National Institute Economic Review (2024), 1–11
doi:10.1017/nie.2024.6

ARTICLE

CAN THE UK ACHIEVE NET ZERO GREENHOUSE GAS EMISSIONS BY 2050?

Jennifer L. Castle[1] and David F. Hendry[2]

[1]Magdalen College and Climate Econometrics, University of Oxford, Oxford, UK and [2]Nuffield College and Climate Econometrics, University of Oxford, Oxford, UK
Corresponding author: David F. Hendry; Email: david.hendry@nuffield.ox.ac.uk

Abstract
Net zero greenhouse gas emissions by 2050, the UK's current target, requires bridging a dramatic energy transition and eliminating all other net sources of emissions while ensuring a just transition. Key components like renewable electricity generation and electric vehicles are well developed, but many issues remain. Public support for a green economy may wane if the economic costs are too high or seen as unfair. Therefore, although renewable energy is cheaper than fossil fuels, it is essential to maintain employment, real per capita growth and reduced inequality. Decarbonizing the UK economy requires an integrated sequential approach and need not be delayed while dealing with the aftermath of the COVID-19 pandemic, energy crisis and resulting inflation.

Keywords: decarbonizing; economic growth; greenhouse gas emissions; net zero; renewable electricity

JEL codes: C5; Q54

1. Introduction

The UK's Climate Change Act of 2008 (CCA08) was the world's first legally binding legislation on greenhouse gas (GHG) emissions. It set a target of an 80% reduction in net GHG emissions by 2050. The CCA08 created the Climate Change Committee as an independent statutory body to monitor, analyse, advise and report to Parliament on progress towards the target: their recent report has more than 300 policy recommendations. In 2019, the UK Government amended its original target to one of zero net GHG emissions by 2050. Our analysis of the CCA08's impact found a reduction of almost 50 Mt more by 2015 than accounted for by the explanatory variables in the model.

These important steps were strengthened in 2010 by the EU Renewables Directive, which was revised in 2018 and has been legally binding there since June 2021. The United Kingdom has separately banned the sale of all new petrol and diesel cars and vans by 2030. Thus, a legislative and advisory framework is in place, but many issues remain to be tackled. The COVID-19 pandemic, recent energy crisis and resulting inflation have added awkward but relatively temporary hurdles seen against a near 30-year time frame to achieve net zero, and in some respects could accelerate progress towards that goal with more emphasis on energy security provided by domestic renewables.

UK total energy use in 2019 was approximately 2200 terawatt hours (TWh = billion kWh) from using roughly 190 million tonnes of oil equivalent (Mtoe). That comprised roughly 70 Mtoe petroleum, 75 Mtoe natural gas (mainly methane) and 45 Mtoe non-CO_2 energy, with negligible coal, as seen in Figure 1.

© The Author(s), 2024. Published by Cambridge University Press on behalf of National Institute Economic Review. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (http://creativecommons.org/licenses/by/4.0), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

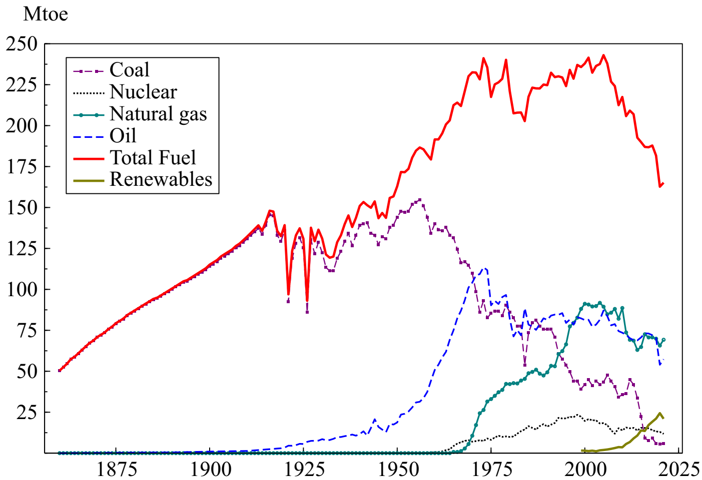

Figure 1. UK total energy use, calculated as the sum of coal, oil, natural gas, nuclear and other non-GHG, all in Mtoe.

Total UK energy increased almost five times from 1860 to its peak in 1973, with violent oscillations in the interwar period, but has stabilised since then, falling by 25% in per capita terms. Coal provided nearly all energy till the 1950s, with oil use rising rapidly till the mid-1970s oil crises, then natural gas becoming important after the North Sea discoveries, now with rapidly rising renewable energy.

The volumes of GHGs emitted by consuming fossil fuels in kilograms (kgs) of CO_2 emitted per 1000 kWh of energy produced are 3.4 from coal, 2.5 from oil and 1.9 from natural gas; source: US Department of Energy. Figure 2(a,b) records CO_2 emissions in tons per annum per capita (tpapc) for the United Kingdom and United States, respectively from the middle of the nineteenth century till recently. UK territorial emissions have fallen from more than 12 tpapc to around 4.5 tpapc since the mid-1970s, mainly by eliminating coal from energy production, so are below the UK's 1860 values, but even at their peak were less than the United States in 2019. Agriculture, cement, chemicals and waste emit methane and nitrous oxide, which as GHGs have weights of 25 and 300 in CO_2 equivalents (CO_2Eq). Panel (c) shows UK total territorial GHG emissions that are substantially higher but still falling, although recent research suggests the UK underestimates its methane emissions. Finally, Panel (d) plots the log-ratio of UK CO_2 emissions to its capital stock, which dropped by more than 90% over the period from a large increase in fossil fuel efficiency partly due to the change in fuel mix (see Kaufmann, 1992) but also, e.g., LED lighting and petrol vehicle miles per gallon (mpg) rising from around 20 mpg in 1920 to more than 50 mpg in 2020.

The UK's 5-year GHG emissions targets over 2008–2012, 2013–2017 and 2018–2022 were 3018, 2782 and 2544 Mt CO_2Eq, where the CO_2 component is approximately 80% of the total. We translated these to annual magnitudes, starting 20 Mt above and ending 20 Mt below. Allowing 20% for other GHG emissions, Figure 3(a) shows 2020 UK CO_2 emissions were well below its targets.

Thus, the United Kingdom has made considerable progress towards its net zero goal, but replacing coal in energy generation was the easiest way to reduce GHG emissions. While there was little aggregate loss, mining communities bore an excessive share of the costs of that partial transition, exacerbated by related industries also being located in wetter, colder and poorer parts of the United Kingdom. At its peak use in 1955, 155 Mtoe of coal use produced 530 Mt of CO_2, whereas 140 Mtoe of oils and gas combined produced around 340 Mt in 2018. Nevertheless, that still entails two-thirds of fuel supply needs replaced, and the GHG reductions to date also reflect the accidental impacts of 'offshoring dirty production' in response to competitive market pressures rather than to reduce emissions. A major transition must be achieved not only to eliminate all fossil fuel use but to do so justly, exacerbated by the harder problems of

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

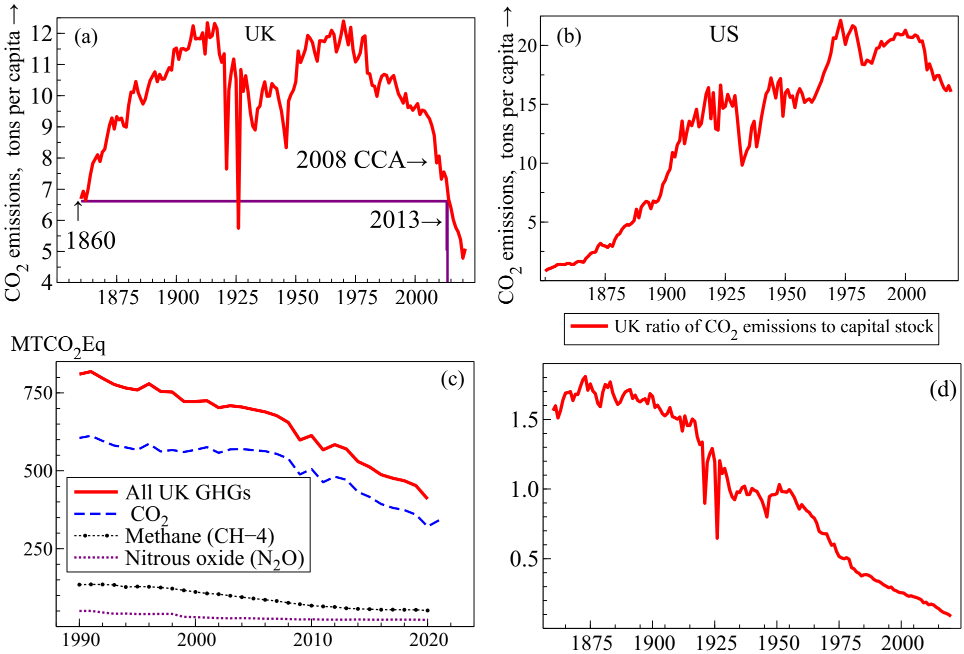

Figure 2. (a) UK CO_2 territorial emissions per capita in tons per annum (p.a.) 1860–2018; (b) US CO_2 emissions per capita, in tons p.a., 1850–2019; (c) UK total GHG emissions in Mt since 1990, all in weighted CO_2Eq and (d) UK ratio of CO_2 emissions to the capital stock on a log scale to 2017.

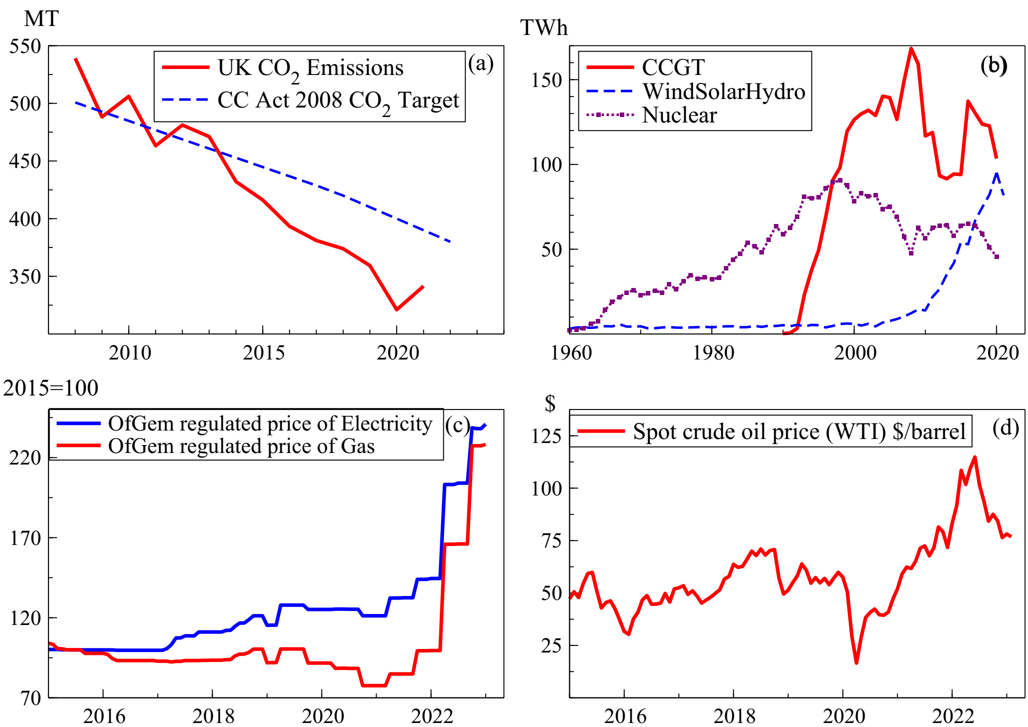

Figure 3. (a) UK CO_2 emissions and CCA08 CO_2 targets annualized (MT); (b) UK electricity generation (CCGT: Combined Cycle Gas Turbine) in TWh; (c) OfGem regulated prices of electricity and gas, 2015 = 100 and (d) spot crude oil price (WTI) $ per barrel.

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

GHG emissions from agriculture, construction, chemicals and waste, possibly partly offset by carbon capture and storage (CCS), reusing CO_2 as a fuel, and perhaps atmospheric CO_2 extraction.

There is a range of policy tools available from legislation, regulation and standards; industrial policy; many possible taxes, tax credits, subsidies and emissions trading schemes *inter alia*. However, incoherent policy and sudden changes to satisfy special interests weaken any net zero strategy. Uncertainty exerts a negative impact on private investment, which is essential for the transition to net zero. Moreover, carbon taxes alone are insufficient: policies must offer viable alternatives that can be adopted economically, and fortunately there are many on offer for renewable electricity generation and its uses, with costs falling rapidly as these are scaled up. Thus, we focus on the feasibility of a net zero transition. Public support for a green economy will wane if the economic or social costs are too high even if renewable energy is cheaper and cleaner than fossil fuels: implementation relies on policymakers persuading public adoption in light of their own interests.

Although we will consider the necessary steps seriatim, they should be implemented as closely as feasible in tandem. Previous analyses with broad coverage beyond just the United Kingdom include MacKay (2009), IPCC reports, Larson *et al.* (2021), IEA (2021), Fries (2021) and Castle and Hendry (2024), as well as United Kingdom focused like the independent Climate Change Committee excellent reports, Dixon *et al.* (2022), who compare seven possible pathways to net zero by 2050 and our UK House of Commons Public Accounts Committee submission. Below we note where our approach differs, including the role for bioenergy with CCS, critically reviewed by Brack *et al.* (2021) and Fajardy and Mac Dowell (2017).

The structure of the article is as follows. Section 2 considers achieving zero GHG electricity generation as a key step. Next, Section 3 discusses decarbonizing ground transportation and the symbiotic role that could play in short-term storage for renewable electricity, while using natural gas to generate electricity until there is sufficient non-GHG to remove oil. Section 4 turns to reducing GHG emissions from households and construction, then Section 5 considers agriculture. Section 6 notes issues needing to be tackled for the chemical industry, manufacturing and waste management, and Section 7 concludes.

2. The route to net zero GHG starts with electricity generation

Total UK electricity supply in 2018 was 334 TWh where 25 TWh was imported and 135 TWh came from non-GHG, with bioelect 36% (Drax), 16% nuclear plus 37% renewables, up nearly 10-fold over the previous decade, (64 TWh by wind turbines from 24 GigaWatts (GW) installed) (see Figure 3(b)). Some coal-fired power stations acted as supplier of the last resort. The 2020 UK government announcement to install an additional 40 GW of wind-power electricity by 2030 (to generate 110 TWh p.a.) roughly doubles current renewables output. However, that could not yet replace natural gas in generating electricity as a much larger supply of electricity will be needed to also power electric vehicles (EVs).

Renewable-energy sources like solar photovoltaics (PVs) and wind turbines have fallen rapidly in price and increased in efficiency over the past two decades. Relying purely on highly variable wind and sun sources requires constantly balancing electricity flow with short-run storage plus a larger backup storage system for windless nights and potentially long winter periods of still, cloudy weather. To sustain massively more power supply, substantial infrastructure and grid expansion are essential with improvements in its resilience facing more powerful storms and highly variable temperatures, as well as upgrading to an 'intelligent system'.

Offshore wind turbines are easier to install than onshore given their 100 m-long blades, create marine reserves and fish sanctuaries when fixed and mix warm and cold layers improving supplies of nutrients and oxygen, when floating (see Dorrell *et al.*, 2022) following the successful Hywind Scotland trial. An 'ocean battery' on the seabed could hold water under pressure analogous to a hydro pump system and avoid shuttering off-shore wind turbines when there is excess output. As slowing wind speeds from smaller temperature differentials between the tropics and the poles (see Solaun & Cerdá, 2020) would reduce their benefits, waves and tides could also generate renewable energy. Geothermal energy could

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

contribute beyond ground-source heat pumps. Additional non-GHG electricity generation methods include hydro (with pump and store and rivers), nuclear and small modular nuclear reactors (SMRs) building from the well-developed safe nuclear-powered engines in submarines. SMRs operate at lower temperatures so might be able to use the 'spent' uranium fuel rods from older reactors, helping reduce the problem of transuranic-waste disposal. Using electron-beam welding Sheffield ForgeMasters have reduced the vessel weld time from about a year to a day, greatly cutting costs. Although nuclear fusion has seen recent advances in superconducting magnets, increasing output efficiency, and reducing damage to tokamaks from helium, it seems unlikely to be a major energy contributor by 2050 (but see Greenwald, 2020).

Natural gas (mainly methane, CH_4) contributes about 40% of electricity output, with 140 megatons (Mt) p.a. CO_2 emissions. Its replacement in electricity generation by non-GHG emitting methods seems feasible by 2050, even adding transport electrification and hydrogen production. The current government's restricting solar farms and banning on-shore wind turbines, rather than crafting a location-specific positive framework, will not help, nevertheless a near zero target for natural gas in electricity generation seems possible without reducing employment or GDP growth, perhaps even increasing them with new opportunities. The benefits to the United Kingdom would certainly be greater if it developed a manufacturing and skills capacity for 'green' energy methods. Although replacing all 2200 TWh of energy purely by renewable electricity starting from the current 120 TWh might seem to require a 20-fold increase in non-GHG electricity—a compound growth rate of 10.5% p.a. over 30 years, even if increased demands from economic growth are offset by efficiency gains—much less is required as electricity is intrinsically more efficient in many uses such as replacing petrol-driven internal combustion engines, where heat losses are large, or heat pumps replacing gas boilers.

The recent large rises in UK electricity prices seen in Figure 3(c) despite extensive renewable supply (Panel (b)) suggest the pricing system is in urgent need of major reforms to remove dependence on the marginal producer (also see Grubb & Newbery, 2018).

3. Prioritize electricity for decarbonizing transportation

Green electricity will be needed in all areas of our lives to achieve net zero, from housing to food to waste, but the priority should be the electrification of transportation as it will play a crucial symbiotic role in providing storage capacity. The demands on electricity capacity will be immense and so natural gas for electricity generation should continue to be used to ensure rapid electrification of the transport network, phasing out the use of natural gas as more green electricity comes on stream.

Distillates of oil are the main fuel for ground, air and sea transport. Taking these in turn, battery powered EVs are gradually replacing internal combustion engine cars. While cheaper over a lifetime, EVs are more expensive to purchase and have a relatively short journey capacity, yet take a non-negligible time to recharge, all of which discourages uptake. Improvements in batteries, standardised connectors, and increased production will help, as would increasing taxes on petrol and diesel as oil prices fall to maintain a constant high 'pump price'.

Carbon nanotubes (CNTs, see, e.g., Sammed *et al.*, 2020) are 'rolled up' sheets of graphene making electrode supercapacitors. These may be able to act as an electricity storage system to supply the battery driving an electric motor, with rapid charging and discharging. Graphene-based lithium-ion and solid-state batteries are also being developed following large cost reductions in graphene production.

When EVs become ubiquitous, supported by sufficient non-GHG electricity supply, having them plugged into the national grid when not in use would create a large electric backup system without additional investment beyond making the grid 'intelligent' to measure time of day flows of electricity to and from every vehicle (see Noel *et al.*, 2019). To encourage vehicle-to-grid (V2G) technology, a higher price could be paid for EV electricity supplied in peak periods. V2G would provide short-term storage to facilitate second by second balancing of electricity flows facing highly variable renewable supplies.

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

By not demonising road transport for its CO_2 footprint and dangerous pollution, cars with internal combustion engines could be replaced at a rate matching their obsolescence, so employment can be maintained in vehicle manufacture and many of its ancillary industries rebased on EVs. A side benefit is eliminating the need for expensive catalytic converters, cutting vehicle production costs, eliminating a target for theft (which then exacerbates air pollution and GHGs, especially nitrous oxide) and reducing palladium mining. CNTs could help solve the UK's rail system problem of a lack of electrification across much of the network by replacing diesel-electric trains, possibly also with hydrogen-driven trains. CNTs are lightweight, so might sustain economical electric-powered aircraft. Hydrogen fuel cells can power heavy vehicles like trucks and buses and offer long distances between charges: they would be almost GHG free if the hydrogen was also GHG free (see Section 4.1).

4. What individuals should do to decarbonise

Individuals should play their part in the move to net zero, supported by policies that include subsidies for investment in dwellings as the United Kingdom has some of the least energy-efficient housing stock in Europe.

Better house insulation is essential to reduce CO_2 emissions from heating and cooling, which could include installing double or triple glazing, better loft insulation, draft reductions, foil between radiators and walls and so forth Installing solar PVs panels and evacuated tube solar collectors on roofs and air and ground source heat pumps would reduce demands on GHG emitting energy sources, as would LED lighting. Fyfe *et al.* (2022) show a benefit–cost ratio of more than four for jointly insulating New Zealand homes and installing heat pumps. Despite a higher proportion of apartment dwellings, France has installed several million heat pumps, so multiple occupancy buildings need not be a barrier, or entire villages. Housing accounts for around 30% of the UK's CO_2 emissions (roughly 150 million tonnes of CO_2), much by heating from natural gas. Retrofitting a Glasgow tenement is a valuable pilot study highlighting what can be achieved.

4.1. Making hydrogen

The United Kingdom consumes around 80 billion cubic meters (m^3) of natural gas, about half of which is imported, roughly 30bm^3 for households, 25bm^3 for generating electricity, 10bm^3 in industry and 15bm^3 for services. Replacing natural gas in household boilers and gas cookers by green hydrogen would need it to be obtained either by electrolysis or by methane pyrolysis. To replace the energy of 30bm^3 domestic methane use p.a. would require about 90bm^3 of hydrogen given its lower energy. The main present method is steam reforming of natural gas where one ton of hydrogen produces around 10 tons of CO_2, which could be captured, but hardly helps decarbonise society. Producing that hydrogen by electrolysis, hopefully using 'surplus' renewables electricity (possibly even at a negative price to avoid switching off wind turbines) would require around 280 TWh of electricity and 28b gallons of water, though seawater could be used. Efficiency improvements by catalyst-based electrolysis (see, e.g., Kuai *et al.*, 2020) would reduce the electricity needed.

Methane has the highest ratio of hydrogen to carbon of hydrocarbons and pyrolysis converts CH_4 to C (black carbon) and $2H_2$ without any GHG released. Converting 30bm^3 methane would make 60bm^3 of hydrogen using around 56 TWh with suitable thermocatalysis (see Sánchez-Bastardo *et al.*, 2021 for a review). New gas piping will be required by any method of supplying H_2 to households (probably plastic based, requiring CCS during its manufacture although microwave deconstruction of commercial plastic can produce hydrogen and multi-walled CNTs (see Jie *et al.*, 2020). However, GHG leaks in the supply chains would have to be eliminated (see, e.g., Timmerberg *et al.*, 2020) as recent measures of methane emissions have revealed large releases from oil drilling, natural gas production and their transportation.

Coal gas containing hydrogen and other hydrocarbons with 540 Btu per cubic foot was replaced from 1969 when switching to natural gas by fitting different burner jets for the correct gas/air mixture given

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

1015 Btu for methane. The conversion cost was £100m (approximately £3b now). A switch back to hydrogen would require twice that for new burners, given the increase in the number of households. Relative to other uses of hydrogen, alternative energy sources for domestic use seem preferable.

'Carbon-neutral' biogenic methane, stored at depth in fresh water lakes (produced from CO_2 absorption by methanogenic *Archaea*, see Bartosiewicz *et al.*, 2021) can be extracted, reducing CH_4 emissions which will otherwise increase as temperatures rise, and providing 'green methane' for electricity generation, already operational on Lake Kivu in a circular system.

Refrigerant gasses are bad for climate change if released into the atmosphere: chlorofluorocarbons (CFCs) were destroying the ozone layer before the Montreal Protocol in 1987, but replacements by halons and halocarbons including hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons are dangerous GHGs. Sulphur hexafluoride (SF_6) protecting electric substations from explosions is an excellent electrical insulator being inorganic colourless, odourless, non-flammable and non-toxic, but like HCFCs is a potent GHG. Fortunately, Lewis superacids enable SF_6 and related gasses to be converted back to sustainable chemicals like sodium bicarbonate ($NaHCO_3$) which is storable in seawater. Research for better refrigerant alternatives could be funded by prizes to avoid patent restrictions (see Hendry, 2011; Hall, 2014). Raising fridge and freezer insulation standards to minimize cold loss should reduce the compressor size needed which would lower prices as well as electricity consumption (Chu's law in action).

4.2. Net zero GHG emissions new dwellings

As well as constructing new dwellings to be net zero emitters, prefabricating highly insulated dwellings, built using low GHG-intensive building materials will reduce their construction emissions. Adding graphene to cement would strengthen it, lowering construction volumes (see Luong *et al.*, 2020); hot mixing induces self-healing against cracks so increases its durability (see the Pantheon in Rome) and magnesium oxides can help absorb CO_2. Glued laminated timber, glulam, reduces the GHG of construction by needing less steel. Reducing the cost of electricity would lower the costs of making glass, and triple glazing provides better insulation. All the non-GHG energy supply solutions for existing dwellings can be easily implemented, removing the need for natural gas. More generally, a hotter more volatile climate requires developing better living environments and landscapes to minimize urban heat, avoid increased flooding and collect rainfall against droughts.

5. Tackling agriculture's carbon 'footprint'

About 56% of the UK's land area of 24 million hectares is farmed and 35% is 'natural' (see Rae, 2017), leaving about 6% built on and about 3% 'green urban': rewilding will only marginally change these. Globally, agriculture has a large carbon 'footprint' of about a third of the anthropogenic GHG annual emissions (see Crippa *et al.*, 2021). Within the United Kingdom, agriculture emits 68% of all nitrous oxide (15 Mt CO_2 Eq) and 47% of methane emissions (25 Mt CO_2Eq), which with CO_2 emissions makes 46 Mt CO_2Eq p.a., slightly below the 1990 level of 53 Mt CO_2Eq; yet, the Government's Environmental Land Management scheme makes no mention of GHGs or how to tackle them.

Nitrous oxide (N_2O) emissions come from nitrogen fertiliser use (see Tian *et al.*, 2020) and globally have doubled in the last 50 years. UK fertiliser prices have tripled since 2020 so substitutes are urgently required both to lower food price inflation and reduce GHG emissions. Based on areas around volcanoes being fertile, ground-up basalt may be a useful fertilizer alternative and soil improver (see Allen, 2024 (who records that agriculture started around the extinct volcano Karacadag in southern Anatolia where a large area of basalt supported einkorn wheat); Beerling *et al.*, 2020; Nunes *et al.*, 2014). Basalt also absorbs atmospheric CO_2 so is doubly beneficial. Burying manure and slurry would reduce ammonia air pollution and improve soil as would pyrolysis of waste biomass to produce biochar, increasing crop yields and reducing GHG emissions (see Woolf *et al.*, 2010). Polyhalite, now being mined in the United Kingdom, is a hydrated sulphate of potassium, calcium and magnesium so is a natural fertilizer substitute.

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

Enteric methane emissions per annum per 100 animals, scaled by their weights, from livestock methanogenic bacteria are around 20 kg from dairy and 10 kg from beef cattle, 8–10 kg from sheep and goats and 5 kg from deer. Changes to farm mammal diets can reduce methane emissions (also saving energy so helping weight gain) such as adding dietary fumaric acid and small amounts of the seaweeds *Asparagopsis armata* or taxiformis (see Roque *et al.*, 2019; Kinley *et al.*, 2020). As cattle inherit low methane production, selective breeding as well as changes to the mix of which species are bred for milk and cheese production would lower emissions. Changes to human diets are also possible, eating less mammal meat and more avian and plant nutrition. Steps to facilitate a shift to healthy diets include reordering menu items and preparing more enticing vegetarian or vegan dishes.

To economize on land, water, fertilizer and food waste, vertical and underground farms are benefitting from the reduced costs of LED lighting and can produce several crops per annum of some vegetables as well as breed fish of various kinds in hydroponic systems. Usually found in cities also saves energy from reduced transport and helps minimize extensions of farming into previously unused land, reducing species extinctions from loss of habitat. Protecting wetlands and peat would save GHG emissions.

Aquaculture is essential to the supply of seafood and seaweeds, but faces health concerns in many areas. More and larger marine reserves and saltwater fish sanctuaries (an incidental benefit of off-shore wind farms) with strong legal protection are needed, a step towards which is the High Seas Treaty aiming for 30% of the seas in protected areas.

6. Reducing GHGs from industry, chemicals and waste

Iron and steel industries are especially carbon intensive making high-heat based products from large and long-lived capital investments, but most forms of manufacturing require substantial energy inputs. However, reducing iron oxide by hydrogen rather than fossil fuels, as in HYBRIT, eliminates about 90% of steelmaking GHG emissions. Potential non-GHG high-heat solutions for manufacturing include electric arc and liquid hydrogen, but substantial new investment in these methods for mitigating large CO_2 emissions is required.

Chemicals and plastics use fossil fuel inputs as well as needing energy, so reducing their GHG emissions entails more open and closed loop recycling where the former creates new but useful products from waste plastic. Reductions to artificial fertiliser use were noted above.

Less waste landfill would reduce methane leakage, and economic incentives can really help: the 5 pence charge per plastic bag in the United Kingdom from 2015 led to an 80% fall in their use, saving almost 13 billion after 2 years: similar charges to reduce other non-recyclable, often single use, items would be useful.

7. Summary and conclusions

Having been first into the Industrial Revolution, which has hugely enriched the world but accidentally created climate change, the United Kingdom should lead the world out. The United Kingdom has reduced its territorial CO_2 emissions by 186 Mt from 554 Mt to 368 Mt (34%) so far this century, while per capita real GDP has risen by more than 25%, despite the 'Great Recession' (excluding pandemic and energy crisis-induced falls). The UK's total 'consumption-induced CO_2Eq' emissions are higher than its territorial level through GHG embodied in net imports, although the large reductions achieved to date in electricity generation have a major domestic component. 'Consumption-induced' GHG will fall as the GHG emissions intensity of imports falls. Border tariffs on imports from high GHG or deforesting countries (adding to pressure to reduce environmental degradation and loss of habitat threatening species extinctions) could accelerate this (see Nordhaus, 2015, 2020).

To achieve net zero GHG emissions requires a joined up approach to decarbonizing to capture virtuous circles: solving some problems can help solve others. Sufficient non-GHG electricity generation is achievable with known technologies, but faces storage problems for periods when renewables do not

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

generate power. Using EVs as storage units connected to the grid would facilitate short-term balancing of electricity flows. Conversely, once renewables capacity has greatly expanded, electrolysis and methane pyrolysis production of hydrogen would sustain 100% capacity renewables generation at 'off-peak', and via liquid hydrogen provide a potential high heat source for industry as well as medium-term storage as part of 'power-to-X' (hydro pump and store, batteries, flywheels, supercapacitors and ocean batteries on the seabed etc.). New buildings must be constructed with low GHG emissions and be net zero. Nitrous oxide, methane and other GHG emissions from food production can be reduced by replacing some nitrogen fertiliser by basalt dust, which also absorbs carbon dioxide and by biochar, and methane by dietary changes to ruminants. Human dietary changes are also feasible. These developments interact and would maintain employment and real per capita growth during the transition in both new industries and retrofitting transport and housing with upgrading of labour skills.

Carbon pricing (see Sterner *et al.*, 2020) might facilitate GHG reductions where economical alternatives exist (although evidence of public opposition in some countries suggests limitations even when the revenue raised is rebated), as could cap and trade (successful for sulphur dioxide reductions implemented in the 1990 US Clean Air Act) where the EU Emissions Trading System has reduced GHGs.

Investments in non-GHG power generation including storage, infrastructure upgrades and EV charging points can be repaid via earnings on electricity sales. Natural obsolescence and scrapping of vehicles and domestic heating equipment anyway entails a replacement need, and economies of scale and efficiency improvements (Way *et al.*, 2022) should see costs become increasingly favourable for doing so by EVs, heat pumps and domestic solar panels, but perhaps less so for SMRs and batteries. Retrofitting for better insulation will cut heating and cooling costs but will probably need to be subsidised, as will conversions of some industrial and chemical equipment to non-GHG power. Farming changes should reduce costs. Thus, although the gross investments over 25–30 years may total several £ trillions, similar sums would be needed to maintain the status quo of 'business as usual'.

Castle and Hendry (2020) find little evidence of aggregate costs from the UK's GHG reductions to date, but workers in industries being replaced by technological change have usually bourn what should be social costs. Mitigating the inequality impacts on 'stranded workers' and regions from climate-related policies matters to maintain public support for a just transition to a 'green economy', not just warning about the risks to investors of 'stranded assets' in carbon intensive activities should future legislation suddenly impose zero GHG emissions after a serious deterioration in the climate. Political strategies to overcome climate policy obstructionism deserve consideration. Recovery from the pandemic and energy crisis does not preclude tackling burgeoning climate issues, building on hosting CoP26 in Glasgow despite its ineffectiveness globally: the United Kingdom could achieve a huge reduction in its GHG emissions if it adopted and maintained a coherent strategy. Indeed, if every country operated on a feasible, bespoke plan, many elements of what is a global problem could be solved.

Funding statement. Financial support from the Robertson Foundation (award 9907422) and Nuffield College is gratefully acknowledged, as are helpful comments from participants at the CoP26-linked conference in The Hutton Series on Climate Change at Panmure House, Edinburgh and three anonymous referees.

Competing interest. The authors declare no competing interests. Email: jennifer.castle@magd.ox.ac.uk and david.hendry@nuffield.ox.ac.uk

References

Allen, R.C. (2024), 'The Neolithic Revolution in the Middle East: A survey and speculation article for the *Economic History Review*', *Economic History Review*. https://doi.org/10.1111/ehr.13307.

Bartosiewicz, M., Rzepka, P. and Lehmann, M.F. (2021), 'Tapping freshwaters for methane and energy,' *Environmental Science and Technology*, **55**. https://doi.org/10.1021/acs.est.0c06210.

Beerling, D.J., Kantzas, E.P. and Lomas, M.R. et al. (2020), 'Potential for large-scale CO_2 removal via enhanced rock weathering with croplands', *Nature*, **583**, pp. 242–248. https://doi.org/10.1038/s41586-020-2448-9.

Brack, D., Birdsey, R. and Walker, W. (2021), 'Greenhouse gas emissions from burning US-sourced woody biomass in the EU and UK', Research paper 14, Chatham House, London, UK.

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

Castle, J.L. and Hendry, D.F. (2020), 'Climate econometrics: An overview', *Foundations and Trends in Econometrics*, **10**, 145–322. https://doi.org/10.1561/0800000037.

Castle, J.L. and Hendry, D.F. (2024), 'Five sensitive intervention points to achieve climate neutrality by 2050, illustrated by the UK', *Renewable Energy*, **226**, 120445. https://doi.org/10.1016/j.renene.2024.120445.

Crippa, M., Solazzo, E. and Guizzardi, D. et al. (2021), 'Food systems are responsible for a third of global anthropogenic GHG emissions', *Nature Food*, **2**, 198–209. https://doi.org/10.1038/s43016-021-00225-9.

Dixon, J., Bell, K. and Brush, S. (2022), 'Which way to net zero? A comparative analysis of seven UK 2050 decarbonisation pathways', *Renewable and Sustainable Energy Transition*, **2**, 100016. https://www.sciencedirect.com/science/article/pii/S2667095X21000167.

Dorrell, R.M., Lloyd, C.J. and Lincoln, B.J. et al. (2022), 'Anthropogenic mixing of seasonally stratified shelf seas by offshore wind farm infrastructure', *Frontiers in Marine Science*, **9**, 830927. https://doi.org/10.3389/fmars.2022.830927.

Fajardy, M. and Mac Dowell, N. (2017), Can BECCS deliver sustainable and resource efficient negative emissions? *Energy Environmental Science*, **10**, 1389–1426. https://doi.org/10.1039/C7EE00465F.

Fries, S. (2021), *Transforming Energy Systems: Economics, Policies and Change*, Cheltenham, UK: Edward Elgar.

Fyfe, C., Grimes, A., Minehan, S. and Taptiklis, P. (2022), 'Evaluation of the Warmer Kiwis Homes programme', Working paper 22-13, Motu Economic and Public Policy Research, Wellington, New Zealand. https://www.motu.nz/about-us/news/warmer-kiwis-study/.

Greenwald, M. (2020), 'Status of the SPARC physics basis', *Journal of Plasma Physics*, **86**(5), 861860501. https://doi.org/10.1017/S0022377820001063.

Grubb, M. and Newbery, D. (2018), 'UK electricity market reform and the energy transition: Emerging lessons', *The Energy Journal*, **39**(6), 1–26. https://www.jstor.org/stable/26606242.

Hall, B.H. (2014), 'Does patent protection help or hinder technology transfer?', in S. Ahn, B.H. Hall and K. Lee (Eds.), *Intellectual Property for Economic Development: Issues and Policy Implications*, Chapter 2, Aldershot: Edward Elgar Publishing.

Hendry, D.F. (2011), 'Climate change: Lessons for our future from the distant past', in S. Dietz, J. Michie and C. Oughton (Eds.), *The Political Economy of the Environment*, pp. 19–43, London: Routledge. Also see http://www.voxeu.org/article/climate-change-lessons-our-future-distant-past.

IEA (2021), *Net zero by 2050*, Paris: IEA. https://doi.org/10.15131/shef.data.5266495.v1

Jie, X., Li, W. and Slocombe, D. et al. (2020), 'Microwave-initiated catalytic deconstruction of plastic waste into hydrogen and high-value carbons', *Nature Catalysis*, **3**, 902–912. https://doi.org/10.1038/s41929-020-00518-5

Kaufmann, R.K. (1992), 'A biophysical analysis of the energy/real GDP ratio: implications for substitution and technical change', *Ecological Economics*, **6**, 35–56. https://doi.org/10.1016/0921-8009(92)90037-S

Kinley, R.D., Martinez-Fernandez, G. and Matthews, M.K. et al. (2020), 'Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed', *Journal of Cleaner Production*, **259**, 120836. https://doi.org/10.1016/j.jclepro.2020.120836

Kuai, C., Xu, Z. and Xi, C. et al. (2020), 'Phase segregation reversibility in mixed-metal hydroxide water oxidation catalysts', *Nature Catalysis*, **3**, 743–753. https://doi.org/10.1038/s41929-020-0496-z

Larson, E., Greig, C. and Jenkins, J. et al. (2021), 'Net-zero America: Potential pathways, infrastructure, and impacts', *Joule*, **5**, 2755–2761. https://www.cell.com/joule/pdf/S2542-4351(21)00493-1.pdf.

Luong, D., Bets, K. and Algozeeb, W. et al. (2020), 'Gram-scale bottom-up flash graphene synthesis', *Nature*, **577**, 647–651. https://doi.org/10.1038/s41586-020-1938-0

MacKay, D.J.C. (2009), 'Sustainable energy—Without the hot air. Internet publication', UIT Cambridge Ltd., PO Box 145, Cambridge, UK. http://www.withouthotair.com/download.html.

Noel, L., de Rubens, G.Z., Kester, J. and Sovacool, B. (Eds.) (2019), *Vehicle-to-Grid: A Sociotechnical Transition Beyond Electric Mobility*, Basingstoke: Palgrave MacMillan.

Nordhaus, W. (2015), 'Climate clubs: Overcoming free-riding in international climate policy', *American Economic Review*, **105** (4), 1339–1370. https://doi.org/10.1257/aer.15000001

Nordhaus, W. (2020), 'The climate club: How to fix a failing global effort', *Foreign Affairs*, **99**(3), 10–17. https://www.foreignaffairs.com/articles/united-states/2020-04-10/climate-club

Nunes, J., Kautzmann, R. and Oliveira, C. (2014), 'Evaluation of the natural fertilizing potential of basalt dust wastes from the mining district of Nova Prata (Brazil)', *Journal of Cleaner Production*, **84**, 649–656. https://doi.org/10.1016/j.jclepro.2014.04.032

Rae, A. (2017), 'A land cover atlas of the United Kingdom', Atlas: University of Sheffield. https://doi.org/10.15131/shef.data.5266495.v1

Roque, B.M., Salwen, J.K., Kinley, R. and Kebreab, E. (2019), 'Inclusion of *Asparagopsis armata* in lactating dairy cows' diet reduces enteric methane emission by over 50 percent', *Journal of Cleaner Production*, **234**, 132–138. https://doi.org/10.1016/j.jclepro.2019.06.193

Sammed, K., Pan, L., Asif, M. et al. (2020), 'Reduced holey graphene oxide film and carbon nanotubes sandwich structure as a binder-free electrode material for supercapcitor', *Science Reports*, **10**, 2315. https://doi.org/10.1038/s41598–020–58162–9

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press

Sánchez-Bastardo, N., Schlögl, R. and Ruland, H. (2021), 'Methane pyrolysis for zero-emission hydrogen production: A potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy', *Industrial & Engineering Chemistry Research*. 11855–11881, https://doi.org/10.1021/acs.iecr.1c01679

Solaun, K. and Cerdá, E. (2020), 'Impacts of climate change on wind energy power: Four wind farms in Spain', *Renewable Energy*, **145**, 1306–1316. https://doi.org/10.1016/j.renene.2019.06.129

Sterner, T. et al. (2020), 'Funding inclusive green transition through greenhouse gas pricing', IFO DICE Report, I/2020 18, 3–8. https://www.ifo.de/en/publications/2020/article-journal/funding-inclusive-green-transition-through-greenhouse-gas-pricing.

Tian, H., Xu, R., Canadell, J. et al. (2020), 'A comprehensive quantification of global nitrous oxide sources and sinks', *Nature*, **586**, 248–256. https://doi.org/10.1038/s41586-020-2780-0

Timmerberg, S., Kaltschmitt, M. and Finkbeiner, M. (2020), 'Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas—GHG emissions and costs', *Energy Conversion and Management*, **X**, 7. https://doi.org/10.1016/j.ecmx.2020.100043

Way, R., Ives, M.C., Mealy, P. and Farmer, J.D. (2022), 'Empirically grounded technology forecasts and the energy transition', *Joule*. 2057–2082, https://doi.org/10.1016/j.joule.2022.08.009.

Woolf, D., Amonette, J.E., Street-Perrott, F.A. et al. (2010), 'Sustainable biochar to mitigate global climate change', *Nature Communications*, **1**(5), 56. https://doi.org/10.1038/ncomms1053.

Data definitions and sources

O_t	= Net oil usage, millions of tonnes	[1]
C_t	= Coal volumes in millions of tonnes and MToe	[2]
NG_t	= Natural gas volumes in millions of tonnes and MToe	[3]
NC_t	= Nuclear energy use in TWh and MToe	[4]
RN_t	= Renewable energy usage including wind + solar + hydroelectric all in TWh and MToe	[5]
E_t	= UK total energy use, MToe = $C + O + NG + NC + RN$	[6]
K_t	= Total capital stock, ₹billions, 1985 prices	[7]
$P_{o,t}$	= Oil price index, ₹	[8]
$P_{elect,t}$	= Consumer price inflation for electricity index, 2015 = 100	[9]
$P_{gas,t}$	= Consumer price inflation for gas index, 2015 = 100	[10]
$P_{co,t}$	= Spot crude oil price, West Texas Intermediate (WTI)	[11]

Sources:
[1] Crude oil and petroleum: production, imports and exports 1890–2021, BEIS.
[2] Energy trends, BEIS and carbon brief.
[3] ONS and [4] ONS capital.
[5] Historical gas data: gas production and consumption and fuel input, BEIS.
[6] Renewables (Solar [Large-scale Photovoltaic], Wind Onshore, Wind Offshore Hydro) and Nuclear from Digest of UK Energy Statistics (DUKES), BEIS and Total electricity.
[7] Total energy check.
[8] UN Statistical Yearbooks.
[9] ONS: Dataset consumer price inflation MM23, L53E.
[10] ONS: Dataset consumer price inflation MM23, L53F.
[11] FRED: St Louis Fed, $ per barrel, NSA, WTISPLC.

Cite this article: Castle, J. L. and Hendry, D. F. (2024), 'Can the UK achieve net zero greenhouse gas emissions by 2050?' *National Institute Economic Review*, pp. 1–11. https://doi.org/10.1017/nie.2024.6

https://doi.org/10.1017/nie.2024.6 Published online by Cambridge University Press