

## Review

## Five sensitive intervention points to achieve climate neutrality by 2050, illustrated by the UK

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## ABSTRACT

To achieve net-zero greenhouse gas (GHG) emissions requires a transition from fossil fuel use to renewables, and eliminating GHG emissions from agriculture, construction and waste. Five sensitive intervention points (SIPs) could help change human behavior, building on the renewable energy revolution: (1) installing sufficient non-GHG electricity (removing coal); (2) replacing internal-combustion vehicles by electric (EVs), connecting parked EVs to an intelligent grid for short-run electricity storage (removing oil); (3) utilizing intermittent 'surplus' electricity for hydrogen production and liquefying it for medium-term storage and a high-heat source for industry; (4) changing domestic heating to heat pumps and solar photovoltaics (removing natural gas); (5) harnessing electricity in agriculture (vertical & underground 'farms') and waste. Behavior change requires viable substitute technologies and infrastructures, and timing stages in tandem, but also incentives to overcome perceived and real adjustment costs. Employment, real per-capita incomes, living styles and standards can be maintained while decarbonizing the economy by implementing these SIPs, illustrated for the UK.

## 1. Sensitive intervention points

Climate change is a system externality driven by aggregate greenhouse gas (GHG) emissions from individual human behavior. Humans are creatures of habit and their inertial behavior reflects high perceived costs of economic and psychological adjustments to changes. Economists' mantra of 'carbon taxes' will not be effective even if there are cheaper sources of power than fossil fuels unless most individuals and companies actually switch, but the pace of climate change makes the issue urgent. [1] investigate policy combinations that have led to the largest emissions reductions out of 1500 climate policies implemented between 1998 and 2022 across 41 major emitter countries from six continents. They identify just 63 successful policy interventions with total emission reductions of under 1.8 Gt CO<sub>2</sub> compared to the UN estimates of a median emissions gap of 23 Gt CO<sub>2</sub>eq by 2030. Consequently, we conceptualize the route to accelerate GHG reductions consistent with maintaining living styles and standards and minimizing adjustment costs in five sensitive intervention points (SIPs: see [2]). These SIPs apply when a small change triggers a much larger change

in human behavior that then becomes essentially irreversible. SIPs in the post-carbon transition aim to achieve that outcome for individual and company behavior given policy actions and available technology. Some SIPs must be sequential (e.g., renewable electricity before electric vehicles) and some overlap as we discuss. A mixed policy and technology example is the legally binding UK 2008 Climate Change Act: since the price of coal was higher than both natural gas and renewables for producing electricity, mandating its elimination from making electricity was low cost. Solar photovoltaic and wind are now cheaper sources of energy than fossil fuels so have become a financially preferred investment strategy for energy companies in many countries (see Table 1 for the UK).

In this paper we outline a comprehensive strategy for attaining climate neutrality by focusing on behavior changes that mitigate GHG emissions. We use the United Kingdom to illustrate the approach, partly because [3] have analyzed the UK's success in essentially eliminating coal use, but also given the UK's major historical role in starting the Industrial Revolution, and its 2019 legislation mandating net-zero GHG emissions by 2050. Similar strategies are relevant to other

**Abbreviations:** Sensitive intervention point, (SIP); greenhouse gas, (GHG); carbon dioxide equivalent, (CO<sub>2</sub>eq); 2008 UK Climate Change Act, (CCA08); Intergovernmental Panel on Climate Change, (IPCC); bioenergy with carbon capture and storage, (BECCS); combined cycle gas turbine, (CCGT); electric vehicle, (EV); carbon nanotube, (CNT); small modular nuclear reactor, (SMR); vehicle to grid, (V2G); megatonnes, (Mt); gigatonnes, (Gt); terawatt hours, (TWh); million tonnes of oil equivalent, (Mtoe); GigaWatts, (GW)

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developed economies which are comparable in terms of energy supply resources and energy demand requirements, but need adaptation for the developing world, including [technology transfer and innovation for low-carbon development](#). Given the heterogeneous impacts of climate change across regions and countries (see [4]), the strategies for achieving climate neutrality will need to be tailored to the characteristics of particular regions to maintain employment and real per-capita growth during transition (see e.g. [5], and [6] for an application of SIPs to China).

Despite the UK implementing targets and legislation to mandate zero net emissions by 2050, with a [strategy](#) for achieving such an outcome, the [Independent Review of Net Zero](#) by Chris Skidmore MP highlights that ‘actions were needed from government, industry and individuals to make the most of net zero opportunities’ and the [Climate Change Committee](#) found the UK to be lacking in progress in some areas. Hence, a review paper proposing a strategy to harness large societal changes with minor interventions is timely. The proposed approach is complementary to the established reports of the [IPCC](#), [UN](#), [IEA](#) and [Circularity Gap Report](#), amongst others, as well as the UK’s [Nationally Determined Contributions](#), and the recent American Academy of Arts and Sciences [Forging Climate Solutions](#). The value added of our paper is to draw attention to the relationships between the SIPs, given the transition sequencing that is critical for the generation and storage of renewable electricity to sustain the subsequent shifts. The paper provides a review of established technologies needed for the net zero transition to knit together the required behavioral changes using small interventions to result in rapid change.

Our paper builds on research looking at the UK net zero transition and is complementary to [7] who look at the issue of energy storage in the face of intermittent renewable supply from the perspective of the physics of the system rather than the economics. [8] undertakes a UK study that finds a system of nuclear and renewable energy is 5 times less costly than a system of gas with carbon capture and storage and is more preferable for meeting the UKs 2050 GHG emissions reduction target. [9] looks at the green energy market in the UK in which consumers have choice to switch to green electricity and [10] assesses the contributions of hydrogen and electricity to the UK heat supply to 2050, evaluating the evolution of the cost-effective portfolio of hydrogen sources. This review paper draws on the technical and economic literature in RENEWABLE ENERGY looking at the UK net-zero transition.

The focus on SIPs is because behavior change measures need to be implemented quickly and must have wide reach to be effective and ensure climate neutrality by 2050 can be met. Slowly evolving societal changes will not be rapid enough to ensure a timely transition. [SIPs](#) allow for a small or moderate intervention to lead to positive transformational change via ‘kicks’ (altering a variable in an existing system that triggers a positive feedback dynamic) and ‘shifts’ (fundamentally altering the system), see [2]. We specify why our 5 SIPs are characterized as SIPs and how they propagate behavior change through the complex climate-economic system. This review paper is intended to complement existing strategies outlined by collaborative bodies while making the case for considering interventions through the lens of SIPs to account for feedbacks and reduce adjustment costs.

The structure of this review is as follows. Section 2 outlines the need for SIPs because change is not happening quickly enough. Section 3 discusses moving towards a net-zero GHG emissions economy, outlining the five symbiotic SIPs. Section 4 considers achieving zero-GHG electricity generation as the first key SIP implementing a renewable revolution. The next step is to decarbonize ground transportation. Section 5 argues that replacing internal combustion engines with electric vehicles constitutes a SIP because it will directly reduce oil use and will provide short-term storage through the use of vehicle-to-grid technology. Section 6 proposes utilizing intermittent ‘surplus’ electricity for hydrogen production as well as liquefying it for medium-term storage and for use as a high-heat source for industry, our third SIP.

Section 7 focuses on domestic energy use as the fourth SIP, phasing out natural gas by changing domestic heating to heat pumps, electric boilers and solar photovoltaics along with changes in housing and construction. Section 8 turns to reducing agricultural emissions, our fifth SIP, as again, ‘surplus’ renewable electricity can play an important role. ‘Imported’ and indirect CO<sub>2</sub> are considered in Section 9. Section 10 discusses some likely costs and benefits of the energy transition to a ‘green economy’. Section 11 summarizes the analysis and concludes.

## 2. The need for SIPs

Climate change will continue till well after the target of net zero GHG emissions is achieved globally as oceans and atmospheric temperatures equilibrate. The benefits of rapidly moving towards that target now are likely to dramatically reduce the costs of tackling the problem later. Research (see e.g., [11]) 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](#)) emphasizes that the latter is still just achievable, but rapid action is required to do so.

SIPs provide a framework for implementing rapid change by accounting for the interconnected relationships within a complex system, leveraging behavioral feedback dynamics to result in large changes from relatively small interventions. To identify SIPs we use the nine characteristics outlined by [2] which include (a) speed of impact, (b) size of impact, (c) uncertainty of impact, (d) trade-offs, (e) path dependence, (f) unintended consequences, (g) windows of opportunity, (h) barriers to change and (i) key actors and institutions. We elaborate on these characteristics for each specific SIP below.

Adverse consequences of ever increasing levels of atmospheric CO<sub>2</sub> include extreme weather conditions that can be dangerous to life, high [wet bulb heat](#); [heatdome](#)s as occurred during 2021 in [North America](#); [wild fires](#) world wide, which worsen GHG emissions [12]; increasingly powerful [cyclones](#); sea level rises and worse storm surges causing increased coastal flooding [13] as well as inland flooding from ‘rivers in the sky’ causing great damage recently in Europe, Pakistan and China [14]; yet also more intense and longer droughts [15]. The consequences of such extreme weather impacts include endangering food supplies globally, increased flows of [refugees and migrants](#) with potential conflicts over resources, as well as shifting animal migration patterns, in turn creating ideal conditions for spreading infectious zoonotic diseases (like COVID-19). Such physical damages inflict economic losses, both directly on those affected and via financial markets. There is a potential for climate tipping points [16], since past ice-free Arctic Oceans have led to large-scale methane release from permafrost melting in the tundra, causing rapid climate warming [17]. [18] highlight the danger of species extinctions from climate change, as happened in deep-time (e.g., [19]). The stability of financial systems could be threatened if sudden large reductions in fossil fuel use were mandated by major governments because of dangerous climate changes as commercial banks have lent \$trillions to fossil fuel producers and users. Capital assets and the millions of individuals they employ could both become ‘stranded’, causing large financial losses. In short, the physical, social and economic costs of climate change are likely to be immense, but [2] argue that conventional approaches to mitigating climate change are not working and propose the use of amplification mechanisms in socioeconomic, technological, and political systems. We draw out five such mechanisms in the next sections.

## 3. Moving towards a net-zero target for the UK

There are several published proposals for how to achieve net-zero GHG emissions, including the detailed analyses in [20], the well-known IPCC reports such as [21], and [22] for the USA and from the [UK’s Climate Change Committee](#), [23,24]. [25] provide a comparison of seven possible UK pathways to achieve net zero by 2050. [26]

analyze the impacts of reforms to the UK electricity market in 2013 on its energy transition to a low carbon future. There is widespread agreement that electricity generation systems can be decarbonized by 2050, but less agreement on how to do so reliably. Recent IPCC reports and [22] see an important role for BECCS (Bioenergy with carbon capture and storage), but many developments are needed to make it feasible: [27,28] provide critical reviews. Other uses of the land needed for BECCS (unless based on waste material) seem more valuable by supporting biodiversity, making biochar, and glulam wood for replacing some steel and concrete in construction.

The UK Government's legally binding 2008 *Climate Change Act* (CCA08) target of an 80% reduction in GHG emissions by 2050 was amended in 2019 to one of *net zero* by 2050. The CCA08 created the *Climate Change Committee* as an independent statutory body to monitor, analyze, advise and report to Parliament on progress towards the targets. In 2021, the UK Government published its *Net zero strategy: Build back greener* report which includes both BECCS and hydrogen. The report proposes many of the steps in our evidence to *UK House of Commons Public Accounts Committee*, but with important gaps.

Here we outline five SIPs that could induce behavior change to adopt new technology, and we argue that there are financial incentives to do so if the symbiotic strategy is integrated. Our five SIPs build on the cost of renewable electricity being the cheapest currently, making expanded private investment profitable. However, doing so requires a greatly extended, intelligent and more resilient national grid, which will need major investments that could only be recouped over time by charges to use it, as well as sufficient storage for immediate use from intermittent renewable supply and medium-term storage for long still and cloudy periods.

The first key SIP is installing sufficient renewable electricity to provide all energy needs given its cost advantages, likely to continue, and potential new methods using tides and waves. This SIP stimulates four additional SIPs that will reduce other GHG emissions given sufficient green electricity. The second SIP is replacing internal combustion vehicles with electric (EVs), as their *present life-time costs are similar* for driving 10,000 miles p.a., which could be speeded up by more heavily taxing the former or lowering the costs of the latter. Unfortunately, the first has fomented riotous opposition in a number of countries (e.g., *gilets jaunes* in France), so we propose the latter. As internal combustion vehicles reach the end of the economic life, individuals can be induced to replace them by EVs by increased production lowering prices, cheaper batteries, and faster and more available charging. Expanding EVs will sustain a vehicle to grid (V2G) system that will greatly reduce the system-wide costs of electricity storage for second-by-second adjustments, paying peak-period prices for downloading from car batteries. Once there is sufficient electricity for EVs to replace all internal combustion vehicles, and hence eliminate most use of oil, natural gas generated electricity can be replaced by expanded renewables. This will create the different problem of handling 'surplus' electricity when more is being generated than demanded (e.g., middle of the night) so cannot be sent to the grid. The third SIP is to ensure sufficient uses at near-zero prices to avoid the expensive process of shutting down wind turbines: (a) by electrolysis of hydrogen and oxygen, stored as liquid forms; (b) various manufacturing process needing high heat (e.g., glass) plus pump and store hydro; (c) domestic electric water heaters, heat pumps and battery recharging all at low off-peak prices. En route, housing insulation needs to be dramatically improved in the UK, which is one of the worst in the developed world. The fourth SIP is to do so by incentives to install insulation and heat pumps by rebalancing domestic electricity and natural gas prices from the present system where it costs about 3 times per kWh for the former to the one-third that it should cost. New housing will need legislation and standards to be net zero in construction and use. The final SIP is to use low electricity prices in agriculture to develop vertical and underground farms, replace artificial fertilizers with ground basalt and

biochar, and reduce methane from ruminants by changed feeding and breeding as well as alter human diets.

An important aspect of 'net-zero commitments' by governments is their time horizons of 2050 to 2060. While this may be too late to keep global temperatures below 2 °C, reaching the target will nevertheless help stabilize the climate unlike 'business as usual' continuing unabated. Most vehicles and domestic appliances and much industrial equipment will need replacing over 30 years, so the costs of switching them to non-GHG alternatives are only relative to what would have been needed, and may be negative given rapid technical progress and volume related cost reductions in replacements [29]. To eliminate GHG emissions requires a staged approach that is integrated across all emission sources, which will take many years given the scale of the transition, and may require some significant technological advances as well as major infrastructure expansions to ensure electricity provision on the scale needed, and new skills training for building, servicing and maintaining a green economy.

To meet a net-zero target, all fossil fuel use, namely coal, oil and natural gas, must be reduced to near zero. Then all other sources of GHG emissions must be reduced to a level such that carbon capture and storage (CCS: see e.g., [30], possibly combined with atmospheric CO<sub>2</sub> extraction), can remove the rest (see [31] but compare [32,33] for critical appraisals). Given an irreducible non-zero minimum demand for oil and gas (e.g., for chemicals), since natural absorption alone will be inadequate (*World Resources Institute* predicts systems to remove carbon from the atmosphere will be required at the billion tonne scale by the mid-century) to achieve zero net emissions by 2050 requires major technological developments in CCS with efficient *separation and collection of useful gasses and removing CO<sub>2</sub>* [34], possibly reusing CO<sub>2</sub> as a fuel [35,36].

*Total UK energy use* was approximately 2250 terawatt hours (TWh) in 2018, equivalent to just over 200 million tonnes of oil equivalent (Mtoe). That comprised roughly 70 Mtoe petroleum, 70 Mtoe natural gas (mainly methane) and 60 Mtoe non-CO<sub>2</sub>, 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 a 10–15-fold increase over the next 30 years in non-CO<sub>2</sub> electricity from the current 120 TWh per annum to replace the equivalent of 2250 TWh. That is a compound annual growth rate of near 10% p.a., assuming economic growth is offset by efficiency gains and other net GHG emissions are eliminated. Total UK fuel use has fallen by 91% relative to GDP since its peak in 1879, so efficiency gains have been very large and seem likely to continue as electric vehicles are more efficient than internal combustion by avoiding waste heat.

Coal use has fallen to near zero in the UK since the CCA08, without obvious aggregate costs in terms of per capita GDP (see Fig. 1(a), and [3]). Table 2 records data sources and we comment on local costs below. The key reasons were the availability of 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<sub>2</sub> emissions per capita as shown in Fig. 1(b), now far below 1860 levels when the UK was the 'workshop of the world'. In part, the CO<sub>2</sub> reductions are also due to 'off-shoring' dirty production given uncompetitive domestic production: conversely, the higher territorial levels till 1920 would be far lower if CO<sub>2</sub> embodied in UK exports was subtracted. Eliminating coal from electricity production was the easiest reduction: both oil and natural gas usage must be removed next. As all GHG reductions depend on an adequate supply of non-GHG electricity at a viable cost we first turn to that topic.

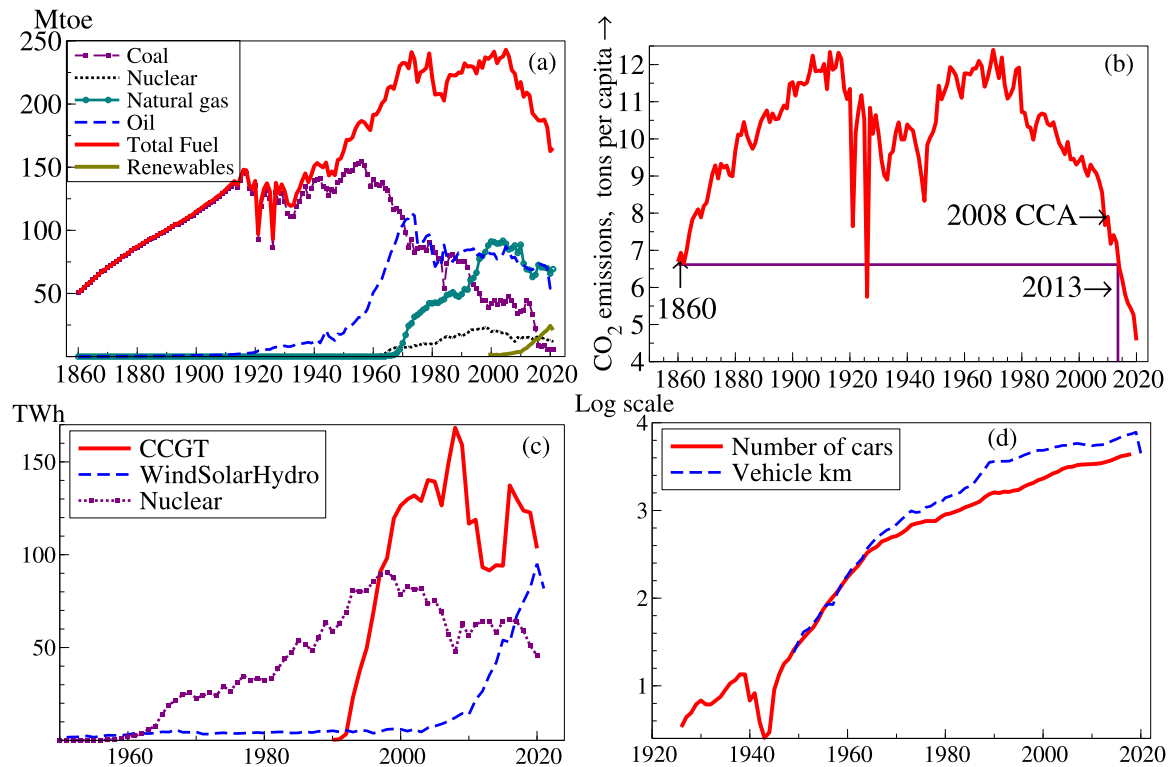


Fig. 1. (a) UK total fuel use, coal, oil, natural gas, nuclear, wind+solar+hydro, all in millions of tonnes of oil equivalent (Mtoe), to 2019; (b) UK territorial per capita CO<sub>2</sub> emissions (tons per annum) till 2020; (c) Main non-coal sources of UK domestically generated electricity (CCGT denotes Combined Cycle Gas Turbine); (d) 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-traveled data start.

#### 4. SIP 1: Zero greenhouse gas electricity generation

Total UK electricity production in 2018 was 350 TWh where 120 TWh came from renewables (a tiny share of total energy as Fig. 1(a) shows), with 64 TWh by wind from 24 GigaWatts (GWs) installed, up nearly 10-fold over the previous decade, plus 16% from nuclear: see Fig. 1(c). The UK government 2020 announcement to install another 40 GW of wind-power electricity by 2030 (generating about 110 TWh p.a., approximately double the current renewables output), 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 70 Mtoe petroleum, as well as replacing natural gas use in housing. As oil produces 30% more CO<sub>2</sub> per kWh than natural gas, first expand electricity generation to power electric vehicles (EVs, which are more energy efficient), before replacing natural gas in electricity generation (despite the 2022 blip in gas prices) and especially in domestic use. Such a sequence initially avoids over-reliance on variable renewables by natural gas electricity generation backup (National Grid estimates 56 TWh storage, mainly liquid hydrogen, will eventually be needed).

The rapidly falling costs of renewable-energy sources like solar photovoltaics and wind turbines combined with improved storage methods, could eliminate oil and gas in electricity production by 2050. Table 1 records present and estimated future costs of alternative electricity generating technologies costs in the UK. Large-scale solar photovoltaics are forecast to be the lowest cost per MWh (for the UK!) if CCS is enforced. [37] map the global geographical distribution of solar photovoltaics.

Offshore wind turbine costs have fallen greatly over the last five years with increased efficiency, to become cheaper than combined-cycle natural gas turbines.<sup>2</sup> For the UK, they offer a low cost alternative,

<sup>2</sup> The 2023 *Electricity Costs Generation Report* by BEIS state the total levelised cost of electricity generation projects commencing in 2025 are £114 per MWh for CCGT H class compared to £44 per MWh for Offshore wind.

with the benefits of being easier to install than onshore given their 100 m-long blades, and creating incidental marine reserves and fish sanctuaries. Allocations of seabed plots from a January 2022 auction for major offshore wind turbine projects around the Scottish coast (ScotWind) awarded a combined potential generating capacity of 25 GW, roughly doubling the present level, achieving a substantial proportion of the Government's 2018 aim (although the 2023 off-shore wind farm auction attracted no bidders facing an unprofitable price). The Hywind Scotland trial of floating wind turbines has demonstrated their viability and the auction included two new floating projects. [38] show that deep-sea wind farms increase mixing of warm and cold layers, improving supplies of nutrients and oxygen. However, there is evidence that wind speeds are falling due to the reduced temperature differentials between the tropics and the poles ([39] for Europe and [40] for China), which could alter the balance of generation costs. Related developments include experiments to generate renewable energy using waves, ongoing near Orkney, and tides off Shetland. Tidal movements are totally predictable, so energy generated using the twice daily ebb and flow will be also, such as by underwater turbines, one of three approaches [41]. Geothermal energy could also contribute beyond ground-source heat pumps.

Zero greenhouse gas electricity generation is therefore a SIP based on a number of characteristics. First, the dynamic effects on cost reduction are rapid as expansion of green electricity equipment drives down the cost. Second, path dependence due to infrastructure investment ensures green electricity generation is 'locked in' and would be expensive to reverse. Third, provided there is policy support in terms of planning and connection to the grid, the speed and size of impact from cheaper power outweighs the costs of transition to 100% green electricity generation. There are barriers from fossil fuel producers and regulatory support should be designed to incentivize the move to green electricity generation. Finally, the present is a window of opportunity, with economic, technological and societal support for the shift to green electricity generation. Thus, zero greenhouse gas electricity generation



satisfies the required characteristics of a SIP, and importantly, leads the other SIPs in stimulating the required changes.

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 cold, cloudy and still weather. In addition to other storage systems in use (hydro pump & store, liquefied gases, flywheels, thermal batteries, supercapacitors, etc.), an ‘ocean battery’ on the sea bed could hold water under pressure analogous to a hydro pump system and avoid shutting off-shore wind turbines when there is excess output. Plugging electric vehicles into an intelligent network (vehicle-to-grid, V2G) would facilitate short-run electricity flow balancing, an issue addressed in the next section. The UK also imported more than 20 TWh of electricity via *interconnectors* in 2019, and such interconnections are being expanded to reduce volatile supply.

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 a role in the UK’s energy supply despite recent construction problems. As governments can borrow for 30 years at relatively 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. *Cogeneration* from nuclear power, such as district heating and high heat for industry, would enhance its role as a baseline energy source in a world of intermittent renewable provision. Globally, nuclear accidents have cast a pall over the technology, although it is much less damaging to health than coal or oil, and has one of the lowest death rates of any fuel when measuring *deaths from accidents and air pollution* per terawatt-hour. An important consideration for many countries is that off-shore wind turbines are little affected by tsunamis or earthquakes that could be dangerous for coastal nuclear power plants, but by maintaining a power supply for cooling, could help avoid nuclear accidents like that at Fukushima Daiichi [42].

#### *Technical issues to research and policy actions to accelerate this SIP*

To achieve SIP 1 sustainably requires establishing short and long term storage systems for renewable electricity generation as flows are variable. Currently, wind turbine blades are difficult to recycle at the end of their lives, an issue that needs attention as their numbers expand.

Since all future technologies are uncertain, research is merited into developing safe small modular nuclear reactors (SMRs) based on the well-developed *nuclear-powered engines in submarines*. Standardization and learning-by-doing when constructing larger numbers of SMRs could make them cost effective. *Sheffield ForgeMasters* have reduced the vessel weld time from about a year to a day using electron-beam welding, greatly cutting costs. 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, helping reduce the serious and potentially costly problem of disposing of current *transuranic-waste*, the cost savings from which should be credited as an offset to SMR costs.

Recent developments in producing green electricity from nuclear fusion include important advances increasing output efficiency of *superconducting magnets*, reducing internal damage to tokamak materials from *helium*, which could be collected to offset a potential shortage, and increased *sustained fusion energy output*. Several fusion reactor experiments are underway, including the Joint European Torus (JET) and International Thermonuclear Experimental Reactor (ITER), as well as laser-based. The UK Government is committing funding to develop methods of connecting potential fusion reactors like ITER to produce energy efficiently. However, it may be possible to produce *electricity directly* from the fusion reaction expanding the plasma into a magnetic field. Although [43] suggest a shorter time frame than our horizon of 30 years, and [44] emphasize the potential advantages of

cooperative international development, nuclear fusion is uncertain, but would help sustain renewable net zero GHG if successful.

SIP 1 requires substantial investment in generation, rapidly and at large scale, but its profitability is encouraging many UK generators to do so and there is considerable public demand for green energy. To sustain an all-electric society necessitates large expansions and inter-connections of most electricity grids, their upgrades to intelligent systems as well as being prepared for stronger storms and higher peak summer heat and colder winters. By appropriate pricing, this could be self-funding from charges for its use. All other SIPs depend on sufficient inexpensive renewable electricity.

### 5. SIP 2: Zero greenhouse gas emissions from transportation

The second SIP is to replace internal-combustion vehicles by electric, accelerated by legislation (the sale of gasoline and diesel cars will end by law in many countries, now 2035 in the UK) but also by their increasing life-time cost advantage. Although high fuel taxes have stimulated ever more efficient internal combustion engines (UK cars improved from roughly 20 miles per imperial gallon (mpg) in 1923 to 50 mpg in 2020), following current strategies will not quickly reduce oil use in transport. UK retail real gasoline prices per litre have doubled since 1950 (fuel duty plus VAT is now approximately 200%), yet distances driven have *increased* more than 10-fold. Fig. 1(d) showed that total distances traveled per annum have also risen relative to car ownership.

Over 30 years, most of the 39.5 million vehicles need replacing—the *average age of a licensed car* in Great Britain is under 9 years—so carbon tax and subsidy changes can ensure an EV future at low additional cost as individuals choose to switch. Electric engines are more efficient than gasoline so have lower running costs, but improvements in batteries are needed to increase their relatively short journey capacity, worsened by taking a non-negligible time to recharge and finding recharging sites that can be connected independently of the *provider*. A major additional benefit once electric vehicles become ubiquitous comes from connecting parked EVs to an intelligent grid for short-run electricity storage (V2G). This would provide a vast short-term electric storage system for no additional investment, with cars acting as a substantial part of a national grid’s short-term storage [45]. An intelligent standardized grid would measure flows of electricity to and from vehicles identified by a code like a credit card, paid peak prices if discharged yet off-peak for re-charging which should in turn encourage adoption of EVs and V2G. UK individuals supplying surplus electricity to the grid have been credited since early adopters of solar panels.

We define this intervention as a SIP because EVs will directly reduce oil use, and in large numbers also have the potential to provide substantial short-run electricity storage, as V2G would facilitate second by second balancing of electricity flows facing variable renewable supplies, maintaining short-term continuity of supply. Path dependence arises because V2G facilitates storage which can be implemented more quickly and efficiently than building national storage systems. The technology is established, creating a reinforcing feedback dynamic to encourage EVs. Internal combustion engine cars could be replaced at a rate matching their obsolescence, about 1.5 million new EVs p.a., providing additional storage as renewables grow. Electric engine manufacture is well established, so employment can be maintained in vehicle production and many of its ancillary industries. Side benefits would include a reduction in mining for palladium by eliminating expensive catalytic converters (a target for theft, exacerbating air pollution and GHGs, especially nitrous oxide). A large increase in non-CO<sub>2</sub> electricity generation would be needed to sustain an electricity-only powered transportation system, albeit symbiotically with V2G. Greater provision of electric-powered public transport systems would also help. Car ownership rates might drop by using sharing systems.

### Technical issues to research and policy actions to accelerate this SIP

Although [46] doubts there are sufficient global resources of lithium, cobalt, and nickel for the numbers of lithium-ion batteries required for this SIP, EV demand should stimulate research to reduce reliance on rare minerals, as with [Lithium-Sulfur](#) batteries, improvements such as blade battery construction (e.g., by Chinese manufacturer BYD, not requiring cobalt or nickel [47]), and advances in solid-state batteries. Graphene-based carbon nanotubes (CNTs [48]) made by 'rolling up' sheets of graphene could act as electrode supercapacitors for an electricity storage system [49]. CNTs are capable of rapid charging and discharging to sustain viable driving distances, and 2-dimensional tri-layers of graphene as an insulator, superconductor and magnet are being developed [50,51] as are [Graphene-based batteries](#). Expanded production capacity of high-quality graphene lowering costs has started with the [European Commission's Graphene Flagship project](#), and could be sustained by variants of Wright's law [52] or Moore's law (see [53,54] for analyses of volume-related cost reductions). 'Graphene in a flash' from plastic or food waste [55] and carbon black from methane pyrolysis, would reduce production costs.

Light, fast-charging power sources might also solve the lack of electrification of parts of rail networks (like the UK's), replacing diesel-electric trains by electric ones, together with progress in [hydrogen fuel-cell](#) driven trains in Germany and the UK. There is also research on hydrogen-based fuel cells for powering heavier vehicles like trucks, and buses (e.g., [Transport for London](#)). As CNTs are so light, they might stimulate [further developments](#) in economical [electric-powered aircraft](#). 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 combination of slow speeds, operational and technical efficiency measures, and the timely retrofitting of ships to use zero-carbon fuels' like green ammonia' to quote [56]. Longer-term storage raises technical and practical issues addressed in the next section.

A key policy to sustain choosing EVs to reduce diesel and petrol vehicles while also providing temporary storage of electricity via V2G is ensuring sufficient capacity on an intelligent standardized infrastructure for charging-discharging points with two-way payments: [3] show the large efficiency gains of the National Grid created by the UK's 1926 Electricity (Supply) Act. In 2023 [Nimblefins](#) reported that the average cost of a new EV in the UK was £50,000, with a range from £22,225 to £157,160, compared to the average price of a combustion engine car of between £19,000 to £32,000. A well designed government funded car scrappage scheme could facilitate switching to EVs given the initially dearer outlay, albeit lower running costs.

### 6. SIP 3: Low-cost hydrogen from 'surplus' renewable energy, liquefied for medium-term storage and industry

Natural gas (mainly methane, CH<sub>4</sub>) usage has increased 3.5 fold in the UK since the mid-1980s, and contributes about 40% of electricity output ([Fig. 1\(c\)](#)), but despite producing less than half the CO<sub>2</sub> of coal per MWh, emits 140 Mt CO<sub>2</sub> p.a.. Sufficient expansion by 2050 of non-CO<sub>2</sub> electricity generation steadily replacing natural gas, seems feasible while both decarbonizing transportation, and sustaining the production of hydrogen by either electrolysis or methane pyrolysis [57]. Nevertheless, over the next 30 years with ever improved technologies and continued cost reductions in non-CO<sub>2</sub> electricity generation, a near zero target for the UK's use of natural gas in that role seems possible without reducing GDP growth.

Next to BECCS, the role of hydrogen in a green economy is most debated, both its method of production and its use to replace natural gas in household heating. Currently the UK consumes around 80 billion cubic meters of natural gas, roughly 30b m<sup>3</sup> for households, and 25b m<sup>3</sup> each for generating electricity and for other uses, including industrial (10b m<sup>3</sup>) and various services (15b m<sup>3</sup>); about half is imported. One

debate concerns whether the UK could switch back from a national natural gas household distribution system to one based on 'green' hydrogen. The UK switched in 1969 to natural gas from coal gas ('town gas', about 50% hydrogen with methane, ethylene and volatile hydrocarbons), which 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 at the time was £100 m. At today's prices, accounting for a doubling of the number of households to 30 million, the cost would be approximately £3bn in current prices, or £850 per house. If the switch from natural gas to hydrogen were to occur, an investment to replace natural gas pipelines and burners with hydrogen based alternatives would require huge investment in gas infrastructures, increasing the [high cost of conversion](#) (generating hydrogen to replace *domestic* natural gas is discussed in the [Appendix](#) as it does not seem economical).

Investment in decarbonizing industries' outputs is essential and is required now, because even if all their energy came from renewables, they would still comprise about 20% of GHG emissions globally [58]. Heavy industry is particularly carbon intensive when making products like iron and steel, using facilities with long lifetimes and high capital investment. Greater energy efficiency and re-using excess heat, such as district heating with combined heat and power, would reduce both costs and GHG emissions. 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.

Using intermittent 'surplus' renewables electricity for low-cost hydrogen production is a SIP because it is a relatively small change to the system but has a large potential impact. The small change (a 'kick' in SIP terminology) is using surplus renewable electricity which occurs when supply is high (windy days) and/or demand is low (middle of the night). Hydrogen production is energy intensive but is low cost when there is excess supply of electricity and offers a low GHG solution for heavy industry. Capital stock replacement in industry requires huge investment which is influenced by policy uncertainty and takes time. Given the dynamics of investment, there is path dependence of the switch to liquid hydrogen which will commit industry to green energy. Policies intended to provide a 'kick' to switch to liquid hydrogen for industry would help ensure this SIP is implemented.

### Technical issues to research and policy actions to accelerate this SIP

Efficient liquid hydrogen production, reformable plastics and capturing and storing carbon emissions (CCS) are all topics of research. Chemicals and plastics remain key areas for recycling and reducing their use of fossil fuels. CO<sub>2</sub> capture with efficient separation and collection of useful gasses, such as converting CO<sub>2</sub> to a fuel, and catalysts to facilitate these are also key areas for research. Improved CCS along with CO<sub>2</sub> absorbers may be needed to achieve net zero.

Policy requires significant investment in supporting carbon intensive industries to develop CCS and move to using electric arc and liquid hydrogen as high heat sources.

### 7. SIP 4: Changing domestic energy to heat pumps and solar photovoltaics

Housing accounts for 30% of UK's CO<sub>2</sub> emissions (150 Mt of CO<sub>2</sub> p.a.), much of it from natural gas. Our fourth SIP aims to phase out domestic use of natural gas after sufficient green electricity is being generated: the ordering of the SIPs is crucial here, as it would be wasteful to use electricity generated by natural gas. By ensuring sufficient green electricity generation, its price should fall and stimulate a switch from domestic natural gas to alternatives. In this section we discuss housing and construction as part of SIP 4 which requires behavioral change to adopt new technologies. This is a SIP lowering GHG emissions, as expansion of heat pump and solar PV demand will reduce their prices, in turn stimulating uptake and driving a positive

feedback dynamic characteristic of a SIP. Subsidies are currently being offered to kick-start this process and trigger a virtuous circle.

Solar PV panels on roofs generate electricity that can be used for heating water, lighting, running heat pumps or electric boilers and charging EVs. France has 8.6 million heat pumps, many fitted to apartments, versus 250,000 in UK. 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, possibly replacing such bad GHGs with alternatives like [barocaloric materials](#). Heat pumps offer both potential cooling and heating, providing up to four units of heat for each unit of electricity consumed, a high coefficient of performance, so should be cheaper to run than gas boilers. However, depending on the type of heat pump (air or ground source), their efficiency varies seasonally with the air or soil temperature and over the long term. [59] 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). [60] show that far better insulation of older homes is required if air heat pumps are to function well—massive retrofitting of the UK housing stock for greatly improved insulation is necessary.

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<sub>2</sub> absorbing cement-based materials are under development (see [61] for a review), although it has long been known that Roman concrete using volcanic ash was both waterproof and grew stronger over time [62], now confirmed as from an [exothermic reaction produced by using quicklime](#). Further, graphene added to cement could strengthen it and lower the volumes needed in construction [55]. Stronger timber, such as glued laminated and cross-laminated [glulam](#) is being increasingly used and reduces the GHG of construction from less concrete and steel. A spectacular example is the arched roof of Malmö railway station constructed in 1924. Glulam wood binds more than 700 kg of CO<sub>2</sub> per m<sup>3</sup>, but widespread use should be staged given the time taken for replacement trees to grow. The UK has just over 3 million hectares of woodland at roughly 1000 trees per hectare, with a government aim of 30,000 ha p.a. additional planting by 2050, as well as restoring 280,000 hectares of peat land, but as the vast majority of UK timber is imported, possibly worsening deforestation, its domestic supply of trees would be inadequate to sustain a large increase in glulam.

Cutting electricity costs would make hydrogen cheaper and so lower the costs of making glass: cheaper triple glazing ensures better insulation. Installing [evacuated-tube solar collectors](#) on roofs for water heating, and especially solar photovoltaics to generate electricity, which [Table 1](#) in the [Appendix](#) shows is 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. [63] 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.

Many of the above steps also apply to existing dwelling to reduce their CO<sub>2</sub> emissions from heating and cooling, and could include cellulose wall coatings, installing double or triple glazing, better loft insulation, and outside cladding, installing solar panels and air heat pumps, and LED lighting, albeit retrofits would need to proceed at very high rates in the UK facing 30 million dwellings. Far better insulation

of older homes is required if air heat pumps are to function well [60]. For smaller dwelling units like apartments where communal systems are infeasible, or where sufficient solar PV is installed, electric boilers could benefit from falls in electricity prices: [64].

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 (SF<sub>6</sub>), 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. Fortunately [Lewis superacids](#) enable SF<sub>6</sub> and related halons to be converted back to sustainable chemicals. Raising fridge and freezer insulation standards to minimize cold loss would reduce compressor sizes, lowering purchase prices as well as electricity consumption, [Chu's law](#) in action.

#### *Technical issues to research and policy actions to accelerate this SIP*

There are many technical issues related to decarbonizing housing including efficient and robust [perovskite solar cells](#) and non-GHG building materials for housing. In appropriate locations, district heating with combined heat and power deserves serious consideration, possibly cogenerated from nuclear plants. Tax increases on fossil fuel use intended to change behavior should be redistributed to families facing fuel poverty as part of a 'just transition'.

The longevity, scale and insulation of Spanish Islamic fortifications built using [rammed earth](#), suggest reconsidering its use, as internal walls could be coated in [lime plaster](#) to minimize CO<sub>2</sub> emissions. Looking further ahead, some new technologies seem promising: halide perovskite-based solar windows that look like tinted glass which could generate electricity [65] and smart glazing material where near-infrared solar radiation is harvested in winter and reflected in summer [66]. Research is needed for alternative non-GHG refrigerants, perhaps funded by prizes to avoid patent restrictions [67,68].

### **8. SIP 5: Harnessing electricity in agriculture**

The fifth SIP concerns harnessing other electricity-based uses in agriculture and waste. We define this as a SIP as excess non-GHG electricity can be put to good use in agriculture and waste as we outline below. Vertical and underground farms have positive feedback channels by reducing transportation which further lowers emissions. The impact on emissions could be substantive given the magnitude of GHG emissions presently resulting from agriculture. [69] calculate that the global GHG emissions of agriculture are around 2 ppm CO<sub>2</sub> equivalent (17 Tg CO<sub>2</sub>eq) of which about 57% comes from [animal production](#). [70] confirm that food systems are responsible for a third of global anthropogenic GHG emissions. There is also an increasing problem from agriculture due to the release of nitrous oxide (N<sub>2</sub>O) from excess use of nitrogen fertilizers [71] such that [N<sub>2</sub>O emissions](#) have doubled in the last 50 years.

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 [72].<sup>3</sup> Best-practice high-yield farming could substantively reduce demands on cropland globally, [73], providing more land for tree planting, which with careful peat and wetland restoration all help absorb CO<sub>2</sub>. [74] show a medium-term reduction of 30% in carbon dioxide fluxes under seed planting

<sup>3</sup> Our [Climate Econometrics blogs](#) discuss reducing food waste and changing human diets by behavioral interventions.



by direct drilling (zero-tillage), and in addition, minimally disturbing the soil can improve the soil microbiome, raising fertility. 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 [75] and given the falls in costs of electricity via LED lighting, and potentially channeled daylight [76]. Food waste and GHG 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 [77]. Saving virgin forest and other previously unused land from farming is becoming imperative to avoid mass extinctions of species from [loss of habitat](#) [19].

Noting that areas around volcanoes are very fertile, ground-up basalt and even basalt dust waste may be an excellent fertilizer additive or alternative, [78,79], grinding using electricity is cheap. Natural absorption of atmospheric CO<sub>2</sub> by basalt post Permian–Triassic was slow but extensive, [80,81], and deliberate action could greatly accelerate similar mechanisms: on-going [experiments in Iceland](#) pumping carbon-rich fluids into ophiolite rock formations show that carbonate minerals can form rapidly. Biochar produced from pyrolysis of biomass also increases crop yields while reducing GHG emissions: see [34], and [82], with [83] proposing doing so efficiently by flash light irradiation on biomass waste. Natural benefits include avoiding deforestation to create new farmland, as well as additional tree planting.

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 [84]. [85] show that seaweed aquaculture is also capable of removing large quantities of excess nitrogen and phosphorus from coastal ecosystems.

#### *Technical issues to research and policy actions to accelerate this SIP*

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%. 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 economizes on their feed intake (reducing their methane production saves energy) [86]. Similar improvements in emission reductions and weight gain have been found for other ruminants fed *Asparagopsis taxiformis* at even lower levels of dietary additions [87]. 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. [88] 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 [89]. Almost as important is reducing the air pollutant ammonia, emitted by manure, slurry and fertilizers, and associated excess nitrates: in addition to methods in [90], an [electrical plasma wave](#) can cut the former by up to 90%. Also [microalgae](#) could help transform farm waste into useful protein animal foods, both developments dependent on ‘surplus’ electricity for cheap usage. Technical issues to research to achieve SIP 5 include how to breed low methane ruminants, biochar production, seaweed farming and high protein meat substitutes.

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, noting sanctuaries are an incidental benefit of offshore wind farms. Policy could also play a role in encouraging [changes to human diets](#) to 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.

## 9. Imported and indirect CO<sub>2</sub>

An unwanted consequence of targeting consumption rather than production emissions 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 also be reduced. Adding ‘consumption induced GHG’ equivalent emissions to the UK’s total would raise its territorially recorded levels because of CO<sub>2</sub> embodied in net imports. However, the UK’s large reductions in GHGs from electricity generation are substantial, and CO<sub>2</sub> ‘embedded’ in imports will fall with reductions in GHG emissions by exporting countries. As analyzed by [91,92], tariffs on all imports from countries not sufficiently reducing their GHG emissions have a role to play in improving both exporters’ and importers’ performance. Border carbon taxes to level imported with domestic emissions will raise the prices of imports for users and probably induce various forms of retaliation by affected countries, so need careful formulation to take account of the [global context](#). Deforestation is now recorded worldwide by [environmental satellites](#) detecting changes in vegetation, so all imports from countries guilty of large-scale deforestation should face a high general tariff on imports. In both cases, 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 which threaten species extinctions [19]. 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.

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. [93,94]. 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. The IEA *Roadmap for the Global Energy Sector* 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 anyway 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, electrolysers, batteries, EVs and storage systems—preceded by producing the manufacturing equipment needed to make these. Skilled workers are also essential to build, service and maintain the resulting equipment—trained at appropriate growth rates.

Renewable electric power is already 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 massive reduction in demand, then that may not happen, so carbon taxes and CCS will become essential. The vast expansion in renewable electric power must be matched by an equivalent expansion of national grid infrastructures to shift wherever power is being generated to where it is needed. A substantial part of both investments should be fundable by charges on the resulting electricity supply so this part of the transition costs to get net zero GHG emissions 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 needing 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 net costs of switching to all-electric cars are just the additional costs (if any) of EVs over internal combustion engines. The extra costs of using V2G to supply storage to sustain an all-renewables electricity generation system are from implementing an intelligent electricity grid that can rapidly charge and discharge the large number of EVs that would replace internal-combustion engine cars. That should be self funding from the profitability of supplying the energy that cars need. This part of the transition costs to get to net zero also seem small. A potential danger is a large increase in the price of essential materials to make batteries for EVs.

Turning to the housing sector, few central heating boilers or cooling systems last as long as 25 years, so again most would need replaced by 2050. Instead of just refitting fossil-fuel powered systems, heat pumps, electric boilers or radiators could be installed depending on the dwelling, possibly 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 net-zero 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 pyrolysis, 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 impossible. Improving agricultural practices could be cost reducing: tackling climate change should not be ‘too expensive’, especially facing the potentially huge costs of climate turbulence.

Cap-and-trade for sulfur dioxide, SO<sub>2</sub>, was successful in rapidly reducing ‘acid rain’, and could help facilitate GHG reductions, and the EU Emissions Trading System (EU ETS) has forced change there. Carbon taxes could also help [95] though evidence of public opposition in a number of countries suggests possible limitations even when the revenue raised is rebated. [96] 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 (e.g., [97,98]) but their levels have been relatively low. 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 like coffee cups** could be equally effective. This suggests that 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<sub>2</sub> 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 facilitate the energy transition process to net zero emissions—which is necessary, but not sufficient. At a global level, the total accumulation of atmospheric GHGs determines temperature increases and climate change, so the trajectory of getting to net-zero matters greatly—the faster emissions are reduced the less damaging the outcome will be. This is in line with [Beinhocker and Farmer](#) who argue accelerating cost reductions in clean energy will rapidly make it the energy source of choice.

## 11. Summary and conclusions

The 18th Century Industrial Revolution created the first major energy transition, powered by steam from coal-fired boilers. The second half of the 19th Century witnessed a second transition to oil, but almost to renewable sources of energy, with an understanding of the pernicious effects of greenhouse gases, and beginning to protect nature. The first fuel cell was invented in 1838 by Sir William Grove [99] and independently by Christian Friedrich Schönbein. Following the creation of the photovoltaic cell by Edmond Becquerel [100], the first commercial photovoltaic solar rooftop panel was developed by Charles Fritts [101]. The first electricity generated in the UK in 1868 was hydro-driven, designed by Sir William Armstrong [102]. Eunice Foote [103] showed that a flask of CO<sub>2</sub> heated greatly in the sun, whereas dry air did not, independently confirmed in experimental evidence by John Tyndall [104]. In 1864, Yosemite was placed under federal protection by Abraham Lincoln. James Blyth built the first wind turbine to generate electricity in 1887 [105], and while unsuccessful in the UK, wind-generated electricity was relatively common on US farms by the 1930s. Fridtjof Nansen’s ship, *Fram*, exploring the Arctic from 1893–6 had a windmill on board to supply [electricity for lighting](#). The first electric-powered cars came in the 1880s after Thomas Parker built a vehicle with a high capacity rechargeable battery [106]: the 1897 Bersey Electrical Cab can be seen at the London Science Museum. The 19th century was rounded out by Svante Arrhenius [107] proving that atmospheric temperature change was proportional to the change in log CO<sub>2</sub>, so both the greenhouse gas problem and its potential solution were known.

[108] 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: a renewable electric powered society goes back to a future where humanity might have been 125 years ago, stimulated by our five proposed SIPs.

While dealing with the impacts of the COVID-19 pandemic and Ukraine war seem to add to the difficulties of transition, noting that even extensive lockdowns only reduced global GHG emissions by under 20 megatonnes (Mt) daily relative to annual emissions of more than 20 gigatonnes [109], it may nevertheless be an opportune time to begin rapidly decarbonizing, building on the behavioral changes these events induced, and the increasingly large cost reductions of generating renewable versus dirty energy.

To achieve net zero GHG emissions targets requires an integrated symbiotic strategy eliminating all fossil fuel uses and all other GHG emitters, less net natural absorption and carbon capture and storage, possibly combined with atmospheric CO<sub>2</sub> extraction. A SIP is defined as 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, all dependent on renewable energy, shown schematically in the graphical abstract.

Our first SIP has already happened: renewable electricity generation is cost effective and achievable with known technologies, so it is financially 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. Nuclear power, especially small modular 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 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 and book-ends the peak demand coverage by V2G. In turn, liquid hydrogen would provide additional medium-term storage, as well as supply a high heat source for industry helping to decarbonize manufacturing. A by-product of methane pyrolysis production of hydrogen gas is black carbon for making graphene. Our fourth SIP concerns domestic use to phase out natural gas by installing heat pumps and solar PVs along with improving insulation. 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'.

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 fertilizer 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 fifth 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 if that is to be achieved globally, [5], potentially facilitated by using prizes to stimulate transition research so patents do not restrict global application [67].

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 modeled its performance in economic and climate terms [3,110]. The UK data provide little evidence of high aggregate costs from its territorial reductions in CO<sub>2</sub> emissions, which have dropped from 554 Mt in 2000 to 351 Mt (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). Our model of UK CO<sub>2</sub> emissions since 1860 has a negative long-run coefficient on GDP, probably from an increase in the share of services, with a positive coefficient on the capital stock.

SIPs are a useful framework to ensure any interventions are assessed for unintended consequences. Potential undesirable or irreversible changes must be rigorously assessed in the context of maintaining employment, social justice and real per-capita growth. The five

SIPs we propose seek to alter individual and company behavior given technology so could impact employment and inequality. 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 must be paid to the local costs of lost jobs as new technologies are implemented: mitigating the inequality impacts of policies introduced to avoid climate change matters in such decisions. 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<sub>2</sub> emissions targets to achieve zero net emissions [111], but jobs in those industries are equally at risk of being 'stranded'. While some of the above proposals are early stage and require further research, they suggest possible strategies for moving towards at least a very low-carbon future by 2050. 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 [112]. As many of the steps will increase living standards and improve health, as well as tackle GHG emissions, they are doubly worthwhile to rapidly move towards a sustainable climate. A joined up approach to decarbonizing is needed as virtuous circles can be missed with isolated thinking not seeing the interacting policies needed for reductions in GHGs as a whole: solving some problems can facilitate solving others. The SIPs framework offers a behavioral approach to adopting technology that forges a path to climate neutrality by 2050 at least for the UK with positive implications for other OECD countries.

#### CRediT authorship contribution statement

**Jennifer L. Castle:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing, Writing – original draft. **David F. Hendry:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

#### Declaration of competing interest

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

#### Data availability

Only publicly available data were used for the research described in the article, beyond that in the Figure and defined in Table 2.

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**Table 1**

Expected levelised costs for UK power generation technologies in £/MWh.

Technology   year	2015	2025	2040	2050
Solar Large-scale PV (Photovoltaic)	80	<b>44</b>	<b>33</b>	<b>41</b>
Onshore Wind	<b>62</b>	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 for 2015–2040: Table 4.18 central case, *Electricity Generation Costs 2020*, UK Department for Business, Energy and Industrial Strategy (BEIS). BEIS rankings assume increasing carbon taxes and falling CCS costs over time. Source for 2050: Table 7.2 in [113]. Expected levelised cost is the discounted lifetime cost of building and operating in £/MWh. The price of £92.50/MWh from 2023 for nuclear power was guaranteed for Hinkley Point C output.

**Table 2**

Data sources.

$E_t$	CO <sub>2</sub> emissions in millions of tonnes (MtCO <sub>2</sub> Eq)	[i], [ii].
$E_{g,t}$	UK total energy use = C+O+NG+NC+RN	
$O_t$	Net oil usage, millions of tonnes (Mt)	[iii].
$C_t$	Coal volumes in millions of tonnes Mt & MToe	[iv].
$NG_t$	Natural gas volumes in MToe	[v].
$NC_t$	Nuclear energy use in TWh & MToe	[vi].
$Bi_{ot}$	Biomass in MToe	[vii].
$RN_t$	Renewable energy in TWh	[viii].
$El_t$	Electricity use in TWh	[ix].
$V_t$	Number of cars (millions)	[x].
$K_t$	Kilometers driven per annum (in billions)	[xi].
$Pop_t$	UK population corrected for departure of Southern Ireland	[xii].

Sources:

- [i] World Resources Institute and UK GHG emissions;
- [ii] Adjustment to GHG emissions data for carbon implicit in UK imports.
- [iii] Crude oil and petroleum: production, imports and exports 1890 to 2021, Department for Business, Energy and Industrial Strategy (Beis);
- [iv] Energy trends, BEIS and Carbon Brief; Also see [114,115] for historical information.
- [v] Historical gas data: gas production and consumption and fuel input, BEIS.
- [vi] Nuclear from Digest of UK Energy Statistics (DUKES), BEIS.
- [vii] Biomass in MToe, ONS.
- [viii] Solar [Large-scale Photovoltaic], Wind Onshore, Wind Offshore, Hydro, D department for Energy Security and Net Zero:  $RN_t$  is biomass in TWh with wind+solar+hydroelectric in TWh.
- [ix] Electricity, BEIS.
- [x] Vehicle statistics, Department for Transport.
- [xi] Road traffic statistics, Department for Transport.
- [xii] [116] since updated from ONS.

## Appendix

### Hydrogen production

Methane (CH<sub>4</sub>) has the highest ratio of hydrogen to carbon of hydrocarbons, but to use methane-based electricity to make hydrogen is self-defeating, so only non-GHG electricity should be used. To replace the kWh energy equivalent of 80b m<sup>3</sup> of methane p.a. would need about 240b m<sup>3</sup> of hydrogen. It takes 18 kg of water to produce 1 kg of H<sub>2</sub> by electrolysis (roughly 11.1 m<sup>3</sup>), using 40 kWh of electricity. To produce 240b m<sup>3</sup> of hydrogen p.a. would require about 380b kg of water (around 65 times the UK's 5.5b kg p.a. use of fresh water, though sea water might be usable), using 850 TWh of electricity, about seven times current UK renewable supply. Efficiency improvements could be achieved by catalyst-based electrolysis [117] using only 'spare' renewables electricity, perhaps at a negative price to avoid switching off renewables facing surplus generation. Hydrogen and oxygen can be stored as liquids but requires more electricity, so electrolysis alone to replace methane by H<sub>2</sub> seems infeasible. Producing hydrogen from methane by steam-methane reforming, can generate more than 5 kg of CO<sub>2</sub> for every kg of hydrogen: with CO<sub>2</sub> captured and used as a fuel, [113] estimate production costs of £39 MWh. But methane pyrolysis converts CH<sub>4</sub> to C (black carbon) and 2H<sub>2</sub> without GHG [118]

using roughly 1 kWh of electricity to convert 1.5 m<sup>3</sup> of CH<sub>4</sub>. 10 m<sup>3</sup> of methane produces about 2.5 kWh, whereas the resulting 20 m<sup>3</sup> of hydrogen yields about 1.2 kWh net after deducting the 0.3 kWh used in production. With 'spare' renewable electricity of 56 TWh, converting the 80b m<sup>3</sup> of methane currently used in the UK would make 160b m<sup>3</sup> of hydrogen with suitable thermocatalysis (the catalyst influences the quality of carbon deposited which can poison the catalyst: see [119] for some solutions). Replacement of natural gas by hydrogen for domestic use over 30 years would require continuously increasing output by around 5 billion m<sup>3</sup> of hydrogen annually, plus any needed for electricity generation back-up which seems feasible. GHG leaks in the supply chain must be tackled [120], and progress in measuring methane emissions, [121], has revealed that much methane release comes from oil drilling and shale oil production of natural gas.

Present estimates of global methane hydrates are over 6 trillion tonnes, 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<sub>2</sub> absorption by methanogenetic *Archaea* [122]. This would reduce CH<sub>4</sub> emissions from lakes, and also provide 'biomethane' for electricity generation, already operational on Lake Kivu. New gas piping, required for supplying H<sub>2</sub>, will probably be plastic based, needing CCS during its manufacture. Microwave deconstruction of commercial plastic using cheap catalysts can produce hydrogen and multi-walled carbon nanotubes, [123], potentially turning the burgeoning problem of plastic waste into part of the solution to climate change using renewable electricity.

## References

- [1] A. Stechemesser, N. Koch, E. Mark, E. Dilger, P. Klösel, L. Menicacci, D. Nachtigall, F. Pretis, N. Ritter, M. Schwarz, H. Vossen, A. Wenzel, Identifying Climate Policies that Achieved Major Emission Reductions: Global Evidence from Two Decades, Mimeo, Potsdam Institute for Climate Impact Research (PIK), Germany, 2023.
- [2] J.D. Farmer, C. Hepburn, M.C. Ives, T. Hale, T. Wetzler, P. Mealy, R. Rafaty, S. Srivastav, R. Way, Sensitive intervention points in the post-carbon transition, *Science* 364 (6436) (2019) 132–134, <https://www.science.org/doi/10.1126/science.aaw7287>.
- [3] J.L. Castle, D.F. Hendry, Climate econometrics: An overview, *Found. Trends Econom.* 10 (2020) 145–322, <http://dx.doi.org/10.1561/08000000037>.
- [4] F. Robert-Nicoud, G. Peri, On the Economic Geography of Climate Change, Vol. October 11, 2021, VoxEU, 2021, <https://cepr.org/voxeu/columns/economic-geography--climate--change>.
- [5] M.A. Pigato, S.J. Black, D. Dussaux, Z. Mao, M. McKenna, R. Rafaty, S. Touboul, Technology Transfer and Innovation for Low-Carbon Development, World Bank, Washington, D.C., 2020.
- [6] B. Heerma van Voss, R. Rafaty, Sensitive intervention points in China's coal phaseout, *Energy Policy* 163 (2022) <http://dx.doi.org/10.1016/j.enpol.2022.112797>.
- [7] P. Cosgrove, T. Roulstone, S. Zachary, Intermittency and periodicity in net-zero renewable energy systems with storage, *Renew. Energy* 212 (2023) 299–307, <http://dx.doi.org/10.1016/j.renene.2023.04.135>.
- [8] A. Hobley, Will gas be gone in the United Kingdom (UK) by 2050? An impact assessment of urban heat decarbonisation and low emission vehicle uptake on future UK energy system scenarios, *Renew. Energy* 142 (2019) 695–705, <http://dx.doi.org/10.1016/j.renene.2019.04.052>.
- [9] J. Lipp, Policy considerations for a sprouting UK green electricity market, *Renew. Energy* 24 (2001) 31–44, [http://dx.doi.org/10.1016/S0960-1481\(00\)00187-7](http://dx.doi.org/10.1016/S0960-1481(00)00187-7).
- [10] M. Aunedi, M. Yiruka, S. Dehghan, A.M. Pantaleo, N. Shah, G. Strbac, Multi-model assessment of heat decarbonisation options in the UK using electricity and hydrogen, *Renew. Energy* 194 (2022) 1261–1276, <http://dx.doi.org/10.1016/j.renene.2022.05.145>.
- [11] M.C. Hänsel, M.A. Drupp, D.J.A. Johansson, F. Nesje, C. Azar, M.C. Freeman, B. Groom, T. Sterner, Climate economics support for the UN climate targets, *Nature Clim. Change* 10 (2020) 781–789, <http://dx.doi.org/10.1038/s41558-020-0833-x>.
- [12] Y. Zhuang, R. Fu, B.D. Santer, R.E. Dickinson, A. Hall, Quantifying contributions of natural variability and anthropogenic forcings on increased fire weather risk over the western United States, *Proc. Natl. Acad. Sci.* 118 (45) (2021) <https://www.pnas.org/content/118/45/e2111875118>.



- [13] S. Vitousek, P. Barnard, C. Fletcher, N. Frazer, L. Erikson, C.D. Storlazzi, Doubling of coastal flooding frequency within decades due to sea-level rise, *Sci. Rep.* 7 (2017) <http://dx.doi.org/10.1038/s41598-017-01362-7>.
- [14] D.A. Lavers, M.J. Rodwell, D.S. Richardson, et al., The gauging and modeling of rivers in the sky, *Geophys. Res. Lett.* 45 (2018) 7828–7834, <http://dx.doi.org/10.1029/2018GL079019>.
- [15] K. Trenberth, A. Dai, G. van der Schrier, P.D. Jones, J. Barichivich, K.R. Briffa, J. Sheffield, Global warming and changes in drought, *Nature Clim. Change* 4 (2014) 17–22, <http://dx.doi.org/10.1038/nclimate2067>.
- [16] N. Wunderling, J.F. Donges, J. Kurths, R. Winkelmann, Interacting tipping elements increase risk of climate domino effects under global warming, *Earth Syst. Dyn.* 12 (2021) 601–619, <https://esd.copernicus.org/articles/12/601/2021/>.
- [17] A. Vaks, A.J. Mason, S.F.M. Breitenbach, et al., Palaeoclimate evidence of vulnerable permafrost during times of low sea ice, *Nature* 577 (2019) 221–225, <http://dx.doi.org/10.1038/s41586-019-1880-1>.
- [18] A. Cahill, M. Aiello-Lammens, M.C. Fisher-Reid, et al., How does climate change cause extinction? *Proc. R. Soc. Ser. B* (2013).
- [19] P. Dasgupta, P. Raven, A. McIvor (Eds.), *Biological Extinction: New Perspectives*, Cambridge University Press, Cambridge, 2019, <http://dx.doi.org/10.1017/9781108668675>.
- [20] D.J.C. MacKay, *Sustainable Energy—Without the Hot Air*, Internet Publication, UIT Cambridge Ltd., PO Box 145, Cambridge, UK, 2009, <http://www.withouthotair.com/download.html>.
- [21] IPCC (Ed.), *AR6 Climate Change 2021: The Physical Science Basis*, Cambridge University Press, 2021, <https://www.ipcc.ch/report/ar6/wg1/>.
- [22] E. Larson, C. Greig, J. Jenkins, et al., *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, Interim Report, Princeton University, Princeton, NJ, 2020, *Mission net-zero America: The nation-building path to a prosperous, net-zero emissions economy*.
- [23] S. Fries, *Transforming Energy Systems: Economics, Policies and Change*, Edward Elgar, 2021.
- [24] IEA, *Net Zero By 2050*, IEA, Paris, 2021, <http://dx.doi.org/10.15131/shef.data.5266495.v1>.
- [25] J. Dixon, K. Bell, S. Brush, Which way to net zero? A comparative analysis of seven UK 2050 decarbonisation pathways, *Renew. Sustain. Energy Transit.* 2 (2022) <https://www.sciencedirect.com/science/article/pii/S2667095X21000167>.
- [26] M. Grubb, D. Newbery, UK electricity market reform and the energy transition: Emerging lessons, *Energy J.* 39 (6) (2018) 1–26, <https://www.jstor.org/stable/26606242>.
- [27] D. Brack, R. Birdsey, W. Walker, *Greenhouse Gas Emissions from Burning US-Sourced Woody Biomass in the EU and UK*, Research Paper 14, Chatham House, London, UK, 2021.
- [28] M. Fajardy, N. Mac Dowell, Can BECCS deliver sustainable and resource efficient negative emissions? *Energy Environ. Sci.* 10 (2017) 1389–1426, <http://dx.doi.org/10.1039/C7EE00465F>.
- [29] F. Lafond, A.G. Bailey, J.D. Bakker, et al., How well do experience curves predict technological progress? A method for making distributional forecasts, *Technol. Forecast. Soc. Change* 128 (2018) 104–117, <http://dx.doi.org/10.1016/j.techfore.2017.11.001>.
- [30] D.Y.C. Leung, G. Caramanna, M.M. Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies, *Renew. Sustain. Energy Rev.* 39 (2014) 426–443, <http://dx.doi.org/10.1016/j.rser.2014.07.093>.
- [31] J. Kothandaraman, J. Saavedra Lopez, Y. Jiang, et al., Integrated capture and conversion of CO<sub>2</sub> to methane using a water-lean, post-combustion CO<sub>2</sub> capture solvent, *ChemSusChem* 14 (2021) 4812–4819, <http://dx.doi.org/10.1002/cssc.202101590>.
- [32] D. McLaren, Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques, *Clim. Change* 162 (2020) 2411–2428, <http://dx.doi.org/10.1007/s10584-020-02732-3>.
- [33] R.L. Tyne, P.H. Barry, M. Lawson, et al., Rapid microbial methanogenesis during CO<sub>2</sub> storage in hydrocarbon reservoirs, *Nature* 600 (2021) 670–6745, <http://dx.doi.org/10.1038/s41586-021-04153-3>.
- [34] C. Hepburn, E. Adlen, J. Beddington, et al., The technological and economic prospects for CO<sub>2</sub> utilization and removal, *Nature* 575 (2019) 87–97, <http://dx.doi.org/10.1038/s41586-019-1681-6>.
- [35] D. Kim, C.S. Kley, Y. Li, P. Yang, Copper nanoparticle ensembles for selective electroreduction of CO<sub>2</sub> to C<sub>2</sub>–C<sub>3</sub> products, *Proc. Natl. Acad. Sci.* 114 (2017) 10560–10565, <https://www.pnas.org/content/114/40/10560>.
- [36] T. Skafte, Z. Guan, M. Machala, et al., Selective high-temperature CO<sub>2</sub> electrolysis enabled by oxidized carbon intermediates, *Nature Energy* 4 (2019) 846–855, <http://dx.doi.org/10.1038/s41560-019-0457-4>.
- [37] L. Kruitwagen, K.T. Story, J. Friedrich, L. Byers, S. Skillman, C. Hepburn, A global inventory of photovoltaic solar energy generating units, *Nature* 598 (2021) 604–610, <http://dx.doi.org/10.1038/s41586-021-03957-7>.
- [38] R.M. Dorrell, C.J. Lloyd, B.J. Lincoln, et al., Anthropogenic Mixing of Seasonally Stratified Shelf Seas By Offshore Wind Farm Infrastructure, Working Paper, 2021, *physics.aop-ph*, [arXiv:2112.12571v1](https://arxiv.org/abs/2112.12571v1).
- [39] K. Solaun, E. Cerdá, Impacts of climate change on wind energy power—four wind farms in Spain, *Renew. Energy* 145 (2020) 1306–1316, <http://dx.doi.org/10.1016/j.renene.2019.06.129>.
- [40] H. Guo, M. Xu, Q. Hub, Changes in near-surface wind speed in China: 1969–2005, *Int. J. Climatol.* 31 (2011) 349–358, <http://dx.doi.org/10.1002/joc.2091>.
- [41] D. Coles, et al., A review of the UK and british channel islands practical tidal stream energy resource, *Proc. R. Soc. A* 477 (2021) <http://dx.doi.org/10.1098/rspa.2021.0469>.
- [42] S. Bhattacharya, K. Goda, Use of offshore wind farms to increase seismic resilience of nuclear power plants, *Soil Dyn. Earthq. Eng.* 80 (2016) 65–68, <https://www.sciencedirect.com/science/article/pii/S0267726115002419>.
- [43] M. Greenwald, Status of the SPARC physics basis, *J. Plasma Phys.* 86 (5) (2020) <http://dx.doi.org/10.1017/S0022377820001063>.
- [44] E.G. Carayannis, J. Draper, I.A. Iftimie, Nuclear fusion diffusion: Theory, policy, practice, and politics perspectives, *IEEE Trans. Eng. Manage.* (2020) 1–15, <https://ieeexplore.ieee.org/document/9078039>.
- [45] L. Noel, G. Zarazua de Rubens, J. Kester, B. Sovacool (Eds.), *Vehicle-to-Grid: A Sociotechnical Transition beyond Electric Mobility*, Palgrave MacMillan, Basingstoke, 2019.
- [46] S.P. Michaux, *The Mining of Minerals and the Limits to Growth*, Report 16/2021, Geological Survey of Finland, GTK, 2021, <https://www.gtk.fi/en/front-page/>.
- [47] X.G. Yang, T. Liu, C.Y. Wang, Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles, *Nature Energy* (2021) <http://dx.doi.org/10.1038/s41560-020-00757-7>.
- [48] K. Sammed, L. Pan, M. Asif, et al., Reduced holey graphene oxide film and carbon nanotubes sandwich structure as a binder-free electrode material for supercapacitor, *Sci. Rep.* 10 (2020) <http://dx.doi.org/10.1038/s41598-020-58162-9>.
- [49] M. Notarianni, J. Liu, F. Mirri, et al., Graphene-based supercapacitor with carbon nanotube film as highly efficient current collector, *Nanotechnology* 25 (43) (2014).
- [50] G. Chen, A. Sharpe, E. Fox, et al., Tunable correlated Chern insulator and ferromagnetism in a Moiré superlattice, *Nature* 579 (2020) 56–61, <http://dx.doi.org/10.1038/s41586-020-2049-7>.
- [51] H. Wang, Y. Diao, Y. Lu, et al., Energy storing bricks for stationary PEDOT supercapacitors, *Nature Commun.* 11 (2020) <http://dx.doi.org/10.1038/s41467-020-17708>.
- [52] T.P. Wright, Factors affecting the cost of airplanes, *J. Aeronaut. Sci.* 3 (4) (1936) 122–128, <http://dx.doi.org/10.2514/8.155>.
- [53] M. Ives, L. Righetti, J. Schiele, et al., *A New Perspective on Decarbonising the Global Energy System*, Report No. 21-04, Smith School of Enterprise and the Environment, University of Oxford, 2021.
- [54] J.D. Farmer, F. Lafond, How predictable is technological progress? *Res. Policy* 45 (2016) 647–665, <http://dx.doi.org/10.1016/j.respol.2015.11.001>.
- [55] D. Luong, K. Bets, W. Algozeeb, et al., Gram-scale bottom-up flash graphene synthesis, *Nature* 577 (2020) 647–651, <http://dx.doi.org/10.1038/s41586-020-1938-0>.
- [56] S. Bullock, J. Mason, J. Broderick, A. Larkin, Shipping and the Paris climate agreement: a focus on committed emissions, *BMC Energy* 2 (5) (2020) <http://dx.doi.org/10.1186/s42500-020-00015-2>.
- [57] N. Sánchez-Bastardo, R. Schlögl, H. Ruland, Methane pyrolysis for CO<sub>2</sub>-free H<sub>2</sub> production: A green process to overcome renewable energies unsteadiness, *Chem. Ing. Tech.* 92 (2020) 1596–1609, <http://dx.doi.org/10.1002/cite.202000029>.
- [58] R. Esparza, *Decarbonizing Industry is Difficult but Possible*, EDF, Washington, DC, 2020, <http://blogs.edf.org/markets/2020/07/10/why-decarbonizing-heavy-industry-is-difficult-but-also-possible/>.
- [59] M. Habibi, A. Hakkaki-Fard, Long-term energy and exergy analysis of heat pumps with different types of ground and air heat exchangers, *Int. J. Refrig.* 100 (2019) 414–433, <http://dx.doi.org/10.1016/j.ijrefrig.2019.02.021>.
- [60] P. Carroll, M. Chesser, P. Lyons, Air source heat pumps field studies: A systematic literature review, *Renew. Sustain. Energy Rev.* 134 (2020) <http://dx.doi.org/10.1016/j.rser.2020.110275>.
- [61] J. Jang, G. Kim, H. Kim, H. Lee, Review on recent advances in CO<sub>2</sub> utilization and sequestration technologies in cement-based materials, *Constr. Build. Mater.* 127 (2016) 762–773, <http://dx.doi.org/10.1016/j.conbuildmat.2016.10.017>.
- [62] M. Jackson, S. Mulcahy, H. Chen, Y. Li, Q. Li, P. Cappelletti, H.-R. Wenk, Phillipsite and Al-tobermorite mineral cements produced through low-temperature water-rock reactions in roman marine concrete, *Am. Mineral.* 102 (2017) 1435–1450, <http://dx.doi.org/10.2138/am-2017-5993CCBY>.
- [63] S. Joshi, S. Mittal, P. Holloway, et al., High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation, *Nature Commun.* 12 (2021) 15738, <http://dx.doi.org/10.1038/s41467-021-25720-2>.
- [64] M.G. Nielsen, J.M. Morales, M. Zugno, T.E. Pedersen, H. Madsen, Economic valuation of heat pumps and electric boilers in the Danish energy system, *Appl. Energy* 167 (2016) 189–200, <http://dx.doi.org/10.1016/j.apenergy.2015.08.115>.
- [65] L. Canil, T. Cramer, B. Fraboni, et al., Tuning halide perovskite energy levels, *Energy Environ. Sci.* (2020) <https://pubs.rsc.org/en/content/articlelanding/2021/ee/d0ee02216k>.

- [66] N. Youngblood, C. Talagrand, B.F. Porter, C.G. Galante, S. Kneepkens, G. Triggs, S. Ghazi Sarwat, D. Yarmolich, R.S. Bonilla, P. Hosseini, R.A. Taylor, H. Bhaskaran, Reconfigurable low-emissivity optical coating using ultrathin phase change materials, *ACS Photon.* (2021) <http://dx.doi.org/10.1021/acsp Photonics.1c01128>.
- [67] D.F. Hendry, Climate change: Lessons for our future from the distant past, in: S. Dietz, J. Michie, C. Oughton (Eds.), *The Political Economy of the Environment*, Routledge, London, 2011, pp. 19–43.
- [68] B.H. Hall, Does patent protection help or hinder technology transfer? in: S. Ahn, B.H. Hall, K. Lee (Eds.), *Intellectual Property for Economic Development: Issues and Policy Implications*, Edward Elgar Publishing, Aldershot, 2014, (Chapter 2).
- [69] X. Xu, P. Sharma, S. Shu, et al., Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods, *Nature Food* 2 (2021) 724–732, <http://dx.doi.org/10.1038/s43016-021-00358-x>.
- [70] M. Crippa, E. Solazzo, D. Guizzardi, et al., Food systems are responsible for a third of global anthropogenic GHG emissions, *Nature Food* 2 (2021) 198–209, <http://dx.doi.org/10.1038/s43016-021-00225-9>.
- [71] H. Tian, R. Xu, J. Canadell, et al., A comprehensive quantification of global nitrous oxide sources and sinks, *Nature* 586 (2020) 248–256, <http://dx.doi.org/10.1038/s41586-020-2780-0>.
- [72] A. Rae, A Land Cover Atlas of the United Kingdom, Atlas, University of Sheffield, 2017, <http://dx.doi.org/10.15131/shef.data.5266495.v1>.
- [73] C. Folberth, N. Khabarov, J. Balković, et al., The global cropland-sparing potential of high-yield farming, *Nat. Sustain.* 3 (2020) 281–289, <http://dx.doi.org/10.1038/s41893-020-0505-x>.
- [74] H.V. Cooper, S. Sjögersten, R.M. Lark, S.J. Mooney, To till or not to till in a temperate ecosystem? Implications for climate change mitigation, *Environ. Res. Lett.* 16 (2021) <http://dx.doi.org/10.1088/1748-9326/abc74e>.
- [75] M. Jans-Singh, K. Leeming, R. Choudhary, M. Girolami, Digital twin of an urban-integrated hydroponic farm, *Data-Cent. Eng.* 1 (2020) <http://dx.doi.org/10.1017/dce.2020.21>.
- [76] C. Goel, S. Yooab, Hybrid daylight harvesting system using static ball lens concentrator and movable optical fiber, *Sol. Energy* 216 (2021) 121–132, <http://dx.doi.org/10.1016/j.solener.2020.12.071>.
- [77] S. Asseng, J.R. Guarín, M. Raman, et al., Wheat yield potential in controlled-environment vertical farms, *Proc. Natl. Acad. Sci.* 117 (32) (2020) 19131–19135, <https://www.pnas.org/content/117/32/19131>.
- [78] D.J. Beerling, E.P. Kantzas, M.R. Lomas, et al., Potential for large-scale CO<sub>2</sub> removal via enhanced rock weathering with croplands, *Nature* 583 (2020) 242–248, <http://dx.doi.org/10.1038/s41586-020-2448-9>.
- [79] J. Nunes, R. Kautzmann, C. Oliveira, Evaluation of the natural fertilizing potential of basal dust wastes from the mining district of Nova Prata (Brazil), *J. Clean. Prod.* 84 (2014) 649–656, <http://dx.doi.org/10.1016/j.jclepro.2014.04.032>.
- [80] R. Berner, GEOCARBSULF: A combined model for phanerozoic atmospheric O<sub>2</sub> and CO<sub>2</sub>, *Geochim. Cosmochim. Acta* 70 (2006) 5653–5664, <http://dx.doi.org/10.1016/j.gca.2005.11.032>.
- [81] J. Parnell, K. Macleod, M.J. Hole, Carbon dioxide drawdown by Devonian lavas, *Earth Environ. Sci. Trans. R. Soc. Edinb.* 105 (2014) 1–8, <http://dx.doi.org/10.1017/S1755691014000152>.
- [82] D. Woolf, J.E. Amonette, F.A. Street-Perrott, et al., Sustainable biochar to mitigate global climate change, *Nature Commun.* 1 (5) (2010) <http://dx.doi.org/10.1038/ncomms1053>.
- [83] W.O. Silva, B. Nagar, M. Soutrenon, H.H. Girault, Banana split: biomass splitting with flash light irradiation, *Chem. Sci.* 13 (2022) 1774–1779, <http://dx.doi.org/10.1039/D1SC06322G>.
- [84] B. Franks, C. Ewell, J. Jacquet, Animal welfare risks of global aquaculture, *Sci. Adv.* (2021).
- [85] P. Racine, A. Marley, H.E. Froehlich, S.D. Gaines, I. Ladner, I. MacAdam-Somer, D. Bradley, A case for seaweed aquaculture inclusion in U.S. nutrient pollution management, *Mar. Policy* 129 (2021) <http://dx.doi.org/10.1016/j.marpol.2021.104506>.
- [86] B.M. Roque, J.K. Salwen, R. Kinley, E. Kebreab, Inclusion of Asparagopsis armata in lactating dairy cows' diet reduces enteric methane emission by over 50 percent, *J. Clean. Prod.* 234 (2019) 132–138, <http://dx.doi.org/10.1016/j.jclepro.2019.06.193>.
- [87] R.D. Kinley, G. Martinez-Fernandez, M.K. Matthews, et al., Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed, *J. Clean. Prod.* 259 (2020) <http://dx.doi.org/10.1016/j.jclepro.2020.120836>.
- [88] M. Honan, X. Feng, J. Tricarico, E. Kebreab, Feed additives as a strategic approach to reduce enteric methane production in cattle: modes of action, effectiveness and safety, *Anim. Prod. Sci.* (2021).
- [89] R.J. Wallace, G. Sasson, P.C. Garnsworthy, et al., A heritable subset of the core rumen microbiome dictates dairy cow productivity and emissions, *Sci. Adv.* 5 (7) (2019).
- [90] S. Guthrie, S. Giles, F. Dunkerley, et al., Impact of Ammonia Emissions from Agriculture on Biodiversity: An Evidence Synthesis, RAND Corporation, Santa Monica, CA, 2018, [https://www.rand.org/pubs/research\\_reports/RR2695.html](https://www.rand.org/pubs/research_reports/RR2695.html).
- [91] W. Nordhaus, Climate clubs: Overcoming free-riding in international climate policy, *Amer. Econ. Rev.* 105 (4) (2015) 1339–1370, <https://www.aeaweb.org/articles?id=10.1257/aer.15000001>.
- [92] W. Nordhaus, The climate club: How to fix a failing global effort, *Foreign Aff.* 99 (3) (2020) 10–17, <https://www.foreignaffairs.com/articles/united-states/2020-04-10/climate-club>.
- [93] M. Robinson, Interview with Mark Carney: climate change, business and finance, *Scott. Geogr. J.* 136 (2020) 108–111, <http://dx.doi.org/10.1080/14702541.2020.1853941>.
- [94] S. Campos-Martins, D.F. Hendry, Geo-Climate, Geopolitics and the Geo-Volatility of Carbon-Intensive Asset Returns, Working Paper, Nuffield College, Oxford University, 2020.
- [95] T. Sterner and, et al., Funding Inclusive Green Transition Through Greenhouse Gas Pricing, ifo DICE Report, I/2020, vol. 18, 2020, pp. 3–8, <https://www.ifo.de/en/publications/2020-article-journal/funding-inclusive-green-transition-through-greenhouse-gas-pricing>.
- [96] R. Wolf, How Carbon Pricing Can Help Britain Achieve Net Zero by 2050, Technical Report, The Zero Carbon Commission, London, 2021, <https://zerocarbon.publicfirst.co.uk/>.
- [97] D. Rosenbloom, J. Markard, F.W. Geels, L. Fuensching, Opinion: Why carbon pricing is not sufficient to mitigate climate change—and how sustainability transition policy can help, *Proc. Natl. Acad. Sci.* 117 (16) (2020) 8664–8668, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7183151/>.
- [98] R. Rafaty, G. Dolphin, F. Pretis, Carbon Pricing and the Elasticity of CO<sub>2</sub> Emissions, Working Paper 140, Institute for New Economic Thinking, University of Oxford, 2020, <http://dx.doi.org/10.36687/inetwp140>.
- [99] A. Appleby, From Sir William Grove to today: fuel cells and the future, *J. Power Sources* 29 (1990) 3–11, [http://dx.doi.org/10.1016/0378-7753\(90\)80002-U](http://dx.doi.org/10.1016/0378-7753(90)80002-U).
- [100] E. Becquerel, Mémoire sur les effets électriques produits sous l'influence des rayons solaires, *C. R.* 9 (1839) 561–567, <https://gallica.bnf.fr/ark:/12148/bpt6k2968p/f561.image.r=Becquerel%20influence%20des%20rayons%20solaires?rk=42918;4>.
- [101] C.E. Fritts, On a new form of selenium photocell and some electrical discoveries made by its use, *Am. J. Sci.* 26 (1883) 465–472, <https://www.ajsonline.org/content/s3-26/156/465>.
- [102] P. Higgins, The origins of hydroelectricity, *Ecologist* 2007 (2007) 6, <https://theecologist.org/2007/sep/06/origins-hydroelectricity>.
- [103] E. Foote, Circumstances affecting the heat of the sun's rays, *Am. J. Sci. Arts* 22 (1856) 382–383, <https://www.proquest.com/scholarly-journals/art-xxi-circumstances-affecting-heat-suns-rays/docview/89589867/se-2>.
- [104] J. Tyndall, Note on the transmission of radiant heat through gaseous bodies, *Proc. R. Soc. Lond.* 10 (1859) 37–39, <http://dx.doi.org/10.1098/rspl.1859.0017>.
- [105] J. Blyth, On the application of wind power to the production of electric currents, *Trans. R. Soc. Sci. Arts* 13 (1894) 170–181.
- [106] P. Freund, Parker, Thomas (1843–1915), in: *Oxford Dictionary of National Biography*, 2013.
- [107] S.A. Arrhenius, On the influence of carbonic acid in the air upon the temperature of the ground, *Lond. Edinb. Dublin Philos. Mag. J. Sci. (Fifth Ser.)* 41 (1896) 237–275, <http://dx.doi.org/10.1080/14786449608620846>.
- [108] J. Taalbi, H. Nielsen, The role of energy infrastructure in shaping early adoption of electric and gasoline cars, *Nature Energy* (2021) <http://dx.doi.org/10.1038/s41560-021-00898-3>.
- [109] Z. Liu, Z. Deng, P. Ciais, J. Tan, B. Zhu, S.J. Davis, R. Andrew, O. Boucher, S.B. Arous, P. Canadell, Global Daily CO<sub>2</sub> Emissions for the Year 2020, *Tech. Rep.*, 2021, [arXiv:2103.02526](https://arxiv.org/abs/2103.02526) [physics.aos-ph]. <https://arxiv.org/abs/2103.02526>.
- [110] J.L. Castle, D.F. Hendry, Econometrics for modelling climate change, in: J. Hamilton (Ed.), *Oxford Research Encyclopedia of Economics and Finance*, Oxford University Press, Oxford, 2022, <http://dx.doi.org/10.1093/acrefore/9780190625979.013.675>.
- [111] A. Pfeiffer, R. Millar, C. Hepburn, E. Beinhöcker, The '2 °C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy, *Appl. Energy* 179 (2016) 1395–1408, <http://dx.doi.org/10.1016/j.apenergy.2016.02.093>.
- [112] R. Fouquet, P.J.G. Pearson, Seven centuries of energy services: The price and use of light in the United Kingdom (1300–2000), *Energy J.* 27 (2006) 139–178, <https://www.jstor.org/stable/23296980>.
- [113] C.C. Committee, Net-Zero: The UK's Contribution to Stopping Global Warming, Report, Climate Change Committee, London, 2019, <https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/>.
- [114] S. Awaworyi Churchill, J. Inekwe, K. Ivanovski, R. Smyth, Human capital and energy consumption: Six centuries of evidence from the United Kingdom, *Energy Econ.* 117 (2023) 106465, <http://dx.doi.org/10.1016/j.eneco.2022.106465>.
- [115] P. Warde, Energy consumption in England and Wales, 1560–2004, in: *Consiglio Nazionale Delle Ricerche, Istituto di Studi sulle Società del Mediterraneo*, Naples, 2007, [https://histecon.fas.harvard.edu/energyhistory/data/Warde\\_Energy%20Consumption%20England.pdf](https://histecon.fas.harvard.edu/energyhistory/data/Warde_Energy%20Consumption%20England.pdf).

- [116] C.H. Feinstein, *National Income, Expenditure and Output of the United Kingdom, 1855–1965*, Cambridge University Press, Cambridge, 1972.
- [117] C. Kuai, Z. Xu, C. Xi, et al., Phase segregation reversibility in mixed-metal hydroxide water oxidation catalysts, *Nature Catal.* 3 (2020) 743–753, <http://dx.doi.org/10.1038/s41929-020-0496-z>.
- [118] J.A.C. McDermott, R. Dagle, J. Hu, R. Kent, 2020 DOE hydrogen and fuel cells program review: Methane pyrolysis for base-grown carbon nanotubes and CO<sub>2</sub>-free H<sub>2</sub> over transition metal catalysts, in: Project ID H2045 Presentation, Pacific Northwest National Laboratory, Richland, WA, 2020.
- [119] C. Palmer, M. Tarazkar, H.H. Kristoffersen, et al., Methane pyrolysis with a molten Cu-Bi alloy catalyst, *ACS Catal.* 9 (2019) 8337–8345, <http://dx.doi.org/10.1021/acscatal.9b01833>.
- [120] S. Timmerberg, M. Kaltschmitt, M. Finkbeiner, Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas—GHG emissions and costs, *Energy Convers. Manage.: X* 7 (2020) <http://dx.doi.org/10.1016/j.ecmx.2020.100043>.
- [121] A. Ravikumar, S. Sreedhara, J. Wang, et al., Single-blind inter-comparison of methane detection technologies—results from the stanford/EDF mobile monitoring challenge, *Elem.: Sci. Anthropol.* 7 (2019) 37, <http://dx.doi.org/10.1525/elementa.373>.
- [122] M. Bartosiewicz, P. Rzepka, M.F. Lehmann, Tapping freshwaters for methane and energy, *Environ. Sci. Technol.* (2021) <https://pubs.acs.org/doi/10.1021/acs.est.0c06210>.
- [123] X. Jie, W. Li, D. Slocombe, et al., Microwave-initiated catalytic deconstruction of plastic waste into hydrogen and high-value carbons, *Nature Catal.* 3 (2020) 902–912, <http://dx.doi.org/10.1038/s41929-020-00518-5>.