economic zone • **Floating turbines:** 8% of UK's exclusive economic zone • 15 MW turbines • Spacing of 7 x turbine diameter between turbines • Average 50% capacity factor
Total solar + wind practical supply	2,896	
Assumed 2050 final energy demand	1,500	• More conservative (higher) than all surveyed studies, including all National Grid *Future Energy Scenarios*

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1. INTRODUCTION

Could Great Britain's (GB's) total energy demand be fully met by its wind and solar resources? If it is technically feasible, is capturing these resources practically and economically viable?[1] Almost everyone agrees that it is *technically* possible for GB to meet all future domestic energy needs.[2] Yet, claimed *practical* and *economic* barriers temper technical assessments. These claimed obstacles

[1] In this paper, "theoretical resource" refers to the embodied energy in the resource itself (*i.e.*, the total energy of the sun spread over a given area), "technical resource" refers to the energy that could be extracted from suitable areas (*e.g.*, areas without a significant slope and away from interfering obstacles), "practical resource" incorporates areas without major barriers to development (*e.g.*, barriers due to public perception or protected sites), and "economic resource" refers to energy that could be recovered economically (this does not incorporate integration costs). Often, the line between *practical* and *economic* resources can be unclear; for instance, a resource might have varied public perception under different economic conditions.

[2] GB land totals 237,000 km^2 (Rae, 2017), average irradiance is approximately 100 W/m^2 (Burnett *et al.*, 2014), spacing requirements reduce capture by 55% (see Section 4.1), and commercial solar cell efficiencies are approaching 25% (see Section 4.2). This gives 23,350 TWh/year. Total European final energy consumption in 2021 was 16,700 TWh and total supply was 22,900 TWh (IEA, 2022).

encompass a range of social factors (Bell, 2005; MacKay, 2008; Pasqualetti, 2011; Segreto *et al.*, 2020), political factors (Cohen 2015; MacKay, 2008; Stokes, 2013) and technological limitations (Cohen, 2015; MacKay, 2008). Many prior studies have proven unnecessarily pessimistic in their assumptions regarding these obstacles (*e.g.*, BEIS, 2016; DECC, 2013; Mott MacDonald, 2010), yet they continue to influence policy and other discourse. This pessimism is part of a wider trend over the last two decades, in which the rapid improvement of solar and wind technologies has been systematically underestimated (Way *et al.*, 2022). In developing future policy, it is important to recognise that past narratives around the limitations of solar and wind energy were based on assumptions that have, in hindsight, turned out to be highly unrealistic.

David MacKay's 2008 book, *Sustainable Energy - without the hot air*, provided a particularly influential survey of the potential limitations of renewable energy in GB, which has influenced fifteen years of discourse (*e.g.,* van der Meyden and Witteveen *in* Kramer and Vermeer, 2014, p. 169; Wilson *in Physics World*, 2020) and policy (Anthesis, 2020; Davey *in* Rustin, 2013; Fordham, 2022; Ridley, 2017; University of Cambridge, 2021). MacKay incorporated social and political criteria, as well as then-current costs, all of which are critical for understanding public acceptance and therefore viability (Sward *et al.*, 2021). This paper explores the time-bound nature of MacKay's assumptions—and conclusions—and provides a revised foundation for discourse.

What has changed in the last fifteen years? First, due to technological learning and innovation, the costs of solar and wind electricity generation assets have decreased dramatically, in parallel with approximately exponential deployment (IRENA, 2022a; Way *et al.*, 2022). Electricity from solar photovoltaic (PV) and onshore wind is now significantly cheaper than most other sources in most places around the world (including the UK), and offshore wind is not far behind. The global average levelized cost of electricity (LCOE) for solar PV fell 88% between 2010 and 2021 while onshore wind fell 68% and offshore wind fell 60% (IRENA, 2022a). In 2022, average UK electricity auction prices ballooned to £203/MWh, from an average of £91/MWh during 2018-2021 (Nord Pool AS, 2023). The average *fuel cost* for UK gas-fired power stations, £63/MWh, (£27/MWh 2018-22 average) (DESNZ, 2023a), exceeded the *combined construction + financing + fuel + running costs* of UK solar (£56/MWh) and wind £47/MWh (see Figure 6).[3] While fuel prices at the time of writing are much lower than in 2022, they remain at a level that many in 2008 would have thought unimaginable.

Technological advances in solar and wind have been both iterative (*e.g.*, more efficient solar panels) and disruptive (*e.g.*, ability to install floating wind turbines), vastly outperforming earlier expectations. Integration costs include storage needs, raising reserve requirements, expanding and strengthening the grid to enable electricity transportation from new supply centres, short-term load balancing, and addressing grid resiliency concerns. Due to rapidly decreasing storage costs and the changing grid, provided prompt investment and policy attention are forthcoming, these integration costs may not be nearly as challenging as many currently believe, and likely not prohibitive. Certainly, they increase at high rates of variable renewable energy (VRE) penetration (Heptonstall and Gross, 2021), yet there are solutions to address them – as is apparent, including in the recent *Independent recommendations from the UK's Electricity Networks Commissioner* (Winser, 2023), it is a question of ambition rather than technical possibility. Indeed, short- and long-term electricity storage and electricity transport technologies have all advanced significantly since much of the existing evidence base on integrations costs was developed. Lithium-ion battery and pumped hydropower storage are used in grid systems worldwide. High-voltage direct current (HVDC) transmission infrastructure is one of many major advances in grid technology. Opportunities for longer-term energy storage in hydrogen and ammonia continue to emerge. While some of these solutions result in efficiency losses, in most cases they are more than offset by the efficiency gains of electrification, or, otherwise, the extreme conservatism of our demand estimates. Intelligent load balancing will also help.

[3] Solar and wind reported in LCOE terms. Gas costs exclude Carbon Price Support levy. For the highest gas price quarter in 2022 (Q3), the gap was significantly wider: average UK auction prices were £295/MWh and the average gas price for power producers was £77/MWh.

Second, energy demand scenarios are lower, driven by increased use of electric vehicles (EVs) (which are much more efficient than internal combustion vehicles), electrification of the economy more widely (in particular, heat), improvements in end-use technologies, and policies to increase energy efficiency.

Third, GB has seen increasing social and political acceptance for mass renewable generation, with 85% of the voting public in favour of renewable energy developments (BEIS, 2023). Substantial majority support exists for all forms of solar and wind generation, with many citizens recognising that they provide *"benefits to the national economy"* (BEIS, 2023). Very few (7-12%) oppose the construction of solar or onshore wind farms in their local area—a major concern of MacKay (2008). While some hurdles remain, the debate has shifted dramatically, and public acceptance has enabled the policy and regulatory environments to incentivise renewable energy solutions as a mainstay of the United Kingdom (UK) Government's plan to reduce emissions by 68% by 2030, compared to 1990 levels (HM Government, 2021).[4]

In section 2, we collect estimates of likely energy demand in GB in 2050.[5] Based on these estimates we then pick a highly conservative level of 2050 GB energy demand for use in this study (i.e., it is higher than estimates found in the academic and policy literature).. In section 3, we derive simple estimates of the practical potential energy supply of wind and, in section 4 we do the same for, solar PV. In section 5, a cost analysis compares incremental generation costs across technology types. We find solar and wind electricity in GB are already the least-cost solutions on an incremental basis, noting that integration costs (including storage) are additional. In section 6, we sum up the findings of the paper and provide recommendations for policymakers.

[4] However, accompanying policy to supply the requisite storage investment is lacking.

[5] This report focusses on GB, *i.e.*, the UK excluding Northern Ireland. Electricity consumption in Northern Ireland accounts for about 2.5% of the UK. The reason for our focus is that Northern Ireland and the Republic of Ireland rely on an integrated electricity wholesale market separate from (but interconnected to) the market in Great Britain.

2. DEMAND FOR ENERGY

Assessing the extent to which solar and wind energy generation could match GB's total energy demand requires a brief review of existing scenarios. In 2021, UK *primary* energy demand was 1,978 TWh and *final* energy demand 1,599 TWh (Harris, 2022, p. 3). This was 4.7% higher than 2020, but 7.8% lower than pre-pandemic levels (Harris, 2022, p. 3). Electricity consumption in GB was 299 TWh (McGarry, 2022). Primary energy demand, final energy demand, and electricity consumption have all trended downward in the UK since 2005 (BP, 2021), driven by fuel switching, efficiency gains, economic restructuring and cost factors (Evans, 2019; Wilson and Staffell, 2018).

How might future demand change? In general, we expect a continued steady decline in GB primary energy consumption alongside a continued increase in economic growth and energy services. With growth in renewable energy, electrification, and increased energy efficiency, less primary energy will be needed to deliver the same final energy (because solar and wind energy avoid heat losses), and less final energy will be necessary to deliver the same energy services, accounting also for improved home insulation. In National Grid's *Future Energy Scenarios* (FES), increased electric vehicle uptake, fuel efficiency, electric heat pump installation, and industrial clustering are all likely to drive energy consumption down (National Grid, 2023), noting the complexity of balancing supply at times of peak demand in a highly electrified system (especially due to electrification of heating). Some of this demand reduction will be partially offset by opposing factors like population growth, or a failure to deliver on policies to develop industrial clusters, integrate hydrogen production into transformation of business demand, and guide fuel switching.

In its Announced Pledges scenario, the IEA projects that total European energy supply will decline 23%, from 21,600 TWh/year in 2020 to 16,600 TWh/year in 2050 (IEA, 2022a). If the UK maintained a 9% share of Europe's energy consumption (IEA, 2022b), this would imply that total energy supply of 1,494 TWh/year would be needed in 2050. The EnerBlue scenario from Enerdata, in which nationally determined contributions are achieved, projects that primary energy consumption in Europe will decline 34%, from 19,700 TWh/year in 2020 to 13,000 TWh/year in 2050, and final energy consumption will decline 29% from 14,500 TWh/year to 10,300 TWh/year (Enerdata, n.d.a; Enerdata, n.d.b). Again, if the UK maintained a 9% share of this then 1,170 TWh/year of primary energy would be needed in 2050. The Department for Business, Energy, & Industrial Strategy (BEIS) suggests that reaching net zero in the UK might imply electricity demand between 575-672 TWh/year, making up half of final energy demand of 1,150 – 1,344 TWh/year (BEIS, 2020a). National Grid's whole-of-system FES anticipates GB final energy consumption declines to 818 - 1,038 TWh/year by 2050 (National Grid, 2023).[6] These alternative scenarios capture a range of assumptions on population growth, energy efficiency, and energy mix.

Based on these studies, and adding a significant factor of conservatism, we take GB's future final energy demand in 2050 as 1,500 TWh/year. This is higher than the scenarios reviewed in the literature, allowing room for unexpected demand increases from both demographic factors (*e.g.*, population growth) and yet unclear roles for emerging energy-intensive green production, potentially including cultivated meats, distributed manufacturing, and Direct Air Carbon Capture and Storage (DACCS) of CO_2.

3. SUPPLY FROM WIND

We find that **2,330 TWh**/year **could be practically available from GB wind**. This consists of:

- **210 TWh**/year **onshore**, assuming 5% of GB land would host turbines (generally collocated with agriculture), spacing at 6 times diameter, and approaching 7 MW in size,
- **560 TWh**/year **fixed offshore**, assuming 2% of GB's exclusive economic zone (EEZ) would be used for turbines, spacing at 7 times diameter, and approaching/exceeding 15 MW, and

[6] These four scenarios are: Consumer Transformation (976 TWh/year), System Transformation (1,157 TWh/year), Leading the Way (980 TWh/year) and Falling Short (1,180 TWh/year).

- **1,560 TWh**/year **floating offshore**, assuming 8% of GB's EEZ would be used for floating platforms, spacing at 7 times diameter, and approaching/exceeding 15 MW.

Table 1 compares our estimates for practical wind potential with prior studies. Supplementary Table 1 provides prior estimates for technical resource and detailed assumptions for replication.

Table 1. Summary of total practical wind resource in this study compared to previous practical and economic resource estimates. All figures in TWh per year.

	Onshore Wind	*Fixed Offshore Wind*	*Floating Offshore Wind*	*Total*
Our Study, GB practical resource	206	563	1,557	2,327
MacKay (2008), UK *technical* resource	449	1,040	NR	1,489
MacKay (2008), UK *practical* resource	67	88	NR	155
Offshore Valuation Group (2010), UK *practical* resource	NR	374-436	860-1,533	NR
Cavazzi and Dutton (2016), UK *economic* resource	NR	675-2,890		NR
Hundleby and Freeman (2017), UK *economic* resource	1,580-2,700			1,580-2,700
Vivid Economics and Imperial College London (2019), UK *economic* resource	96-214	NR	NR	NR

Notes: NR = not reported. MacKay's fixed offshore wind assessment did not differentiate between waters appropriate for fixed and floating. Assumptions and calculations are detailed in the next sections. Fixed offshore wind includes already licensed farms. A summary of prior technical and economic resource estimates is available in Supplementary Table 1.

GB is notoriously windy, boasting some of Europe's strongest sited wind energy resources (Lu *et al.*, 2009). At writing, GB's operational wind capacity is significant, but less than others in Europe (Germany and Spain) (IRENA, 2023). UK wind capacity totals 28.5 GW comprising 14.7 GW onshore and 13.8 GW offshore (DESNZ, 2023b). For comparison, German installed wind capacity is 66 GW, the US 141 GW, and China 366 GW (IRENA, 2023).

In GB, wind electricity is generated at onshore, fixed offshore, and floating offshore sites. Often onshore turbine sites are restricted in height and farm size, ostensibly to maintain visual amenity and reduce impact on land and air. Fixed offshore generation–from turbines with foundations on the sea floor—are also restricted in height, due in part to technology, subsea engineering challenges and cost optimisation. Floating offshore turbines are situated on purpose-built floating platforms, connected to the seabed using chains, cables, or another mechanism. In both offshore cases, electricity is delivered from the turbine to the grid with undersea cables. In GB, floating offshore generation remains nascent, with only two small floating wind farms installed off the coast of Scotland, although there is a significant pipeline of over 50 British projects in development (Principle Power, 2021; RenewableUK, 2022). Internationally much larger facilities, up to 1.3 GW, are in the planning stage of development (Buljan, 2022). The Crown Estate announced their intention to lease Celtic Sea waters in mid-2023, targeting 4GW of floating offshore wind generation by 2035 (Crown Estate, 2022).

In 2008, MacKay provided a "generous" estimate that wind could *technically* provide up to 1,040 TWh/year to the UK, but suggested that high costs and a lack of social acceptance of wind turbines would lead to a *practical* potential of just 86 TWh/year "*after public consultation*" (Mackay, 2008). Our updates suggest MacKay's technical assessment underestimated the strength of the UK wind resource although he used generous assumptions for total useable area.[7] His practical assessment was based on expensive cost assumptions that are now well out of date and social assumptions that have shifted. He also did not foresee a role for floating offshore wind, although recognised that "*floating wind turbines may change the economics*" (Mackay, 2008). These technologies are now becoming viable at scale, as evidenced by UK government ambition to deliver 5GW of floating wind by 2030 (BEIS *et al.*, 2022), and so there is a need to adjust MacKay's estimates.

Beyond MacKay, prior studies have considered technical, practical, and economic wind resources in the UK. However, they have infrequently considered all three production categories (onshore, fixed offshore, and floating offshore) for the entirety of Great Britain. Lu *et al.* (2009) provided a technical estimate of 10,600 TWh/year, calculating over non-forested, non-urban, low depth areas in the UK and using old turbine technology (4,400 TWh/year onshore and 6,200 TWh/year fixed offshore). Weiss *et al.* (2018) suggested that an appropriate technical figure for offshore wind might be 17,640

[7] MacKay overlooked how above-average wind conditions can significantly increase the extractable power. His calculations were based on average wind speed, rather than average wind speed cubed (wind power is a cubic function of wind speed) – he acknowledges this simplification in his technical (supplementary) chapter on wind (MacKay, 2008, p. 266).

TWh/year.[8] Their assumptions called for a larger turbine radius but considered feasible offshore operating depths only to 500m. In one of the earliest and most comprehensive assessments, the Offshore Valuation Group (OVG, 2010) estimated the practical resource of 1,939 TWh. They estimated this within a low-high range of 1,315-2,313 TWh/year (376-436 TWh/year fixed offshore and 860-1,533 TWh/year floating offshore). BVG Associates provided a theoretical estimate of almost 20,000 TWh/year and technical estimate of around 5,500 TWh/year.[1]

On economic potential, Cavazzi and Dutton (2016) suggested that 1,450 TWh/year is available offshore at an LCOE less than £140/MWh.[9] However, we consider this LCOE benchmark to be outdated and too high for any updated assessment as LCOEs for offshore wind have declined rapidly in the past decade. We note that OVG's (2010) central LCOE estimate for 2050 is higher than BEIS' most recent LCOE estimates for 2025 (BEIS, 2020, p. 34) – costs declines are 25 years ahead of 2010 expectations. An analysis from BVG Associates (Hundleby and Freeman, 2017) suggested that in a scenario of strong technological improvement, 2,700 TWh/year in UK wind resources would be available for less than £65/MWh by 2030 (with 1,580 TWh/year for less than £60/MWh). Again, faster-than-expected declines in the costs of offshore wind construction should ensure that this resource is available at an even lower LCOE by 2030. In their 2020 report, BEIS shows that their 2030 LCOE estimate for onshore (offshore) wind declined 30% (54%) in the four years between their 2016 and 2020 estimates (BEIS, 2020, p. 34). Vivid Economics and Imperial College London (2019) agreed with the BVG estimates for offshore wind, updating estimates on onshore economic resource to 96-214 TWh/year. Arup notes that on a capacity basis, UK net zero ambitions require offshore wind deployment of 40GW by 2030 and around 140GW by 2050, equivalent to 175 TWh/year and 610 TWh/year with a 50% capacity factor (Arup, 2022).

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[8] This figure is annualised from a reported figure of 1470 TWh/month in Weiss *et al.* (2018).
[9] In their study, 675 GW is available at a cost less than £120/MWh and 2,890 GW at less than £160/MWh.

The practical potential for wind in our estimates is driven by two key assumptions: i) the land/water area available to build wind turbines and (ii) the turbine used (including its height, diameter, and efficiency). The first assumption, area available for wind farms, influences the number of turbines that can be installed at a given array spacing. When it comes to the selected turbine, height assumptions are particularly important to define—wind speed increases non-linearly with height, meaning that wind power is very sensitive to height. A 10% increase in wind speed corresponds to a 33% increase in power.[10] Turbine diameter defines necessary spacing. Turbine efficiency considers how much electrical energy can be generated by kinetic wind energy, defining an effective power profile or capacity factor. Other assumptions are relatively uncontentious, such as observed average wind energy at high-potential GB site locations and predictable losses that come in the process of generating electricity. The rest of this section provides explanation for each of the key assumptions in turn, comparing these to the influential estimates of MacKay (2008).

3.1 Approach

We used a bottom-up approach based on existing literature to quantify the practical wind energy resource of GB in three categories: onshore, fixed offshore, and floating offshore wind. For each category, we identify the relevant land/water area and selected these zones in the Global Wind Atlas v3.0 (GWA3; Davis *et al.*, 2019). The Atlas provides downscaled data on global wind speeds for the windiest decile of selected locations over time, attributes most of interest for commercial developers. We consider at a resolution of 250m and at five different heights (from ERA5 reanalysis; see Hersbach *et al.*, 2020).[11] Exporting generalized wind climate files from the Atlas, we found average wind characteristics for the relevant areas (see Figure 1), reported as Weibull shape and scale parameters.[12]

[10] $Power = \frac{1}{2}\ x\ air\ density\ x\ swept\ area\ x\ wind\ speed^3$, *i.e.*, $P = \frac{1}{2}\rho A v^3$.

[11] It appears that ERA5 provides better estimates than the closest alternative, MERRA-2, however, it is so far not clear that GWA3 provides any improvement in simulation quality beyond ERA5 (Gruber *et al.*, 2022). For our purposes, providing average figures across large areas, differences in site-level accuracy are less concerning – GWA3 data was preferred over MERRA-2 for ease of accessibility.

[12] When combined in a two-factor Weibull distribution function, these parameters can accurately describe the distribution of wind speed in most given locations. The Weibull distribution model is a particularly versatile probability density function.

Scotland—on the aggregate—presents greater wind speeds than Wales or Britain, tending to be more exposed to east-moving Atlantic depressions and bearing the brunt of North Sea gusts. Next, we used the Weibull parameters to extrapolate average wind speed distribution.[13] We combined the average wind speed distribution with the power curve of an archetypal turbine,[14] finding a weighted measure of power output per turbine.[15]

To determine the number of turbines that might be practically installed, we considered the portion of land and water areas that is likely to be exploited for wind energy. To do so, we initially benchmarked against prior studies that restrict available land by technical factors like the slope of the land, existing vegetation, and distance to dwellings. We overlaid our own socio-political assumption, incorporating perspectives on political feasibility and success of social complaints against planning proposals. Next, we divided the total available land and water area by the effective footprint of an archetypal turbine to calculate the potential number of turbines.[16]

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[13] This was computed using a probability density function of typical two-factor Weibull form:

$$f(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot e^{-\left(\frac{v}{c}\right)^{k}}, c > 0, k > 0, v > 0,$$

where v is wind speed, c is the scale parameter, and k is the shape parameter.

[14] Power at a given wind speed (Pg) was calculated using function $g(v)$, where the shape of g varies by turbine but is broadly defined as *0* below cut-in wind speed, some value between *0* and the maximum (Pg_{max} when v is between cut-in speed and rated speed, Pg_{max} when v is between rated speed and cut-out speed, and 0 when v is above the cut-out speed.

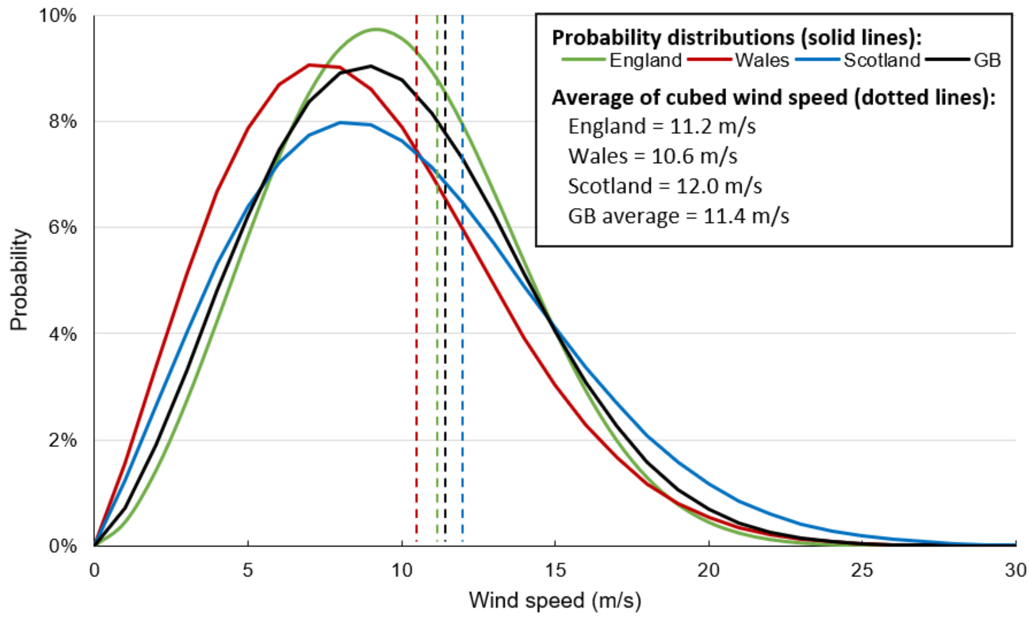
[15] Weighted power per turbine ($P_{turbine}$ was calculated as:

$$P_{turbine} = \sum_{0}^{v=max} f(v) \cdot g(v)$$

[16] Number of turbines, N was calculated from area practically available for turbines, A_p, and turbine blade diameter, D. Assumed spacing, on consultation with colleagues in wind engineering, is 7 times D, *i.e.*, width and length both equal to seven times the diameter of the turbine.

$$N = \frac{A_p}{7 \cdot D}$$

Figure 1. Wind speed distribution in the top decile of windiest areas in England, Wales, and Scotland.



Notes: Determined using the Global Wind Atlas v3.0 (GWA3; Davis *et al.*, 2019). GB average assumes wind generation will be split between constituent countries based on respective area (*i.e.*, weighted by land mass). Dotted lines indicate the average of cubed wind speed in each constituent country.

To compute total practical wind power available, we multiply the number of turbines by the expected power output per turbine.[17] We apply a discount that addresses array and downtime losses, collectively covering maintenance losses, wake impacts, and other effects not captured by the reference power curves (*i.e.*, net losses compared to technical optimum).[18] After calculating theoretical outputs using archetypal reference turbines and GB wind resources, we *further* discount our estimates with a *practical loss assumption* to recognise that calculated capacity factors approach widely accepted forward estimates of 35% for onshore and 55% for offshore.[19] Physical and loss assumptions are further described and discussed in the supplementary methods.

[17] *i.e.*, $P_{beforelosses} = P_{turbine} \cdot N$

[18] Total Power, P, is calculated by subtracting array losses, α, from $P_{beforelosses}$

$$i.e., P = P_{beforelosses} \cdot (1 - \alpha)$$

[19] For offshore, DNV GL (2019) suggested load factors to 52.9% by the 2030s, while BEIS (2019) provided a factor estimate of 58.4% in its Contracts for Difference Allocation Round 3 Framework. Edwardes-Evans (2020) reported that BEIS' offshore benchmarks will rise to 57% in 2030 and 63% in 2040. The BEIS estimate seems in line with the pathway of current technological trends – for instance, Energy Numbers (2022) shows that Hywind Scotland has a lifetime capacity factor of 53%, while the highest prior capacity factor comes from a farm only three years older, Westermost Rough, 47%, and the highest prior to that (three years older again) is Walney phase 2, 45%. For onshore, Edwardes-Evans (2020) reports that BEIS' offshore benchmarks will rise to 34% in 2025 – it seems inevitable that these will rise further in subsequent years.

3.2 Area assumptions

3.2.1 Area for onshore wind

The total land area of GB is just over 237,000 km^2 (Rae, 2017). In his 2008 book, MacKay suggested that 10% of UK land might be the upper limit for wind turbines based on technical factors. After "public consultation" (although it is unclear when, which subjects, and what methodology his hypothetical consultation was assumed to follow), he implied that a practical figure was more like 1.5%. McKenna *et al.* (2015), Eurek *et al.* (2017), Enevoldsen *et al.* (2019), and Ryberg *et al.* (2020) suggested much higher technical figures. Respectively, they considered that on technical grounds, about 18%,[20] 44%,[21] 26%,[22] and 24%[23] of land is suitable for capturing high winds, after accounting for buildings, infrastructure, conservation areas, and other restricted areas. What might explain the difference between these estimates and MacKay? In comparison to these other estimates, Mackay's technical figure appears arbitrarily selected and the low practical estimate is likely linked to hypotheses on public perception. MacKay was exposed to "a very noisy and vociferous" opposition to wind energy (Bell *in* Reuters Staff, 2012) but a decade later, 74% of surveyed British voters said they would support more windfarms on UK soil (Opinium, 2022).[24] Even in the constituencies most opposed to onshore

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[20] McKenna *et al.* (2015) used a suitability factor matrix to identify what portion of each land type might, on average, be suitable for wind turbines. For instance, 0% of estuaries but 40% of areas used for agriculture and forestry. These suitability factors are derived from Held (2010) and Hoogwijk *et al.* (2004). The suitability criteria are harsher than later studies but do not incorporate a consideration of wind speed.

[21] Eurek *et al.* (2017) excluded protected areas, permafrost, elevations above 2,500 m, and slopes above 20%. They then applied a suitability matrix, discounting available land by a certain percentage according to type (*e.g.*, rainfed croplands are discounted by 30%) using Hoogwijk *et al.* (2004). Their estimate is significantly higher than Enevoldsen *et al.* (2019) and Ryberg *et al.* (2020), because they only consider paved surfaces as "urban", while the others take those surfaces and apply a buffer area around them for safety or social reasons.

[22] Enevoldsen *et al.* (2019) describe their estimate as a "socio-technical analysis". The factors considered are similar to those in a purely technical analyses except that buffer zones are incorporated to eliminate land nearby to prior structures (rather than consider only the physical footprint of the structure). The motivation for buffer areas is partly a social one – to avoid complaints from the public. In this way, it might be considered somewhere between a technical analysis and an optimistic practical analysis. The authors account for infrastructure, buildings (including existing turbines), and protected areas, with buffer zones (200m for infrastructure and 1km for buildings). They did not use suitability criteria as others do. Using figures from their supplementary materials we assumed that available area in Great Britain is roughly comparable to the British Isles, calculating available area of (1 - 232,235 km^2 / 313,883 km^2) x 100% = 26.0%.

[23] Ryberg *et al.* (2020) provided perhaps the most comprehensive analysis, similar to the Enevoldsen approach, except with a suitability matrix, buffer zones that vary by infrastructure type, and extra exclusion criteria based on wind speed (only includes average speed >4 m/s), proximity to grid connections, and access points.

[24] This poll also showed consensus along political lines. 79% of voters supporting the Tories said they were in favour, compared to 83% of those supporting Labour and 88% of those supporting the Liberal Democrats.

wind today, a vast majority – 64% of people – support more installations (RenewableUK, 2022).[25] A US study found that residents living near wind turbines have positive attitudes towards the facilities, with polled participants expressing a willingness to pay to *keep* a nearby wind turbine in place – compared to a willingness to pay to *remove* a nearby coal facility (Thomson and Kempton, 2018). However, polls considering hypothetical scenarios do not necessarily reflect practical public acceptability, particularly when it comes to local infrastructure (*i.e.*, the not in my back yard phenomena, NIMBY) and this should not be taken for granted. While most people may support more wind, they may do so quietly, with their voices drowned by a minority in noisy opposition.

There is significant scope to increase acceptability for onshore wind, both by elevating the voices of those already in support and by demonstrating value to those in opposition. For example, through emphasising local community benefits of investment (Walker et al., 2014). The Winser report highlights opportunities for Government information campaigns to build greater understanding of the importance of energy system transformation across the UK (Winser, 2023). Further work can build from the understanding that more exposure to wind projects and greater concern for climate change have both likely contributed to higher public acceptability already in the UK (Cronin et al., 2021; Umit and Schaffer, 2022). There has also been greater understanding that wind turbines tend to be co-located with cropping and livestock rearing – they do not require significant changes to current British farming practices. Wind farms may even provide a minor boost to crop yields by supporting positive microclimate changes to factors like temperature, moisture, and CO_2 levels (Kaffine, 2019). The Farm Business Survey further indicates that community ownership and smaller-scale wind farms on existing agricultural or degraded land allows for diversified revenue streams for farmers (DEFRA, 2015).

For this study, we conservatively estimate that 5% of British land might be practically available in the near term for collocation of onshore wind with agriculture, accounting for one thirteenth of total agricultural lands (the figure could be higher with further social shifts to 2050) (DLUHC, 2022). This

[25] In the most favourable constituencies, over 94% of people support more onshore wind.

would mean only 0.05% of GB land being physically covered by turbine infrastructure (*i.e.*, for turbine towers, roads, and associated infrastructure) – by comparison, 0.9% of English land is disfigured for mining and quarrying (Bloodworth et al., 2009). To arrive at the 5% figure, we took an average over McKenna *et al.* (2015), Enevoldsen *et al.* (2019), and Ryberg *et al.* (2020), to find that the socio-technical portion of onshore land that might be considered for onshore wind is in the vicinity of 23%. We then, conservatively, discounted this figure by 75% and rounded down, to recognize that (a) not all landowners (mostly farmers and loggers) might be open to installing turbines on their land, even if financially compensated and (b), although it is shrinking, there remains a portion of politicians and community members who are likely to counter attempts to install new turbines.[26] We imagine that over time, short-term political and social complaints might be superseded by the long-term environmental, economic, and social interests of GB. In this latter case, discounting of the technical potential for wind might be based more on land use practicalities than political considerations.[27]

3.2.2 Area for offshore wind

We find practical estimates of 2,500-12,000 km^2 and 62,000 km^2 for fixed offshore and floating offshore wind respectively. Estimating offshore area is bounded by fewer technical constraints compared to onshore. Suitable locations are those that do not overlap with existing marine protected areas, commercial shipping or transit lanes, or military zones. Locations must be in zones of sufficiently high wind speed, far enough away from the shore to not overly impair any existing visual amenity. Appropriate tracts need to be large enough to make development commercially viable (considering connection and administrative costs). For fixed turbines, water depth and the gradient of the ocean floor are also important. OVG apply these constraints to identify 3,400-16,000 km^2 available for additional fixed wind and around 62,000 km^2 for floating, of which around 34,000 km^2 is within 100

[26] At the time of writing, an effective moratorium on new onshore wind is in place in the UK.

[27] Here, *land use practicalities* refer to case-by-case physical or other obstructions that might constrain installation in some locations. For example, existing hedging might mean that a buffer zone to a particular agricultural home need be 1km rather than the 800m threshold used in Ryberg *et al.* (2020).

nautical miles of shore.[28, 29] Respectively, this is equivalent to 0.4-2% and 8% of the UK's EEZ.[30] Vivid Economics and Imperial College London (2019) confirm the validity of the OVG approach and findings.

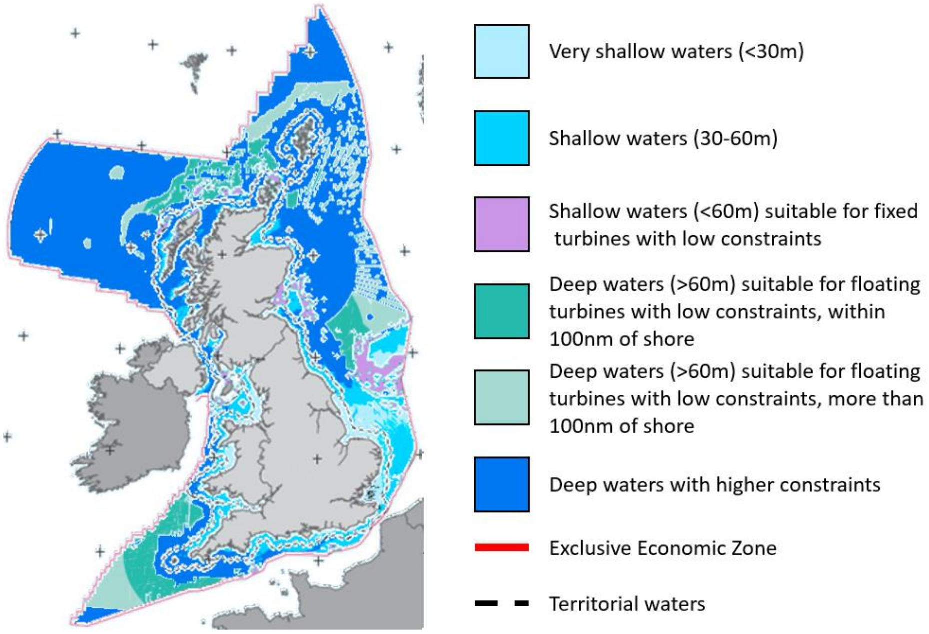
For a practical estimate, we conservatively discounted available fixed area by 25% to account for social and political concerns related to visual amenity. We considered that turbines located within 25 miles of shore might impose minor visual impact, while those situated more than 25 miles from shore would have negligible impact (NYSERDA, 2017). Since the majority of OVG's fixed resource is located more than 25 miles from shore (Figure 2), the fixed wind discounting is relatively minor. We do not apply such a discount for floating offshore wind; most deep locations are out of sight, and do not face substantial political or community opposition. We note OVG's estimates incorporate a range of physical restrictions.

[28] Assumptions in this analysis include that the minimum area for commercial viability is 10 km^2, that a depth limit of 60m is relevant for fixed offshore "in line with the deep-water sites allocated by The Crown Estate in round 3", and a depth limit of 700m for floating wind based on limits in anchoring technology. We expect the fixed offshore depth constraint to relax with improved technology; Paya and Zizeng Du (2020) consider that 80m depths might be within reach thanks to structural advances, better mapping of soil, wind, wave and climate conditions and improved manufacturing capabilities.

[29] In terms of geographic spread, sea adjacent to the English coastline contains ~55%-60% of the total fixed and floating resource while Scottish waters contain ~40% of fixed and ~35% of floating. Welsh waters contain the balance.

[30] The EEZ overlaps directly with the UK Renewable Energy Zone (REZ) declared in the Energy Act 2004 as the area of the sea available for energy production.

Figure 2: Offshore areas with low constraints and high wind speeds.



Note: Adapted from Cavazzi and Dutton (2016), OVG (2010). Low constraint zones in deep waters are those with <20% constraint aggregates in OVG. Regions already offered in CfD's Licensing Rounds 1-3 are highly constrained for the purpose of our analysis and not shown.

Both our technical and practical estimates are higher than those considered by MacKay (Table 2). MacKay estimated 120,000 km^2 technically available for offshore, considering depths to 50m only. To account for shipping corridors and other competing uses, he applied a two-thirds discount, offering technical estimates of 40,000 km^2. He then further discounted to a practical estimate of 5,000 km^2 "after public consultation", ostensibly to incorporate concerns associated with cost, engineering difficulty and public acceptance (regardless of distance to shore). His estimates are only 7-8% of our calculations. We explain this discrepancy with three considerations. First, much like onshore wind, we have seen strong improvements in structural engineering for fixed offshore wind. Most obviously, fixed turbines could soon be commercially feasible at up to 80m depth (Paya and Zizeng Du, 2020), deeper than the 50m technical limit that MacKay had imagined. Indeed, Mackay described all depths beyond 30m as "not economically feasible". Secondly, the advent of floating turbines has provided access to the full EEZ of GB, opening enormous swaths of the sea closed during MacKay's analysis. We conservatively accounted in our calculations for a much broader range of competing uses for the ocean. While MacKay's primary concern was shipping routes, in using OVG's estimates, we also accounted for marine areas, military zones, proximity to shore, and low wind speed locations. However, even after accounting for these extra limiting factors, our technical estimates remain higher than MacKay's because of the technological advances. Finally, much like with onshore wind, on social and political factors, we are much more optimistic than MacKay.

Table 2. Offshore wind area assumptions in this study compared to MacKay (2010).

	Our study	**MacKay (2010)**
Technical area (km^2)		
• Fixed	3,400-16,000	40,000
• Floating	62,000	0
• Total	65,400-78,000	40,000
Practical area (km^2)		
• Fixed	2,500-12,000	5,000
• Floating	62,000	0
• Total	64,500-74,000	5,000

3.3 Turbine selection

3.3.1 Turbine selection for onshore wind

Wind turbine technology has advanced significantly since MacKay's (2008) assessment, resulting in lower costs and higher capacity to reliably capture wind energy (IRENA, 2022a). Thanks to lighter and stronger materials, rotor diameters have increased – more energy can now be captured per turbine, with increased efficiency and lower variability (Johnson, 2021). Following improvements in structural engineering, towers have become taller, allowing turbines to access stronger and more consistent wind speeds at higher altitudes (Lantz *et al.*, 2019). Turbine blades have become more aerodynamic, reducing turbulence and noise and increasing power output. Turbines are now equipped with more sophisticated control systems that optimize energy capture, improve reliability, and reduce downtime (Traiger, 2018). Such improvements have enabled higher capacity factors, improved operational consistency and greater energy output, in turn bringing benefits for cost-effectiveness and of reduced environmental harm. DNV GL (2019) provides a list of additional technological developments set to further improve the commercial attractiveness of wind.

In our study, we consider the NREL 7 MW 2020 reference turbine as archetypal for future onshore UK wind; we provide power curve data for eight other turbine types of various size (see Supplementary

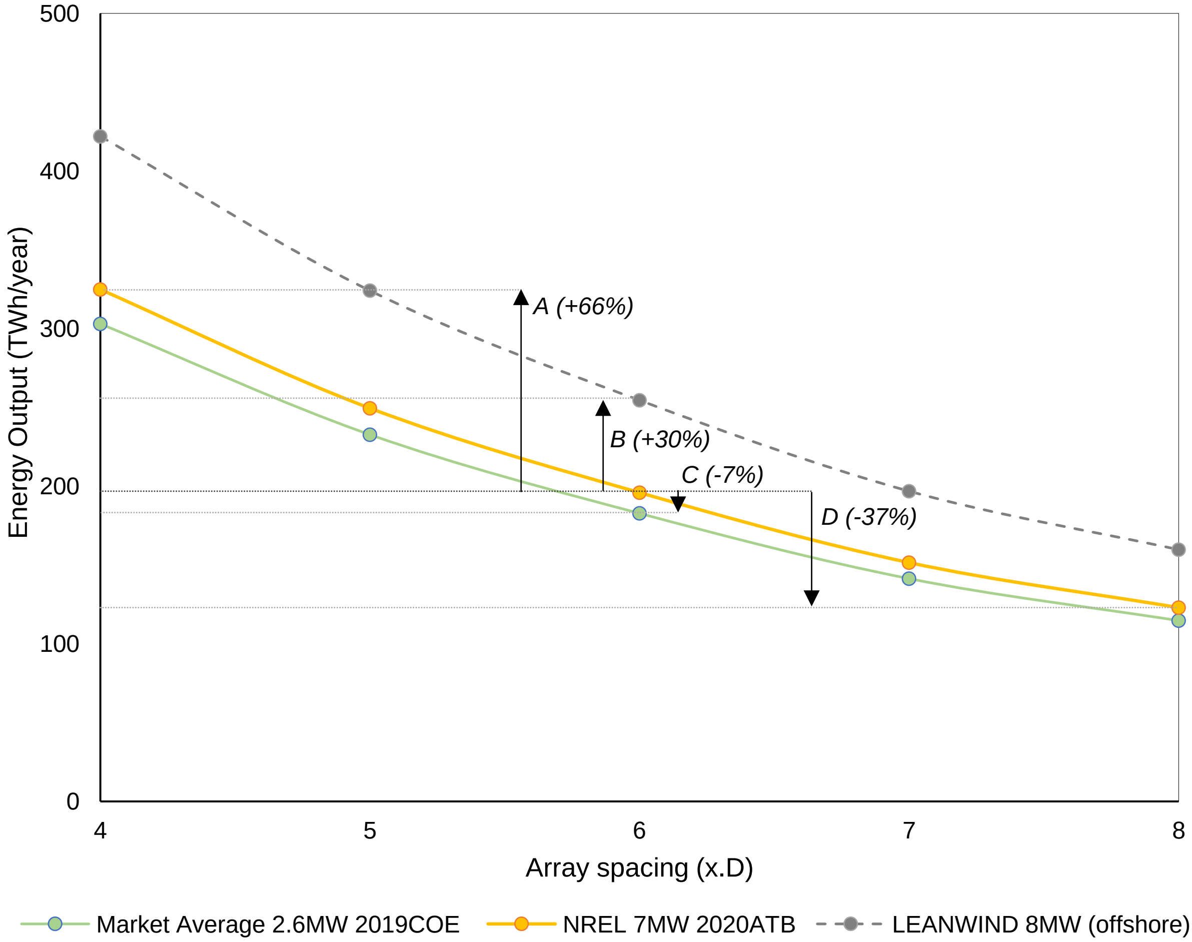
Figure 1). While the average installed onshore GB turbine currently has 1.6 MW capacity (UKWED, 2022), this figure is heavily influenced by older turbines of past technological generations. 6.6 MW turbines were selected for the Scottish Longhill Burn project in 2021 (Ford, 2021) and similarly sized turbines were included in the Environmental Impact Assessment for the Scottish Teviot project (Rajgor, 2022). Vestas are producing 7.2 MW 199m tall turbines (Vestas, 2022a).

The selected reference turbine, although large, is conservative in its output, modelled to generate only 7% more energy across GB compared to the current market average.[31, 32] There are many open questions on the accuracy of reference turbine power curves, particularly when applied across large arrays (Lee *et al.*, 2020; Sohoni *et al.*, 2016); we therefore provide supplementary data for the reader to experiment with other turbine types and spacing assumptions.

[31] A US market average reference turbine was used in the absence of UK data (2.3 MW 2019COE compiled by Stehly *et al.*, 2020). IEC normalised industry composites and WTK validation turbines were not considered due to the absence of information on rotor diameters.

[32] How can this be? After accounting for height increases, higher turbine power capacity tends to depend on longer blades, which in turn increase spacing. In other words, using larger turbines means we cannot use as many turbines. Furthermore, the larger reference turbines have been designed for relatively slower wind speeds than those in the UK (*i.e.*, we have taken a conservative approach).

Figure 3. Impact of turbine selection and array spacing on modelled GB onshore wind power.



Notes: Relative to our central assumption of a NREL 7 MW turbine, spaced at 6D, arrows and italicised figures indicate sensitivity in energy output. These are calculated, respectively, for (A) our selected turbine at the selected array spacing to the same turbine at a lower spacing, (B) our selected turbine at the selected array spacing to a larger capacity turbine at a the same spacing, (C) our selected turbine at the selected array spacing to the smaller, 2019 US market average, turbine at a lower spacing, and (D) our selected turbine at the selected array spacing to the same turbine at a higher spacing. Changes in array losses, due to changes in spacing, were based on approximate author estimates.

3.3.2 Turbine selection for fixed and floating offshore wind

For consistency with our onshore turbine selection, we again considered NREL/IEA reference turbines. We selected the NREL 15 MW 2020ATB (NREL, 2020) as 15 MW turbines are some of the largest size commercially available and have already been selected for fixed wind in British (Memija, 2022) and Korean floating wind projects (Vestas Asia Pacific, 2022b). It is likely that turbine capacity will approach and exceed 20 MW (see Shields *et al.*, 2021), however without reference turbines of that scale, we are unable to compute generated energy.[33] Therefore, we conservatively settle our estimates on the NREL 15 MW turbine.

3.4 Wind results

3.4.1 Results for onshore wind

We estimate that onshore wind energy output could practically approach 206 TWh/year in GB over the next decade (Table 1, see Supplementary Table 1 for detailed results) and with increased political and social appetite, possibly much higher by 2050. This figure is over three times that proposed by MacKay but less than his technical resource. It is only 5% of the technical resource suggested by Lu *et al.* (2009) (see Supplementary Table 1 for other prior estimates). There are three primary reasons for higher estimates than MacKay: i) a taller reference height, ii) improved social acceptability, and iii) an application of a methodology that is more technically appropriate in determining optimal power outputs.

Rated turbine power is a lesser factor for total energy output but a major factor for the number of turbines required. In Supplementary Figure 2, we demonstrate the impact of increasing reference height while holding all else constant. To reach the practical estimate (206TWh/year), around 8,200 7 MW turbines would be required (58GW total). Alternatively, this could be done with 22,500 smaller 2.6 MW turbines and a lower spacing requirement.

The physical land required for the 7 MW turbines is approximately 170 km^2, 0.07% of GB land.[34] For the 2.6 MW turbines, the figure is similar. This affirms that agricultural production would be unchallenged by massively expanded onshore wind. We note the increasing trend for land between turbines being shared with alternative productive economic activity, including cropping, forestry,

[33] Sartori *et al.* (2018) provide a definition for a 20 MW turbine, however they focus on design characteristics and do not include a reference power curve.

[34] Calculated using NREL's 2009 guide of 0.3 hectares per MW of rated capacity. This figure considers permanently impacted land for access roads, substations, and tower pads, but might be an overestimate; Harrison-Atlas *et al.* (2022) suggested that land use intensity is trending downwards.

transportation, and even utility-scale solar farms. Lovins (2011) suggested that "saying that wind turbines 'use' the land between them is like saying that the lampposts in a parking lot have the same area as the parking lot: in fact, ~99% of its area remains available to drive, park, and walk in".

Perhaps the most ambitious onshore wind target considered by the UK government to date was 45 GW of installed onshore wind by 2035 (Riley-Smith, 2022). Based on our estimates, this appears practically highly feasible.

3.4.2 Results for fixed and floating offshore wind

We estimate that energy output from offshore wind could practically exceed 2,100 TWh/year in GB (Table 1, see Supplementary Table 1 for detailed results). This incorporates the theoretical capacity of zones auctioned in the first three UK leasing rounds and in the Scottish Territorial Waters (47.3 GW, 165 TWh/year).[35] In context, this total figure is 140% that of our conservative estimate of total energy demand in 2050. We consider this a significant opportunity. As with onshore wind, the estimate is significantly higher (24 times) than the practical resource proposed by MacKay. The primary drivers of the increased estimate are i) stronger political and social support in favour of offshore wind, ii) improved technology allowing for more efficient turbines, and (iii), the advent of commercially-viable floating wind turbine foundations.

To provide 2,100 TWh/year, around 30,000 15 MW turbines would be required (460 GW total), each providing power output of approximately 209 W/m^2 of rotor area (177 W/m^2 after loss factors) or 2.6 W/m^2 of sea area (2.2 W/m^2 after loss factors). Together, these turbines would influence approximately 23,500 km^2 of the British sea, equivalent to 3.0% of the EEZ.[36]

[35] It is necessary to add these to the calculation as the area estimates of OVG considered only opportunities for offshore in unauctioned zones, using 2010 as its base year.

[36] Space required is based on a conservative 500m exclusion zone around each turbine, less than the spacing requirement (Maritime & Coastguard Agency, 2022). The physical footprint of new turbines is roughly 0.00008% of the EEZ for fixed offshore and 0.0003% for floating offshore.

4. SUPPLY FROM SOLAR

We find that **569 TWh/year could be practically available from GB solar**. This is based on assumed adjusted solar irradiance of 52.4 W/m^2 (the average incoming solar energy per unit area of solar farm over a 24-hour period) and solar cell efficiency of 25% (the portion of incoming energy captured by the cell). We find both rooftop solar and utility-scale solar farms provide potential in the UK, although utility-scale solar estimates are considerably higher:

- **544 TWh/year utility scale**, assuming 2% of GB land area (4,740km^2) would hold panels, and
- **25 TWh/year rooftop**, assuming 8% of GB roof area (217 km^2) would hold panels.

Solar potential is calculated as (*irradiance × cell efficiency × available land × hours in a year*).[37] Table 3 summarises our estimates for practical solar potential and major assumptions. The supplementary materials contain detailed calculations for solar panel spacing and tilt factors.

Table 3. Summary of Great Britain's total solar resource.

	Utility-scale solar	*Solar on rooftops*
Effective irradiance (W/m^2)	52.4	52.4
Efficiency (%)	25.0%	25.0%
Area (km^2)	4,740 (2% of GB land)	217 (8.3% of roof space)
Hours/year	8,760	8,760
Total energy per annum (TWh/year)	**544**	**25**

In 2022, the UK had 14 GW of installed solar capacity, of which over 5 GW was rooftop panels (Solar Energy UK, 2022; IRENA, 2023). For comparison, France had 17 GW, the Netherlands has 23 GW, and Italy had 25 GW (IRENA, 2023). High cloud cover limits the hours of strong solar irradiation in GB, however, significant technological advances mean that GB solar installations in 2023 could generate

[37] For example, for utility-scale solar, $52.4\frac{W}{m^2} \times 25\% \times 4{,}740km^2 \times (365 days \times 24 hours per day) = 544\,TWh/year$. 4,740 km^2 is 2% of GB land.

as much, or more, energy as some sunny Australian locations in the early 2000s.[38] In other words, GB's relative lack of sunshine is not prohibitive to large-scale solar electricity generation. In fact, solar can be a critical addition to wind and battery or other storage for load-balancing in a high-renewables grid.

Prior works to establish solar potential in the UK include MacKay (2008) on theoretical, technical, and practical resource, Palmer *et al.* (2019) on technical and practical resource, and Vivid Economics and Imperial College London (2019) on practical/economic potential. Several other studies have considered only rooftop potential, for instance Joshi *et al.* (2021) who find that UK rooftop solar could generate somewhere between 57-343 TWh/year depending on panel efficiency and rooftop scaling factor.[39] Given the pace of technological development in solar PV, many of the results in these studies are now out of date, however, their methodologies are insightful. MacKay (2008) calculated a utility-scale technical resource of 1,100 TWh/year assuming 10% of UK land, 10% cell efficiency, and irradiance of 110 W/m^2. He also estimated that 10% efficient cells covering all south-facing rooftops would deliver 108 TWh/year. Moving from technical resource to practical resource, he characterised solar as too expensive in the long run to substantially contribute to the UK's energy mix, reducing total potential to 43 TWh/year. Palmer *et al.* (2019) took a first-principles approach, considering suitable land under seven constraint factors including irradiation, land type, distance to grid, and slope. They estimated a potential of 479 GW in solar power for the UK, variable to tightening or loosening exclusion criteria. Vivid Economics and Imperial College London (2019) estimated that 616-1,102 GW of large-scale solar and 37 GW of rooftop solar is practically and economically available under tight constraints and over 1,102 GW under loose constraints. That said, the authors did not consider social or political desirability.

[38] Average irradiance in the UK is 101.2 W/m^2 (Burnett *et al.*, 2014). Average irradiance in Sydney, Australia is approximately double this (Paltridge and Proctor, 1976). The efficiency of commercially available solar cells has more than doubled since the early 2000s.

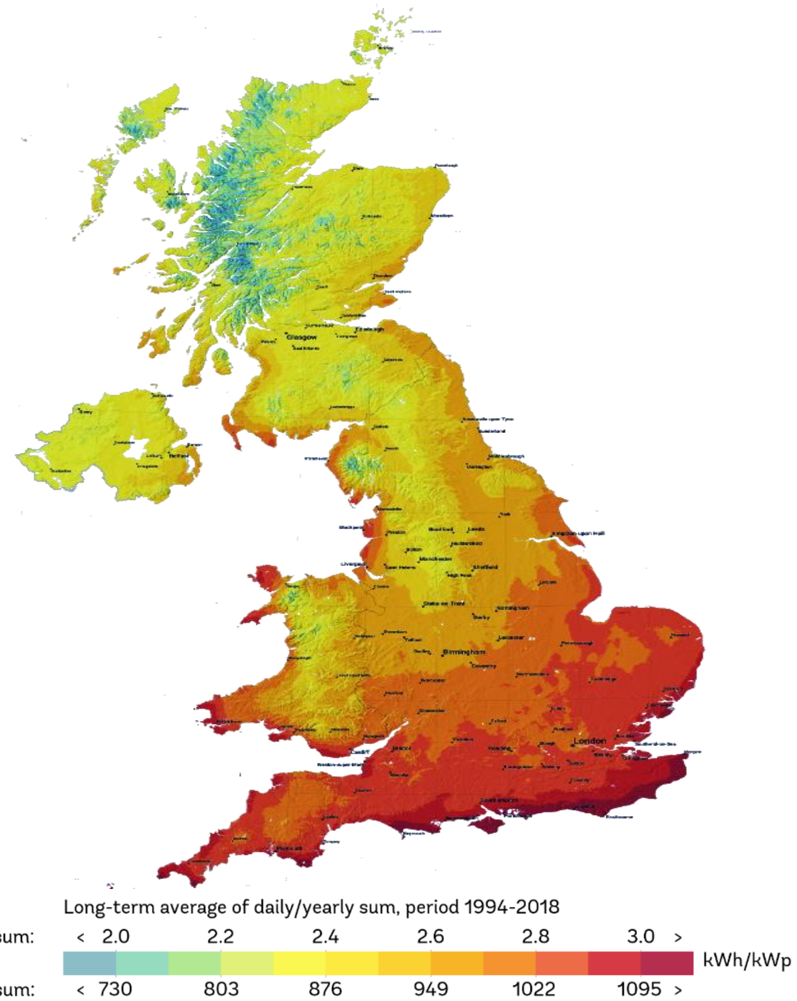
[39] 343 TWh/year occurs with panel efficiency of 18% and rooftop scaling factor of 80%. The rooftop scaling factor proxies to reduce total rooftop area through considering orientation, slope, and roof superstructures (*i.e.*, other structures taking up roof space).

The rest of this section provides explanation for each of our three key solar assumptions In turn, comparing these to other estimates and particularly to that of MacKay (2008).

4.1 Irradiance assumption

Solar irradiance averages 101.2 W/m^2 across the UK, ranging from 128.4 W/m^2 in southern England to 71.8 W/m^2 in northwest Scotland (Burnett *et al.*, 2014). These figures are averages, rather than peaks, meaning they account for hours of cloud cover as well as nighttime. As the UK continues to expand its solar electricity generation, we expect that a higher portion of utility-scale panels may be constructed in the South of England, where irradiance is higher (Figure 4).

Figure 4. Average solar PV electricity potential across the UK.



Notes: The figure incorporates global horizontal irradiation and direct normal irradiation, measured in kilowatt-hours of produced energy (kWh) per kilowatt-peak of installed capacity (kWp), representing the annual energy yield of a solar installation. Adapted from World Bank Group (2020) image created with Global Solar Atlas 2.0 data.

Captured irradiance can be increased by tilting solar panels towards the sun. Breyer and Schmid (2010) showed that effective irradiance can be increased by 10-20% in the UK with optimal panel tilting (around 40˚), or even higher if panels 'track' the sun by mechanically changing their angle during the day. Viridian Solar (n.d.) found that optimal angles in the UK are around 35˚, which fortunately matches the slope of most roofs.

However, there is an interdependency between the tilt of a panel and the spacing between panels. The angle of panel tilt is optimised based on latitude (a greater tilt is required further away from the equator). However, higher tilts entail larger shadows, especially in the winter months when solar declination is low. Higher shadows lead to a higher spacing requirement between panel rows. In addition to spacing between rows, edge spacing is needed to give distance from trees and other obstructions. Indicative total relative spacing required for solar farms at different locations in GB can be found in Table 4. We base our estimates of average solar potential on the irradiance in Birmingham, which is conservative because a disproportionate number of solar farms are likely to be installed further south.

Table 4. Solar farm spacing requirements for differing GB locations.

Location	*Spacing*	
	Unit Spacing (%)	**Net Spacing (%)**
Edinburgh	**43%**	**60%**
Birmingham	**34%**	**55%**
Plymouth	**31%**	**52%**

Notes: Unit spacing considers spacing between solar panel rows. Net spacing incorporates both unit spacing and additional spacing around the perimeter of each field, considering a small (conservative) field of dimensions 120m x 120m.

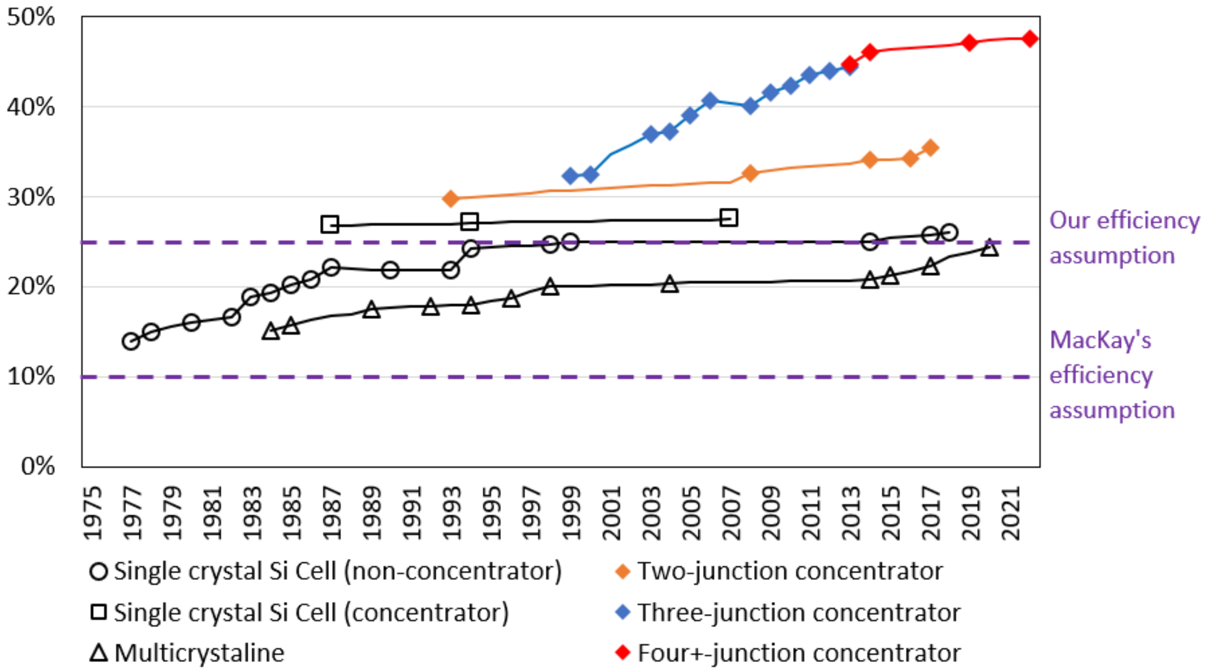
Considering an average irradiance for GB of 101.2 W/m^2, we cut our estimate by 55% for spacing (net), and add 15% for optimised tilt, to reach an adjusted GB irradiance of 52.4 W/m^2 for solar farms.[40]

[40] *I.e.,* (1-55%) x (1+15%) x 101.2 W/m^2 = 52.4 W/m^2.

4.2 Cell efficiency assumption

The efficiency with which solar (PV) cells can convert light energy into electricity is increasing rapidly (Figure 5). In 2022, Fraunhofer ISE set a new record for cell efficiency: 47.6% percent, using a four-junction solar cell (Fraunhofer ISE, 2022). Also in 2022, researchers exceeded 30% efficiency for the first time without a multi-junction cell, using a tandem perovskite solar cell (see Ernst, 2022). Emerging technologies like perovskite solar could significantly increase cell efficiency and broaden the use cases for solar technologies, for example, by integrating the technology into household paint to capture solar energy on exterior walls.

Figure 5. In-lab solar cell efficiency records.



Notes: our solar cell efficiency assumption (25%) and MacKay's assumption (10%) included as pink dotted lines. Data source: NREL, 2022.

It is unlikely that anything other than bulk-standard single crystal silicon cells were considered by MacKay. Indeed, he noted that it would be "quite remarkable" for commercially available panels to achieve efficiencies greater than 30%. We can now expect that panels with even higher efficiencies will be cost competitive in the future, especially as such products become commercially available and benefit from economies of scale (Gallucci, 2021; Green *et al.*, 2023).

Already, mass-produced n-type solar modules are available at efficiencies above 25%, although many are in the 20-25% range (see Bellini, 2022; Longi, 2022). We expect that continued technological progress will continue to drive up efficiencies for mass-produced modules. On the other hand, practical installed panel efficiencies are lower than technical power conversion efficiencies and it is important to also consider the effect of dirt accumulation on reducing available electricity. Taking these factors into account, we assume 25% efficiency for PV cells.

4.3 Area assumption

4.3.1 Utility-scale solar

As discussed in the wind analysis, the total land area of GB is just over 237,000 km^2 (Rae, 2017). In England, 63% of land is agricultural, 21% forest, open land and water, 8% 'developed' (*e.g.*, urban areas, transportation, utilities, and industry), 1% undeveloped or vacant, and 0.1% minerals and landfill (MHCLG, 2020). In Scotland and Wales, land use skews even more strongly to agriculture; about 80% of Scottish land is agricultural. However, a significant portion of ostensibly agricultural lands is non- or under-productive (Scottish Government, 2018).

This might provide opportunity for dual-use "agrivoltaic" systems, where solar is mounted above lower-maintenance crops or grass grown for livestock, with multifarious benefits including for biodiversity (Adeh *et al.*, 2019; Montag et al., 2016). MacKay doubted any substantial use of arable land for solar would be politically plausible, let alone economically viable. He considered that 'Brits like using their countryside for farming and recreation rather than solar-panel husbandry'. However, this one-or-the-other approach seems to be less relevant today. Furthermore, as with wind, public sentiment for solar has improved dramatically; recent surveys reveal that 89% of the British public are supportive of further solar projects (BEIS, 2023). Political concerns are also less prominent now than in 2008, particularly as solar projects have been demonstrated at scale, and support narratives on strengthening domestic energy security.

There is some literature evaluating the appropriateness of GB land for utility-scale solar, although far less than what is available for wind. Palmer *et al.* (2019) considered suitable land under seven constraint factors, including irradiation, land type, distance to grid, and slope, estimating that the UK could build 9,580 km^2 of solar (4.0% of UK area).[41] Under tighter constraints, excluding Grades 1,2, and 3 agricultural land, national parks, wooded areas, and flood zones, only 500 km^2 is available (0.2%). Under looser constraints, with a maximum distance of 10 km to the nearest grid connection, 80,820 km^2 of potential solar could be available (33.0%). Building from Palmer *et al.* (2019) and incorporating their own economic considerations, Vivid Economics and Imperial College London (2019) suggest 6-11% of GB land area is "potentially suitable for [solar] development".

Based on these prior works, and relatively low social or political pressure against new solar, we suggest that 2% of GB land could practically host solar (compared to MacKay's assumption of 5%). This could involve repurposing half of currently undeveloped land (1.5% of English land is undeveloped and percentages are higher in Scotland and Wales; DLUHC and MHCLG, 2019) and collocating solar PV with 2-5% of current agricultural land to solar PV.

4.3.2 Rooftop solar

As for rooftop solar, we focused exclusively on rooftops in England, which are more numerous and have exposure to higher solar irradiance. This is, of course, conservative, as many rooftops in Wales and Scotland are also suitable. The area occupied by buildings (domestic and non-domestic) in England is around 2% of total land area, or 2,600 km^2 (GLUD, 2005 as cited in Davies et al., 2011, p. 368). We assumed conservatively that total building area will remain the same (in reality, net building stock will continue to increase). Next, we assumed that, if encouraged by suitable incentives, half of all buildings might house solar panels by 2050.[42] However, not all roofs are suitably oriented, so we conservatively divided by three to account for mainly South-facing rooftops being used for panels (although,

[41] 479 GW multiplied by Palmer *et al.*'s (2019) 0.02 km^2 / MW "conversion factor".
[42] Almost one third of Australian roofs already host solar panels (Mercer, 2022).

certainly, East- and West-facing roofs can also generate significant power). We further reduced available area by 50% to account for purchased panels not exactly fitting roof area, and other restrictions (*e.g.*, chimneys and skylights) that prevent rectangular panels being effectively fitted. On this basis, we estimated that around 8.3% of the country's total roof area, 217 km^2, might be covered by solar panels by 2050.[43]

Based on their machine learning-supported geospatial analysis, Joshi *et al.* (2021) suggest that from 2,400 km^2 of available area, applying a conservative 20% rooftop scaling factor, 478 km^2 might be suitable for rooftop solar. This is very close to Jacobson's (2017) estimate of 488 km^2 under similar constraints. If the scaling factor is increased to Joshi *et al.*'s (2021) baseline of 40%, available area for rooftop solar rises to 960 km^2. In this context, our practical estimate of 217 km^2 appears very low, however we maintain it to be conservative.

4.4 Solar results

We estimate that **solar energy output could practically approach 596 TWh/year in GB, of which 544 TWh/year could come from utility-scale installations and 25 TWh/year from rooftop solar** (Table 3). This figure is close to half the technical figure proposed by MacKay in 2008 (1,100 TWh/year) but 13 times higher than his adjusted figure (45 TWh/year), which came "after public consultation" and his view of costs. It is 44 times higher than 2021-22 UK generation, which totalled 13.4 TWh (DESNZ, 2023b). The primary reasons for a higher practical estimate than MacKay's are: i) a higher value for solar cell efficiency, driven by significantly improved and cheaper technology, ii) the consideration that solar arrays can be collocated with certain types of agricultural production, and iii) the public's greatly improved perspective on the need for more solar energy.

Recently, the UK government set a target for 70 GW of solar energy in 2030. At a capacity factor of 11% (DESNZ, 2023b), this equates to 67.5 TWh/year. Based on our estimates this target appears not

[43] *I.e.*, 2,600 km^2 x 50% of all roofs x 1/3 x 50% effective roof area = 217 km^2.

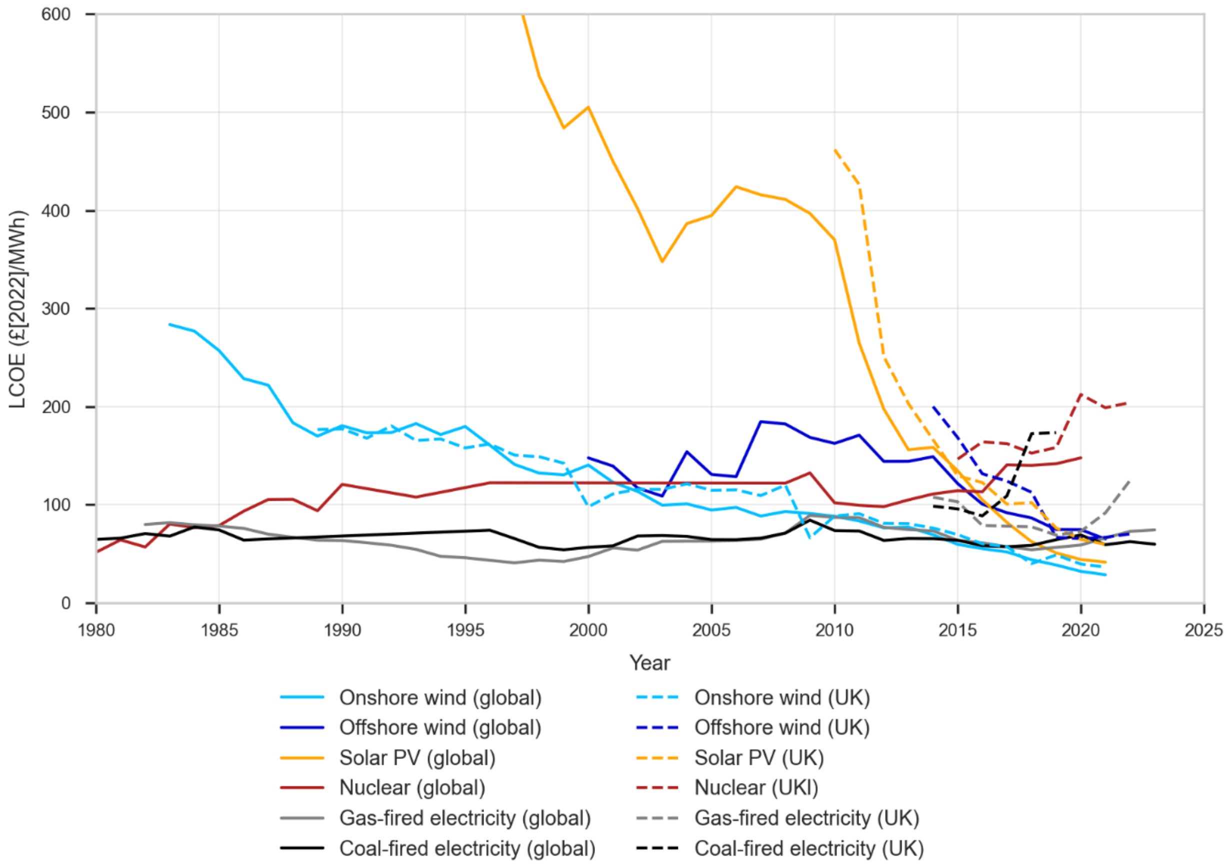
only readily attainable but lacking in ambition (provided that grid balancing and other integration needs are provided adequate attention). For context, by 2022 Germany already had 67 GW of solar PV, Japan had 79 GW, and between 2021 and 2022 alone, China *added* 86 GW of new solar PV capacity (IRENA, 2023).

5. COST CONSIDERATIONS

MacKay (2008) reduced his technical estimates of wind and solar electricity generation potential based on the socio-political climate of the time as well as prevailing costs. However, as discussed, the situation has dramatically improved in favour of renewable energy, due to rapid technological progress and cost declines, and a wider understanding of the urgency of climate change mitigation. As a result, there is no need to adjust our technical resource estimates downwards to yield practical resource estimates as Mackay did – they are identical. We like to think that MacKay would concur given his reliance on data in constructing his arguments.

Between 2008, when MacKay wrote his book, and 2022, the global average levelized cost of electricity for solar PV fell 91%, from around £405/MWh to £38/MWh (in constant 2022 dollars), for onshore wind it fell 60%, from around £93/MWh to £38/MWh, and for offshore wind it fell 62%, from around £183/MWh to £69/MWh (Lazard, 2008; IRENA, 2022a; BNEF, 2023a). On a global average LCOE basis, solar and wind are now cheaper than coal (£60/MWh), gas (£74/MWh), and nuclear power (£182/MWh) (BNEF, 2023a; all figures in constant 2022 pounds sterling), and are expected to remain so (Way *et al.,* 2022). Lithium-ion batteries declined in cost by 79% between 2008 and 2022, from £580/kWh to £122/kWh in 2022 terms (IEA, 2018, BNEF, 2023b). As a result, short-term grid-scale storage is now economic in many cases, and two-, three- and four-wheel electric vehicles are both widely available and, in many places, cheaper to own and run than internal combustion engine vehicles (IEA, 2023). As shown in Figure 6, these cost declines are part of much longer, stable, cost improvement trends, driven by efforts in research and development (R&D), innovation and commercialisation (Farmer and Lafond, 2016).

Figure 6. Long run trends in UK and global average levelized costs of electricity from various sources.



Notes: Data from IRENA, BNEF, and other sources described in Way *et al.* (2022).

These long-run cost trends have occurred in tandem with approximately exponentially increasing deployment, giving rise to a pattern known as the learning curve (or experience curve, or learning-by-doing), in which costs decrease by a constant percentage for every doubling of cumulative production (the percentage decrease is specific to each technology). Some technologies, especially those related to electronics and computing (including solar, wind, and batteries), follow relatively steep learning curves compared to other technologies, so that accelerated investment, R&D, and deployment is expected to lead to lower costs faster (Lafond et al., 2018). Despite these cost trends being well known since the early 2000s (Wene, 2000; Perlin, 2002; Nemet, 2006; Kohler et al. 2006), energy technology analysts have systematically overestimated future costs of solar, wind, batteries, and electrolyzers (Way *et al.,* 2022). Perhaps reflecting the energy system models of the time, Mackay also did not anticipate significant cost declines for solar and wind.

Modern models that use up-to-date cost data, and appropriately account for observed progress trends (among other features), find that energy transition pathways that are in line with the Paris Agreement, and therefore include high wind and solar deployment, are not only economically and practically achievable, but are most likely economically *beneficial* relative *to* slower decarbonization pathways (Glanemann *et al.,* 2020; Hänsel *et al.,* 2020; Way *et al.,* 2022; Van Der Wijst *et al.,* 2023). There is therefore no reason to consider costs – whether electricity generation, storage, or transportation costs – an inherent barrier to a high solar and wind future.

Regarding UK costs in particular, over the period 2010-2021 the installed cost of solar PV systems fell 86% from £5,363/kW to £734/kW (IRENA, 2022a), and the new-build LCOE fell 87%, from £462/MWh to £60/MWh. For onshore and offshore wind, despite capital costs only falling 17% and 36%, respectively, over 2010-21, the LCOE of newly commissioned installations fell 59% and 74%, to £36/MWh and £47/MWh, respectively. Through target commissioning years 2015/16-2023/24, the administrative strike price for UK Contracts for Difference (CfD) onshore wind allocations (>5MW) fell 54% from £95/MWh (£114.5/MWh in 2022 terms) to £53/MWh (National Grid Delivery Body, 2014; BEIS, 2022). For solar PV (>5MW), the administrative strike price fell 71% over the same period, from £120/MWh (£163.8/MWh in 2022 terms) to £47/MWh. The CfD price reductions reflect an expectation of reduced capital costs, increased benefits from larger scale facilities, greater turbine sizes, longer lifetimes, and improved project designs, amongst other things. Installation costs of new plants have also been driven down by reductions in turbine costs and new technologies like floating foundations. Beyond technological progress, over the last decade, financing costs and hurdle rates for wind and solar have fallen, thanks to improved understanding of the technologies, reduced risk, and reduced risk perception. According to BEIS, 2020 discount rates for solar, onshore, and offshore wind projects were 5.0%, 5.2%, and 6.3% respectively in the UK, down from 6.5%, 6.7%, and 8.9% in 2015 (BEIS, 2020b). The unit cost of maintenance has also decreased as experience in the renewable sector has grown.

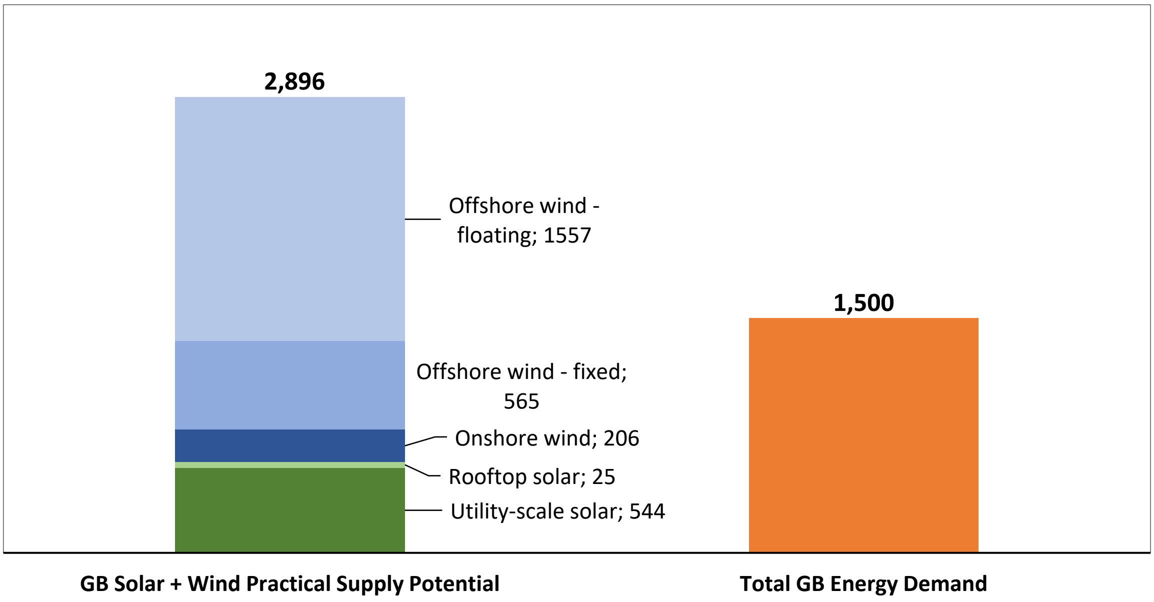
Will such trends continue? The British government seems to think so, with BEIS' most recent central case estimates for offshore wind projects commissioned in 2040 42% lower against 2035 capital and pre-development costs (BEIS, 2020b). The same is true for 'large-scale solar'—a further drop of 25% is expected (BEIS, 2020b). At the time of writing, increased financing costs, supply chain constraints, and other market-based influences, have led to an increase in construction costs for some UK installations, notably offshore wind (Twidale, 2023). However, we consider these increases to be temporary, with long-term costs likely to revert downwards over time. Similar to other technologies whose costs have dropped exponentially with deployment, it is likely that the long-term downward cost trends for wind or solar will continue in the future. Crucially, the rise in financing costs is not unique to renewables; it affects non-renewable energy investments as well (sometimes even more so), ensuring that, comparatively, solar and wind remain competitive. Costs to build enabling infrastructure for rapidly scaled renewable energy, for example extra ports to install offshore turbines, should not be prohibitive.

It is important to note that the whole-system costs of VRE sources exceed the costs of incremental generation. Whole-system costs include both storage needs, to ensure security of supply on all time scales, and non-storage integration costs, to support the electricity grid. As previously noted, non-storage integration costs can include raising reserve requirements, expanding and strengthening the grid to enable electricity transportation from new supply centres, short-term load balancing, and addressing grid resiliency concerns (*e.g.*, reduced inertia). On the other hand, higher VRE penetration can enhance grid flexibility and resilience, as energy assets can be more widely distributed across the grid, reducing the impact of any one power source failing. Furthermore, many grid technologies rely on information processing, electronics, and computing. These are among the fastest improving of all technologies (Koh and Magee, 2006; Farmer and Lafond, 2016), and since higher VRE penetration would require greater use of these technologies, this may lead to improved demand-management and overall efficiency. The magnitude of these costs and benefits is not a focus of this paper (see Heptonstall and Gross, 2021 for some estimates), however, we observe from the experiences of other grid systems, like the Australian Energy Market Operator, that higher rates of renewable energy penetration benefit from early and sizeable investment in the grid. What seems most apparent is that dramatically accelerating an energy transition in the UK is cost effective.

6. CONCLUSION

We found that the practical potential for wind and solar energy in GB (2,896 TWh/year) easily exceeds 2050 final energy demand forecasts (conservatively taken as 1,500 TWh/year) (Figure 7). Respectively, onshore wind, offshore wind, utility-scale solar, and rooftop solar could provide 206 TWh/year, 2,121 TWh/year, 544 TWh/year, and 25 TWh/year. The offshore wind estimate is dominated by generation from floating turbines (1,557 TWh/year), indeed, floating wind alone could meet the entirety of the UK's energy needs in 2050. Even without floating, current electricity needs could be met purely by solar or purely by fixed offshore wind, provided that sufficient storage were available. For added conservatism, Northern Ireland was not considered in this analysis – if it were, its low energy demand plus high land availability would further strengthen our results.

Figure 7. Comparison of GB practical supply and demand estimates (TWh/year).



On the evidence provided in this paper, it is clear that the UK could gain net energy independence using solely wind and solar energy, provided storage and other grid integration needs are met.

Meeting these needs is certainly possible, but requires immediate attention. Regardless of whether net energy independence is achieved, significant energy storage will be needed; clean fuels will still need to be imported and exported to meet chemical production and other needs; and interconnection to other electricity markets will be extremely beneficial, although it would be prudent to design a system that could be self-sufficient in times of distress. Based on our findings, we provide three recommendations for policy makers:

- **Remove barriers to new solar and wind energy capacity.** Limiting solar and wind energy construction constrains UK growth, now and in the future, and slows down energy independence. Bans on renewable energy installations are out of step with the British public, who overwhelmingly support more renewable energy in the UK in opinion polls. Planning delays and grid connection delays for solar and wind also need to be addressed with urgency as they are a major bottleneck to the energy transition and deter further investment. The Winser report details an additional set of recommendations to accelerate the deployment of electricity transmission infrastructure (Winser, 2023).
- **Continue to incentivise accelerated solar and wind energy investment.** The UK might consider opening additional and larger CfD licensing rounds at an accelerated pace. It might also explore alternative policy mechanisms, including further tax incentives, and improved locational signals, prompting new investment to reduce network congestion. Finally, following a wealth of evidence to suggest that green fiscal policy can support economic priorities (Hepburn et al., 2020; O'Callaghan et al., 2022), government should reduce explicit and implicit subsidies for fossil fuel production (see Parry et al., 2021) and, where it might boost domestic productivity, support fiscal incentives for renewable energy.
- **Invest in storage solutions, grid upgrades and, where necessary, grid services.** An inadequate grid will further limit renewable energy investment at higher rates of penetration. Swift action, including through new incentives for storage and potential

market redesign, as well as integrating local and national flexibility markets, could crowd-in more private finance and provide positive market signals to support an accelerated transition. A recent report on energy storage from the Royal Society provides useful guidance (The Royal Society, 2023).

Future works should consider the options to further accelerate domestic investment in renewable energy and storage solutions. They should also investigate the impacts of a fast-paced UK energy transition on service and resource demands, including skills requirements and ethical procurement of component products. Finally, given that resource, technology, and cost factors are no longer limiting barriers to an accelerated energy transition, they should consider questions of political economy.

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SUPPLEMENTARY TABLES

Supplementary Table 1. Detailed list of assumptions for practical wind resource estimates for Great Britain with comparison to precedent studies. All figures in TWh/year.

	Onshore Wind	*Fixed Offshore Wind*	*Floating Offshore Wind*
Our study, practical resource	**206**	**563**	**1,557**
Area assumption	*5% of GB land*	*2% of EEZ*	*8% of EEZ*
Area (km^2)	*11,850*	*16,000*	*62,000*
Archetypal reference turbine	*NREL 7MW 2020ATB*	*NREL 15MW 2020ATB*	*NREL 15MW 2020ATB*
Turbine hub height (m)	*175 m*	*150 m*	*150 m*
Rotor diameter (m)	*200 m*	*240 m*	*240 m*
Turbine swept area (m^2)	*31,416 m^2*	*45,239 m^2*	*45,239 m^2*
Turbine spacing	*6 x diameter*	*7 x diameter*	*7 x diameter*
Cut-in wind speed (m/s)	*3.25*	*4*	*4*
Rated speed (m/s)	*9.75*	*11*	*11*
Cut out wind speed (m/s)	*25*	*25*	*25*
Site parameters			
Air density (kg/m^3)	*1.225*	*1.225*	*1.225*
Average Weibull shape parameter	*2.42*	*2.16*	*2.18*
Average Weibull scale parameter	*11.68*	*11.81*	*11.88*
Roughness length (m)	*0.1*	*0*	*0*
Speed multiplier	*1.08*	*1.01*	*1.01*
Number of turbines	*~8,000*	*~8,000*	*~22,000*
Space required for turbines (km2; % of GB land/sea)	*173; 0.07%*	*6,300; 0.6%*	*17,250; 2.2%*
Array, down time, and atmospheric losses (%)	*11%*	*11%*	*11%*
Additional practical losses (manual adj)	*40%*	*0%*	*0%*
Total rated power (GW)	*58*	*132*	*330*
Technical resource			
Hundleby and Freeman, 2017	**5,500**		
Lu *et al.*, 2009	**4,400**	**6,200**	**NR**
MacKay, 2008	**449**	**1,040**	**NR**
Weiss *et al.*, 2018	**NR**	**17,640 ^**	
Practical resource			
MacKay, 2008	**67**	**88**	**NR**
Offshore Valuation Group (OVG), 2010	**NR**	**374-436**	**860-1,533**
Economic resource			
Hundleby and Freeman, 2017	**1,580-2,700**		
Cavazzi and Dutton, 2016	**NR**	**675-2,890 ^^**	
Vivid Economics and Imperial College London, 2019	**96-214**	**NR ^^^**	

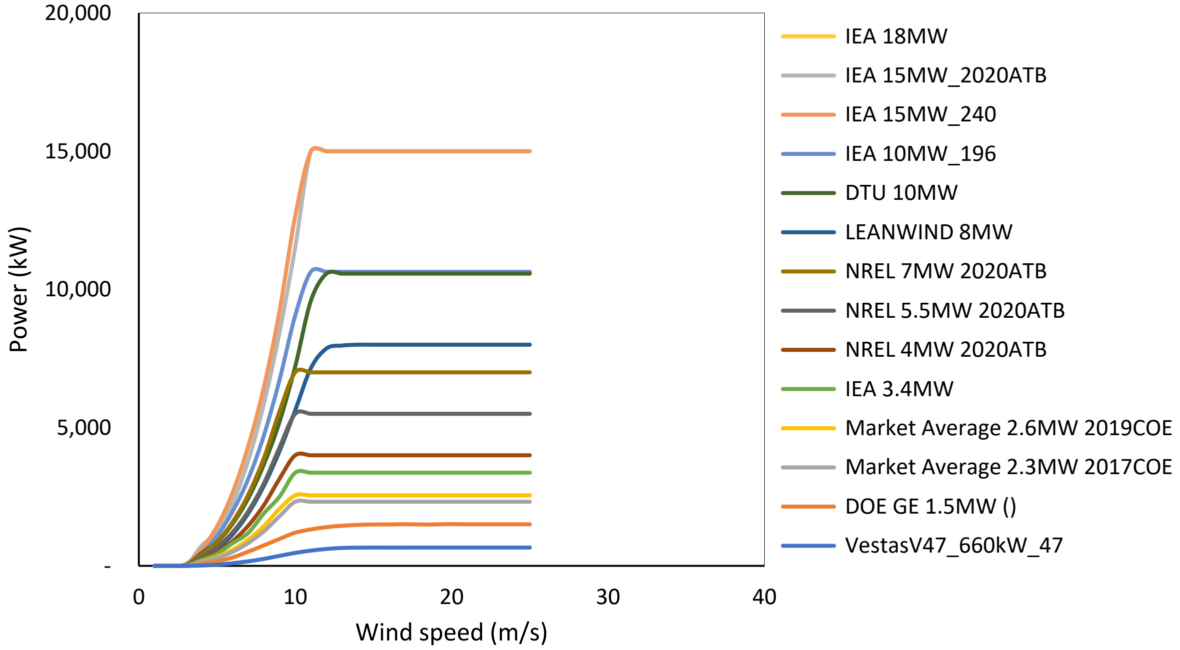
Notes: NR = not reported; ^: only depths to 500m considered; ^^: considering LCOEs less than £120/MWh at the lower end of the range and £160/MWh at the upper end; ^^^: the authors consider the Hundleby and Freeman (2017) estimates to be appropriate, subject to some revisions downward. Power output is provided after application of loss factors. Fixed offshore includes already licensed farms. For space required, given figure considers a 500m exclusion zone around each turbine (Maritime & Coastguard Agency, 2022). Physical footprint is roughly 0.00006% for fixed offshore and 0.0002% for floating offshore.

Supplementary Table 2. Summary of solar angles and spacing in Edinburgh, Birmingham, and Plymouth.

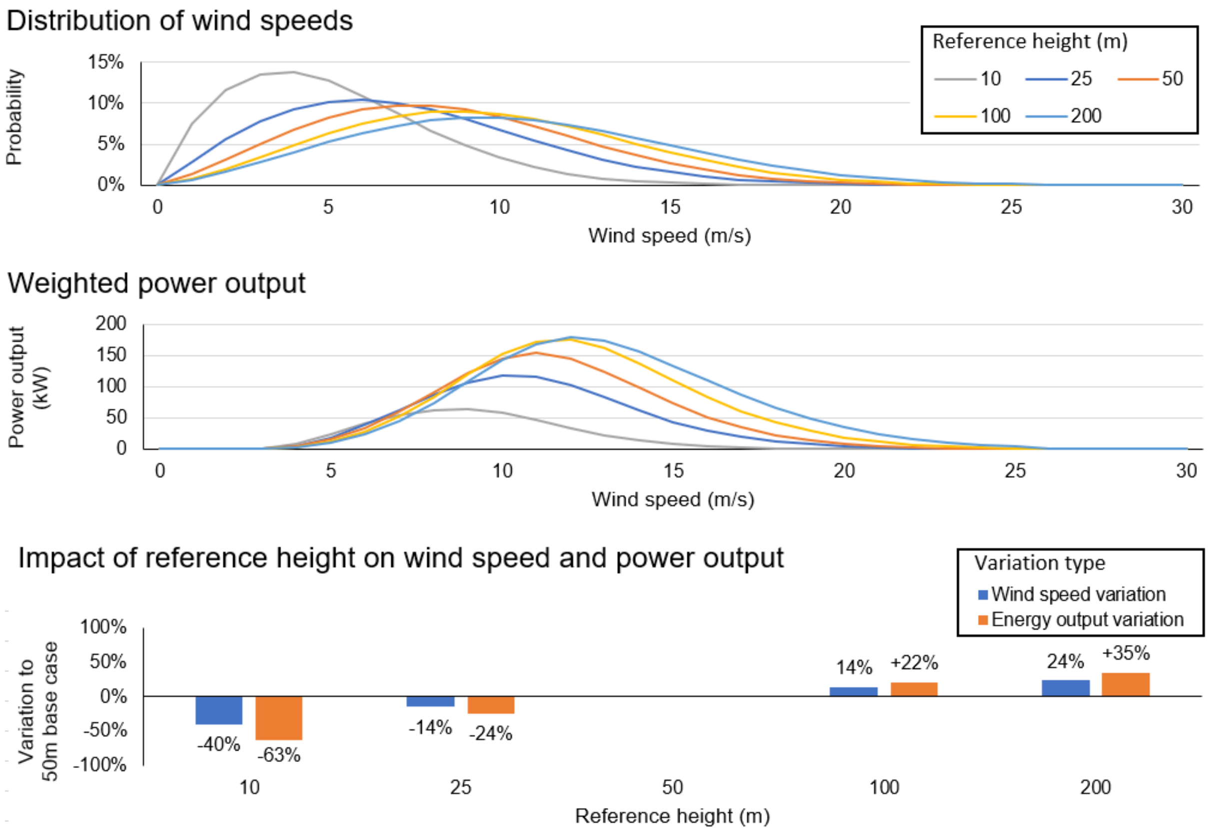
Location	Solar Elevation (θ)	Solar Azimuth (ϕ)	Unit Spacing	Net Spacing
Edinburgh	$7°$	$28°$	43%	60%
Birmingham	$10°$	$28°$	34%	55%
Plymouth	$11.5°$	$28°$	31%	52%

SUPPLEMENTARY FIGURES

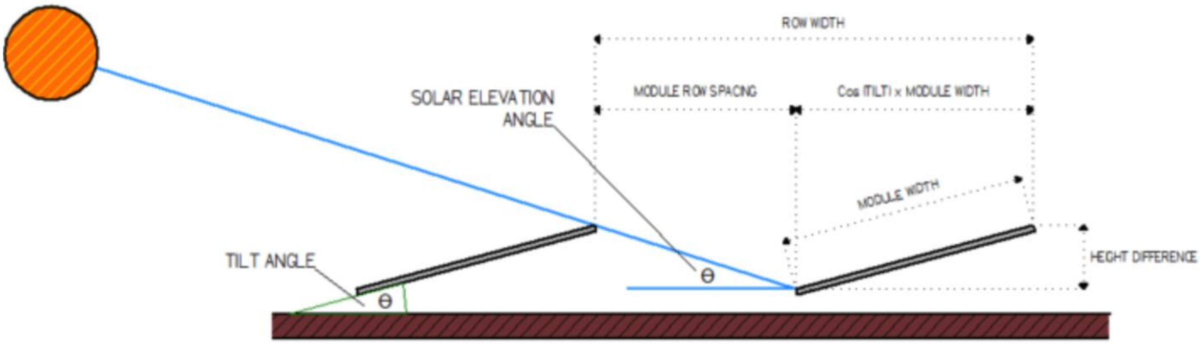
Supplementary Figure 1. Power curves for reference turbines. Tabulated data available at NREL (2021).



Supplementary Figure 2. Impact of turbine reference height on wind speeds and power outputs.

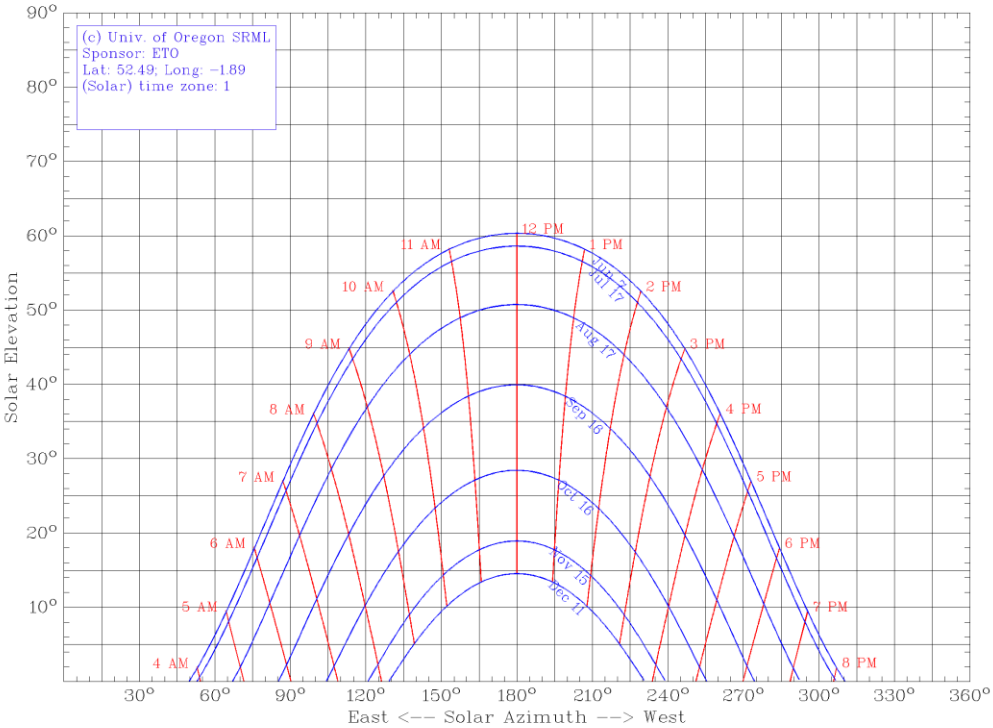


Supplementary Figure 3. Diagram of internal solar array spacing dimensions.



Source: reprinted from Diehl (2020).

Supplementary Figure 4. Birmingham sun chart.



Source: reprinted from University of Oregon Solar Radiation Monitoring Laboratory (2022).

SUPPLEMENTARY METHODS

S1. Physical and array assumptions for wind resource calculations

A few physical assumptions were required in this analysis. Wind is 'slowed' by vegetation (*e.g.,* trees and variable terrain) surrounding turbines, creating a 'roughness length' that needs to be considered. We applied an average roughness length of 0.1 for onshore turbines, suggesting that the average turbine is situated amidst low crops and occasional large obstacles, typical to the British countryside. We applied an average roughness length of 0.0 for offshore turbines, suggesting limited impact of surface features, as is the case in the open ocean.[44] We assumed average air density of 1.225 kg/m^3, although this will vary seasonally and geographically with altitude.

Assumptions for average array spacing, and relatedly, array losses, were made based on existing literature. For our practical analysis, we considered optimal array spacing based on practical profitability objectives of developers rather than energy maximisation objectives, which might be used in technical analyses.[45] This led to multi-dimensional cost optimisation involving the per-unit land costs and the commissioning, operating and connecting (*e.g.*, electrical connectivity) costs associated with an archetypal turbine. When the ratio of the cost of a turbine to the cost of land is higher, higher spacing is preferred. In the UK, based on existing installations, a good guideline for onshore turbines is five times the turbine diameter (5D). However, larger, and more expensive wind farms should increase the spacing preference—we conservatively assume six times the turbine diameter (6D) spacing and 11% total additional losses (10% for array losses and 1% for transmission and other losses). For much larger offshore installations, where turbine units might count into the thousands, higher spacing is important to ensure that the force of the wind does not dissipate throughout the

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[44] In reality, surface roughness is non-zero in the open ocean. A more accurate estimate for rough seas perhaps around 0.006 (Golbazi and Archer, 2019). The two closest roughness options in GWA3 are 0.0 and 0.03; 0.0 is selected as it is closer to 0.006.

[45] If a government were seeking to maximise energy output, they might mandate a certain minimum turbine array spacing.

farm array (Meyers and Meneveau, 2011).[46] We therefore settle on a conservative offshore spacing of 7D and 15% additional losses.[47]

S2. Co-Optimising solar panel spacing and tilt factors

In developing optimal solar farm layout, developers work to maximise their discounted return and overall return on investment (ROI). Practically this simplifies to maximising net effective irradiance per pound invested. The optimisation process reduces to an exercise in maximising captured irradiance on a per square meter basis. In other words, the question is how panels can be best used to maximise captured sunlight for a given piece of land.

For any geography, two factors dictate captured or "effective" irradiance for stationary solar panels, namely the spacing of rows and the upward tilt of panels. Importantly, these factors are interdependent. Higher panel tilt angles lead to higher shadowing and require more spacing between panel rows.

Optimised panel tilt increases the number of hours that a stationary panel captures sunlight over a year. More specifically, the optimal tilt angle is that which maximises Global Horizontal Irradiance (GHI) on the panel surface. As such the optimal tilt angle is principally a function of latitude, solar declination, and weather conditions. Hafez *et al.*, (2017) discuss the many approaches in current literature for optimising tilt using mathematical models. In short, tilting solar panels upwards from the horizontal acts to increase total captured solar irradiance to the point of reaching optimal tilt. The magnitude of this tilt is generally higher in latitudes further away from the equator and lower in

[46] In other words, there is a need to minimise boundary layer interactions.

[47] Meyers and Meneveau (2011) suggested an optimal spacing of 15D using 2011 cost assumptions. However, their assumptions did not incorporate the costs of offshore installation, which are higher than onshore and that ocean leases tend to be cheaper than land leases (both factors would tend to drive spacing requirements higher). On the other hand, since 2011, wind turbine prices have dropped over 50%, from USD1,750 / kW to USD800-950 / kW (Lawrence Berkeley National Laboratory 2022, Meyers and Meneveau, 2011) and the cost of ocean leases have increased. Taking all factors into consideration, we expect cost factors for GB offshore to drive spacing lower. This is supported by Stevens *et al.* (2016), who incorporated offshore cost additions to show that practical offshore spacing was in the range of 6-10D at the time of their study.

latitudes near to the equator. Greater expected cloud cover also leads to higher tilting as clouds act to increase diffuse radiation and decrease direct radiation.

Higher solar panel tilt brings longer shadows, particularly in winter months when solar declination is low. An increase in shadowing naturally requires greater spacing of solar panel rows and hence captured irradiance per unit area decreases. Given that utility electricity supply incentives are often higher in morning/evening shoulder periods to meet demand, utility-scale plants are generally designed in accordance with the worst-case scenario, *i.e.*, solar declination in the middle of winter without shadow interference between 10am-2pm, December (Helioscope, n.d.).

Minimum Module Row Spacing (MMRS, Δ) is derived from Module Width (w_{mod}), tilt angle (α) and two factors based on geographic location, Angle of Solar Zenith (θ) and Solar Azimuth (ϕ) where:

$$\Delta = \frac{w_{mod} \cdot sin\alpha \cdot cos\phi}{tan\theta}$$

Using Supplementary Figure 3, the width of land ($w_{mod,\ land}$) occupied by each solar module is:

$$w_{mod,land} = w_{mod} \cdot cos\alpha$$

Then total row width w_{row} is:

$$w_{row} = \Delta + w_{mod,land} = \frac{w_{mod} \cdot sin\alpha \cdot cos\phi}{tan\theta} + w_{mod} \cdot cos\alpha$$

Then, unit spacing (%) in the middle of a solar array is:

$$UnitSpacing = \frac{\frac{\Delta}{2} \cdot 2}{\frac{\Delta}{2} \cdot 2 + w_{mod,land}} = \frac{\Delta}{w_{row}}$$

Expressed algebraically:

$$UnitSpacing = \frac{\frac{w_{mod} \cdot sin\alpha \cdot cos\phi}{tan\theta}}{\frac{w_{mod} \cdot sin\alpha \cdot cos\phi}{tan\theta} + w_{mod} \cdot cos\alpha}$$

$$UnitSpacing = \frac{sin\alpha \cdot cos\phi \cdot cot(\theta)}{sin\alpha \cdot cos\phi \cdot cot(\theta) + cos\alpha}$$

The solar zenith and solar azimuth angles are found by consulting cartesian sun charts for the location under consideration. The University of Oregon Solar Radiation Monitoring Laboratory (2022) provides charts free of charge for any location in the world. In the United Kingdom, we expect significant skew in future solar installations to Southern locations given significantly higher GHI (and hence expected financial return) in these locations. Hence, for the purposes of an 'average' location for UK solar, Birmingham seems apt (see average PV heatmap in Supplementary Figure 4). Using a window of 10am-2pm in December (as above), $\theta_{Birmingham} = 10°$ and $\phi_{Birmingham} = 28°$. Then, if $\alpha_{optimal} = 6°$ (see below), Unit Spacing = 34%. Assuming the same inputs, unit spacing varies across the UK from 31% in Plymouth to 43% in Edinburgh (Supplementary Table 2).

Hedging between fields is a second limit on panel placement. Spacing between the outermost panel and hedging can be significant given potential shading from hedges, trees, and other obstructions. We derived the edge spacing percentage using an assumed distance between the edge of the outermost panel module to the hedge (S_{edge}) as well as the total width of the site w_{site} and length of the site l_{site}. Then:

$$EdgeSpacing = \frac{2 \cdot S_{edge}\left(w_{site} + l_{site} - 2 \cdot S_{edge}\right)}{l_{site} \cdot w_{site}}$$

Hence, for an archetypal small (conservative) solar field of dimensions 120m x 120m and distance from hedge to panel of 10m, *Edge Spacing = 31%*.

Net spacing (%) for a solar farm thus has two components, unit spacing and edge spacing. Net spacing is derived as:

$$NetSpacing = \frac{EdgeSpacing \cdot w_{site} \cdot l_{site} + UnitSpacing \cdot \left(w_{site} - 2 \cdot S_{edge}\right) \cdot \left(l_{site} - 2 \cdot S_{edge}\right)}{l_{site} \cdot w_{site}}$$

Or:

$$NetSpacing = \frac{2S_{edge} \cdot \left(w_{site} \cdot l_{site} - 2S_{edge}\right) + \frac{sin\alpha \cdot cos\phi \cdot cot(\theta)}{sin\alpha \cdot cos\phi \cdot cot(\theta) + cos\alpha} \cdot \left(w_{site} - 2 \cdot S_{edge}\right) \cdot \left(l_{site} - 2 \cdot S_{edge}\right)}{l_{site} \cdot w_{site}}$$

For the archetypal GB solar farm, net spacing is therefore 54%. The net area covered by solar panels is then 46%. To make this manageable we round down to 45%.

In theory, panel tilt and module spacing are two parties to a necessary co-optimisation procedure. However, at high latitudes the relative increase to effective irradiance from one additional degree of tilt is dwarfed by the reductions to solar coverage (due to larger spacing requirements). For instance, while increasing tilt from $0°$ to $35°$ can increase effective GHI by 20% it also requires a 170% increase in spacing (using the numbers from above examples; see Viridian Solar, n.d.). Similarly, a tilt increase from $0°$ to$15°$ brings an effective GHI increase of 15% but an 123% increase in required spacing.

As of 2022, round trip efficiencies of new batteries range between 90 – 96.5%. The average grid transmissions losses in the UK are around 1.7%, with distribution losses around 5-8%. After factoring in these losses, we can expect a total loss of 13 – 16 % for solar PVs. This loss can be reduced to solely the battery efficiency for solar rooftops since the electricity doesn't travel through transmission or distribution networks.

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