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Decarbonising UK transport: Implications for electricity generation, land use and policy

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A B S T R A C T

To ensure the UK's net zero targets are met, the transition from conventionally fueled transport to low emission alternatives is necessary. The impact from increased decarbonised electricity generation on ecosystem services (ES) and natural capital (NC) are not currently quantified, with decarbonisation required to minimise impacts from climate change. This study aims to project the future electric and hydrogen energy demand between 2020 and 2050 for car, bus, and train to better understand the land/sea area that would be required to support energy generation. In this work, predictions of the geospatial impact of renewable energy (onshore/offshore wind and solar), nuclear and fossil fuels on ES and NC were made, considering generation mix, number of generation installations and energy density. Results show that electric transport will require ~136,599 GWh for all vehicle types analysed in 2050, much less than hydrogen transport at ~425,532 GWh. We estimate that to power electric transport, at least 1515 km^2 will be required for solar, 1672 km^2 for wind and 5 km^2 for nuclear. Hydrogen approximately doubles this requirement. Results provide an approximation of the future demands from the transport sector on land and sea area use, indicating that a combined electric and hydrogen network will be needed to accommodate a range of socio-economic requirements. While robust assessments of ES and NC impacts are critical in future policies and planning, significant reductions in energy demands through a modal shift to (low emission) public transport will be most effective in ensuring a sustainable transport future.

Introduction

Under ratification of the Paris Agreement, the UK has set a target of net zero greenhouse gas (GHG) emissions by 2050. Domestic transport remains the leading GHG emitting sector producing 27 % of the UK's total emissions in 2019, followed by the energy supply emitting 21 % of emissions (Department for Transport, 2021). For the successful decarbonisation of transport, an interdisciplinary approach across these sectors needs to be taken as energy used by transport has increased by ~16.1 % since 1990 (Brand et al., 2020). Integration of electricity and hydrogen transport are recognised as an essential part of the solution to reduce anthropogenic climate change (Howard et al., 2013), as these technologies are often considered 'zero emission' at their point of use. However their true environmental impact is dependent upon the degree to which the electricity for 'fuel' is decarbonised and its source (Ajanovic and Haas, 2021). This impact can be viewed in terms of natural capital (NC) and ecosystem services (ES) and with the potential to impact other sectors, the effect of large expansions of low emission energy generation should be considered carefully (Logan et al., 2022).

Making the transition towards net zero will require consideration of the 'energy trilemma' which focuses on three fundamental objectives for an affordable, secure and sustainable energy system (Foxon, 2013; Hammond and O'Grady, 2017; Jenkins et al., 2016; Logan et al., 2022). This will require a just transition with focus placed on a secure and low carbon energy network that is affordable for all individuals to meet their daily needs. Often adopted by national governments, net zero targets, often focus on decarbonising the whole economy, including energy supply and demand, as well as other emission sources including transport, industrial processes and agriculture etc. (Pye et al., 2021). However, ensuring a clear definition of net zero is key as what policies and

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targets countries implement differs from country to country (Rogelj et al., 2015). The UK's net zero target focuses on reducing all GHG emissions being either equal or less than the emissions the UK has removed from the environment, through a combination of emission reduction and emission removal through technologies such as carbon capture and storage (CCS) (BEIS, 2019a; ONS, 2019). This is an important distinction as some countries focus only on carbon dioxide (CO_2) emissions (Rogelj et al., 2021). Alternatively, some countries aim to solely compensate emission reductions with offset technologies (Rogelj et al., 2021). It has been argued that although targets can be considered vague, having targets is better than not having targets, but with the emerging 'climate emergency' without clear policy and strategies for decarbonisation, net zero targets will be difficult to be met (Pye et al., 2021; Rogelj et al., 2021).

The objective of this paper is to estimate the total electricity required, if hypothetically, all cars, buses and trains in the UK are to be either fully electric or hydrogen between 2020 and 2050. This paper also projects the amount of electricity required based on energy type (i.e., fossil fuels, nuclear and renewables), based on the National Grid two-degree projects to 2050, to meet the energy demand as well as the land/sea area required for these energy types. This paper focuses on the policy related research and uses the UK as a case study to highlight the interdisciplinary understanding of transport and energy decarbonisation required to meet transport related targets. This will help policymakers better understand the potential land/sea demands to reduce environmental impact on ecosystem services (ES) and natural capital (NC). This analysis is important as although increasing the share of renewable energy will remain in line with UK and international policy, a whole systems approach is required to reduce environmental impact and to minimise environmental trade-offs.

Although land area for energy systems has historically had a relatively small land footprint, future low carbon electricity systems are expected to transition towards more land extensive technologies to meet energy demands. This has the potential to dramatically alter current landscapes. Whilst technologies are being developed to be integrated into current landscapes, such as solar photovoltaics (PV) being built on rooftops, over parking lots, as floating solar PV(floatovoltaics) (Cagle et al., 2020; Exley et al., 2021a, 2021b) or being built on degraded, contaminated land, or on top of agricultural land, the exponential increases in electricity demands and reliability outcomes are yet to be determined (Khan et al., 2021; Lovering et al., 2022). This transition towards low carbon electricity generation is likely to have implications on both NC and ES through habitat and biodiversity loss, food security and other environmental and social priorities (Lovering et al., 2022).

Policies to meet decarbonisation objectives in the UK

Decarbonisation and energy policy

Decarbonisation is defined as the reduction in (total and transport related) carbon emissions of the whole economy (Tapio et al., 2007). The rate at which decarbonisation occurs is instrumental in meeting climate change targets set out in the Paris Agreement. For the UK to meet these targets, the UK Government has developed a whole systems policy approach to integrate and aggregate decarbonisation initiatives across key sectors and infrastructure (Haugen et al., 2022; UK Council for Science and Technology, 2020) through the 'Net Zero Strategy: Build Back Greener' in 2021 (BEIS, 2021). This strategy sets out policies and proposals for decarbonising all of the UK economy to meet the 2050 emission reduction target (BEIS, 2021) with policies in the energy sector targeting a fully decarbonised power system by 2035. For the transport sector, decarbonisation policies for road transportation focus on removing all tailpipe road emissions. To achieve this there are two leading possibilities which focus on the introduction of electric and/or hydrogen transport, which will require the UK's energy system to remain in line with the 'Ten Point Plan for a Green Industrial Revolution' (Haugen et al., 2022; HM Government, 2020), emphasising the need for an interdisciplinary approach to decarbonisation.

Due to global political changes, the 'British Energy Security Strategy' was introduced in 2022 by the UK Government, building on the Ten Point Plan for a Green Industrial Revolution and the Net Zero Strategy, which prioritises support for technologies including hydrogen and nuclear energy with longer lead timings and away from fossil fuels (BEIS, 2022). For the purposes of this paper, we examine the policies that have been implemented within the transport and energy sectors which have been designed to aid emission reduction and decarbonisation.

To ensure emissions objectives are met in the UK, the Committee on Climate Change (CCC), an independent advisory board to the UK Government, monitors progress and conducts independent analysis and has called for a set of '*clear, stable and well-designed policies*' to be introduced to reduce emissions across the economy, as they believe current policy is insufficient to meet net zero (CCC, 2019a). The CCC has stated that getting to net zero is '*technically feasible but highly challenging*' (CCC, 2019b). The CCC has set five-yearly carbon budgets which currently run to 2032 and define the allowable level of GHG emissions that the UK can legally emit within a five-year period. The third carbon budget running from 2018 to 2022 is currently on track to achieve the target of keeping emissions below 2544 $MtCO_2e$, a ~37 % reduction of GHG emissions compared to 1990 levels (Priestley, 2019). However, the fourth (2023–2027) and fifth (2028–2032) carbon budgets will be difficult to achieve without further mitigating measures put in place (Priestley, 2019). The sixth carbon budget was announced in December 2020 which would see the UK emissions capped at 965 $MtCO_2e$ between 2033 and 2037 (CCC, 2020). This would be a 78 % reduction in emissions from 1990 based on the CCC's Balanced Net Zero Pathway and for the first time also incorporate the UK's share of international aviation and shipping emissions (CCC, 2020). Although the CCC targets themselves are not legally binding, the long-term target for 2050 is, therefore, to keep in line with 2050 target, and so the CCC's incremental targets need to be met.

As the UK is no longer part of the EU, a Trade and Cooperation Agreement has been introduced between the UK and the EU for the future of electricity trading across interconnectors between the UK and EU to come into effect in 2022. The UK currently continues alignment with the European Energy Directive (2018/2001/EU), which is a binding updated target set for at least 32 % of all electricity generated to be renewable by 2030 (BEIS, 2020). This target incorporates a sub-target of a minimum of 14 % of electricity to be consumed by the transport sector (Clancy et al., 2018; Prussi et al., 2019). These targets are designed to instigate changes at the policy level sooner than may otherwise be attempted due to the political ramifications of the required societal and industry development and 'new normal' approaches required. In 2020, renewable energy generation in the UK reached ~42 % driven by national legislation, including the Renewable Energy Action Plan for the UK (2009/28/EC). The share of renewables has continued to grow in 2021, with the highest growth in capacity attributed to offshore wind (8.4 %), which accounted for 49 % of the total UK growth in 2021 (Spry, 2022). In addition, during 2021, onshore wind grew by 3 %, with 80 % of this new capacity in Scotland, solar PV grew by 2.8 % with Wales having the largest percentage increase at 23 % and bioenergy increased by 1.3 % overall (Spry, 2022).

The UK Government expects a shift towards renewable energy with the National Grid projecting a shift from 27.5 % renewables in 2017 to 69.7 % by 2050 under a two degree scenario (i.e., scenario where it expects to meet the Paris Agreement requirements), enabling the consequent decrease of GHG emissions. For example, in 2017, there was a 6.6 % decrease in GHG emissions in the electricity supply sector, predominantly driven by a reduction in the use of coal and gas power stations (BEIS, 2018a). Renewable energy technologies cause comparatively low carbon emissions and produce an increasingly competitive levelised cost of energy (Raybould et al., 2020; Simons and Cheung, 2016). This is achieved through a decrease in capital, operation, and maintenance costs due to technology improvement for renewable sources (wind, wave, tidal, and solar PV). This also enables less land and/or fewer devices to be needed to achieve the required level of generation capacity.

Nuclear power supplies around one fifth of the UK electricity demand with continual development in England with the construction of Hinkley Point C, designed to generate 3260 MW of electricity. Scotland currently has two EDF-owned nuclear power stations (Hunterston B and Torness) and three Nuclear Decommissioning Authority (NDA) owned civil nuclear sites at advanced stages of decommissioning (Chaplecross, Dounreay and Hunterston A). Together these generated ~42.8 % of Scotland's total electricity in 2016 (SEPA, 2019). However, the Scottish Government announced in 2017, that they plan to phase out and decommission their use and will not permit new nuclear plants to be built (Scottish Government, 2017). Therefore, when Scotland's nuclear power stations become decommissioned in 2023 and 2030, electricity will need to be generated from other, low carbon, sources. Furthermore, in 2018, there was an increase in the electricity emissions as one reactor was shut down and another put on reduced power so Peterhead's combined cycle gas turbine (CCGT), which is a contingency supplier had to be used for an extended period. This is an example of the need to ensure low carbon alternatives are available to fill any energy gaps.

In 2023, the UK will cease abated coal thermal electricity generation; this has been achieved by a transition to CCGT generation infrastructure which started with the discovery of North Sea Gas in the 1960′s. Coal is currently only used for supply at peak demand. As intermittent renewable generation capacity is increased, CCGT generation is increasingly used for dispatchable power to fill the shortfall when solar and wind cannot deliver due to unfavourable weather etc. or peak winter periods. Using gas generation for gap filling in this manner is not carbon neutral and will require CCS to be implemented to remove the majority of carbon that would otherwise be emitted from CCGT power stations.

Natural capital and ecosystem services

Natural capital (NC) is defined as '*the elements of nature that produce value or benefits to people (directly and indirectly), such as the stock of forests, rivers, land, minerals and oceans, as well as the natural processes and functions that underpin their operation*' (NCC, 2014). NC comprises of the relationships that allow nature's capacity to continue based on physical, biological, and chemical processes (Mace, 2019). NC comes in two broad types: renewables and non-renewables. Renewables are what nature provides for 'free' and keeps giving for free, provided it does not deplete below its threshold for sustainable reproduction where applicable (Helm, 2019). Alternatively, non-renewables are objects that nature provides which do not regenerate and tend to be inanimate such as fuels including, although not limited to oil, gas, coal, and metal ores such as copper and lead (Helm, 2019).

Ecosystem services (ES) are defined as the outputs from the ecosystem from which humans can benefit directly or indirectly, with the NC assets (soil, air, water, scenic sites etc.) that produce them becoming increasingly critical for decision makers to protect in the search for long term sustainability (Delafield et al., 2021; Farley and Costanza, 2010; Lovett et al., 2015; Martnínez-Harms and Balvanera, 2012; Rudman et al., 2017). ES are the direct and indirect contributions of ecosystems to human well-being and can be split into three categories. Firstly, provisioning services which includes any goods obtained directly from the environment such as food, fibre, or fresh water (Wallace, 2007). Secondly, regulating services which are the benefits obtained from regulating (or maintaining) ecosystem processes (such as air, climate or water regulation, soil erosion regulation etc.) (Wallace, 2007). Finally, cultural services which included recreation and leisure, spiritual and intellectual interactions and cultural diversity (Wallace, 2007). The interaction between multiple services, and the underpinning role of supporting services have led to further refinements enabling economic evaluation which requires both the separation of the final ES that provides the goods and values to humans from the underpinning ecological and environmental processes within ecosystems and the distinction between final ES and goods (Mace et al., 2012).

Like most modern technologies, all energy systems consume ES in the form of minerals, land, water for example, whilst providing energy, impacting NC and ES in distinct ways. With an increase in electric and hydrogen transport, renewable generation energy sources require a substantial land footprint and thus will impact NC and could conflict with the provision of another ES. For example, electricity generated through solar PV requires a large land area defined by the energy density of solar radiation at that geographical location. This land use requirement conflicts with food production and natural ecosystems, impacting both ES and NC (Murphy et al., 2015; Randle-Boggis et al., 2020).

The long term sustainability of NC and ES has been interpreted as economic, market or tangible value and has direct links between different services that have related economic benefits (Carpenter and Turner, 2000; Gee and Burkhard, 2010; Millennium Ecosystem Assessment, 2005). Quantifying the economic value of NC and ES encourages incentives to be implemented for conservation purposes, however this only encapsulates part of the total cost of the ecosystem (Bateman et al., 2016, 2013; Gee and Burkhard, 2010; Vejre et al., 2010). Paying a monetary value for any additional area required for energy generation when shifting the UK's transport network to electric and hydrogen is an economic based solution, with negative impacts still likely. Regulator permissions and valuing is needed to balance the long term benefits of emission reductions against the current quantifiable ES loss at the development site (BEIS, 2018b; European Commission, 2020).

With this increase in demand for greater renewable sourced generation the potential loss of biodiversity and ES are a considerable challenge with substantial effort required in the UK to reduce GHG emissions (Halpern et al., 2008; Holland et al., 2018). When making the decision to switch towards electric and hydrogen transport, policymakers do not often consider how these low emission vehicles are being 'fuelled' and need to take into consideration electricity generation. Whilst a switch to renewables may decrease emissions in comparison to fossil fuel usage, the impact on ES and NC is reliant on renewable mix when it comes to quantifying the impact from increasing electric and hydrogen-based transport (Bateman et al., 2013; Randle-Boggis et al., 2020). To evaluate the sustainability of electric and hydrogen transport, the impact of energy generation on both NC and ES and what they provide must be considered. This enables the transition of sustainable transport to be quantifiably compared to energy generation including wind, solar or nuclear and to be benchmarked against fossil fuel emitting energy generation.

Methodology

The methodology is presented in four sub-sections. Section "Total number of cars, buses and trains and the average distance travelled annually" estimates the total number of cars, buses and trains and the total distances (weighted by size) travelled between 2020 and 2050 using the Transport Energy and Air Pollution Model for the UK (TEAM-UK). Section "Energy generation for electric and hydrogen cars, buses, and trains" is used to project the total amount of electricity generation required if private road transport (cars, buses, and trains of different sizes) were fuelled by either electricity or hydrogen. These results are then used in Section "Electricity generation mix" to estimate the electricity generation mix, with generation split into three groups: renewables (onshore and offshore wind and solar), nuclear (average nuclear power station and a Hinkley Point C equivalent) and fossil fuels (gas power station), to ensure enough electricity was generated to meet the energy demands. Using these results, Section "Capacity and area requirements" estimates the total capacity of the different energy technologies before estimating the total land and sea area required for these different technologies.

Total number of cars, buses and trains and the average distance travelled annually

The total number of cars, buses, trains and their respective average distance travelled were projected by TEAM-UK using data obtained from a range of local, national and regional databases (BEIS, 2018a; Brand et al., 2019b; National Grid, 2019). TEAM-UK is a disaggregated, bottom-up modelling framework of the UK transport-energy-environment system, built around a set of exogenous scenarios of socio-economic, socio-technical and political developments (Brand et al., 2020; Brand et al., 2019a, 2019b, 2012; Brand and Anable, 2019; Logan et al., 2021).

The vehicle number and distance travelled projections were used to estimate the energy requirements for the three primary transport modes (cars, buses and trains) which enabled analysis of modal influencing energy demands. Cars were segmented into small, medium, and large and buses into minibuses, urban buses, and coaches. Trains were categorized as urban, intercity, regional, and high-speed. Size categories of each transport type were used during calculation as the TEAM-UK provides varying fuel efficiencies for the different size categories (Brand et al., 2019a; Brand et al., 2019b). Results are presented as overall transport type (car, bus, train) totals (See Appendix A for a full breakdown). Table 1 gives an overview of the average distances travelled and number of cars, buses, and trains between 2020 and 2050.

Energy generation for electric and hydrogen cars, buses, and trains

To calculate the total energy required for electric and hydrogen cars, buses, and trains in the UK between 2020 and 2050, Eq. (1) was used. Eq. (1) incorporates the correctional factor for energy production and transfer inefficiencies. Electricity generation was given a correctional factor of 1.18. This value was estimated as ~8 % of electricity lost through transmission and between ~3.1 % and ~10 % lost through distribution network operators (The UK Parliment, 2014). The higher value was chosen as this would lead to an upper estimate of total level of energy produced and the required level of electricity generation, thereby enabling worst case scenario estimation.

Electricity for hydrogen production by electrolysis was corrected by a factor of 2.03. This was calculated by multiplying the electricity generation losses by hydrogen generation losses. For every 1 GJ of H_2 to be produced, 479 kWh of electricity needs to be generated from the energy source. Therefore 1 GJ of H_2 was converted to kWh by dividing by 3600 (giving 277 kWh), with the generation efficiency of the hydrogen energy being calculated by dividing the input energy by the output energy, i.e. 479 kWh was divided by 277 kWh giving a value of 1.72 (Fernández-Dacosta et al., 2019). This was then multiplied by the electricity correctional factor of 1.18, giving a correctional factor of 2.03.

$$TE = \sum \left(V_{s,t} {*} D_{s,t} {*} I {*} F\right) \quad (1)$$

where TE = sum of energy need to power each given transport type (t) of a given size (s), v_{st} = the total number of vehicles given transport type (t) of a given size (s), $D_{s,t}$ = the average distance travelled (kilometre) given transport type (t) of a given size (s), I = the energy consumption (kWh km^{-1}) and F = the correctional factor for energy production and distribution inefficiencies (electric = 1.18, hydrogen = 2.03). Data units are converted to present in GWh.

For the energy consumption of each transport type, the average energy consumption was defined for electric and hydrogen transport types (Table 2). Due to uncertainties in the rate of efficiency improvements, for all electric and hydrogen transport, we assumed a worst-case scenario of no improvement from 2020 throughout the study period.

For BEVs, energy consumption values from the Nissan Leaf were used as this vehicle was the top registered battery powered EV advertised as a small family car and could therefore carry at least four individuals, using a value of 0.23 kWh km^{-1}. The value chosen was based upon worst case scenario data within a laboratory setting (Green ncap, 2019). For hydrogen vehicles, as of 2020, there were currently three publicly available vehicles: the Toyota Mirai, Hyundai Nexo and the Honda Clarity (Purnima and Jayanti, 2020). As all three HV types are relatively new on the market and are mid-sized vehicles, the same values for the energy efficiency were selected using the most popular HV for all three vehicles sizes the Toyota Mirai. To do this, the extra high technical specification value of 1.24 kg 100 km^{-1} was multiplied by the energy density of 1 kg of H_2 (33.3 kWh kg^{-1}) giving a value of 0.41 kWh km^{-1} (Grange, 2020).

For electric buses, the annual average vehicle energy consumption was given a value of 1.2 kWh km^{-1} (Vepsäläinen et al., 2019) and hydrogen buses given a value of 1.8 kWh km^{-1} (Graurs et al., 2015).

For electric trains, the average electric train energy consumption ranges between 3.5 and 5.5 kWh km^{-1} (Gattusoa and Restuccia, 2014; Jong and Chang, 2005). As we are implementing a worst case approach the maximum annual vehicle energy consumption was chosen at 5.5 kWh km^{-1}. For hydrogen trains, the available European consumption value was given as 10 kWh km^{-1} (Progressive Energy ltd, 2019).

Electricity generation mix

In this section, the electricity generation mix has been considered with generation split into three groups: renewables, nuclear and fossil fuels. Table 3 provides an overview of the projected electricity generation mix between 2020 and 2050 from the National Grid under a two-degree scenario. Under this scenario, it was assumed that no energy used was from interconnectors as it is unclear how this energy is

Table 2
Average energy consumption in kWh km^{-1} for electric and hydrogen cars, buses and trains (Source: Gattusoa and Restuccia, 2014; Grange, 2020; Graurs et al., 2015; Green ncap, 2019; Jong and Chang, 2005; Progressive Energy Ltd, 2019; Vepsäläinen et al., 2019).

	Car (kWh km^{-1})	Bus (kWh km^{-1})	Train (kWh km^{-1})
Electric	0.23	1.20	5.50
Hydrogen	0.41	1.80	10.0

Table 1
Overview of data for cars, buses, and trains between 2020 and 2050 from TEAM-UK (Brand et al., 2019b).

	Number of vehicles				Average distance travelled per vehicle (km)			
	Cars	Buses	Trains	Total	Cars	Buses	Trains	Total
2020	31,946,122	145,271	6394	32,097,787	13,038	27,289	83,403	123,730
2025	33,217,292	153,370	6413	33,377,075	12,866	26,512	85,053	124,431
2030	34,388,118	157,427	6428	34,551,973	12,689	26,371	86,257	125,317
2035	35,541,771	160,126	6440	35,708,337	12,497	26,377	87,148	126,022
2040	36,746,424	163,008	6448	36,915,880	12,279	26,382	88,341	127,002
2045	37,901,486	166,121	6453	38,074,060	12,109	26,387	89,919	128,415
2050	39,001,012	168,836	6454	39,176,302	11,948	26,391	91,300	129,639

Source: Brand et al., 2019a, 2019b

Table 3
Percentage breakdown of the UK electricity supply into three categories: renewables, nuclear and fossil fuels between 2020 and 2035 before being extrapolated to 2050 (Source: National Grid, 2018).

	Percentage (%)						
	2020	2025	2030	2035	2040	2045	2050
Renewables	45.1	65.7	72.1	71.0	68.2	69.1	69.7
Nuclear	21.7	11.4	18.9	24.6	28.7	28.0	27.1
Fossil Fuel	33.2	22.4	9.0	5.0	3.1	3.1	3.2

generated from the countries within this network. It was also assumed that any waste was from fossil fuels. There are fluctuations from nuclear energy, and this is due to a significant number of power stations due to be decommissioned between 2020 and 2030. Using these values, we calculated the electricity carbon intensity required to be generated to fuel electric and hydrogen transport.

Capacity and area requirements

In this section, we discuss the capacity requirements for the different energy types (onshore/offshore wind, solar and nuclear) as well as land and sea area projected for the number of onshore and offshore wind turbines and solar panels that would be required to meet the renewable energy generation mix from Table 3.

For renewable energy generation from wind for only the transport sector, Eq. (2) was used to estimate the total number of wind turbines required to meet the energy generation demand from solely renewable energy from Table 3. This also took into consideration the 2019 split of 24 % onshore: 76 % offshore wind turbines. The total expected energy demand (TE) input into Eq. (2) is the sum of the energy requirements for each transport type as calculated in Eq. (1).

$$No.sources_t = \frac{\left(\frac{\left(\frac{TE^*PS_e}{365}\right)}{24}\right)}{(CF_e{}^*CR_e)} \quad (2)$$

where TE is as calculated in Eq. (1), PS_e = percentage of supply resource given with the (e) type of energy generation (onshore/offshore wind, solar or nuclear), CF_e = capacity factor of a single generation source with the (e) type of energy generation and CR_e = power capacity of a single generation source with the (e) type of energy generation.

Area requirements are separated in to onshore and offshore wind categories as their development and capacity ratings are significantly different. The proportion of supply (PS_t) resource is taken from Table 3 with the proportion of renewables broken down into type including onshore and offshore wind, and solar. PS_t is also used in Eq. (2) as a multiplication factor on the energy required (TE) so number of turbines predicted is representative of the wind resource (land or marine). For solar and nuclear this value is set as one as there are no significant differences between reactor types in terms of generation density.

To calculate the required area for each energy type we used Eq. (3). Eq. (3) estimates the land or ocean area required to provide the energy required from the given energy source. This was calculated for both energy demand for electric and energy demand for hydrogen as estimated by Eq. (1).

$$Area = \frac{((PR^*PS_e)^*TE)}{GD} \quad (3)$$

where Area = area required by each energy type, PR = resource proportion of renewable generation in that year, PS_e = percentage of supply resource with the (e) = type of energy generation (0.24 onshore, 0.76 offshore, 1 for nuclear and solar), TE = as calculated in Eq. (1) and GD = generation density.

Onshore and offshore wind turbines

The normalised capacity factor (CF) of an onshore and offshore wind turbine was used, 26.4 % and 40.1 % respectively in 2018 (DUKES, 2019). It is almost impossible to robustly estimate the future average wind speeds which drive real world capacity factor ratings, i.e., average power generated over a period divided by peak power rating. Due to wind speed variation, 100 % peak power is rarely, if ever achieved, with capacity factor influenced by the effectiveness of blades to a given wind speed. As the industry develops it would be expected that technological improvements improve the effectiveness of turbine operating ranges, increasing total power output and therefore increasing the capacity factor. As this change is reliant on design-to-wind-density technical abilities, we assume today's average capacity factors throughout the time scale.

For onshore wind turbines, it was assumed that each wind turbine had an average maximum output (CR) of 2.7 MW (Wind Europe, 2019). Taking these technological advances into consideration, for each five-year timestep between 2020 and 2050, wind turbine capacity increased by 0.5 MW, increasing to 5.7 MW over the time frame. For offshore wind turbines, it was assumed that wind turbines had an average maximum output (CR) of 7 MW (Wind Europe, 2019). Similarly, taking into consideration technological improvements, offshore wind turbine capacity was increased by 0.5 MW for each timestep, increasing to 10 MW by 2050.

To estimate the land/sea area, Eq. (3) was used. Although wind energy density varies with location, for the purpose of this study we assume the mean annual generation density for onshore wind was 3 MW km^{-2} and offshore 5.4 MW km^{-2} which represents the average wind energy density in Europe (Denholm et al., 2009; Wind Europe, 2019). We assume there is no change in percentage split between onshore and offshore wind over time as it is highly regulator dependent (as highlighted by the UKs recent changes in onshore wind policy approach), nor there is an increase in wind energy density due to climate change. The values for the resource proportion of renewable generation can be found in Table 3.

Solar panels

To estimate the total number of solar panels that would be required to meet total energy demand for electric or hydrogen transport, Eq. (2) was used. Over time, the capacity factor (CF) of a solar panel has increased from ~10.9 % in 2014 to ~11.3 % by 2018 (DUKES, 2019). For the purposes of this study, the capacity factor (CF) remained constant at a value of 11.3 %. Capacity factor can be influenced by array design (sun tracking technology) and location (solar declination and weather influencing cloud cover). Here we assumed that, as solar has a very small total capacity in the UK, any expansion of solar farms within the UK would use the latest sun tracking technology. Whilst this has the potential for over estimation at the larger farm scale dependent on design, tracking technology is rarely utilised on new buildings where solar expansion has great potential, therefore our outputs would be an underestimation of area required. No data is available to inform the balance between this factor of scale. The over and under estimations at the different scales are therefore assumed to balance out.

For solar panels, to account for the increase of solar energy conversion to electricity it was assumed that panel arrays had an initial maximum output (CR) of up to ~5 MW assuming a clear day in the middle of summer (BEIS, 2018c). With technological advances it was assumed an improvement of 0.5 MW for each five-year analysed up to 8 MW by 2050.

5 W m^2 was used as the value of mean generation density for solar panels. This is the mean annual solar power for a south facing surface in the UK (MacKay, 2009). There will be variation in output due to the latitude, and sun's declination and cloudiness will also vary throughout the season which influences the method as described above. This assumption means outputs describe the average requirements for the UK. If more spatially explicit targets are required, then this approach

would require a spatial density extension to identify where in the UK may be most appropriate for solar developments (see "Discussion").

Nuclear power stations

The newest nuclear power station in the UK is Hinkley Point C which can generate 3260 MW for ~60 years. This has two new design pressurised water reactors. All 15 UK existing nuclear power stations have a combined maximum capacity of 8883 MWe, as most nuclear power stations are at the end of their life and some are operating at a lower capacity for safety reasons. The contrasting capacities of the different generations of nuclear reactor leaves a complex situation when estimating land use. Current nuclear reactors may be extended past their current expected end of life dates (latest currently 2035) or they may be replaced by new reactors similar to Hinkley Point C, such as the plans with Sizewell C.

We therefore estimate both the number of reactors (Eq. (2)) and the land requirements (Eq. (3)) for nuclear power twice, firstly using the current nuclear capacity (CR) average of 592 MW per reactor excluding the larger capacity reactors and secondly assuming the larger capacity 3260 MW per reactor. This equates to 250 MW km^{-2} and 1874 MW km^{-2} energy generation density respectively (Cheng and Hammond, 2017). The capacity factor of nuclear power stations is largely controllable and depends on energy demand. The literature derived value of 80 % (CF) was used in estimations of new nuclear power stations and assumed consistent throughout the time period (Cheng and Hammond, 2017) with older nuclear power stations using the value of 1. This is because the average energy generated from old nuclear power stations already has already taken into consideration energy loss.

Gas power station

Although the UK is transitioning away from fossil fuels for grid generation by closing down all coal-fired power stations by 2025, there are currently 32 gas fired power stations in use averaging a ~0.95 GW capacity (PR). On average gas power stations are only working at between 55 and 60 % capacity due to their use for dispatchable power, therefore within our research, due to increased renewable energy to lower capacity a value of 55 % was used (Bao et al., 2019). The total area required for a gas power station was not found within literature, therefore the area use was the same as a standard nuclear power station of 250 MW km^{-2}. This also includes the gas processing, storage and pipelines, however it does not take into consideration the railways and port facilities required for fuel.

Limitations within the methodology

The implementation and success of low emission transport will depend on planner and policymakers use of studies such as this which quantify in simple terms the spatial area required to be allocated to provide the energy demanded by the transport sector.

The energy mix input data is based on projections by the National Grid (National Grid, 2019), which are effectively targets of what they need to achieve to meet the two-degree Paris Agreement commitment. Our results will likely change significantly if changes in, for example offshore wind uptake, occur to meet the 1.5 degree target. Additionally, renewable density was increased by 0.5 MW density every five years. This assumption is on the development of larger devices such as 12 MW claiming a capacity factor of up to 63 % of the newest generation likely becoming the new norm, with array design also likely to change to improve efficiencies. Both of these factors will change the generation density, with developments likely improving energy outputs across the wind range (GE Renewable Energy, 2020). Furthermore, it was also assumed that the share of onshore and offshore wind turbines would remain constant. Due to the slowdown caused by public objections to onshore wind developments, it is likely that the ratio of onshore to offshore wind will shift more towards offshore wind generation in the future to 2050, with offshore wind development potentially expediting this process. This is not accounted for in the analysis as the scale and timing of consented developments is unpredictable for both onshore and offshore power. While enabling incorporation of some realism within the model, outputs are sensitive depending on the pace of technological improvements.

Results

The results are presented in three sub-sections by transport type (Section "Projected energy demand") before outputs concerning the scale of energy developments are presented (Section "Electricity generation mix for electric and hydrogen transport"). The approach used predicted how much energy will be required to power each transport type and will consider the energy share at five-year increments from 2020 onward. Impact on ES and NC will be made through calculations of area required to provide the energy needed (Section "Area required for renewable energy").

Projected energy demand

Table 4 highlights the total energy required if all cars, buses and trains were electric or hydrogen between 2020 and 2050. Within the time frame, there is an increase in electricity demand for both fuel types, with electricity demand and hydrogen demand increasing by 12 %. Due to the simplicity of this model, the change is driven purely by the number of vehicles and distance travelled. A fully hydrogen powered transport network will require a little over three times the energy of a fully electric powered transport network. Furthermore, Table 4 indicates that cars required the highest proportion of energy demand of the transport types. Electric cars required 92.5 % of total electricity demand in 2020 and 2050, with 93.3 % of the total electricity demand required for hydrogen transport in 2020 and 2050.

Electric and hydrogen cars

To better understand the total energy required for small, medium, and large electric and hydrogen cars, results are shown in Figs. 1 and 2.

Results for BEVs, as seen in Fig. 1, demonstrate a continual increase in the energy required to fuel these vehicles with total energy demand increase of 12 % from 113,040 GWh in 2020 to 126,465 GWh in 2050. Small BEVs saw an increase in energy demand by 15 % from 37,793 GWh to 43,327 GWh between 2020 and 2050. During the same time frame, medium sized BEVs show an increase in energy demand by 7 % from 46,629 GWh to 49,676 GWh. Large BEVs saw the largest increase of 17 % from 28,618 GWh to 33,462 GWh due to the larger vehicles having an increasing market share in the UK due to consumers purchase behaviour expected the time frame with the TEAM (UK) model.

For HVs (Fig. 2), there is an expected increase in energy demand of 12 % from 355,112 GWh in 2020 to 397,289 GWh by 2050. Small HVs saw an increase in energy demand by 15 % from 118,725 GWh to 136,112 GWh between 2020 and 2050. During the same time frame, medium HVs increase in energy demand by 7 % from 146,484 GWh to 156,058 GWh. Large HVs show an increase of 17 % from 89,903 GWh to 105,120 GWh.

Electric and hydrogen buses

Figs. 3 and 4 demonstrate the total energy required for electric and hydrogen minibuses, urban buses, and coaches.

Total energy demand for electric minibuses, urban buses and coaches increased by 12 % from 5613 GWh in 2020 to 6309 GWh in 2050. Electric minibuses show an increase of 13 % from 1661 GWh to 1869 GWh within the time frame. Electric urban buses increase 12 % from 3439 GWh to 3852 GWh within the time frame. Electric coaches show the greatest percentage increase in energy demand by 15 % from 513 GWh to 588 GWh.

HBs required more energy than electric buses with a total energy demand increase of 12 % from 14,485 GWh to 16,281 GWh between

Table 4
Total energy demand to meet a full fleet of electric or hydrogen cars, buses, and trains between 2020 and 2050.

	Electric Transport (GWh)				Hydrogen Transport (GWh)			
	Cars	Buses	Trains	Total	Cars	Buses	Trains	Total
2020	113,040	5613	3461	122,114	355,112	14,485	10,826	380,424
2025	115,988	5758	3540	125,285	364,374	14,858	11,073	390,304
2030	118,422	5879	3598	127,899	372,021	15,170	11,256	398,446
2035	120,542	5981	3642	130,165	378,682	15,433	11,393	405,508
2040	122,457	6090	3697	132,244	384,698	15,714	11,563	411,975
2045	124,561	6207	3766	134,533	391,306	16,017	11,779	419,102
2050	126,465	6309	3824	136,599	397,289	16,281	11,962	425,532

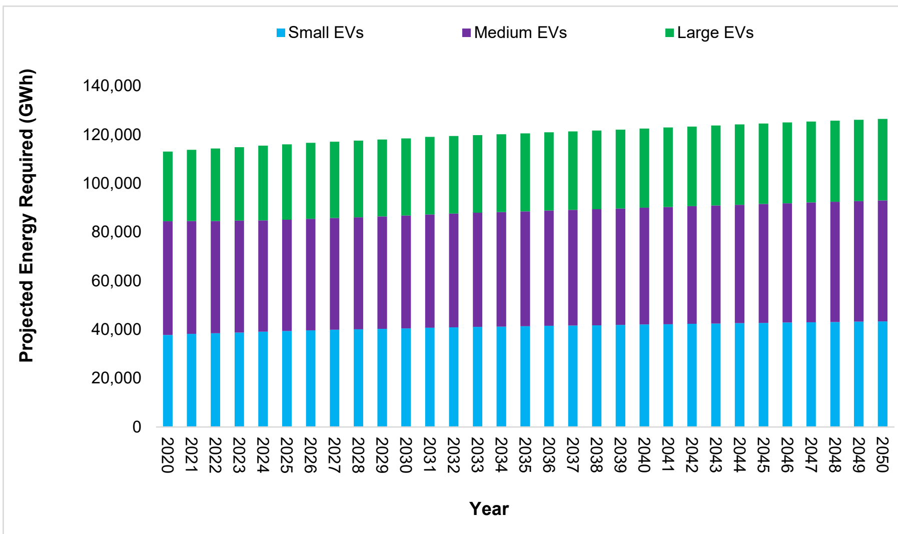

Fig. 1. Projected energy demand for 100% small, medium, and large electric cars between 2020 and 2050 in the UK.

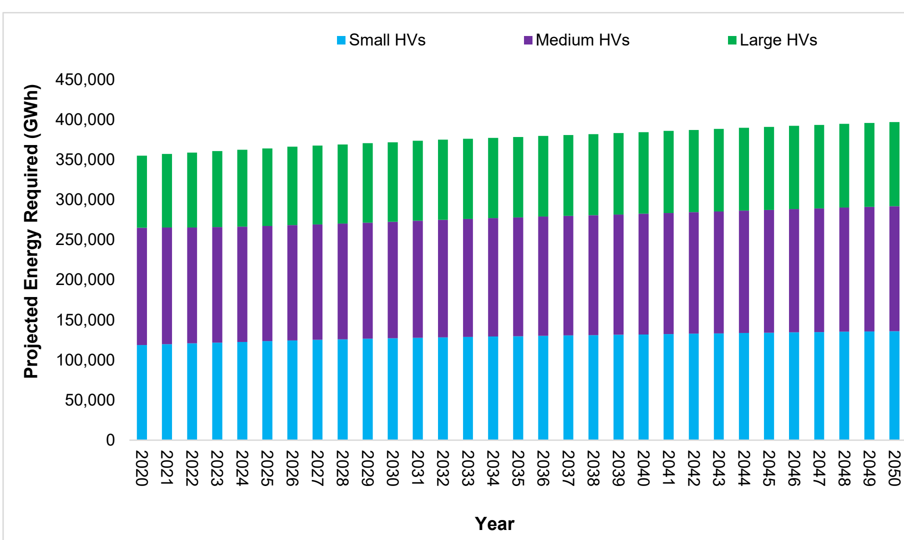

Fig. 2. Projected energy demand for 100% small, medium, and large hydrogen cars between 2020 and 2050 in the UK.

2020 and 2050 (see Fig. 4). Hydrogen minibuses show an increase of 13 % from 4287 GWh to 4824 GWh within the time frame. Hydrogen urban buses increase 12 % from 8874 GWh to 9941 GWh within the time frame. Hydrogen coaches show the greatest percentage increase in energy demand by 15 % from 1324 GWh to 1517 GWh.

Electric and hydrogen trains

Projected energy demand for electric and hydrogen for urban, regional, intercity, and high-speed trains can be seen in Figs. 5 and 6.

Fig. 5 demonstrate the total energy demand for electric trains which increases by 10 % from 3461 GWh to 3824 GWh from 2020 to 2050. Electric urban trains show an increase in energy demand by 11 % from 407 GWh to 450 GWh within the time frame. Electric regional trains

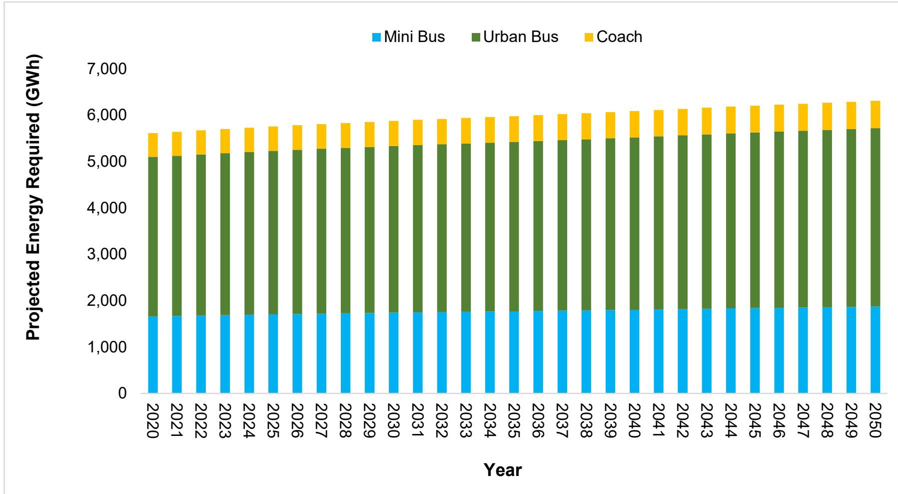

Fig. 3. Projected energy demand for electric minibuses, urban buses, and coaches between 2020 and 2050 in the UK.

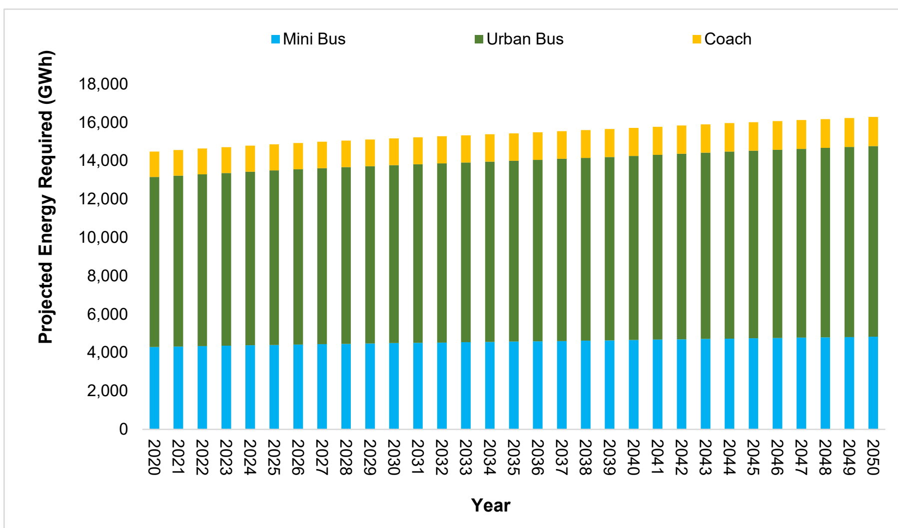

Fig. 4. Projected energy demand for hydrogen minibuses, urban buses, and coaches between 2020 and 2050 in the UK.

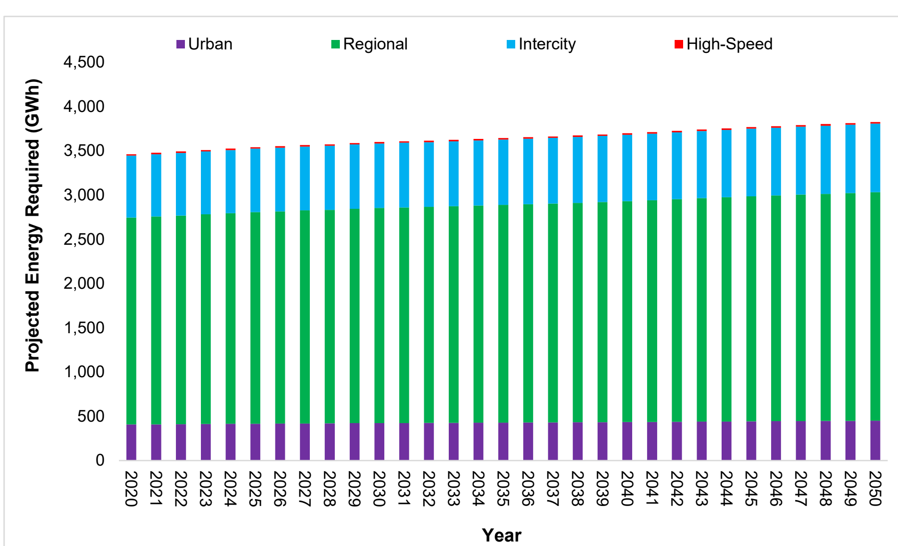

Fig. 5. Projected energy demand for 100% electric urban, regional, intercity, and high- speed trains between 2020 and 2050 in the UK.

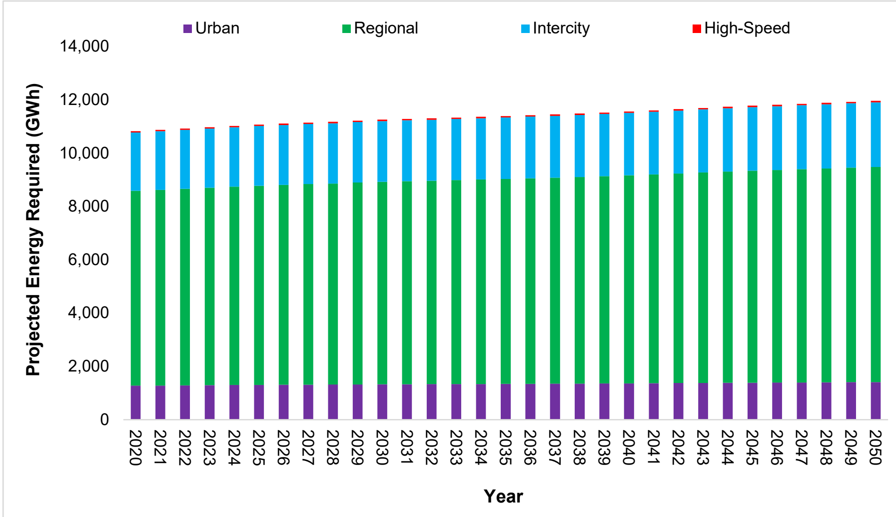

Fig. 6. Projected energy demand for 100% hydrogen urban, regional, intercity and high-speed trains between 2020 and 2050 in the UK.

increase 10 % from 2337 GWh to 2582 GWh. Electric intercity trains show an increase of 11 % from 701 GWh to 775 GWh and electric high-speed trains increase by 13 % from 16 GWh to 18 GWh.

Hydrogen trains require more energy than electric trains with total energy demand increasing by 11 % from 10,826 GWh to 11,962 GWh within the time frame as seen in Fig. 6. Hydrogen urban trains show an increase in energy demand by 11 % from 1273 GWh to 1407 GWh within the time frame. Hydrogen regional trains increase 19 % from 7310 GWh to 8706 GWh. Hydrogen intercity trains increase 10 % from 2193 GWh to 2423 GWh and hydrogen high-speed trains show an increase by 10 % from 50 GWh to 55 GWh.

Electricity generation mix for electric and hydrogen transport

With the total electricity projected for a full fleet of electric and hydrogen cars, buses and trains as calculated in Table 4, the breakdown of energy generation requirements from the three different electricity sectors (renewables, nuclear and fossil fuels) as seen in Table 3 was calculated.

Energy generation for electric and hydrogen transport

Table 5 demonstrates the megawatt of electricity required if all transport was all electric or hydrogen, as calculated using Eq. (1).

Over time, as highlighted in Section "Projected energy demand", energy demand for transport is expected to increase. Results indicate that between 2020 and 2050, renewable energy generation will be the primary energy generation source, with total capacity required peaking in 2050 and 2040 for renewables and nuclear respectively. As the result of the significant emissions reduction policies that are required to meet the two degree requirements, fossil fuels are expected to reduce to almost 10 % of its 2020 energy generation.

Technology installation to meet energy demand

Table 6 demonstrates the total number of energy sources required to meet the energy required by transport weighted by the expected network generation share between generation sources (National Grid, 2019) (as seen in Table 3). Wind is broken down into its component parts as there are expected to be significant differences in development trajectories between onshore and offshore wind. A similar approach is used for nuclear power stations, with the average energy generated from a current, outgoing nuclear power station compared to new generations of nuclear power stations using more advanced technology like at Hinkley Point C.

It is important to note that the numbers presented represent the number of energy sources required to be 'allocated' to powering low emission transport from the given energy source. For example, for onshore wind, the values presented indicate the number of turbines to provide 24 % of the 69 % of energy required by transport in 2050 (Table 3).

Across the time frame the total number of onshore and offshore wind turbines are expected to decrease overall due to technological advances, with turbines required expected to peak in 2030. Onshore wind turbines required are expected to peak in 2025 with 2669 turbines before decreasing to 1733 by 2050. Offshore wind turbine requirements are expected to peak in 2040 with 912 turbines, before decreasing to 801 in 2050 to meet the transport energy demands by 2050. To meet the energy

Table 5
Installed generating capacity required for electric and hydrogen cars, buses and trains based on the energy generation mix from Table 3 (which represents extrapolated values from National Grid data) split into renewables (R), nuclear (N) and fossil fuels (FF) in MW between 2020 and 2050 in the UK.

		Energy generation capacity (MW)						
		2020	2025	2030	2035	2040	2045	2050
Electric Transport	R	8659	12,942	14,499	14,531	14,181	14,617	14,970
	N	4167	2246	3801	5035	5968	5923	5821
	FF	6375	4413	1810	1023	645	656	687
	Total	19,200	19,601	20,110	20,589	20,793	21,195	21,478
Hydrogen Transport	R	19,586	29,273	32,795	32,867	32,074	33,059	33,858
	N	9424	5079	8597	11,388	13,497	33,059	13,164
	FF	14,418	9980	4094	2315	1458	1483	1555
	Total	43,427	44,333	45,485	46,569	47,029	67,602	48,577

Table 6
Estimated number of onshore and offshore wind turbines, solar panels and nuclear power stations (average nuclear power stations and a Hinkley Point C equivalent) and gas power station to meet energy source type share of demand for electric and hydrogen transport, based on the energy generation mix Table 3 between 2020 and 2050 in the UK. The share of offshore and onshore wind was based on the 2019 turbine split with total number of combined turbines also reported.

	Electric Transport							Hydrogen Transport						
	2020	2025	2030	2035	2040	2045	2050	2020	2025	2030	2035	2040	2045	2050
Onshore wind turbines (24 % split)	1786	2669	2586	2284	1991	1855	1733	5564	8316	8058	7114	6204	5780	5400
Offshore wind turbines (63 % split)	819	412	654	815	912	858	801	5303	7397	7769	7328	6754	6595	6417
Total wind turbines	2605	3081	3240	3099	2904	2713	2534	10,867	15,713	15,827	14,442	12,958	12,375	11,817
Solar panels	11,127	15,119	15,526	14,363	13,016	12,522	12,023	34,665	47,100	48,369	44,747	40,548	39,008	37,454
Average nuclear power station	11	16	18	18	17	18	18	16	9	15	19	23	23	22
Hinkley Point C equivalent	1	1	1	1	2	2	2	4	2	3	4	5	5	5
Gas power station	9	6	3	1	1	1	1	28	19	8	4	3	3	3

demand for hydrogen transport, the total number of onshore and offshore wind turbines are expected to increase over time, as would be expected with increases in energy requirements. For onshore wind, turbine requirements are expected to peak in 2025 with 8316 turbines before decreasing to 5400 by 2050. Offshore wind turbines are expected to peak in 2030 with 7769 turbines, before decreasing to 6417 in 2050 which is likely due to technological advances.

Solar panels for electric show an increase between 2020 and 2050, peaking in 2030 at 15,526. Solar panels for hydrogen show an increase between 2020 and 2050, peaking in 2030 at 15,119.

Results indicate that 11 nuclear power stations producing a capacity of ~592 MW are required to power 100 % low emission electric transport in 2020 before increasing to 18 by 2050, though this rapidly changes with the changes in percentage share of power generation between types. For nuclear power stations with the capacity of Hinkley Point C, an additional one nuclear power station between 2020 and 2035, before increasing to two from 2040 would be needed to provide the nuclear power share of transport energy. Results indicate that for hydrogen an addition of 16 nuclear power stations producing a capacity of ~592 MW are required, before increasing to 22. For nuclear power stations with the capacity of Hinkley Point C, an additional four nuclear power stations in 2020 are needed, before increasing to five by 2050. As the lifespan of nuclear power stations is 40 years before decommissioning, the most effective approaches would be utilising the high capacity Hinkley Point type as any over capacity would be useable in other sectors whilst requiring the least amount of infrastructure and investment with greatest ES and NC impact savings.

For gas power stations, there would be a decrease in requirements from an additional nine gas stations before decreasing to one within the time frame. This decrease is due to the UK phasing out fossil fuel use in favour of renewables. For hydrogen transport, there would be a decrease from an additional 28 gas stations before decreasing to three within the time frame. This decrease is due to the UK phasing out fossil fuel use in favour of renewables.

The predictions that around 2030/2035 will be the peak of power generation source requirements indicate the cross over point where number of sources and technological improvements within the predictions outstrip the increases in energy demand from transport. This would suggest that the development of clean energy sources is particularly critical within the next ten years to provide required energy from transport within the context of the trend of increasing energy demands from many other sectors. Our results do not suggest that renewables do not need to be continually expanding after this peak period. Clean energy expansion past the number of sources shown here will still be required for other sectors.

Area required for renewable energy

To generate enough energy to meet energy demand from renewables, construction of new energy generation sources will be required. Table 7 demonstrates the total land and sea area required for each source between 2020 and 2050. Overall, offshore wind turbines will approximately contribute one third of total area required for energy generation. This is of particular interest as it is currently the least well-developed energy source, highlighting impacts on NC and ES that are yet to be seen.

For electric transport, results indicate that sea area required for offshore wind turbines increases between 2020 and 2050 from 399 km^2 to 1066 km^2, with sea area peaking in 2030 at 1068 km^2. Additionally, land area required for onshore wind turbines increases from 227 km^2 to 606 km^2, also peaking in 607 km^2. Land area required for solar panels increased from 567 km^2 to 1518 km^2 peaking in 2030 at 1515 km^2. For nuclear power stations, the average area required increases from 3 km^2 in 2020 to 5 km^2 by 2050, having decreased to 1 km^2 in 2025. This small area required is likely a result of the decreasing amount of energy required for nuclear power in the UK, for example, Scotland phasing out nuclear power. For nuclear power stations with the capacity of Hinkley Point C, area increases to 1 km^2. For gas power stations, area decreased from 6 km^2 to 0 km^2 as the share of fossil fuels decreases.

For hydrogen transport, results indicate that sea area required for offshore wind turbines over increases from 1243 km^2 in 2020 before peaking in 2035 at 3384 km^2, decreasing to 3321 km^2 by 2050. Land area required for onshore wind turbines increases from 707 km^2 in 2020, peaking at 1892 km^2 in 2030, decreasing to 1888 km^2 by 2050. Land area required for solar panels increased from 1767 km^2, peaking in 2030 at 4729 km^2 before decreasing to 4720 km^2 by 2050. For nuclear power stations, the average area required 20 km^2 in 2020, before decreasing to 6 km^2 in 2030 and increasing to 28 km^2 by 2050. For nuclear power stations with the capacity of Hinkley Point C, area increases from 4 km^2 to 5 km^2 by 2050, however reliance on nuclear decreases in 2025 to 2 km^2. For gas power stations, area decreased from 19 km^2 to 0 km^2 as the share of fossil fuels decreases.

Discussion

This paper presents a policy-focussed approach to projecting the additional electricity required to meet the UK's electricity demands for an entirely electric or hydrogen road transport fleet and consider the area of land/sea required to support this electricity infrastructure. Results from the analysis indicate that substantial investment into energy generation will be required if the UK is to successfully switch to electric and hydrogen transport. Between 2020 and 2050, electric transport will require almost half the energy of hydrogen transport, which is due to the additional stages required to generate hydrogen. Increases in energy demand from transport over time are due to the increase in the number

Table 7
Total area required for onshore and offshore wind turbines, solar panels, nuclear power stations (average nuclear power stations and a Hinkley Point C equivalent) and gas power stations to meet electricity demand for total electric and hydrogen transport, based on the energy generation mix Table 3 between 2020 and 2050 in the UK. The final row with total area takes into consideration the average nuclear power station size, with the bracketed numbers representing the Hinkley Point C equivalent.

	Electric Transport (km^2)							Hydrogen Transport (km^2)						
	2020	2025	2030	2035	2040	2045	2050	2020	2025	2030	2035	2040	2045	2050
Onshore wind turbines (24 % split)	227	494	607	599	562	587	606	707	1539	1892	1867	1750	1828	1888
Offshore wind turbines (76 % split)	399	869	1068	1054	988	1032	1066	1243	2707	3328	3284	3079	3215	3321
Total wind turbines	626	1363	1675	1653	1550	1619	1672	1950	4245	5219	5151	4829	5043	5209
Solar panels	567	1235	1518	1498	1404	1467	1515	1767	3846	4729	4667	4375	4569	4720
Average nuclear power stations	3	1	2	4	5	5	5	20	11	6	24	28	28	28
Hinkley Point C equivalent	0	0	0	0	1	1	1	4	2	3	4	5	5	5
Gas power station	6	3	0	0	0	0	0	19	9	1	0	0	0	0
Total area	1214 (1199)	2608 (2601)	3195 (3193)	3155 (3151)	2959 (2955)	3091 (3087)	3192 (3188)	3794 (3740)	8129 (8102)	9957 (9952)	9842 (9822)	9232 (9209)	9640 (9617)	9957 (9934)

of vehicles projected to be in use. Importantly, policymakers must fully consider the energy source implications of these projections. To ensure the Paris Agreement targets are met, low carbon electricity generation capacity requires rapid expansion, the extent of which is dependent on the pace of technological development. Results show large-scale offshore wind energy being the most area-use efficient means of emissions reduction due to the energy capacity generated per kilometre squared compared to the other energy types, however this will likely impact both NC and ES.

Results have highlighted that the location of renewable generation will be extremely important to consider for policymakers seeking to reduce the impact on NC and ES. Whilst a parsimonious approach, this study's outputs provide a robust approximation of the future demands from the transport sector on land and sea area use. More advanced modelling may be able to give a more spatially explicit output on this same question, however this study provides a rapid assessment on the scale of transport decarbonisation effects on NC and ES in the UK. It is important to consider that the requirement for up to ~2 % UK land area (from the total UK land area of 242,495 km^2) to be utilised for transport energy supply represents mitigating ~33 % of emissions (BEIS, 2018a). It will therefore be necessary to increase wind and solar generation while further considering the context of all area uses, energy demand and the subsequent conflicts with other ES. There are current conflicts between laws and policies regarding increases in renewable generation, with energy laws not fully considering the spatial interaction of ES and NC and generation infrastructure in the UK (Woolley, 2015).

For personal vehicles, the amount of energy required would be expected to be 92.5 % and 93.3 % of the total energy demand required for buses, and trains in 2050, highlighting how resource intensive this transport type is. Furthermore, large BEVs saw the largest increase of 17 % within the time frame, which is likely to be due to individuals purchasing larger passenger vehicles, in particular increased purchases of sports utility vehicles (SUVs) (Brand et al., 2020; Vögele et al., 2021; Watson et al., 2019). Incorporating vehicle size within methodologies is important to highlight societal preferences in vehicle size which have consequences for energy demands.

Urban buses required the highest energy demand from the three bus types. This is likely due to urban buses being more widely used than minibuses and coaches. EBs are more suited to shorter routes within cities due as they have a smaller range than HBs (Logan et al., 2020a). Increasing the battery capacity to increase the driving range incurs an expensive solution, with the additional weight also having potential to limit ridership (Basma et al., 2020; Lajunen, 2014). HBs have a larger range and may be better suited for longer distances since they can store higher amounts of electricity when travelling between cities and in rural services, as has been demonstrated in Aberdeen (Fuel Cells Bulletin, 2012; Pagliaro and Meneguzzo, 2019). Therefore, although energy demand for urban HBs are higher, it will likely be a combination of both EBs and HBs that is used to reduce GHG emissions within the bus sector. Coaches produced the lowest level of emissions for the bus types which is likely due to a shift towards trains for similar long-distance journeys at a greater speed.

Taking into consideration longer distance travel, emission savings initiatives need to be backed up with sufficient infrastructure. France has recently introduced a ban on domestic short-haul flights if the journey can be made by train in less than 2.5 hours, which may increase the utilisation of certain land transport alternatives. However, although France has a well utilised train network, this may inadvertently encourage the uptake of travel using personal vehicles for lower cost and convenience. Ensuring that low emission charging and power supply facilities for both personal and public transport is available throughout the country and at a competitive cost is essential for short-haul flight bans/restrictions to be effective (Logan et al., 2022).

Impact on natural capital and ecosystem services

Considering the demands of increased energy requirements together with transport infrastructure requirements within city and regional planning, should lead to incorporating minimum solar PV roof area within city design regulations; this can reduce impacts on ES and NC. Shifting lower energy density generation types to areas unsuitable for higher value ES will minimise land use conflicts and minimise impacts on ES and NC optimizing land use. Future planning for sustainable cities should ensure both compact and energy-efficient designs as well as allowing a maintainable and liveable landscape (Kalantari et al., 2017). Without this consideration, increasing energy generation from solar PV would have a greater impact on ES and NC. The implications of this are important to consider when structuring policy approaches for implementing additional infrastructure that will be needed for the UK to switch to electric and hydrogen transport to meet net zero emission targets.

The spatial location of energy sources should be a consideration within all future development planning across the spatial scales. Electricity and hydrogen production and refuelling stations should be installed with consideration of site characteristics and utilisation feasibility. For example, new building designs could be compelled by building regulations to incorporate solar panels, which would reduce land use conflicts elsewhere as solar requires the most land area. Adding solar to roofs can reduce ES and NC conflicts as few if any other services can utilise roof areas. This has the added benefit of localising energy production for either electricity or hydrogen transport, if linked to a parking structure for example, or to reduce the network reliance of the buildings.

To meet the expected demand, marine wind developments are scheduled to be further offshore and marine renewable energy sources such as tidal are already at commercial deployment even if on a small scale. Rural areas have the space to develop renewable electricity generation so that whilst public transport may be more difficult to implement in rural areas, the supply of local low carbon energy as electricity or via hydrogen production, may be more easily implemented and have less impact on ES and NC than connecting rural areas to national grid networks. Tidal and wind electricity can be used to produce hydrogen locally to avoid transporting hydrogen long distances if grid connection in remote areas is not currently available (e.g. Orkney). Utilisation of hydrogen energy locally can avoid restrictions that currently hinder the development of low emission transport. Additionally, this has the benefit of reducing local area land use ES conflicts in densely populated areas. The area requirements described in this study account for up to ~2 % of UK land area in some cases, with land use by arable farms approximately the same proportion. Adding generating capacity areas that aren't suitable for other developments (mountain ranges etc.) and already developed areas highlights that planning for the required large-scale renewable energy expansion requires coordination between policies across scales to minimise adverse impacts and conflicts with ES. Furthermore, to meet the needs of hydrogen transport, significantly more investment is required into renewable energy than for electric transport. To reduce the environmental impact on both ES and NC in terms of land area required to meet hydrogen demands, emphasis on hydrogen generation from SMR with CCS will be required as this will require the least land area for hydrogen production. Furthermore, Budinis et al. (2018) determined that CO_2 could be stored at the current emissions rate for 100 years in the UK North Sea if CCS was fully deployed, highlighting the mitigation potential of CCS in the UK. This will also take advantage of the oil industries transition to net zero as infrastructure can be repurposed.

The approach this study uses is average energy density values to calculate area requirements. Spatially explicit modelling of land use and energy density (wind and tidal) is required to design the spatial distribution of the overall additional energy infrastructure quantifies in this study. The area requirements for offshore and onshore wind and solar panels are important to consider in terms of impact on ES (disruption to hydrological process or scenic spots) and therefore on NC. The area calculation for offshore wind is an essential aspect for marine spatial planners to consider when allocating areas for development as increased electrification of transport networks will have indirect effects on NC and the economy through impacts on fisheries, shipping networks and other sea users. Offshore wind is currently viewed as an underexploited resource with new draft plan options coming online within the next few years. Due to the slowdown caused by public objections to onshore wind developments, it is likely there will be a greater transition towards offshore wind generation towards 2050.

Over time the cost of technology is expected to decrease, with several studies already proposing wind and solar or hybrid solar-wind systems that are lower cost than previously (Dispenza et al., 2017; Micena et al., 2020; Nistor et al., 2016). However, to produce hydrogen, the cost of wind energy remains lower ranging in price from 5.27 to 8.01 US$/kg compared to solar from 3.41 to 16.01 US$/kg (El-Emam and Özcan, 2019). Over time, the cost of renewable energy technology should decrease as technology develops. Furthermore, other processes including CCS will also require significant investment and land to reduce the level of emissions produced. For example, a combined cycle gas turbine (CCGT) post-CCS will have a total site footprint of ~62,000 m^2, however for the construction of the CCGT with pre-combustion capture total area will be ~50,000 m^2 (DECC, 2009). Therefore, if CCS is considered before the implementation stages the total area required could be decreased and would reduce the impact on ES and NC.

Decarbonising electric and hydrogen transport

As the results have indicated significant additional electricity generation will be required to meet the energy demand of electric and hydrogen transport. To reduce the emissions, electricity should be generated by renewable or nuclear generation as fossil fuels are phased out, with residual fossil fuel emissions being reduced as far as possible and the introduction of CCS to enable the UK to decarbonize energy and transport. CCS permanently stores CO_2 emissions produced from fossil fuel stations in geological formations underground. CCS will help to mitigate emissions produced from residual fossil electricity generation that provide dispatchable power to cover the intermittency of renewable generation and reduce the overall impact on ES and NC. This study calculates the number of gas power stations required to power the fossil fuel component of the electricity required, though it's likely that more fossil fuel power stations will be used to ensure overall electrical energy security of other sectors in the short term.

Encouraging electric and hydrogen transport needs to occur simultaneously with the decarbonisation of electricity generation. Although there is an increasing share of renewable energy technology through various legislations the UK has committed to, fossil fuels may be required to ensure energy security. For example, in Scotland closing nuclear energy generation will require some form of dispatchable electricity provision be it fossil or storage to cover periods of renewable intermittency.

Around one fifth of the UK population live in rural areas with a lower and more dispersed demand for travel which cannot always be sustained through conventional public transport structures (Mounce et al., 2018). In addition, local authorities often have funding limitations due to having to provide services over a wider area. This leads to increased costs to individuals as current subsidy streams for public transport are not large enough to bring public services on par with personal transport options (Mulley and Nelson, 2009). Therefore, many individuals in rural areas are heavily reliant on (predominantly petrol and diesel fuelled cars) with 94 % of residents in villages, hamlets or isolated dwellings owning a car compared to 66 % in urban areas in 2014/15 in England (Defra, 2019). In addition, 59 % of those households within villages, hamlets or isolated dwellings owned two or more cars/vans compared with 25 % of those in urban conurbations in England (Defra, 2019).

Low emission transport and society

Although the UK left the EU in early 2020, the transition period agreed upon in the EU-UK Withdrawal Agreement finished at the end of 2020. However, the UK was subject to EU legislation during the Brexit transition. The UK has stated that they want to seek cooperation with the EU to support the delivery of cost efficient, clean and secure supplies of electricity and gas, based on competitive markets and non-discriminatory access to networks as the UK recognises the shared interest in global action to mitigate climate change (BEIS, 2019b).

Assuming a 100 % electric and hydrogen market share enables us to discuss the implication on ES and NC from switching the low emission vehicles. The energy requirements described here are further dependant on the size category breakdown of the electric transport vehicles. The increase in the numbers of cars projected using the TEAM-UK model indicates an overall increase of 25 %, linked to population size. Within this data however there is a market share shift of 4 % into larger vehicles sizes, as has been highlighted previously in the literature (Brand et al., 2020). Market shifts to larger vehicle sizes will further increase the energy demand as smaller cars are generally more efficient.

With an increase in electric and hydrogen transport, increases in infrastructure including public charging infrastructure will be required. If the current vehicle fleet is replaced directly with BEVs, significant amounts of charging infrastructure would be needed to ensure low emission vehicles take up is more rapid during the transition period by reducing range anxiety, the predominant restraint (other than financial) that currently dissuades consumers from buying electric cars (Marabete et al., 2022). Although it is assumed that charging infrastructure availability will increase with the number BEVs on the roads, it is also assumed that most individuals will charge their vehicle either at home or at their place of work. The demand for public charging stations that integrate into the mobility pattern of BEV drivers increases and becomes more necessary (Schmidt et al., 2020). In addition, to meet demand, additional infrastructure will need to be built for hydrogen refuelling stations.

Integration of electric transport is not always a viable option for all levels of society, for example, individuals living in rural areas who are more dependent on their vehicles may suffer from range anxiety. The average electric car has a capacity to travel ~170 km on a full charge, and the average individual only travels ~40 km each day. However, without the guarantee they can easily recharge their vehicle, the risk of not being able to recharge becomes too great a cost of vehicle ownership (Bonges and Lusk, 2016; Krupa et al., 2014). This has led individuals within higher income groups in the UK more likely to consider a battery electric car as a second vehicle due to range anxiety, which would likely increase transport emissions due to having a second vehicle (Skippon and Garwood, 2011). However, hydrogen cars have an average range of ~500 km before needing recharged/refuelled; therefore, to reduce anxiety within rural areas, hydrogen transport may be a more favoured approach to reduce GHG emissions from transport. Although beyond the scope of this study, it is important to consider that there will likely be a mixture of both electric and hydrogen transport in the UK, allowing individuals to feel more in control of their transport needs by reducing their range anxiety whilst simultaneously reducing transport emissions. Similarly, regional rail lines and buses within rural areas would benefit from being fuelled by hydrogen, instead of electricity due to the associated increase in range (Logan et al., 2020a, 2020b). Societal changes from urban or suburban to rural living will significantly influence the energy demand in terms of scale and location and therefore emissions in real terms, though the scale of this impact would be region specific.

Although there is an increase in the number of trains and buses, energy and emissions are lower per person per km travelled than for cars (Logan et al., 2020a, 2020b). This highlights the importance of switching to public transport as with this increase in personal vehicle demand, comes an increase in energy demand. To encourage this modal shift, the introduction of several push and pull travel demand management (TDM) initiatives will need to be implemented (Logan et al., 2020c). For example, public transport use in London has grown over the past few decades with the introduction of the Oyster card that allows for integrated travel between different public transport modes whilst capping daily travel cost. This has coincided with de-incentivisation methods against personal transport such as the introduction of congestion zones and high parking fees in both residential and business areas raising the costs of car ownership. If more widescale implementation of such measures was possible across the UK, this could result in a greater decrease in the level of energy demand and emissions produced from personal transport. Furthermore, as a result of the COVID-19 pandemic, companies and individuals themselves may prefer to work from home where possible (Rahman Fatmi et al., 2022). This switch may result in individuals not travelling as regularly however, this may result in an increase in personal vehicle use (at the expense of public transport) even after restrictions are reduced. This is because individuals are more likely to choose convenience if they are travelling to their workplace once or twice a week as they will see it as an overall reduction in travel (Logan et al., 2022). As a result of COVID-19 there has seen a decrease in the number of trips taken by public transport (Rasca et al., 2021; Sträuli et al., 2022; Tiikkaja and Viri, 2021). Therefore, how the UK Government approaches management of travel behaviour in the "next normal" will be an important factor to consider when designing approaches to encourage low emission travel.

Furthermore, in real terms the infrastructure provision is likely to be different between transport types as buses are likely to have charging infrastructure locally whereas trains are more likely to have refuelling facilities at the end and start of their journey or an electrical supply along the line. The location of renewable energy generation within transport networks is therefore crucial to facilitate the most efficient transition and sustainability of converting public transport networks to hydrogen or electric power.

However, with the anticipated shift towards electric and hydrogen fuelled transport several issues may arise. Key amongst these are where and when BEVs can be charged and where and when additional infrastructure can be introduced for both charging and generation infrastructure. This has been further emphasised in several studies which suggest that local urban and regional plans and policies can help trigger action and through implementing publicly acceptable technologies that can aid place based decarbonisation (Geels et al., 2020; Hansen and Coenen, 2015; Hillman and Sandén, 2008; Magnusson et al., 2020; Nilsson and Nykvist, 2016). Therefore, for this to be a successful transition, placement at these local levels will need to be taken into consideration. In addition, BEVs adoption in rural areas has been slow predominantly due to lack of infrastructure and higher than average distances travelled. Although the most popular BEVs have a range of ~270 km, many individuals have 'range anxiety' (Bonges and Lusk, 2016) and prefer the perceived required 'distance safety net' provided by ICEVs. This contrasts with urban and suburban areas where BEV range is more than adequate for the average journey distance of ~28.8 km travelled by personal vehicle per day and there is generally more charging infrastructure available. Research has demonstrated that consumer's decision to buy an BEV can be directly related to the availability of recharging stations (Krupa et al., 2014; Li et al., 2017). With an increased number of charging facilities and regular bus and train stops, rural dwellers will have more opportunities to make sustainable transport choices.

Conclusion and policy implications

Previous work has shown that the switch to lower emission energy sources will have comparatively positive impacts on ES and NC by mitigating climate change. The implementation and success of low emission transport will depend on planner and policymakers use of studies such as this which quantify in simple terms the spatial area required to be allocated to provide the energy demanded by the transport sector.

Our study demonstrates the scale of effort required in terms of physical energy generation sources and that switching to electric and hydrogen transport will result in an increase level of land use required. This is the equivalent of a minimum of 1515 km^2 for electric transport and 4720 km^2 for hydrogen transport in 2050 (using solar panels as an example as they require less land and sea area than wind). This represents 0.6 % and 2 % of the UK land area. Although this does not sound significant, currently only ~6 % of UK land area is developed (Rae, 2017). This would mean the UK would need to develop at least another 10 % of what the UK currently have available to meet demand. This poses significant difficulties for policy makers to ensure decarbonisation without long term implications in terms of ES and NC. Electric transport should be prioritised over a hydrogen network based upon electrolysis as it will require approximately double the electrical power (in terms of number of sources and energy required) and therefore will be harder to achieve. On the other hand, hydrogen generation by SMR coupled with CCS may be a sustainable option in the short term.

To ensure minimal impact on NC and ES, technological improvements of energy generation should be a priority as it will ensure a reduction in area required for these technology types. This will require a significant investment in renewable energy technologies, but generation infrastructure developments should not wait for more efficient technologies as the sooner additional renewable generation is installed the greater the reduction of cumulative emissions and the reduced impact on ES and NC. Offshore wind turbines have significant potential to provide the additional energy to fuel electric and hydrogen transport and requires significant investment. During the transition, the addition of CCGT-CCS will be required to reduce emissions in the short term.

To ensure the impact of NC and ES is limited, further research should focus on more spatially explicit modelling to provide a better understanding of the localised interactions that may favour site selection for both energy generation and localised infrastructure. Furthermore, successful implementation of low emission policies and initiatives at both government and community scale will rely upon sufficient stakeholder involvement as well as infrastructure investment.

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CRediT authorship contribution statement

Kathryn G. Logan: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Data curation, Visualization, Formal analysis. **John D. Nelson:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision. **James D. Chapman:** Conceptualization, Methodology, Writing – review & editing. **Jenny Milne:** Conceptualization, Writing – review & editing. **Astley Hastings:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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