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Can the UK Achieve Net-zero Greenhouse Gas Emissions by 2050?

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Abstract

Net-zero greenhouse gas (GHG) emissions are an excellent target, but difficult to achieve by having to bridge a dramatic energy transition from fossil fuels to renewables, as well as eliminate other sources of GHG emissions from agriculture, construction and waste. A comprehensive strategy for doing so is essential, and although components like renewable electricity generation and electric vehicles are well developed, many issues remain, especially timing the stages in tandem. The key sensitive intervention points (SIPs) are (a) installing sufficient non-GHG electricity, (b) having electric vehicles connected to the grid for large-scale short-run backup storage, (c) utilising intermittent 'surplus' energy for nearly free hydrogen production, (d) some liquified for medium-term storage and a high-heat for industry, and (e) other electricity-based uses such as in agriculture. Public support for a purely green economy will wane if the economic costs are too high, so it is essential to maintain employment and real per-capita incomes. Decarbonizing the economy while also dealing with the economic costs of the COVID-19 pandemic can occur by using an integrated stepped approach.

JEL classifications: C5, Q54.
Keywords Greenhouse-Gas Emissions, Net-Zero Target, Decarbonizing, Economic Growth, Carbon Nanotubes, Renewable Electricity Generation

1 Introduction

Climate change will continue until well after the target of net zero greenhouse gas (GHG) emissions is achieved. The benefits of starting towards that target now seem likely to far exceed the costs of tackling the problem later. Recent research (see e.g., Hänsel *et al.*, 2020) increasingly supports the aim of the Paris Accord at CoP21 to limit temperature increases to less than 2°C, and 'to pursue efforts to limit it to 1.5°C'. The Special Report by the Intergovernmental Panel on Climate Change (IPCC: https://www.ipcc.ch/sr15/) emphasises that the latter is still just achievable, but rapid action is required if it is to be achieved. Among the major likely adverse consequences of ever increasing levels of atmospheric CO_2 are extreme weather conditions that can be dangerous to life, including high 'wet bulb' heat, heat domes in Southern Europe and North America wild fires, which worsen GHG emissions, as seen recently in the USA west coast, Amazon, Siberia and Australia, increasingly powerful cyclones, increased coastal flooding (see Vitousek *et al.*, 2017) as well as inland flooding from 'rivers in the sky' (see Lavers *et al.*, 2018), yet also more intense and longer droughts (see Trenberth *et al.*, 2014) endangering food supplies globally.[1]

[1] See https://research.noaa.gov/article/ArtMID/587/ArticleID/2621/Dangerous-humid-heat-extremes-occurring-decades-before-expected; https://www.rmets.org/metmatters/what-heat-dome and

Moreover, there is the potential for climate tipping points (see Wunderling *et al.* 2021), such as when an ice-free Arctic Ocean in the past has led to large-scale methane release from permafrost melting in the tundra, causing further rapid climate warming (see Vaks *et al.*, 2019). Cahill *et al.* (2013) highlight the added danger of species extinctions, as happened in deep-time from climate changes (see e.g., Dasgupta, Raven, and McIvor, 2019), also threatening food security, and hence increased flows of refugees and migrants with potential conflicts over resources.[2]

More positively, sensitive intervention points (SIPs: see Farmer *et al.*, 2019) in the post-carbon transition could leverage both policy actions and technology developments. A sensitive intervention point is when a system is near a critical (or tipping) point so a small change triggers a much larger change that then becomes irreversible. Two examples are the legally binding 2008 UK Climate Change Act (CCA08) leading to the recent major changes announced by the UK Government; and when solar PV and wind became cheaper sources of energy than fossil fuels, so electrification of the economy became preferred.

Some countries have moved towards decarbonizing their economies by increased use of both renewable (solar and wind) and non-greenhouse gas methods (nuclear, geo-thermal, hydro, green hydrogen and biomass) for generating electricity, using that supply to reduce other GHG emitters based on fossil fuels such as replacing gasoline fueled by electric vehicles. To date, doing so has not greatly reduced global GHG emissions as economic activity has expanded and vast value is invested in existing 'dirty' energy production. Despite targets and even legislation in many countries mandating zero net emissions, few have proposed comprehensive strategies for achieving such an outcome, and public support for a purely green economy will wane if the short-run economic or social costs become too high—irrespective of much higher long-run costs of not transitioning. Facing some recent adverse reactions to increased 'green' taxes, improved incentives to switch technologies may be the only viable route, which will be our focus here. Net zero emissions at a global level is an excellent target, but incredibly difficult to achieve, especially when maintaining employment and real per-capita growth, and how to do so will vary greatly across regions and countries, as will the costs of not doing so (see https://voxeu.org/article/economic-geography-climate-change for a summary). While dealing with the impacts of the COVID-19 pandemic seems to add to the difficulties of transition, noting that even extensive lockdowns only reduced GHG emissions by under 20 megatonnes (Mt) daily relative to annual emissions of more than 20 gigatonnes (see Liu, Deng, Ciais, and et al., 2021), it may nevertheless be an opportune time to begin rapidly decarbonizing economies by building on the many behavioral changes that have occurred, as well as the increasingly major reductions in the costs of generating green versus dirty energy.

There are several published proposals for how to achieve net-zero GHG emissions, including the detailed analyses in MacKay (2009), the well-known IPCC reports such as IPCC (2021), and Larson, Greig, and Jenkins *et al.* (2020) for the USA, https://www.theccc.org.uk/publication/sixth-carbon-budget/ from the UK's Climate Change Committee, and IEA (2021). There is widespread agreement that electricity generation systems can be decarbonized by 2050, though less agreement on how to do so reliably. Recent IPCC reports and Larson *et al.* (2020) see an important role for BECCS (Bioenergy with carbon capture and storage), but many developments are needed to make it feasible: Brack, Birdsey, and Walker (2021) provide a critical review and Fajardy and Mac Dowell (2017) conclude "the sustainability of BECCS relies heavily on intelligent management of the supply chain". Other uses of the land needed for BECCS (unless based on using waste material) seem more useful, such as supporting biodiversity,

https://www.rmets.org/metmatters/record-breaking-heat-canada;
https://www.c2es.org/content/wildfires-and-climate-change/ and
https://disasterphilanthropy.org/disaster/2019-australian-wildfires/; and
https://yaleclimateconnections.org/2020/08/climate-change-is-causing-more-rapid-intensification-of-atlantic-hurricanes/ respectively.

[2] See https://www.gov.uk/government/publications/migration-and-global-environmental-change-future-challenges-and-opportunities

making biochar, and glulam type wood for replacing some steel and concrete in construction. On 19th October 2021, the UK Government published its *Net zero strategy: Build back greener* report which also includes BECCS as part of its strategy.[3] The report proposes many of the steps in our *Evidence to Forty-Sixth Report of Session 2019–21, UK House of Commons Public Accounts Committee*.[4] However, there are important gaps. The additional SIPs that we argue will help reduce other GHG emissions are (b) electric vehicles connected to the grid providing large-scale short-run backup storage to balance the grid facing variable renewables generation and uncertain future weather, (c) using intermittent 'surplus' renewables electricity for low-cost hydrogen production, some liquified as medium-term storage and (d) a high-heat source for industry, as well as (e) sustaining other electricity-based uses in agriculture.

An important aspect of 'net-zero commitments' by governments is their time horizons of 2050 to 2060. On the one hand, while these dates may be too late to keep global temperatures below 2°C, reaching the target will nevertheless help stabilise the climate unlike 'business as usual' continuing unabated. Further, most vehicles and domestic appliances and much industrial equipment will need replacing anyway over 30 years, so the costs of switching them to non-GHG alternatives are only relative to what would have been needed, and may indeed be negative given rapid technical progress as well as volume related cost reductions in their replacements (see e.g., Lafond, Bailey, and Bakker *et al.*, 2018). To eliminate GHG emissions requires a staged approach that is integrated across all emitters, which will take many years given the scale of the transition, and requiring some significant technological advances, albeit not science-fiction, as well as major infrastructure expansions to ensure electricity provision on the scale needed, and the new skills training for building, servicing and maintaining a green economy.

The structure of this review is as follows. Section 2 notes the background precedent that an all-electric-based, rather than fossil-fuel-based, economy began to emerge at the end of the 19th century before being out-competed by cheap oil. Section 3 discusses moving towards a net-zero GHG emissions economy. Section 4 considers achieving zero-GHG electricity generation as the first key SIP. Then section 5 turns to decarbonizing ground transportation based on zero-GHG electricity and the symbiotic role doing so could play as a short-run storage system for renewable electricity using vehicle-to grid, our second SIP. Section 6 discusses the use of electricity to decarbonize households directly and from hydrogen production, our third SIP, as well reduce GHG emissions in construction. Section 7 turns to reducing the 'foodprint' of agriculture, our fourth SIP, as again, 'surplus' renewable electricity can play an important role. Section 8 notes some of the issues needing to be tackled for waste management, the chemical industry, and manufacturing where the use of liquid hydrogen as a high heat source is our fifth SIP, whereas 'imported' and indirect CO_2 are considered in section 9. Section 10 briefly discusses some likely costs and benefits of the energy transition to a 'green economy'. Section 11 summarizes the analysis and concludes. We use the United Kingdom as our illustrative example, partly because in Castle and Hendry (2020) we have analysed the UK's success in essentially eliminating coal use, but also given its major historical role in starting the Industrial Revolution (which they also discuss), and its 2019 legislation mandating net-zero GHG emissions by 2050. Similar strategies are relevant to other developed economies, but need considerable adaptation for the developing world.

2 Background history

The Industrial Revolution in the 18th Century was the first major energy transition, powered by steam from coal-fired boilers, a process that has continued into the modern world, but now also powered by oil and gas. The second half of the 19th Century almost witnessed a second transition to renewable sources of energy. The first fuel cell was invented in 1838 by Sir William Grove and independently by Christian

[3] https://step.ukaea.uk/ https://www.gov.uk/government/publications/net-zero-strategy

[4] https://committees.parliament.uk/writtenevidence/21638/html/

Friedrich Schönbein; the first electricity generated in the UK in 1868 was hydro-driven, designed by Sir William Armstrong (see Higgins, 2007), and the first commercial photovoltaic solar rooftop panel was developed by Charles Fritts (1883), following up on the creation of the photovoltaic cell by Edmond Becquerel (1839). James Blyth built the first wind turbine to generate electricity in 1887 (see Blyth, 1894), and while it proved unsuccessful in the UK, wind-generated electricity was relatively common on US farms by the 1930s. The first electric-powered cars also date back to the 1880s after Thomas Parker built a vehicle with a high capacity rechargeable battery (see Freund, 2013): the 1897 Bersey Electrical Cab can still be seen at the Science Museum.

Figure 1: Source: https://collection.sciencemuseumgroup.org.uk/objects/co24902/bersey-electric-taxi-cab-taxis.

Taalbi and Nielsen (2021) argue that the lack of an electric grid was key in early US buyers and motor manufacturers switching to gasoline and diesel powered vehicles as more attractive, and these soon outcompeted electric cars in both total cost and distances that could be traveled. A reversal of these attributes is in sight again: an all-electric powered society is going back to a future where humanity might have been 125 years ago.

3 Moving the UK towards a net-zero target

The UK Government's legally binding 2008 Climate Change Act (CCA08) target of an 80% reduction in GHG emissions by 2050 (see https://www.legislation.gov.uk/ukpga/2008/27/contents) was amended in 2019 to one of net zero by 2050 https://www.legislation.gov.uk/ukdsi/2019/9780111187654. The CCA08 created the Climate Change Committee (https://www.theccc.org.uk/) as an independent statutory body to monitor, analyse, advise and report to Parliament on progress towards the targets. To meet a net zero target, all fossil fuel use must be reduced to near zero, namely coal, oil and natural gas. Then all other sources of GHG emissions must be reduced to a level such that carbon capture and storage (CCS: see e.g., Leung *et al.*, 2014), combined with atmospheric CO_2 extraction methods, can remove the rest (but see McLaren, 2020, for a critical appraisal). Given an irreducible non-zero minimum demand for oil and gas (e.g., for chemicals), since natural absorption alone will be inadequate, to achieve zero net emissions by 2050 requires major technological developments in CCS with efficient separation and collection of useful gasses (see https://doi.org/10.1016/j.xcrp.2020.100210) and removing CO_2 (see e.g., https://phys.org/news/2014-09-carbon.html, and Hepburn *et al.*, 2019), possibly reusing existing CO_2 as a fuel (see Kim *et al.*, 2017, and Skafte *et al.*, 2019) .

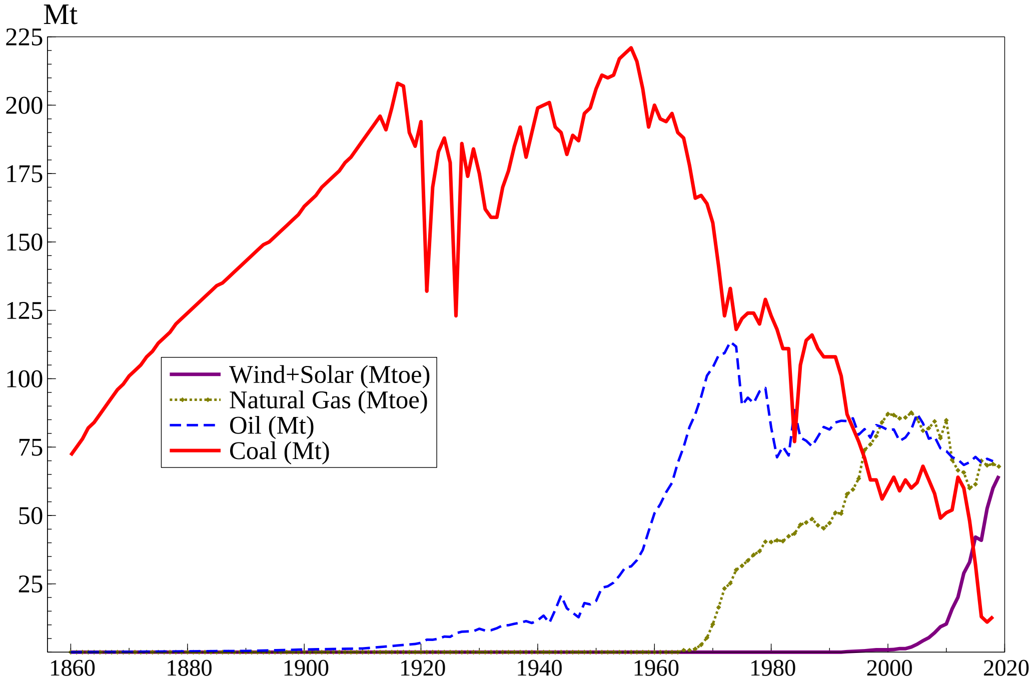

Figure 2: UK coal (millions of tonnes, Mt), oil (Mt), natural gas (millions of tonnes of oil equivalent, Mtoe) and wind+solar (Mtoe), all to 2019.

Total UK energy use was approximately 2250 terawatt hours (TWh) in 2018, equivalent to just over 200 million tonnes of oil equivalent (Mtoe).[5] That comprised roughly 70Mtoe petroleum, 70Mtoe natural gas (which is mainly methane) and 60Mtoe non-CO_2, with almost negligible coal use. To replace all remaining fossil fuel use and create a non-GHG emitting electricity generation system with appropriate back-up storage, supplying an all-electric transport system, replacing natural gas use (either directly by electricity or indirectly via hydrogen, the production of which requires electricity) will necessitate at least a 20-fold increase over the next 30 years in non-CO_2 electricity from the current 120TWh per annum. That is a compound annual growth rate of 10.5% p.a., even assuming economic growth is offset by efficiency gains in the use of electricity. In addition, net GHG emissions from construction, agriculture, chemical and manufacturing industries, and waste must be eliminated which will require additional electricity.

Coal use has fallen to near zero in the UK since the CCA08, without obvious aggregate costs in terms of per capita GDP (see Figure 2, and Castle and Hendry, 2020): we comment on local costs below. The key reasons were the availability of reasonably competitive replacement methods for generating electricity (natural gas and renewables) and legislation on coal-use reduction in power stations. The impact of greatly reduced coal use has been a major reduction in UK territorial CO_2 emissions per capita as shown in Figure 3, now far below 1860 levels when the UK was the 'workshop of the world'. In part, the CO_2 reductions are also due to 'off-shoring' dirty production,: conversely, the higher levels till 1920 would be far lower if CO_2 embodied in UK exports was subtracted.

However, these were the easiest reductions: both oil and natural gas usage must be removed next. Section 4 describes how they can be removed from electricity production by increased non-GHG sources, so we assume both oil and natural gas will be replaced in that role by 2050. On that basis, section 5

[5]See §1.6 in https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2019

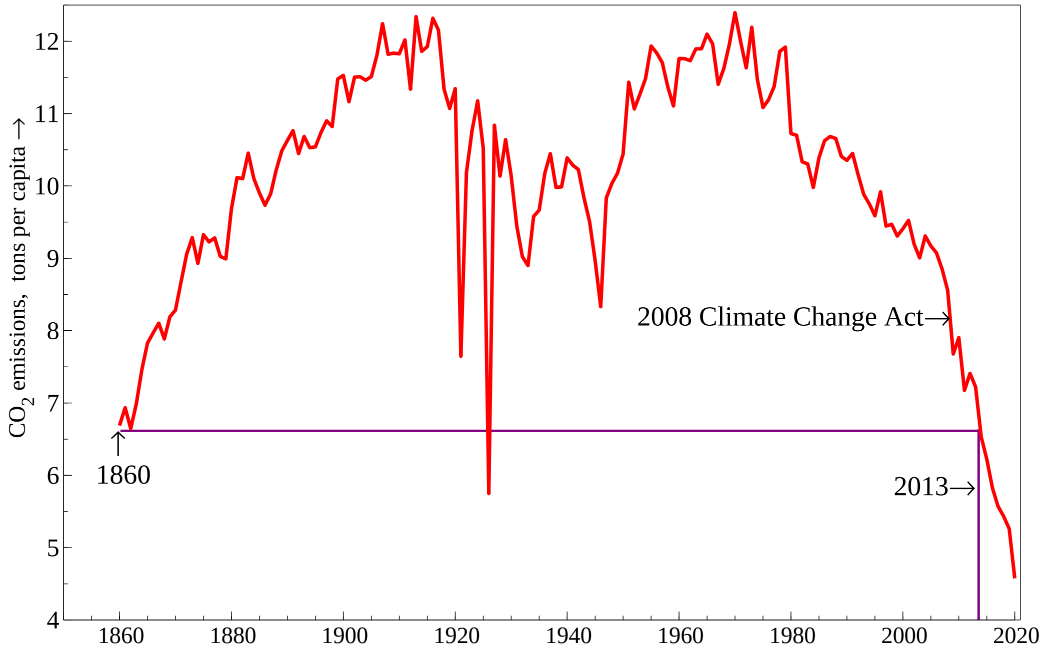

Figure 3: UK territorial per capita CO_2 emissions (tons per annum) till 2020.

considers the removal of oil from ground transportation, leading to possible solutions to both short-term electricity storage and grid balancing problems that result from variable renewables generation. However, as oil produces 30% more CO_2 per kwh than natural gas first expand non-GHG electricity generation to power electric vehicles before replacing natural gas in electricity generation.

Section 6 then considers the replacement of natural gas (methane) by hydrogen as well as by electricity in household space heating, cooking and heating water. Solar PV panels on roofs can generate electricity for heating water as well as direct uses like lighting and running heat pumps or electric boilers. Another possibility for households is for the UK to switch back from a national distribution system using natural gas to one based on 'green' hydrogen: prior to 1969, its gas grid supplied coal gas ('town gas'), containing about 50% hydrogen, after which it switched to natural gas. That change required converting household equipment to burn natural gas, so switching to a hydrogen system would also be going back to the future. Although household natural gas (and some oil) usage could be reduced by appropriate subsidies and increased taxes, massive retrofitting of the housing stock for greatly improved insulation is likely to be necessary to get to net zero gas use. Tax increases on natural gas use with tax reductions on electricity consumed, such as by VAT or other charges on household fuel, seem essential: as they are intended to change behavior, any net revenue raised should be redistributed to families facing fuel poverty as part of a 'just transition'. The UK Government proposes installing 600,000 heat pumps per annum, but important issues need to be addressed including the supply thereof and skilled installers, as well as ensuring their F-gases do not leak. On the one hand, heat pumps not only provide both cooling and heating potential, they can provide up to four units of heat for each unit of electricity consumed, which is a high coefficient of performance (COP), so should be cheaper to run than say gas boilers. However, depending on the type of heat pump (air or ground source), their COP varies seasonally with the air or soil temperature and over the long term. Habibi and Hakkaki-Fard (2019) found that ground source had the best performance, a problem with air source being that they perform least well when most needed in very cold weather. Ground source heat pumps are more expensive to install, as are air-to-water (for central heating) than air-to-air (which just provide hot–or cold–air). However, Carroll, Chesser, and Lyons (2020) show that far better insulation of older homes is required if air heat pumps are to function well. Specialist skills are needed to install and maintain heat pumps, skills that are in very short supply in the UK currently with no plans for rapid increases in training, and of course many dwelling units do not have the space to install heat pumps so would need electric boilers.

Section 7 discusses reducing GHG emissions from agriculture, and section 8 from chemical industry, manufacturing and waste management. But as all GHG reductions depend on an adequate supply of non-GHG electricity at a viable cost, we first turn to that topic.

4 Zero greenhouse gas electricity generation

Total UK electricity production in 2018 was 350TWh (roughly 1/6th of energy used) where 120TWh came from renewables (34%), of which 64TWh came from wind (from 24GigaWatts installed), up nearly 10-fold over the previous decade but still a small percentage, plus 16% from nuclear: see Figure 4.

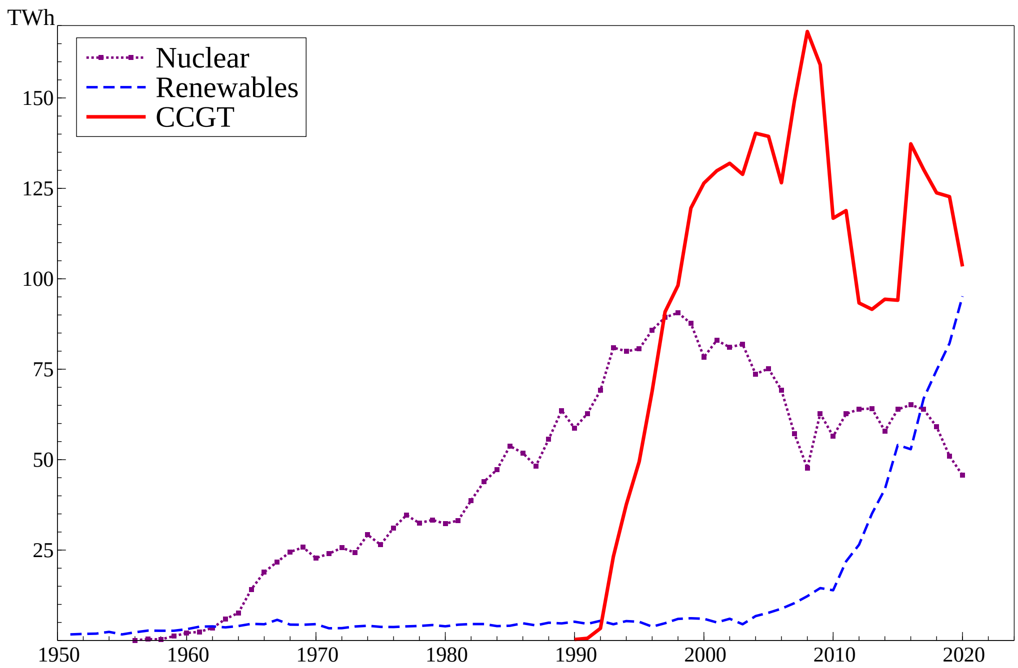

Figure 4: Main non-coal sources of UK domestically generated electricity (CCGT denotes Combined Cycle Gas Turbine).

Grubb and Newbery (2018) analyze the impacts of reforms to the UK electricity market in 2013 on its energy transition to a low carbon future. The UK government announcement in 2020 of installing another 40GW of wind-power electricity by 2030 (which would generate around 110TWh pa) roughly doubles its current renewables output, so could replace most natural gas used in generating electricity. However, a far larger increase is needed if ground transport is also to be electrified to replace 70Mtoe petroleum, as well as replacing natural gas use in housing. Since burning diesel or gasoline emits roughly 30% more CO_2 per kWh equivalent than natural gas, and electric engines are more efficient than petrol in energy use, the first steps should be expanding non-GHG electricity generation to replace internal-combustion cars by EVs, rather than replacing natural gas in electricity generation (despite the 2021 blip in gas prices). Initially, such a sequence also avoids over-reliance on variable renewables by having natural gas electricity generation backup.

Table 1: Expected levelised costs for power generation technologies in £/MWh.

Technology | year	2015	2025	2040	2050
Solar Large-scale PV (Photovoltaic)	80	**44**	**33**	**41**
Onshore Wind	**62**	46	44	-
Offshore Wind	102	57	40	51
Biomass	87	87	98	125
Nuclear PWR (Pressurized Water Reactor)	93	93	93	98
Natural Gas Combined Cycle Gas Turbine	66	85	125	-
CCGT with CCS	110	85	82	79

Notes: Lowest cost for each year in **bold**. Source 2015–2040: Table 4.18 central case, *Electricity Generation Costs* 2020, UK Department for Business, Energy and Industrial Strategy (BEIS). The BEIS rankings assume increasing carbon taxes and falling CCS costs over time. Source 2050: Table 7.2 in Committee on Climate Change (2019). Levelised (life-cycle) cost is the discounted lifetime cost of building and operating in £/MWh: the different expected costs are determined by various differences in assumptions. The price of £92.50/MWh from 2023 for nuclear power was guaranteed for the output from Hinkley Point C.

The rapidly falling costs of renewable-energy sources like solar photovoltaics and wind turbines combined with improved storage methods, could however almost eliminate oil and gas in electricity production by 2050. Table 1 records the present and estimated future costs of alternative electricity generating technology costs in the UK. Large-scale solar photovoltaics are forecast to be the lowest cost per MWh (and this is for the UK!) if CCS is enforced.

Offshore wind turbines have fallen greatly in cost and increased in efficiency over the past two decades, so that for the UK at least they offer a low cost alternative, with the benefits of being easier to install than onshore given their 100 meter-long blades, and creating incidental marine reserves and fish sanctuaries. In just over five years, they have fallen from one of the most expensive forms of energy to be cheaper than combined-cycle natural gas turbines even before adding the costs of CCS that would be needed for net zero emissions. The Hywind Scotland trial of floating wind turbines has demonstrated their viability. The benefits would be considerably greater for the UK if it developed a much larger manufacturing and installation capacity for wind turbines. Kruitwagen *et al.* (2021) map their global geographical distribution.

Related developments include experiments using waves (see https://www.emec.org.uk/about-us/emec ongoing near Orkney), and tides to generate energy (https://www.shetland.org/blog/energy-shetland-tides off Shetland). Tidal movements are totally predictable, so the energy generated by methods using the twice daily ebb and flow will be as well, such as underwater turbines, one of three approaches.

Renewables generated more electricity for the UK than fossil fuels for the first time in 2020: see https://www.offshorewind.biz/2021/03/25/renewable-energy-outperforms-fossil-fuels-in-uk/. However, relying only on highly variable wind and sun sources of electricity requires constantly balancing electricity flow as well as a large backup storage system for windless nights and potentially long winter periods of cloudy and still weather. There is evidence that wind speeds are falling due to the reduced temperature differentials between the tropics and the poles (see Solaun and Cerdá, 2020, for Europe and Guo, Xu, and Hub, 2011, for China), which could substantively alter the balance of generation costs. In addition to other storage systems in use (hydro pump & store, liquid gases, flywheels, supercapacitors, etc.), plugging electric vehicles into an intelligent network connected to the grid would be a valuable addition and facilitate short-run balancing electricity flow, an issue addressed in the next section. The UK also imported more than 20TWh of electricity via interconnectors in 2019, and such connections are being expanded: see https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/interconnectors.

Natural gas (mainly methane, CH_4) usage has increased 3.5 fold in the UK since the mid-1980s, and contributes about 40% of electricity output, emitting 140 megatonnes (Mt) p.a. CO_2—despite producing less than half the CO_2 of coal per MWh. Sufficient expansion of non-CO_2 electricity generation seems feasible by 2050 while decarbonising transportation, but steadily replacing natural gas in electricity generation to also sustain the production of hydrogen by either electrolysis or methane pyrolysis will require the large increase in electricity output noted above. Nevertheless, over the next 30 years with ever improved technologies and continued cost reductions in non-CO_2 electricity generation, a near zero target for the UK's use of natural gas in that role seems possible without reducing GDP growth, perhaps even increasing it with new opportunities.

The UK opened the first nuclear power station in 1956, and has since generated 15%–25% of its electricity that way. Large-scale nuclear fission reactors seem likely to play an important role in the UK's energy supply despite recent construction problems. As governments can borrow for 30 years at low interest rates, that should be the route for funding huge investments that take years to come on stream. Nuclear power has been a successful low-cost producer for many years in France, delivering about 70% of its electricity, consumed both domestically and exported. Globally, nuclear accidents have cast a pall over the technology, although it has one of the lowest death rates of any fuel, and is much less damaging to health than coal or oil: see https://ourworldindata.org/grapher/death-rates-from-energy-production-per-twh which measures deaths from accidents and air pollution per terawatt-hour. While not an important consideration for the UK, off-shore wind turbines are little affected by tsunamis that could be dangerous for coastal nuclear power plants, so by maintaining a power supply for cooling, could help avoid nuclear accidents like that at Fukushima Daiichi, see Bhattacharya and Goda (2016).

Since all future technologies are uncertain, as an option, research is merited into developing safe small modular nuclear reactors (SMRs) based on the well-developed nuclear-powered engines in submarines.[6] Standardisation and learning-by-doing when constructing larger numbers of SMRs could make them cost effective. Variants of SMRs might be able to use non-fissionable thorium or the 'spent' uranium fuel rods from older reactors, as might large molten-salt waste-burner nuclear power stations (see http://www.whatisnuclear.com/reactors/msr.html), helping reduce the serious and potentially costly problem of disposing of current transuranic-waste (see e.g., https://www.seaborg.co/), the cost savings from which should be credited as an offset to their costs.

Recent developments in nuclear fusion include important advances increasing output efficiency of superconducting magnets, and reducing internal damage to tokamak materials from helium (which could be collected, offsetting a potential shortage): see https://www.psfc.mit.edu/ and https://futurism.com/helium-resistant-material-usher-nuclear-fusion. Several fusion reactor experiments are underway, including the JET (Joint European Torus) and ITER (International Thermonuclear Experimental Reactor), as well as laser-based, and the UK Government is committing funding to develop methods of connecting potential fusion reactors like ITER to efficient energy production (see https://www.nature.com/articles/d41586-019-03039-9). However, https://www.helionenergy.com/ aims to produce electricity directly from the fusion reaction expanding the plasma into a magnetic field. While some calculations suggest the prospect of a shorter time frame than our horizon of 30 years (see Greenwald, 2020), and others emphasise the potential advantages of cooperative international development (see Carayannis, Draper, and Iftimie, 2020), nuclear fusion remains an uncertain electrical energy contributor but if any of the many projects were successful, would greatly reduce the timetable for net zero.

[6] See https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx and https://www.business-review-webinars.com/webinar/Energy/The_economics_of_small_reactors-8k2NJVBC

5 Zero greenhouse gas emissions from transportation

UK retail real gasoline prices per litre have risen 20-fold since 1950, yet distances driven have *increased* more than 10-fold. Figure 5 shows that total distances travelled per annum have risen relative to car ownership—despite fuel duty plus VAT now being approximately 200%.

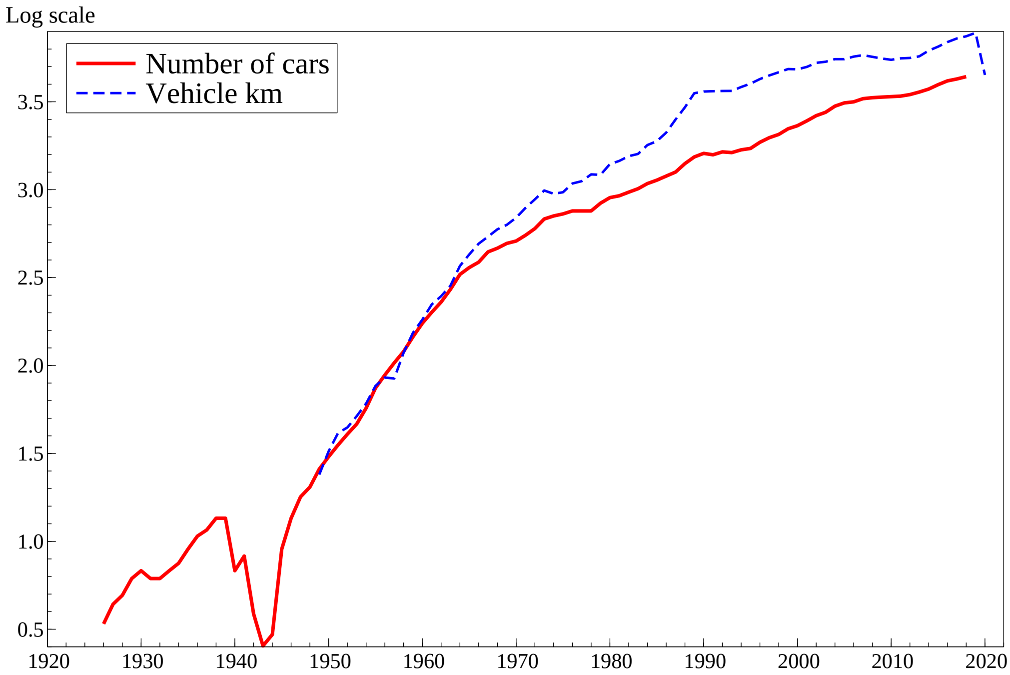

Figure 5: Number of cars (in millions) and kilometers driven per annum (in billions) in the UK on a log scale, adjusted to match in 1949 when distance-travelled data start.

Although a derived benefit of high fuel taxes is more efficient internal combustion engines, reducing oil use in transport will not occur quickly following current strategies, even with much more efficient engines and potentially higher taxes on gasoline. Consequently, the sale of gasoline and diesel cars will end by law in the UK in 2030 (new diesel vehicles should be phased out earlier given its toxic pollutants). Over 30 years, most vehicles will need replacing—the average age of a licensed car in Great Britain is under 9 years (https://www.racfoundation.org/motoring-faqs)—hence small carbon tax or subsidy changes may be sufficient to ensure an electric vehicle (EV) future at low additional cost. Electric engines are more efficient than gasoline so have lower running costs, but major improvements in lithium-ion batteries are needed to increase their relatively short journey capacity, worsened by taking a non-negligible time to recharge, both currently discouraging the replacement of internal combustion engines by electric powered cars.

However, recent advances promise such improvements as with blade battery construction (e.g., by Chinese manufacturer BYD, also not requiring cobalt or nickel, and claiming 400km when fully charged, with a million km recharging life: see e.g., Yang, Liu, and Wang, 2021) as well as advances in solid-state batteries: Michaux (2021) doubts there are sufficient global resources of lithium, cobalt, and nickel. Moreover, graphene-based carbon nanotubes (CNTs: see Sammed *et al.*, 2020) made by 'rolling up' sheets of graphene (see https://phys.org/news/2019-09-graphene-d.html) could act as electrode super-capacitors for an electricity storage system. Built into a vehicle's body panels protected by Faraday cages, they could provide sufficient energy to supply the battery powering the electric motor, so the vehicle becomes the storage unit: see Notarianni, Liu, and Mirri et al. (2014). CNTs are capable of rapid charging and discharging, and should be able to sustain viable driving distances. There is much ongoing research, such as developing 2-dimensional tri-layers of graphene as an insulator, superconductor and magnet: see Chen *et al.* (2020) and Wang *et al.* (2020). Graphene-based batteries are also being developed (see https://www.science-engineering.co.uk/graphene-battery/). Expanding capacity in production of high-quality graphene leading to cost reductions has already occurred following the European Commission's Graphene Flagship project, and could be sustained by variants of Wright's law (see Theodore Paul Wright, 1936) or Moore's law based on processing power of computers doubling every two years (see Ives, Righetti, and Schiele *et al.*, 2021, and Farmer and Lafond, 2016 for analyses of volume-related cost reductions). Potentially large falls in its cost of production could come from 'graphene in a flash' using plastic or food waste (see e.g., Luong *et al.*, 2020), as well as using carbon black as a by-product of methane pyrolysis discussed in Section 6.

Once electric vehicles become ubiquitous, by having them plugged into a grid when not in use, a vast short-term electric storage system would be available for no additional investment, with cars acting as a substantial part of the national grid's short-term storage: see Noel *et al.* (2019). An intelligent standardised grid would be needed to measure flows of electricity to and from every vehicle identified by a code like a credit card. Charging batteries when driving requires locating available sources of electricity supply and connecting to them independently of the provider, which is already available in apps like https://www.zap-map.com/. A discharging system that credits individuals for using their power has been available since early adopters of solar panels were paid for supplying their surplus electricity to the grid. That vehicles plugged in as a storage unit when not used would get paid peak prices if discharged yet pay off-peak for re-charging should encourage the widespread adoption of vehicle-to-grid (V2G) technology. Plugging electric vehicles into an intelligent network connected to the grid and managed by its controller would also facilitate balancing second by second electricity flows in an otherwise increasingly non-resilient system dependent on highly variable renewable supplies. Thus, renewable sources of electricity could be adopted more extensively without worrying about short-term continuity of supply, although longer-term is more problematic, and undoubtedly many technical and practical issues need solving to ensure such a V2G system would work reliably.

The potential benefits of such a storage source would be a huge SIP. Cars powered by internal combustion engines could be replaced at a rate either matching their obsolescence or the need for additional storage from an extension of renewables. Electric engine manufacture is well established, so employment can be maintained in vehicle production and many of its ancillary industries, potentially including CNTs. Side benefits would include a reduction in mining for palladium by eliminating the need for expensive catalytic converters (a target for theft, which then exacerbates air pollution and GHGs, especially nitrous oxide). But as noted above, a large increase in non-CO_2 electricity generation would be needed to sustain an electricity-only powered transportation system, albeit symbiotically with V2G, and better electric-powered public transport systems would also help. A potential drawback is if car ownership rates drop substantially by using sharing systems, but improved high capacity batteries and CNTs might offset such a trend.

Light, fast-charging power sources might also solve the UK's rail system lack of electrification across much of its network by replacing diesel-electric trains by electric ones, together with progress in hydrogen fuel-cell driven trains in Germany and the UK: see e.g.,
https://www.birmingham.ac.uk/research/spotlights/rail-decarbonisation.aspx. There is also research on hydrogen-based fuel cells for powering heavier vehicles like trucks, and Transport for London is planning to introduce buses powered that way. As CNTs are so light, they might stimulate further developments in economical electric-powered aircraft.[7] As ships have useful lives in excess of 25 years, committed GHG emissions from shipping will be persistent, but premature scrappage could be avoided 'through a

[7]See https://www.aerosociety.com/news/a-new-british-electric-aircraft/ and
https://spectrum.ieee.org/aerospace/aviation/10-electric-planes-to-watch.

combination of slow speeds, operational and technical efficiency measures, and the timely retrofitting of ships to use zero-carbon fuels' to quote Bullock *et al.* (2020).

6 Reducing housing GHG emissions

Housing accounts for around 30% of all the UK's CO_2 emissions (roughly 150 million tonnes of CO_2). Much of this is by burning natural gas. Currently the UK consumes around 80 billion cubic meters of natural gas, roughly 30b m^3 for households, and 25b m^3 each for generating electricity and for other uses, including industrial (10b m^3) and various services (15b m^3). About half of the UK's natural gas is now imported. Section 4 discussed replacing natural gas in electricity production, possibly other than as a back-up instead of coal-fired plants. Section 8 considers its replacement in manufacturing. Here we consider the household sector, which also covers some services. From 1969 onwards natural gas usage in household boilers and gas cookers replaced coal gas (50% hydrogen with methane, ethylene and volatile hydrocarbons), so a possible solution is reversing that change to use hydrogen, as the UK intends to ban the sale of fossil-fuel heating systems from 2035. To be non-GHG emitting, hydrogen would need to be obtained either by electrolysis or by methane pyrolysis (see Sánchez-Bastardo, Schlögl, and Ruland, 2020), noting that methane has the highest ratio of hydrogen to carbon of hydrocarbons: we consider these routes in turn. It would be self-defeating to use methane-based electricity to make hydrogen, so only non-GHG electricity should be used, especially when replacing methane by liquid hydrogen in industry.

To replace the kWh energy equivalent of 80b m^3 of methane p.a. would need about 240b m^3 of hydrogen. It takes 18kg of water to produce 1kg of H_2 by electrolysis, which is roughly 11.1 m^3, using 40kWh of electricity to do so. Thus, to produce 240b m^3 of hydrogen p.a. would require about 380b kg of water, around 65 times the UK's use of fresh water (5.5b kg p.a., although sea water might be usable) using 850TWh of electricity, about seven times current UK renewable supply of electricity. Both hydrogen and oxygen could be stored as liquids since both are valuable in that capacity, requiring more electricity. Efficiency improvements in electricity used in hydrogen production can be achieved by catalyst-based electrolysis (see e.g., Kuai *et al.*, 2020), and it could be produced when there is 'spare' renewables electricity, which might be at a negative price as currently National Grid pays some renewables suppliers to switch off when generation is in excess of use. Even replacing all electricity currently generated from methane by renewables, and heating household water by electricity just roughly halves the requirements to 120b m^3 of hydrogen, so using electrolysis alone to generate sufficient H_2 seems infeasible.

Methods of producing hydrogen from methane, like steam-methane reforming, can generate more than 5 kg of CO_2 for every kg of hydrogen collected (with CO_2 captured and used as a fuel, Committee on Climate Change, 2019, estimate production costs of £39MWh). Alternatively, methane pyrolysis converts CH_4 to C (black carbon) and $2H_2$ without any GHG released (see e.g., McDermott *et al.*, 2020), using roughly 1kWh of electricity converting 1.5 m^3 of CH_4. Burning 10 m^3 of methane to produce power would deliver about 2.5kWh, whereas burning the resulting 20 m^3 of hydrogen yields about 1.5kWh less the 0.3kWh used in production, so approximately 1.2kWh net. Assuming 'spare' renewable electricity will be available at various times of the day or night, converting the 80b m^3 of methane currently used for all purposes would make 160b m^3 of hydrogen with suitable thermocatalysis: the type of catalyst can influence the quality of the carbon deposited, and hence its potential uses, but the carbon byproduct can poison the catalyst (see e.g., Palmer *et al.* 2019, for some solutions). This could provide 80b m^3 H_2 for each of households and non-electric uses, delivering somewhat more energy to each than now. The electricity required would be around 56TWh, whether free or not. This seems feasible, and although GHG leaks in the supply chain have to be tackled (see e.g., Timmerberg *et al.* 2020), considerable progress has been made in measuring methane emissions (see e.g., Ravikumar *et al.* 2019). This has revealed that much of the current large volume of methane release comes from oil drilling and from excess shale oil production of natural gas (see https://acp.copernicus.org/preprints/acp-2020-1175/).

Current estimates of the world's methane hydrates are over 6 trillion tonnes which is roughly twice the carbon content of all other fossil fuels. A recent proposal is to extract carbon-neutral biogenic methane from fresh water lakes where it is stored at depth in large volumes, produced from CO_2 absorption by methanogenetic *Archaea* (see Bartosiewicz *et al.* 2021). This would reduce CH_4 emissions from lakes, which might otherwise increase as temperatures rise, and also provide 'biomethane' for backup electricity generation, already operational on Lake Kivu. New gas piping, likely to be required by any method of producing H_2, will probably be plastic based, so will need CCS during its manufacture. Recently, microwave deconstruction of commercial plastic using cheap catalysts has been shown to produce hydrogen and multi-walled carbon nanotubes (see Jie *et al.*, 2020), potentially turning a burgeoning problem, here of plastic waste, into part of the solution to climate change again using non-GHG electricity. Gradual replacement of natural gas by hydrogen for domestic use over 30 years would require continuously increasing output by around 5 billion m^3 of hydrogen annually, assuming none will be needed for electricity generation except possibly as a back-up, which if based on liquid hydrogen again requires electricity. Employment in pipe manufacture and laying as well as boiler and gas cooker conversions would result.

6.1 New dwellings

Ensuring that new dwellings are highly-insulated and constructed using almost no GHG-intensive building material is essential to greatly reduce their life-time emissions. A variety of CO_2 absorbing cement-based materials are under development (see Jang *et al.*, 2016, for a review), although it has long been known that Roman cement, using volcanic ash, was both waterproof and grew stronger over time (see e.g., Jackson, *et al.*, 2017). Graphene added to cement could strengthen it and lower the volumes needed in construction (see Luong *et al.*, 2020). Stronger timber, such as glued laminated (glulam) and cross-laminated, is being increasingly used and reduces the GHG of construction from less concrete and steel.[8] Glulam wood also binds more than 700 kg of CO_2 per m^3, but widespread use should be staged given the time taken for replacement trees to grow. A spectacular example is the arched roof of Malmö railway station constructed in 1924. The UK has just over 3 million hectares of woodland at roughly 1000 trees per hectare, with a government mim of 30,000 ha p.a. additional planting. However, both the stock and flow of trees would be quite inadequate to sustain a large increase in glulam as the vast majority of UK timber is imported.

Cutting electricity costs would make hydrogen cheaper and so lower the costs of making glass: cheaper triple glazing will help ensure better insulation. Installing evacuated-tube solar collectors on roofs for water heating, and especially solar photovoltaics to generate electricity, which Table 1 showed was one of the cheapest options even for the UK: linked back to the grid and with battery storage, dwellings could also be part of the backup needed for national electricity supply. Joshi, Mittal, and Holloway (2021) argue that world-wide solar PV could generate much of the energy to replace fossil fuels, although intermittency and locations entail the need for considerable storage and potentially greatly extended grid infrastructure within and between countries. Ground and air source heat pumps could be installed for internal heating and cooling, as well as electric boilers for the former. Other proposals for new dwellings include better designed urban environments and landscapes for a hotter world with probably more volatile weather, and more use of collected rain water, whereas natural gas from the grid should be terminated.

[8] See https://www.ice.org.uk/news-and-insight/the-civil-engineer/june-2015/timber-growing-in-construction

Looking further ahead, but less certain, some new technologies seem promising: efficient and robust perovskite solar cells (see https://www.energy.gov/eere/solar/perovskite-solar-cells) and halide perovskite-based solar windows that look like tinted glass which could generate electricity (see Canil *et al.*, 2020).

6.2 Retrofitting existing dwellings

Better insulation of existing dwelling is essential to reduce their CO_2 emissions from heating and cooling, and could include installing double or even triple glazing, better loft insulation, outside cladding, foil between radiators and outside walls, etc. As with new dwellings, installing solar panels and air heat pumps would reduce demands on GHG emitting energy sources, as would LED lighting, albeit requiring installation at very high rates facing 30 million dwellings. However, Carroll, Chesser, and Lyons (2020) show that far better insulation of older homes is required if air heat pumps are to function well. For smaller dwelling units like apartments where communal systems are infeasible, or where sufficient solar PV is installed, electric boilers could gradually replace gas boilers, and could benefit from falls in electricity prices: see e.g. Nielsen *et al.* (2016).

Refrigerant gasses can be 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 F-gases like hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) used in heat pumps are dangerous greenhouse gases. Sulfur hexafluoride (SF6), to date essential in protecting electric sub-stations from explosions, is an excellent electrical insulator, being inorganic, colorless, odorless, non-flammable and non-toxic, but is an extremely potent greenhouse gas like HCFCs. Research is needed for better alternatives, perhaps funded by prizes to avoid patent restrictions (see Hendry, 2011, and Hall, 2014). Raising fridge and freezer insulation standards to minimize cold loss should also reduce the compressor size needed, in turn lowering purchase prices as well as electricity consumption, Chu's law in action: see https://www.eenews.net/stories/1059965900.

Coal gas replacement when the UK switched to natural gas required fitting different-sized burner jets for the correct gas/air mixture, as coal gas had calorific energy about half that of methane. The total cost of the conversion was £100m at the time, so approximately £3b in current prices or £1000 per house. If the switch from natural gas to hydrogen occurs, an investment in new burners of about twice that may be required, given the increase in the number of households, as well as required pipeline improvements.

7 Lowering the GHG 'foodprint' of UK agriculture

Satellite images reveal that less than 6% of the UK's land area is built on (with around 3% classified as 'green urban'), and although the impact of built-up areas is felt well beyond their physical footprint, about 56% is farmed and 35% natural: see Rae (2017). At present, greatly lowering agriculture's GHG 'foodprint' looks problematic, although there is progress in efficiency improvements in some areas. Xu *et al.* (2021) calculate that the *global* GHG emissions of agriculture are around 2ppm CO_2 equivalent ($17TgCO_2eq$) of which about 57% comes from animal production.[9] Best-practice high-yield farming could substantively reduce demands on global cropland (see Folberth *et al.*, 2020), providing more land for tree planting, which with careful peat and wetland restoration can all help absorb CO_2. Also Cooper *et al.* (2021) show a medium-term reduction of 30% in carbon dioxide fluxes under seed planting by direct drilling (zero-tillage). Inner-city vertical and underground farms (in unused tunnels) economize on land, water, fertilizer and energy (partly from transport reductions), and are increasingly viable, especially under digital control (see Jans-Singh *et al.* 2020), and given the falls in costs of electricity via LED lighting, and potentially channeled daylight (see Goel and Yooab, 2021). Transport costs, food waste

[9]See https://www.gov.uk/government/publications/future-of-food-and-farming for an earlier report.

and potential emissions are reduced and multiple crops can be grown per year. Fish of various kinds can be bred in the water used for hydroponic systems. When grown in a vertical farm, a commonly low yielding crop such as wheat has a yield increase of 600 times compared to that grown in the field: see Asseng *et al.* (2020). Saving virgin forest and other previously unused land from farming is becoming imperative to avoid mass extinctions of species from loss of habitat: see https://www.cbd.int/sp/targets/ and Dasgupta, Raven, and McIvor (2019). Meanwhile, the COVID-19 pandemic has seen a surge in home working, which if it persists could see many vacant multi-storey buildings, with potentially large falls in their prices.

There is considerable research on altering farm-mammal diets to reduce methane emissions, including adding dietary fumaric acid (in plants like lichen and Iceland moss, but also made synthetically as a food additive), where lambs showed a reduction by up to 70%:
see https://phys.org/news/2008-03-scientists-cow-flatulence.html. On the island of North Ronaldsay in the Orkneys, the local breed of sheep are forced to live off seaweed by a dry stone dyke surrounding the island to keep them on the beach areas because a high grass diet can be dangerous for them from copper intake. Eating the seaweed controls the usual methanogenic bacterial activity in ruminants, so the sheep belch far less methane than grass-fed relatives elsewhere. Feeding lactating dairy cows on a diet including just 1% of the seaweed Asparagopsis armata reduces their methane output by up to 2/3rds as well as economises on their feed intake (reducing their methane production saves energy): see Roque *et al.* (2019). Similar improvements in emission reductions and weight gain have been found for other ruminants fed Asparagopsis taxiformis at even lower levels of dietary additions (see Kinley *et al.*, 2020) with 'the potential to revolutionize management of greenhouse gas emissions across the ruminant livestock sector with complementary benefits to the environment, and economy of the wider agriculture sector'. On a global scale, adoption would require substantial aquafarming if adequate supplies of Asparagopsis are to be available, but attempts to do so are ongoing. The key bioactives (including methylene chloride) have been identified and could be synthesized as additives. Honan *et al.* (2021) evaluate the safety and effectiveness of feed additives in reducing enteric methane emissions in cattle. Genetic studies have shown that cattle inherit low methane production, so selective breeding could also help reduce emissions: see Wallace *et al.* (2019). Almost as important is reducing the air pollutant amonia, emitted by manure, slurry and fertilizers, and in addition to the methods discussed in Guthrie *et al.*, an electrical plasma wave can cut these by up to 90%: see https://www.fwi.co.uk/livestock/dairy/plasma-treatment-cuts-ammonia-loss-by-up-to-90, again dependent on 'surplus' electricity for cheap usage.

Another increasing problem from agriculture is the release of nitrous oxide (N_2O) from excess use of nitrogen fertilisers (see Tian *et al.*, 2020) such that N_2O emissions have doubled in the last 50 years (see https://www.eia.gov/environment/emissions/ghg_report/). Noting that areas around volcanoes are very fertile, ground-up basalt and even basalt dust waste may be an excellent fertilizer additive or alternative: see Beerling *et al.* (2020) and Nunes *et al.* (2014): grinding is cheap, but again uses electricity. Moreover, basalt is a major source of atmospheric CO_2 removal as shown by on-going experiments in Iceland: pumping carbon-rich fluids into ophiolite rock formations show that carbonate minerals can form very rapidly (see https://www.carbfix.com/). Natural absorption of atmospheric CO_2 by basalt post Permian–Triassic was slow but extensive (see e.g., Berner, 2006, and Parnell, Macleod, and Hole, 2014), and deliberate action could greatly accelerate similar mechanisms. Biochar produced from pyrolysis of biomass also increases crop yields while reducing GHG emissions: see Woolf *et al.* (2010) and Hepburn, Adlen, and Beddington *et al.* (2019). Natural benefits include avoiding deforestation to create new farmland, as well as additional tree planting: by 2050, the UK Government aims for 30,000 hectares p.a., as well as restoring 280,000 hectares of peat land; whereas the Climate Change Committee 2020 report recommends up to 70,000 hectares p.a. of tree planting and 1 million hectares of peat land by 2035.

Aquaculture seems essential to continue the supply of seafood and seaweeds like Asparagopsis, but needs serious productivity improvements in many areas and faces health concerns in others (see e.g., Franks *et al.*, 2021). Racine *et al.* (2021) show that seaweed aquaculture is also capable of removing large quantities of excess nitrogen and phosphorus from coastal ecosystems. To enhance the supply of 'wild seafood', more and larger marine reserves and saltwater fish sanctuaries with strong legal protection must be mandated. Other than policing against illegitimate fishing, these are relatively low cost, and above we noted sanctuaries were an incidental benefit of off-shore wind farms.

Changes to human diets also need encouraging, eating less mammal meat and more avian and plant nutrition. Simple steps can facilitate that shift, such as just reordering items on a menu, and preparing more enticing vegetarian and vegan meals both improving dietary health:
see https://www.gu.se/en/news/nudging-makes-us-eat-more-vegetarian-food.

8 Reducing industrial and chemical manufacturing and waste GHGs

Decarbonizing heavy industries' direct emissions is essential because even if all their indirect energy sources came from renewables, they would still comprise at least 20% of GHG emissions globally: see Esparza (2020). Heavy industry is particularly carbon intensive when making products like iron and steel, using facilities with long lifetimes and high capital investment. However, Lawrence Livermore National Laboratory estimates that only 40% of US energy is used productively, so greater efficiency and re-using excess heat would both reduce costs and GHG emissions. Investment in mitigating industries' large direct emissions of CO_2 is required now. Low-carbon high-heat solutions for manufacturing include electric arc and liquid hydrogen, highlighting the key role this gas could play in a zero-net emissions world.[10]

Chemicals and plastics remain key areas for research on reducing, removing or capturing their carbon emissions. The 3 new 'R's are repair, reuse, recycle: wider and more efficient recycling, converting more waste to fuel, with less landfill to reduce methane leakage are all essential, as is increased research on catalysts to facilitate these. The 5 pence charge from 2015 per plastic bag in the UK led to an 80% fall in their use (almost 13 billion fewer bags after 2 years): similar charges for other non-recyclable items could be equally effective.[11] The purchasing power of large retail chains could also pressure suppliers to genuinely reduce their GHG emissions, as (e.g.) Walmart is doing.[12] Currently, wind turbine blades are difficult to recycle at the end of their lives, an issue that needs attention as their numbers expand.

9 Imported and indirect CO_2

Adding 'consumption induced GHG' equivalent emissions to the UK's total would raise its territorially recorded levels because of CO_2 embodied in net imports. However, the UK's large reductions in GHGs from electricity generation are substantial, and CO_2 'embedded' in imports will fall with reductions in GHG emissions by exporting countries. An unwanted consequence of targeting consumption emissions (rather than production) is to reduce the incentives for emitting industries or exporting countries to reduce their GHG emissions as these would no longer be attributed to them: this argues against nationally decided contributions–NDCs– being calculated on a consumption basis. Likewise, direct GHG emissions from transport and packaging industries should not be transferred to the food sector, retail outlets or consumers, although their own emissions must be reduced. Consequently, as analyzed by Nordhaus (2015, 2020), tariffs on all imports from countries not sufficiently reducing their GHG emissions have a role to play in improving both exporters' and importers' performance. Equally, deforestation—which

[10] https://www.energypolicy.columbia.edu/research/report/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today
[11] https://bankunderground.co.uk/2020/05/11/bank-of-england-and-financial-times-schools-blogging-competition-and-the-winner-is-3
[12] https://corporate.walmart.com/newsroom/2019/05/08/walmart-on-track-to-reduce-1-billion-metric-tons-of-emissions-from-global-supply-chains-by-2030

destroys CO_2 absorption for increased agricultural output—is now recorded worldwide by environmental satellites detecting changes in vegetation (see e.g., https://www.nicfi.no/), and again all imports from countries guilty of large-scale deforestation should face a high general tariff on imports. In both cases, having border tariffs will make exporting companies who are penalized despite not being the GHG sources put internal pressure to reduce emissions and cease destruction, adding to international pressure to reduce environmental degradation and loss of habitat, threatening species extinctions (see Dasgupta, Raven, and McIvor, 2019). The LEAF Coalition (lowering emissions by accelerating forest finance) proposed by the US, UK and Norway will use satellite detection similarly to make deforestation less attractive financially than retention: see http://www.leafcoalition.org/.

A key indirect impact is through the financial system, both as a funder of fossil fuel suppliers and users, and as facing both transition and physical risks from climate change: see e.g. Robinson (2020) and Campos-Martins and Hendry (2020). Managing these risks by reducing financial exposure to agencies that create GHGs can move the economic system towards a low carbon future. Increased transparency of where investments are allocated and stress tests of resilience to a disorderly transition if climate change worsens dramatically can also help. Equally, highlighting investment opportunities in a growing 'green' economy should speed transition.

10 How great are the costs of the energy transition to a 'green economy'?

Costs of the transition to get to net zero by 2050 will vary by country and by their current methods of supplying energy, but should be calculated net of expenditures that would be needed anyway over the next 30 years even under business as usual. https://www.iea.org/reports/net-zero-by-2050 states that "To reach net zero emissions by 2050, annual clean energy investment worldwide will need to more than triple by 2030 to around $4 trillion", but it is unclear what would have been needed in 'dirty energy' investment. Adjustment costs are often underestimated, especially from disruptive changes. Supply chains are key to providing the materials (many of which are relatively rare) that are needed to construct non-GHG electricity-generating equipment such as wind turbines, solar PVs and SMRs, as well as heat pumps, electrolisers, batteries, EVs and storage systems–preceded by producing the manufacturing equipment needed to make these. But skilled workers are also essential to build, sevice and maintain the resulting equipment—and the growth rates of these need to be matched.

Already renewable electric power is cheaper than other sources, and many fossil-fuel-fired power stations will become uneconomic by 2050 and need decommissioned anyway. However, if fossil fuel prices collapse from the massive reduction in demand, then that may not happen, so CCS will become essential. Investment in alternative approaches to doing so is merited, and is already happening. The vast expansion in renewable electric power will need to be matched by an equivalent expansion of national grid infrastructures to shift wherever power is being generated to where it is needed. Again, a substantial part of both investments should be fundable by the profits from the resulting electricity supply. Consequently, this part of the transition costs to get net zero seem relatively small.

In 2020, the average life of a car, and some other vehicles, even with good maintenance was under 15 years (or around 200,000 miles) before it needed replaced. Thus, banning new combustion engine cars by 2035 entails that most extant vehicles would need to be replaced before 2050 irrespective of their fuel source, so the real costs of switching to all-electric cars are just the additional costs (if any) of EVs over internal combustion engines. Using V2G, such EVs could then supply a substantial part of the storage system to sustain an all-renewables electricity generation system. The additional costs of doing that are from implementing an intelligent grid that can rapidly charge and discharge the large number of EVs that would replace internal-combustion engine cars. Again, that grid should be self funding from the profitability of supplying the energy that cars need. Consequently, this part of the transition costs to get to net zero also seem small. The potential danger is a large increase in the price of essential materials to build EVs.

Turning to the housing sector, few central heating boilers or cooling systems last as long as 20 years, so again most would need replaced by 2050. Instead of just refitting fossil-fuel powered systems, heat pumps, electric boilers or hydrogen fired systems could be installed depending on the dwelling, albeit with additional costs to ensure roughly equivalent comfort. A related analysis applies to improved insulation, which could repay its costs by reduced fuel bills, especially if undertaken in the course of offsetting natural building depreciation. The additional costs of properly insulating and net-zero powering new dwellings are not likely to be large once scale production of the relevant materials is attained.

Avoiding GHG emissions from waste could again be profitable using captured methane for pyrolosis, from efficient recycling, or burning with CCS to generate electricity. Changing industrial processes and chemical manufacturing for green methods is likely to be more expensive, but not on the scale of trillions of US dollars per annum. And we have noted that improving agricultural practices should be cost reducing. Consequently, tackling climate change should not be 'too expensive', especially given the potentially huge costs of climate turbulence.

Cap and trade could help facilitate GHG reductions, and the EU Emissions Trading System (EU ETS) has forced change there, as could carbon taxes (see Sterner *et al.*, 2020), though evidence of public opposition in a number of countries suggests possible limitations even when the revenue raised is rebated. Wolf (2021) provides an analysis of the potential roles of carbon pricing across all the sectors considered above. Empirical studies of carbon-tax-based approaches do not show much effectiveness to date (see e.g., Rosenbloom *et al.*, 2020, and Rafaty *et al.*, 2020), but their levesl have been relatively low. Conversely, the 5 pence charge per plastic bag led to an 80% fall in their use, so small carefully designed taxes or charges can be effective: phasing out subsidies to fossil fuel consumption would be a useful first step in reducing their use. A tax of £100 per ton on UK territorial CO_2 emissions translates into about £450 per person per annum at current levels, and while obviously falling as the economy becomes greener, would have differential impacts across households, so much of the approximately £30 billion raised would need to be redistributed to less well off groups in society. To prevent 'dirty' production being off-shored, a border tax would be an essential accompaniment. Given mixed evidence on the effectiveness of carbon taxes, our discussion focused on potential additional SIPs that would incentivise or facilitate the energy transition process to net zero.

11 Summary and Conclusions

To achieve net zero greenhouse gas (GHG) emissions targets requires an integrated symbiotic strategy across all fossil fuel uses and all other GHG emitters, less natural absorption and carbon capture and storage, possibly combined with atmospheric CO_2 extraction. A sensitive intervention point (SIP) is when a small change in one part of a system precipitates large changes elsewhere. We described five symbiotically linked SIPs in the transition to net zero GHG emissions. Our first SIP has already happened: clean electricity generation is cost effective and achievable with known technologies, so it is beneficial to switch to renewable electricity, almost incidentally tackling climate change. However, doing so faces a major storage problem for periods when renewables do not generate power. Small modular nuclear reactors (SMRs) could help with background supply, but our second SIP was that short-term storage can be facilitated by decarbonizing the transport sector and using electric vehicles as storage units plugged into an intelligent network connected to the grid to also facilitate balancing electricity flow. Current battery technologies need to be improved to be able to repeatedly charge and discharge rapidly and store sufficient power for distance driving, which would facilitate the uptake of electric vehicles, could also supply railway trains in place of diesel-electric, and help developments in electric-powered aircraft.

Major infrastructure expansions are needed to ensure electricity provision on the scale needed. With V2G supporting short-term continuity of electricity supply, renewables capacity can be expanded which led to our third SIP: cheap electrolysis and methane pyrolysis production of hydrogen when other electricity demands are low. This feeds back by maintaining 100% capacity renewables' generation at 'off-peak' saving the costs of turning it off.

In turn, hydrogen gas could replace methane use by households, and liquid hydrogen would provide additional medium-term storage, as well as supply a high heat source for industry helping to decarbonise manufacturing, which was our fifth SIP. A by-product of methane pyrolosis is black carbon, which could add to the material available for making graphene, though waste plastic could also be used. New buildings must be constructed to be net zero. These developments interact and would maintain employment and real per-capita growth in new industries with steady and coordinated expansion during the transition, as well as in retrofitting both vehicles and housing, avoiding 'stranded workers'. A joined up approach to decarbonizing is needed as virtuous circles can be missed when there is isolated thinking rather than seeing the interacting policies needed for reductions in GHGs as a whole: solving some problems can facilitate solving others.

Turning to agriculture, methane, nitrous oxide and carbon dioxide emissions are all by-products of modern food production. Ruminant methane emissions can be reduced by dietary changes and selective breeding, and nitrous oxide by reducing nitrogen fertiliser use, replacing some by basalt dust that also absorbs carbon dioxide and by biochar, both increasing crop yields while reducing GHG emissions. This was our fourth SIP: these developments are facilitated by cheap electricity, as is plasma treatment of slurry to reduce ammonia pollution. Crop production efficiency can be improved by adopting best practice, benefitting the environment and reducing cropland, along with vertical and underground farms. Aquaculture (including seaweed production) could be greatly improved: off-shore wind farms can also act as marine reserves. Human dietary changes to eating less mammal meat are feasible. Carbon pricing, cap & trade, and research support tools remain available if carefully used. To achieve a net-zero world will require considerable research and innovation on all aspects of low-carbon living and its consequences, with rapid technology transfer to developing countries potentially facilitated by using prizes to stimulate transition research so patents do not restrict global application (see e.g., Hendry, 2011).

The analysis was illustrated by UK data as it started the Industrial Revolution leading to the greenhouse gas problem; its Climate Change Act of 2008 has markedly reduced its territorial emissions at little aggregate cost; and we have modelled its performance in economic and climate terms (see Castle and Hendry, 2020). The UK data provide little evidence of high aggregate costs from its territorial reductions in CO_2 emissions, which have dropped by 203Mt annually from 554Mt in 2000 to 351Mt (36%) by 2019, during which period real GDP per capita has risen by more than 25%, despite the 'Great Recession' (neither includes the recent pandemic-induced changes). Some of this has been from an increase in the share of services in UK GDP, as our model has a negative long-run coefficient on GDP in the equation for CO_2 emissions, and a positive coefficient for the capital stock.

Historically, people in an industry that was being replaced from technical progress (usually by machines) lost out and had to bear what should be the social costs of change, from cottage spinners, weavers and artisans in the late 18th–early 19th centuries (inducing 'Luddites'), to recent times (from a million coal miners in 1900 to almost none today). Greater attention needs to be focused on the local costs of lost jobs as new technologies are implemented: mitigating the inequality impacts of policies introduced to avoid climate change must matter in such decisions. In any case, new skills training is essential for building, servicing and maintaining a green economy.

Given the important role of the capital stock in production, 'stranded assets' in carbon producing industries are potentially problematic as future legislation imposes ever lower CO_2 emissions targets to achieve zero net emissions (see e.g., Pfeiffer *et al.*, 2016), but jobs in those industries are equally at risk of being 'stranded'. While some of the above proposals are early stage and require substantial further research, they suggest possible strategies for moving towards at least a very low-carbon future by 2050, but also requires rapid technology transfer to developing countries if that is to be achieved globally: see e.g., Pigato *et al.* (2020). An excellent 'role model' that offers hope for major reductions in energy use is the dramatic increase in lumen-hours per capita consumed since 1300CE of approximately 100,000 fold yet at one twenty-thousandth the price per lumen-hour (see Fouquet and Pearson, 2006). As many of the steps will increase living standards and improve health, as well as tackle GHG emissions, they are doubly worthwhile. Let's not waste the recovery from the pandemic by ignoring the chance to tackle burgeoning climate issues, and offer CoP26 in Glasgow a route towards a sustainable climate.

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