The UK *Industrial Decarbonisation Strategy* Revisited†

Geoffrey P. Hammond[a,b,*]

[a]Department of Mechanical Engineering, University of Bath, Bath. BA2 7AY. United Kingdom.

[b]Institute for Sustainable Energy and the Environment (*I•SEE*), University of Bath, Bath. BA2 7AY. United Kingdom.

ABSTRACT

In the period since 2010 successive UK Governments have produced various decarbonisation strategies for industry. This article scrutinises the most recent version that was published in March 2021: the *Industrial Decarbonisation Strategy* (IDS). It contrasts the policy content of the IDS with previous industrial roadmaps, action plans and strategies (including the *Clean Growth Strategy* of 2017). In addition, it compares the proposals in the IDS with the latest recommendations of the UK Government's independent *Climate Change Committee*, as well as drawing on lessons learned from the techno-economic assessments published by the author and his collaborators for a number of key 'Foundation Industries'. The latter emit significant shares of UK industrial carbon dioxide (CO_2) emissions: the iron and steel (~25%), chemicals (~19%), cement (~8%), pulp and paper (~6%), and glass (~3%) sectors. They also produce some 28 million tonnes of materials per year, which are worth £52 billion to the UK economy, and account for ~10% of UK total CO_2 emissions.

Keywords: Energy; Climate change; Business

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*Corresponding author. Tel.: +44 1225 868195;; *E-mail*: G.P.Hammond@bath.ac.uk
(ORCiD: 0000-0002-0922-8728)

1. INTRODUCTION

1.1 The Climate Change Challenge

'Global warming' (see, for example, Nybo *et al*., 2017), caused by the enhanced *greenhouse effect* resulting principally from fossil fuel burning, presents the inhabitants of *Planet Earth* increases in atmospheric concentrations of carbon dioxide [CO_2; the dominant 'greenhouse gas' (GHG)]. CO_2 has an atmospheric residence time of 50-200 years with 20–60% remaining airborne for a thousand years or longer (Archer and Brovkin, 2008). These CO_2 concentrations have risen from 330 *parts per million* (ppm) in 1975 to about 430 ppm currently. The most recent (2021) scientific assessment by the *Intergovernmental Panel on Climate Change* [IPCC] asserts that observed increases in well-mixed atmospheric GHG concentrations since around 1750 are "unequivocally caused by human activities" (IPCC, 2021). Such changes in GHG concentrations affect the energy balance of the global climate system, and potentially lead to extreme weather events that could have significant impacts on the biosphere and human lives on every continent (WMO, 2019). Consequently, the *World Meteorological Organisation* [WMO] contend that humanity is not on track to meet the climate change targets recommended at the *2015 Paris Agreement* on climate change (Ares and Hirst, 2015; IPCC, 2015; UNFCCC, 2015). These aim to restrict atmospheric temperature increases to 1.5-2°C (WMO, 2019). Indeed, the IPCC argued, in their recent 'special report' on the implications of keeping temperatures down to 1.5°C, that CO_2 removal [i.e., 'negative emissions' (Kruger and Darton, 2013; Gough *et al.*, 2018)] technologies would be needed to compensate for residual GHG emissions and return global warming to 1.5°C, following a peak in about 2030 (IPCC, 2015). Humanity would then be required to take significant action in order to bring these emissions down to zero between 2050 and 2070.

In the light of the climate challenge, the *2015 Paris Agreement* (Ares and Hirst, 2015; UNFCCC, 2015) stressed the need to achieve a transition pathway towards net-zero GHG emissions. The *United Kingdom of Great Britain and Northern Ireland* (UK) introduced in June 2019 a legally-binding target for achieving net-zero (or 'carbon neutrality') by 2050, i.e., balancing emissions with CO_2 removal. A few other European countries (Hammond, 2020) have adopted even more stringent targets of 2030 (Norway), 2035 (Finland), 2040 (Iceland), and 2045 (Sweden). However, these Nordic nations are relatively well placed in terms of low-carbon energy resources (various combinations of biomass, hydroelectric and geothermal schemes, as well as nuclear power plants in the cases of Finland and Sweden) that make rapidly securing a net-zero target rather easier than in other countries within northern, central and southern (Mediterranean) Europe (Hammond, 2020). The larger European nations, such as France, Germany, Italy, Spain and The Netherlands, have recently followed the UK example of setting a 2050 target date or supporting its introduction across the *European Union* (EU-27). Thus, on 4 March 2020, the *European Commission* proposed to enshrine a 2050 climate-neutrality target into its first *European Climate Law* as part of a broader *European Green Deal* (EP, 2020).

In June 2019, the UK Government amended its original *Climate Change Act* (CCA, 2019) in order to incorporate the revised net-zero emissions target. They had previously asked its independent, statutory *Climate Change Committee* (CCC) to evaluate whether such a net-zero target could realistically be achieved by 2050. This Committee argued in their subsequent report (CCC, 2019a) that such a target was "achievable with known technologies, alongside improvements in people's lives, and within the expected economic cost" (CCC, 2019a). They made the case for an approach that would incentivise industry to reduce their GHG emissions through a combination of improved energy and resource efficiency methods, greater electrification [via low-carbon generators, i.e., nuclear power and renewable energy technologies (RETs)], enhanced low-carbon *hydrogen* (H_2) usage, and the implementation of *carbon capture, usage and storage* (CCUS) facilities coupled to industrial process plants "in ways that do not adversely affect their competitiveness" (CCC, 2019a; 2019b). The CCC periodically review progress in meeting a sequence of carbon budgets out to 2050. Its most recent report dealt with the *Sixth Carbon Budget* covering the period 2033-2037, and recommended a budget that "would achieve well over half of the required emissions reduction to 2050 in the next 15 years" (CCC, 2020). The latest UK carbon dioxide equivalent (CO_{2e}) emission pathways and associated 'carbon budgets' recommended by the CCC are illustrated in Fig. 1.

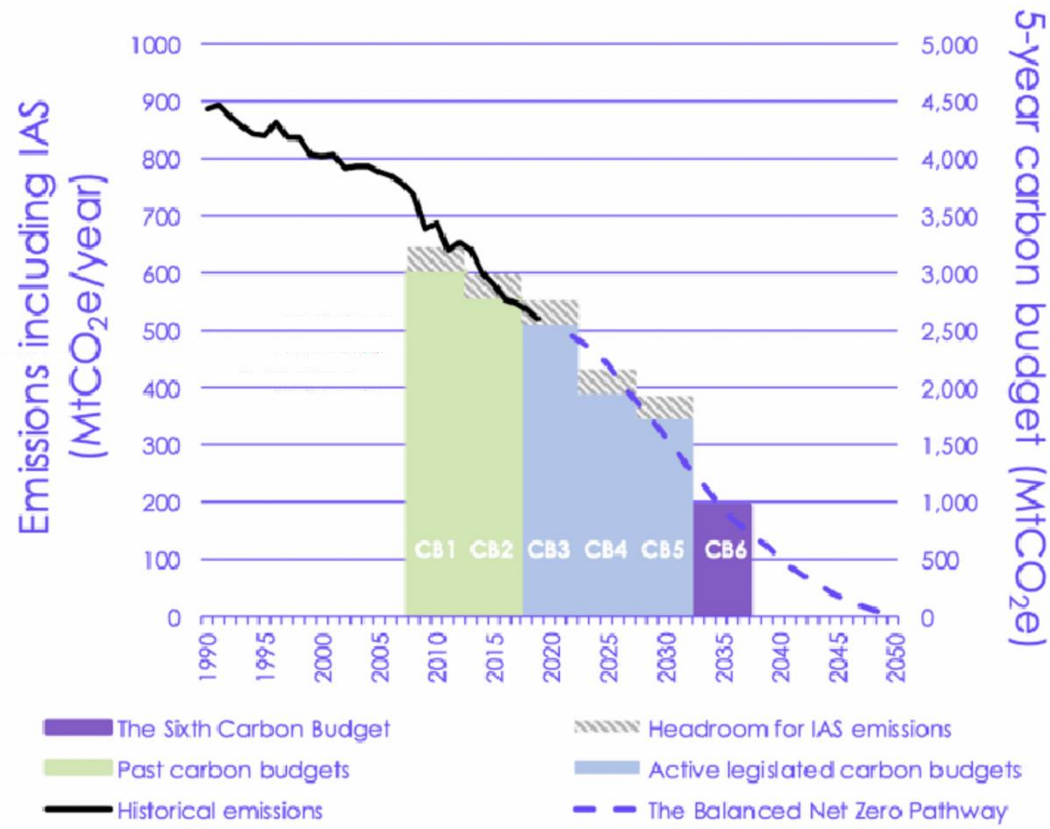

Fig. 1. The UK *greenhouse gas* (GHG) emissions pathway to 2050 and associated 'carbon budgets' as recommended by the *Climate Change Committee*. IAS = International Aviation and Shipping. *Source:* adapted from CCC (2020).

1.2 The UK Industrial Sector and Its Decarbonisation

The industrial sector in the UK accounts for 19% of primary energy equivalent consumption in 2019 (BEIS, 2020b) and a corresponding 14% of GHG emissions (BEIS, 2020c). There are large differences between industrial sub-sectors in the end-use applications of energy, especially in terms of products manufactured, processes undertaken and technologies employed. UK industry overall has been found to consist of some 350 separate combinations of sub-sectors, devices and technologies (Dyer *et al.*, 2008; Griffin *et al.*, 2016). The diversity of manufacturing processes, ranging from highly *energy-intensive* (EI) steel production and chemicals processing to *non-energy-intensive* (NEI) electronics fabrication, presents a substantial variation in the main challenge to an energy analysis of the industrial sector. Energy intensity, the percentage of costs represented by energy and water usage, and the mean energy use per enterprise (represented by the area of the data points or 'bubbles') for the different UK industrial subsectors are illustrated in Fig. 2. A high value in any of these measures suggests that the subsector is EI, according to Griffin *et al.* (2018a). These subsectors typically employs large quantities of (often high-temperature) process energy, whereas its NEI counterpart tends to be dominated by energy uses associated with space heating. Industry is the only end-use energy demand sector in the UK that has experienced a significant fall of ~65% in final energy consumption over the period 1970-2019 (BEIS, 2020b). However, the aggregate reduction in energy intensity [MJ/£ of *Gross Value Added* (GVA)] fell by about *one-third* between 2000-2019 (BEIS, 2020b), but this masks several different underlying causes: *end-use efficiency* [accounting for around 80% of the fall in industrial energy intensity; largely induced by the carbon price mechanism (Dyer *et al.*, 2008; Griffin *et al.*, 2016)]; *structural changes in industry*

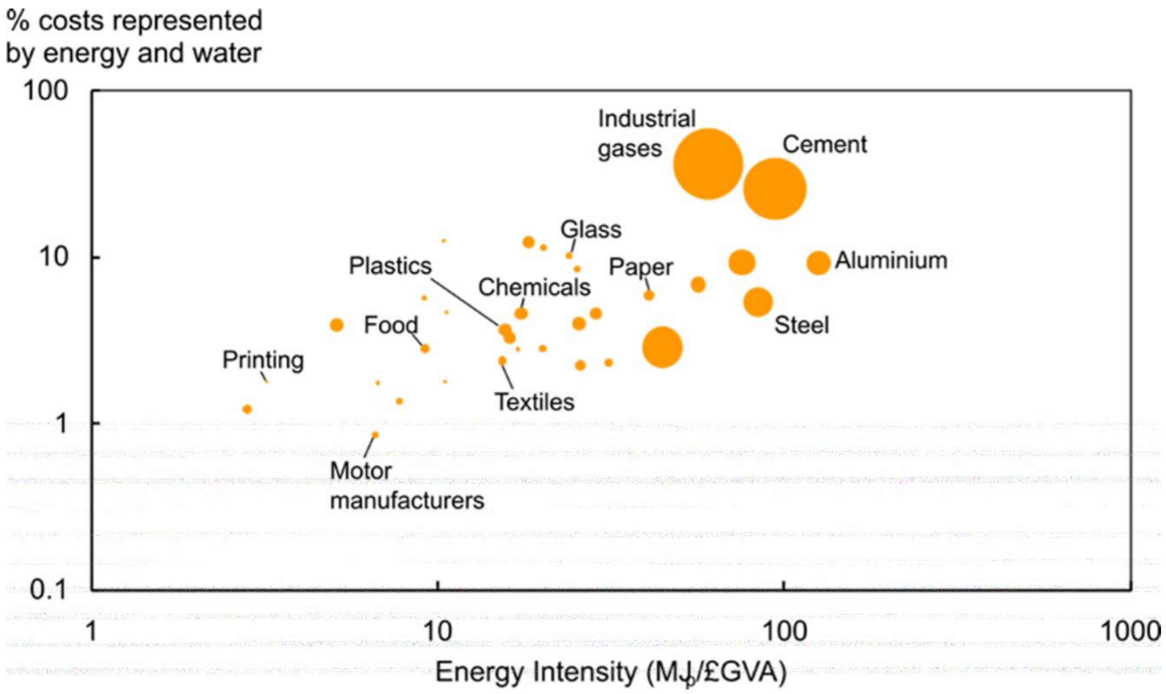

Fig. 2. Primary energy intensity, percentage of costs represented by energy and water, and mean primary energy use per enterprise (represented by the area of the data points or 'bubbles'). *Source:* Griffin *et al.* (2018a).

[a move away from EI industries towards NEI ones, including services (Dyer *et al.*, 2008; Griffin *et al.*, 2016)]; and *fuel switching* [from coal and oil to natural gas and electricity that are cleaner, more readily controllable, and arguably cheaper for the businesses concerned (Griffin *et al.*, 2016)].

The GHG emissions from the UK industrial sector split by subsector are illustrated in the pie chart presented as Fig. 3. This includes both emissions from energy use (including those indirectly emitted via electricity use) and process emissions. Thus, the production of cement (Griffin *et al.*, 2014; Griffin *et al.*, 2016; Cooper and Hammond, 2018), for example, releases pure CO_2 directly into the atmosphere when calcium carbonate is heated to produce lime (calcium oxide; in a process known as *calcining*) which, in turn, requires energy input for the heating process itself (giving rise to fuel-related CO_2 emissions, as well as leading to additional emissions upstream). Subsectors with significant process emissions are therefore steel, chemicals, cement, aluminium, glass, ceramics, and lime. Recently the *UK Research and Innovation* (UKRI), a non-departmental UK public body [sponsored by the *Department for Business, Energy and Industrial Strategy* (BEIS)], responsible for supporting research and knowledge exchange at higher education institutions, as well as for the UK's innovation agency [*Innovate UK*], has characterised a number of key industrial sectors as '*Foundation Industries*' [FI]. These include the metals, glass, ceramics, paper, cement and bulk chemicals sectors, which are viewed by UKRI as being vital for UK manufacturing. They produce 28 million tonnes (Mt) of materials per year, which are worth £52 billion (bn) to the UK economy and account for ~10% of UK total CO_2 emissions.

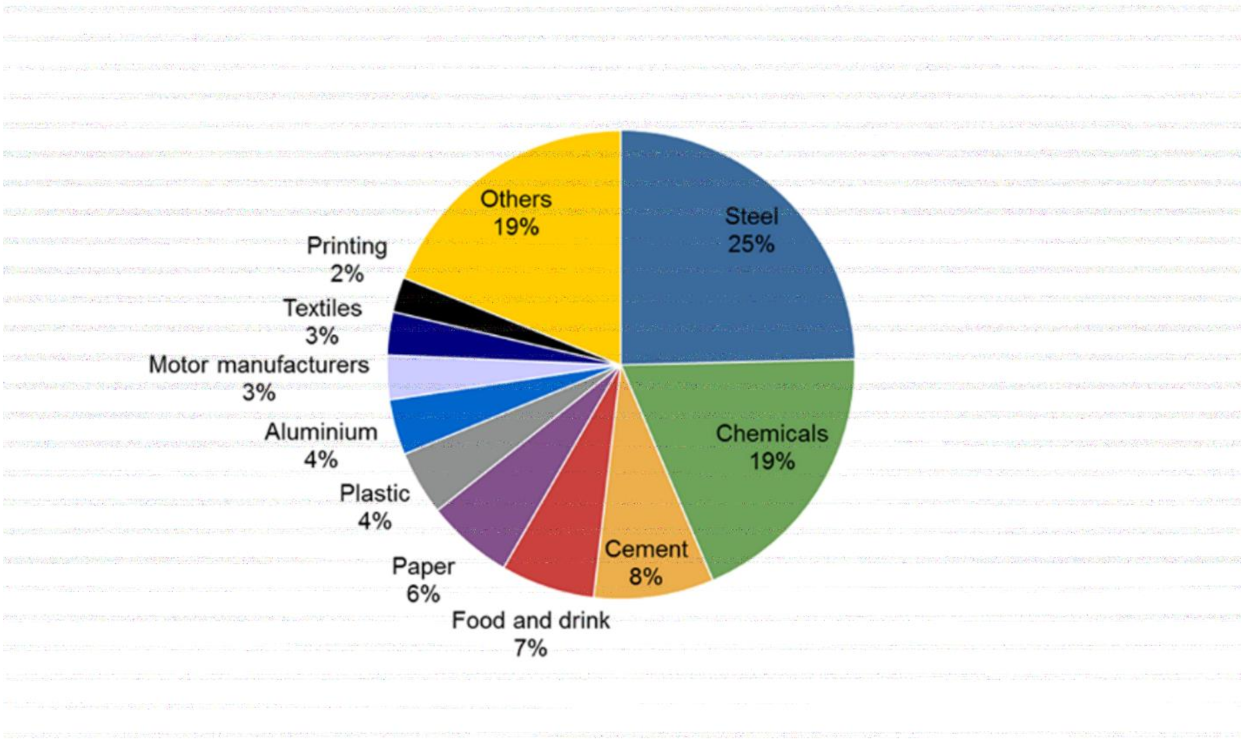

Fig. 3. *Greenhouse gas* (GHG) emissions from UK industry. *Source:* Griffin *et al.* (2018a; 2018b).

1.3 The Issues Considered

Cooper and Hammond (2018) produced a critical review of the UK Government's *Clean Growth Strategy* published in October 2017, and associated industrial decarbonisation technology roadmaps. They argued that these roadmaps exhibited quite large uncertainties, and decarbonisation over the long-term would depend particularly on the adoption of a small number of key technologies, alongside the decarbonisation of electricity supply. Insights were drawn from a series of techno-economic assessment studies across various UK industrial sectors. Those examined by the author and his collaborators included iron and steel (around 25% of UK industrial CO_{2e} emissions - Griffin and Hammond, 2019; 2021), chemicals (19% - Griffin *et al.*, 2018a), cement (8% - Griffin *et al.*, 2014; 2016), pulp and paper (6% - Griffin *et al.*, 2018b), and glass (3% - Griffin *et al.*, 2021). Thus, these five sectors account for just over 60% of the total GHG emissions from UK industry; both from energy use and process emissions (see again Fig. 3).

Reducing industrial energy demand and improving resource efficiency could make a substantial contribution towards the UK Government's goal of net-zero GHG emissions by 2050 (Cooper and Hammond, 2018), whilst simultaneously improving productivity and creating employment opportunities. Both fossil fuel and process GHG emissions will need to be significantly reduced over this timeframe. Ultimately, all industrial energy use and emissions result from the demand for goods and services. Energy is required at each stage in the manufacture of a product, or 'life-cycle', from raw material extraction through to the final distribution and eventual disposal. Energy use and associated GHG emissions at different points along these UK supply chains emanate from many different countries, due to the growth of globalization. They are often termed 'consumption emissions' (Barrett *et al.*, 2018), in contrast to 'terrestrial emissions' produced within the national boundary of Great Britain (GB). In the period since 2010, successive British governments have produced various decarbonisation strategies for industry. Here, the most recent version – the *Industrial Decarbonisation Strategy* (IDS) published in March 2021 (HMG, 2021a) - is critically evaluated. Its policy content is contrasted with previous UK Government-sponsored industrial roadmaps, action plans and strategies (including the *Clean Growth Strategy* of 2017). In addition, it compares the new IDS with the latest recommendations of the UK Government's independent *Climate Change Committee* and with findings of the techno-economic assessments published by the author and his collaborators for a number of key 'Foundation Industries' (Griffin *et al.*, 2014; 2016; 2018a; 2018b; 2021; Griffin and Hammond, 2019; 2021).

2. INDUSTRIAL DECARBONISATION OPTIONS

2.1 The Background

The UK Government is legally committed to achieving net-zero GHG emissions (i.e., 100% abatement) by 2050 across <u>the economy as a whole</u> (CCA, 2019; CCC, 2019a; 2019b), but the use of 'negative emissions' technologies (Solano Rodriguez *et al.*, 2017; Gough *et al.*, 2018a; Griffin *et al.*, 2018a; 2018b) in some sectors – such as buildings and electricity generation -

will provide leeway for less stringent emissions reduction in industry (CCC, 2018a). There are a number of hard-to-abate industrial sub-sectors that may need to take advantage of this ‘headroom’ in achieving net-zero emission targets: the steel industry is certainly one of those (Griffin and Hammond, 2021). In the short term, in the period up to around 2020-2030, decarbonisation will rely on the adoption of existing or currently available technologies. Dyer *et al.* (2008) observed that the routes and priorities over this period are relatively clear. However, the prospects for the commercial exploitation of innovative technologies by the middle of the 21st Century are highly speculative (Dyer *et al.*, 2008). Indeed, a number of low-CO_2 pathways have indicated a broad range of possible UK industrial GHG reductions and uncertainties out to 2050 (Griffin *et al.,* 2014; 2016; 2018a; 2018b; 2021; Griffin and Hammond, 2019; 2021; WSP/PB and DNV.GL, 2015).

2.2 Incremental Methods for Reducing Energy Demand and ‘Greenhouse Gas’ Emissions

Incremental methods of reducing energy demand and GHG emissions, such as energy efficiency and heat recovery techniques, are readily available. These include improved thermal insulation of industrial buildings, furnaces, and process equipment; modern heat exchangers; *combined heat & power* (CHP) plants (particularly biomass-CHP); and industrial heat pumps (Griffin *et al.,* 2016; Cooper and Hammond, 2018). In addition, ‘circular economy’ (CE) interventions or resource efficiency improvements seek to reorganise products and services by designing out waste, recycling, and reusing materials (Barrett *et al.*, 2018), i.e., ‘reduce, reuse, recycle’. They often require ‘industrial symbiosis’, or ‘value chain collaboration’, but minimise a range of negative side-effects (Cooper and Hammond, 2018). Such CE approaches can be viewed as an alternative to the conventional *linear ‘take-make-consume-dispose’* economic model, which attempt to minimise waste and material inputs to the economy through eco-design, recycling and reusing products (Barrett *et al.*, 2018). However, the *Ellen MacArthur Foundation* (EMF, 2013) present CE interventions more broadly in terms of expanding the ‘waste hierarchy’, ‘circling longer’, or enabling cascaded use. The *Foundation* claims that these approaches increase employment, more effectively capture value, mitigate exposure to supply chain and market risks, and better develop customer relationships. The impact on energy use of applying a wide range of CE methods were studied by Cooper *et al*. (2017) in a global context, across the EU-27, and in the UK. They found that generally techniques for ‘*getting more out*’ (e.g., life extension through the reuse or repurpose of components) had greater potential in a UK context than those associated with ‘*putting less in*’ [e.g., reducing the content of products (via the use of stronger materials) or reducing losses of material throughout the supply chain].

2.3 Deep Decarbonisation, Breakthrough, or Disruptive Technologies

Over the longer-term, deep decarbonisation or disruptive technologies will be needed to achieve the UK’s net-zero target now legally bound into the *Climate Change Act* (CCA, 2019); amended in 2019 to focus on the goal of ‘carbon neutrality’. Indeed, most of the industrialised nations now view the challenge of climate change and reductions in CO_2 emissions as “the currency of debate in a climate-constrained world” (Hammond, 2020). There are a number of alternative ways to secure the ‘deep’ decarbonisation of industry via ‘breakthrough’ or disruptive technologies: (i) *CO_2 capture, usage and storage* (CCUS), (ii) the greater uptake of *bioenergy resources*; (iii) the use of *renewable (or 'green') hydrogen*; (iv) *electrification* again based on low-carbon power supply from nuclear or renewable sources; and (v) deindustrialisation. These alternative options may therefore be compared and contrasted (Griffin and Hammond, 2019; 2021). CCUS, the use of biomass, and decarbonised electricity are all key options identified in the FI technology roadmaps produced by WSP/PB and DNV.GL (2015), as well as those of Griffin *et al*. (2014; 2016; 2018a; 2018b; 2021) and Griffin and Hammond (2019; 2021). However, each of these options is the source of considerable uncertainty in terms of their availability to industry. Several exhibit adverse impacts.

- ***CO_2 capture, usage and storage (CCUS):*** The British Government view CCUS as being key technologies for securing CO_2 mitigation from EI industrial subsectors [see Fig. 2 (Griffin *et al*., 2016; 2018a)]. Obviously, innovations in capture technologies are likely to occur over the timespan out to 2050 (Griffin *et al*., 2016; 2018a; Leeson *et al*., 2017; Wesseling *et al*., 2017; Bataille *et al*., 2018; Cooper and Hammond, 2018). The development of CO_2 transport hubs will require an interlinking of industrial and power station networks for onward storage beneath the North Sea. These CCUS clusters hold out the prospect of providing integrated CO_2 pipeline networks, which could be formed of multiple branches that link individual sources to a common hub and main pipeline; thereby sharing CCUS infrastructure (Cooper and Hammond, 2018). The distribution of CO_2 point sources and potential UK CCS cluster regions identified by the UK Government are illustrated in Fig. 4 (Griffin *et al*., 2018a). Such clusters could significantly decrease the costs of transport, particularly from smaller CO_2 sources. They would principally provide storage sites under both the North Sea and the North East part of the Irish Sea (Cooper and Hammond, 2018). Clearly, this type of clustering would require ongoing RD&D as part of a collaborative programme with the manufacturing/processing sectors, as well as electricity and gas supply utilities.
- ***The greater uptake of bioenergy resources:*** Another means of decarbonising industry is via fuel replacement, for example, of coal with bioenergy resources (Griffin *et al.*, 2018b; Griffin and Hammond, 2021). Bioenergy can be produced from either biomass (any purpose-grown material such as crops, forestry or algae) or biogenic waste (including household, food and commercial waste, agricultural or forestry waste, and sewage sludge). 'Sustainable bioenergy' is a renewable resource that is often low-carbon and potentially generates 'negative emissions' when coupled to CCUS facilities (Solano Rodriguez *et al.*, 2017; Gough *et al.*, 2018a; Griffin *et al.*, 2018a; 2018b). However, many industrial sectors will be competing for this resource alongside, for example, power generation. The UK Government's independent, expert *Climate Change* Committee (CCC) has twice undertaken a review of the availability of bioenergy resources and their appropriate use in a low-carbon future. In its most recent report (CCC, 2018a), it concluded that biomass could yield a potentially valued energy resource, if it is prioritised for the most valuable end-uses. The CCC argued that suitable UK biomass resources should be mainly reserved for 'carbon sequestration' purposes. These included the use of wood in construction and in connection with CCUS in industry and in power generation [GHG removal technologies, such as Bioenergy CCS (often denoted as BECCS) or Direct Air CCS] (CCC, 2018a; Gough *et al.*, 2018; HMG, 2021). The CCC suggested that the uptake of BECCS to produce power, hydrogen, aviation biofuels, or in industrial applications would deliver more in terms of GHG abatement than its use in other energy systems (including liquid

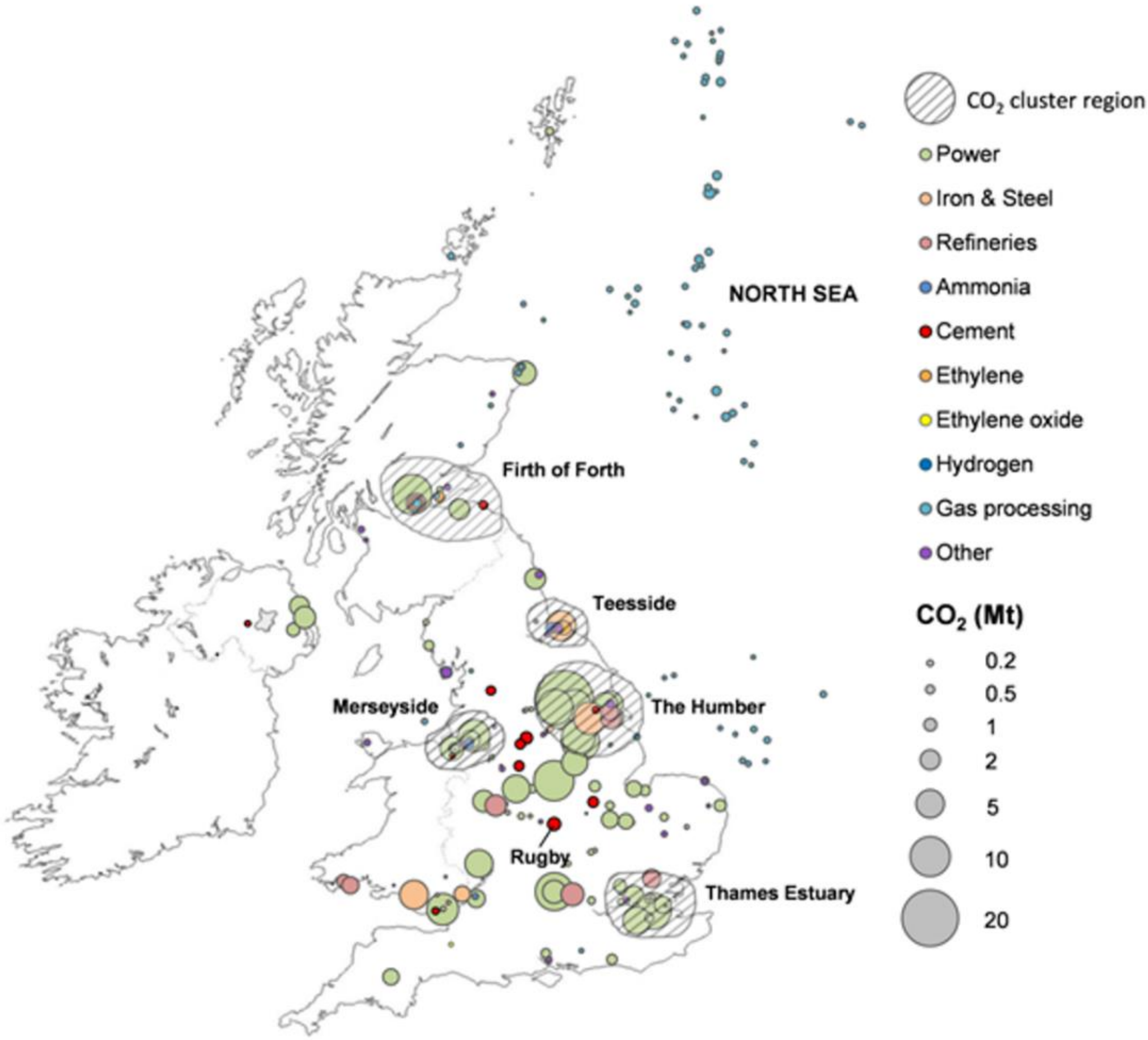

Fig. 4. Distribution of CO_2 point sources and CCUS cluster regions in the UK. *Source:* Griffin *et al.* (2016).

biofuels for road transport). Pulverised biomass or biogenic waste could be adopted to provide high temperature process heat (Griffin *et al.*, 2018a), but that would give rise to dust deposition on heater tubes and an increase in air pollution (possible beyond legal limits). The focus of biomass and biogenic waste gasification in the chemicals sector (Griffin *et al.*, 2018a) is likely to be on burning biogas, hydrogen (replacing steam reforming of natural gas) and syngas going forward. Nonetheless, burners designed for natural gas would need to be adjusted as gaseous bioenergy has a lower calorific value (Griffin *et al.*, 2018a).

- ***The use of 'sustainable' hydrogen:*** Hydrogen (H_2) is potentially a low or zero-carbon energy carrier; depending on its means of production. The *Royal Society* (of London) published a policy briefing that evaluated the prospects for generating 'sustainable hydrogen' at scale (RoySoc, 2018). This identified a number of processes for obtaining low-carbon H_2 in order to tackle climate change and poor (mainly urban) air quality. The document itself was developed via discussions at a specialist workshop and a number of subsequent expert contributions of best available evidence. Options for producing sustainable H_2 included 'thermochemical routes' (such as *Steam Methane Reforming* (SMR) and *Coal/Biomass Gasification*); biological routes (such as *Anaerobic Digestion* (AD), *Photo Fermentation*, and *Bioelectrochemical Systems*); 'electrolytic routes' (such as those utilising an *Alkaline Electrolyser*, *Solid Oxide Electrolyser*, and *Polymer Electrolyte Membrane Electrolyser*); and finally a suite of innovative technologies under the umbrella title of '*solar to fuels*' (or 'artificial photosynthesis'). Hydrogen-based processing is also favoured by a number of research groups in Northern Europe, although they recognise that it is likely to be expensive (Wesseling *et al.*, 2017; Bataille *et al*., 2018). The process conventionally used to produce hydrogen is SMR employing *natural gas* (NG) as the feedstock. SMR plants vary between 150 and 440 MegaWatts (MW) with a typical energy efficiency of about 70%. However, this process continues to emit CO_2 emissions unless used together with CCUS. Some 71-92% of CO_2 releases can be captured in this way, although upstream emissions tend to limit the capture rate depending on the origin of the NG resources (Hammond and O'Grady, 2014). Pipelines from the Russian Federation into the EU, for example, have been shown to be particularly 'leaky'. 'Blue hydrogen' is produced when natural gas is split into H_2 and CO_2, for example, by SMR (RoySoc, 2018; Griffin and Hammond, 2021; Newborough and Cooley, 2020), after which the CO_2 is captured and then stored, i.e., employing CCUS (to yield H_2 at ~40 gCO_{2e}/kWh). It can be contrasted with 'green' H_2 processing via the electrolysis routes (RoySoc, 2018) that greatly reduces the generation of CO_2 emissions to produce H_2 at ~14 gCO_{2e}/kWh (Griffin and Hammond, 2021). Newborough and Cooley (2021) observed that electrolytic hydrogen is the only fuel that is oxygen and water balanced. Consequently, they argue that electrolysers could yield substantial amounts of green H_2 for the energy system, alongside O_2 for the global ecosystem. The gas supply pipeline network in GB (operated by *National Grid*) delivers natural gas at ~204 gCO_{2e}/kWh, whilst 'grey' hydrogen from SMR without CO_2 capture (Newborough and Cooley, 2020; 2021) yields H_2 at ~355 gCO_{2e}/kWh (Griffin and Hammond, 2021). The falling costs of renewable electricity and of electrolysers suggests that cost of green H_2 will become increasingly competitive (Newborough and Cooley, 2020); firstly against blue H_2, then grey H_2, and finally natural gas. The *Hydrogen Council* - a global CEO-led initiative of leading companies – has predicted that green H_2 will be cheaper than its 'grey' counterpart by 2030 (Newborough and Cooley, 2020). In contrast, *DNV* – the Norwegian-headquartered global company that provides technical advisory services to the energy value chain – believe that green H_2 will be less than *one-third* of the cost of its 'blue' competitor by 2050 (Newborough and Cooley, 2020).

- ***The use of renewable electricity:*** Electrification provides another decarbonisation option when based on low-carbon power supply from nuclear or renewable sources. Electricity in the UK is currently resourced from some 41% natural gas, 31% renewable energy technologies (RETs, i.e., wind turbines, solar photovoltaic cells, hydropower and bioenergy), 22% nuclear power, 2% coal, and 4% imports (BEIS, 2020a). The quite dramatic rise in the uptake of RETs over the past few decades are associated with a significant decline in their levelised costs. Higher penetrations of low-cost RETs will then lead to falls in GHG emissions from the UK power sector to near-zero by around 2030-2035 (CCC, 2019a; 2019b; Foxon *et al.*, 2020). Electrification in the steel sector implies a reliance on producing recycled steel from scrap in *Electric Arc Furnaces* (EAFs) (currently only around 30% of the sector output), the generation of electricity from low-CO_2 sources [e.g., nuclear power and RETs (mainly solar photovoltaic arrays and wind turbines)], and the shutting down of *Blast Furnace* (BF)-coke oven production using mainly virgin ores (Griffin and Hammond, 2021). Elsewhere in industry, the use of tools such as *Demand Side Response* (DSR) – where levels of electricity demand are increased, reduced or shifted - and on-site energy storage enable the optimisation of electricity usage. This has major advantages in the context of an energy infrastructure designed to meet occasional peak demands (Griffin *et al*., 2018b). It will be particularly important in the transition towards a low-carbon future (Chilvers *et al.*, 2017). *Industrial and commercial* (I&C) customers can benefit financially, for example, by offering *Demand Side Flexibility* (DSF) services to market actors (e.g., the various 'aggregators' - companies who aggregate small loads and then participate in demand-side markets on behalf of customers - or the *National Grid*, the GB 'System Operator').

- ***Deindustrialisation ('pushing emissions and businesses abroad'):*** Manufacturing output from the UK as a share of real GDP fell from 33% in 1970 (Griffin and Hammond, 2019) to 17.5% in 2018 (in contrast to *services*, which accounted for 71%). This resulted, in part, from cycles of restructuring and changes in ownership of the British industry during the 20th Century. The steel sector, for example, was nationalized in 1951, denationalized in 1953, renationalized in 1967 (as the *British Steel Corporation* (BSC)), and privatized once again in 1988 (Griffin and Hammond, 2019). In the 1990s, ore-based steel-making was spread over three UK integrated steelworks (the Port Talbot, Scunthorpe, and Teesside works) of similar production capacity, and scrap-based steel-making was spread over four electric arc steelworks (Rotherham, Tremorfa, and two sites in Sheffield). The post-2008 economic recession in the UK (and globally elsewhere) resulted in the closure of some large industrial processing plants, including aluminium smelters and steel mills (Griffin and Hammond, 2019). The UK steel industry then underwent its own 'crisis' in 2015-2016, when major plants at Redcar (on Teesside), Scunthorpe (in Lincolnshire) – both in the North East of England - Scotland and South Wales were subject to closure or reduction in capacity. Steel plant closures of this type effectively means 'outsourcing' UK metal processing to other parts of the globalized world (principally China) , i.e., "pushing emissions and business abroad". Relatively cheaper imports of goods from low-cost producers thereby replace indigenous production (Barrett *et al.*, 2018). When UK factories close in this way, their CO_2 emissions are eliminated. It thereby gives rise to the least desirable decarbonisation option (from a national perspective) of 'deindustrialisation'; reduction in industrial capacity resulting in structural (economic and social) change. That is not a process that any government would willingly engage in as a means of decarbonising its industrial sector. In the case of the British steel industry, it would leave major blast furnaces as 'stranded assets' (Griffin and Hammond, 2021).

3. THE 2021 UK *INDUSTRIAL DECARBONISATION STRATEGY*

3.1 Steps Towards Decarbonising UK Industry

The UK Coalition (Conservative-Liberal Democrat) Government formed in May 2010 instigated a process for evaluating the prospects of decarbonising British industry. They contracted a consortium of consultants from *WSP/Parsons Brinckerhoff* [PB] and *DNV.GL* to undertake the development of a set of '*Industrial Roadmaps for Carbon Reduction and Energy Efficiency to 2050*' [see, for example, the *iron & steel* report (WSP/PB and DNV.GL, 2015)]. The robustness of the WSP/PB and DNV.GL approach mirrors the wide-scale industrial stakeholder engagement in this project. Consequently, their sector roadmaps largely reflect back the views of the industry representatives that participated in the sector workshops, face-to-face interviews, site visits, and a cross-sector conference. In order to evaluate the pathways out to 2050 the consultants developed a simplified modelling framework, which realistically yielded a wide range of uncertainties in terms of the delivery of a decarbonised UK industrial sector. In common with earlier studies [like those of Griffin *et al.* (2014); already published at that time] the pathways indicate a broad range of possible UK industrial carbon reductions or uncertainties by 2050. The subsequent UK Conservative Government (May 2015 onwards) released a *Clean Growth Strategy* (CGS) in October 2017 (HMG, 2017a), led by its *Department for Business, Energy and Industrial Strategy* (BEIS). In addition, BEIS produced seven *Industrial Decarbonisation and Energy Efficiency Action Plans*, jointly with industrial partners covering several different industrial sectors. These *Action Plans* contain voluntary commitments to reduce GHG emissions, whilst "maintaining international competitiveness".

The *Carbon Trust* and *Energy Savings Trust*, set up by previous UK governments to encourage industrial decarbonisation and energy saving respectively (but now independent bodies), generally welcomed the content of the CGS (Cooper and Hammond, 2018). The *Climate Change Committee* (CCC) also suggested that it was a move in the right direction. However, they voiced concern over the vagueness of many of the suggested climate change mitigation actions and the potential reliance by the UK Government on what they regard as 'flexibilities' in the 2008 *Climate Change Act* in order to meet the requirements of the then *Fifth Carbon Budget* targets (see again Fig. 1). The CCC view such flexibilities as "banking and borrowing", whereas they believe that future carbon budgets out to 2032 at least should be met by way of domestic UK action (CCC, 2018b). They regard banking emissions from the overachievement in emissions reductions under the *Second* and *Third Carbon Budgets* would be a retrograde step. It could put at risk the UK commitment to achieving the goals of the *Paris Agreement*, which includes a much greater challenge of moving towards 1.5°C global warming than the 2°C target in place when the CCC originally recommended their *Fifth Carbon Budget* goals. They also believed that it would undermine investor confidence in the development of innovative technologies, such as CCUS (CCC, 2018b).

3.2 The 2020 *Ten-Point Plan for a Green Industrial Revolution*

In November 2020 the British Prime Minister announced what he termed a *10-Point Plan* for the so-called '*Green Industrial Revolution*' in the form of a short, 10-page document (HMG, 2020) that was aimed at creating and supporting up to 250,000 'green jobs'. The elements of the *10-Point Plan* included quadrupling output of offshore wind to 40 gigawatts (GW) by 2030, and generating 5 GW of 'low-carbon' hydrogen production capacity by 2030 for industry, transport, power and homes in partnership with industrial firms. It also sought to make the UK a "world leader" in the rollout of CCUS, foster the deployment of new large-scale nuclear power plants – potential sites being Sizewell C and Wylfa - (as well as support for RD&D into the next generation of small and advanced reactors), accelerate the transition to electric vehicles (EVs), and support 'difficult-to-decarbonise industries' becoming greener [via research projects such as for zero-emission aircraft (i.e., so-called 'Jet Zero') and ships]. Outside the manufacturing sector, construction would be aided by making the nation's homes, schools and hospitals "greener, warmer and more energy efficient" (with a target for installing 600,000 heat pumps every year by 2028), developing a national infrastructure to "better support" non-fossil fuel vehicles, upgrading the broadband network, and investing in zero-emission public transport, cycling and walking for the future. It was rounded off by a pledge to protect and restore its natural environment by planting 30,000 hectares of trees every year, and finally a plan to make the City of London the "global centre of green finance". This *10-Point Plan* was intended to provide a 'taster' of what was to come in the subsequent *Industrial Decarbonisation Strategy* (HMG, 2021a). It was greeted, for example, by the *Climate Change Committee* as an indicative pathway to net-zero emissions in just 30 years, while "building back better" from the COVID-19 pandemic. Overall, the *10-Point Plan* was also welcomed by industry, NGOs and several 'green' groups, but received criticism for many "reheated pledges", little new funding, and investment levels significantly lower than equivalent programmes in, for example, France and Germany.

3.3 Delivering on the *Climate Change Committee's* Sixth Carbon Budget Report

The independent *Climate Change Committee* (CCC), established under the *Climate Change Act* (CCA, 2019), reports to the UK Parliament on progress made in reducing these emissions under successive 'carbon budgets' (see again Fig. 1). Its recommendations have often been challenging in policy terms for the UK Government. They separate the British economy into a number of sectors; with the closest to 'industry' as addressed here being 'manufacturing and construction'. The Committee have developed a set of scenarios that illustrate emissions pathways out to 2050 in association with their *Sixth Carbon Budget Report* (CCC, 2020). According to their *Balanced Net Zero* transition pathway, manufacturing and construction emissions fall by 70% by 2035 and 90% by <u>2040</u> against the 2018 level (Doyle, 2021). This was based primarily on fuel-switching, improvements in energy and resource efficiency, and CCUS (see Fig. 5). This pathway presumes that the Government would establish a policy framework to support UK manufacturing to decarbonise UK manufacturing without driving companies overseas, but instead benefits terrestrial investment and job creation. By 2050 the CCC (2020) envisaged that the heavy-lifting on cutting GHG emissions would be achieved via a combination of renewable electricity, low-carbon hydrogen, and CCUS, with smaller contributions from 'material substitution' [a CE intervention (see Section 2.2 above)], energy efficiency, and BECCS.

Sources of potential emissions abatement across the main processes employed within the 'manufacturing and construction' sector by 2050 under the CCC (2020) *Balanced Net Zero* scenario are displayed in Table 1. Electrification measures include electric boilers, switching from on-site generation to a grid connection, EAFs, electric mobile machinery, electric dryers, and electric infrared heaters (CCC, 2020). This transition pathway suggests that improvements in energy and resource efficiency would lead to the biggest fall in GHG emissions during the early 2020s, with smaller contributions from electrification, biofuel use and material substitution. In contrast, switching away from fossil fuels to low-carbon ones contributes the main emissions reduction through the early 2030s (CCC, 2020). It was assumed to be scaled-up from 2025 with infrastructures for CCUS and H_2 developing near industrial clusters. Thus, the major contributions to decarbonisation under the *Balanced Net Zero* pathway by 2050 arise

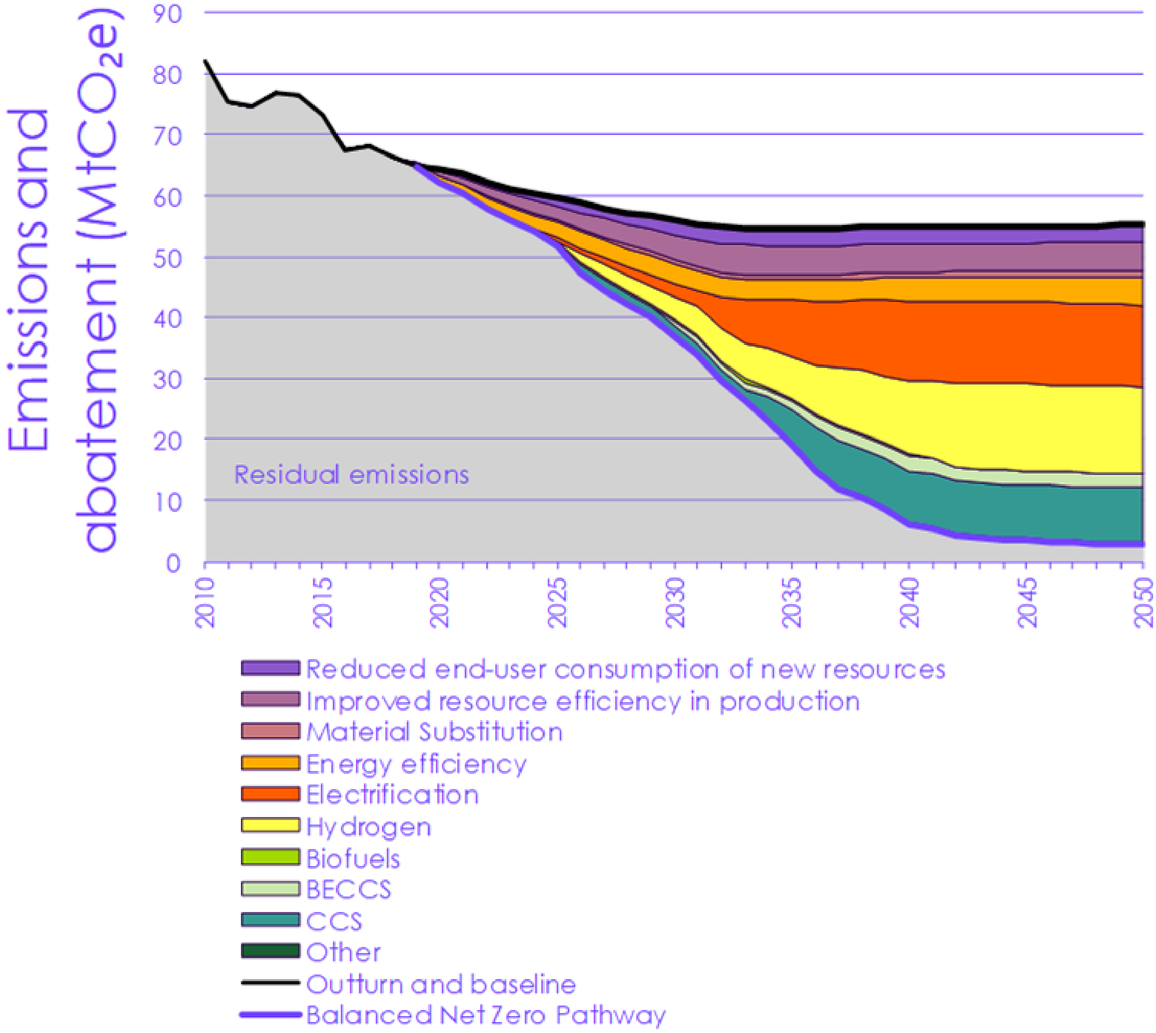

Fig. 5. Sources of abatement in the 'manufacturing and construction' sector under the *Climate Change Committee's 'Balanced Net Zero*' Transition Pathway out to 2050. *Source:* adapted from CCC (2020).

from the adoption of low-carbon hydrogen, electrification, and CCUS respectively (see again Table 1). This is followed by more modest contributions from energy efficiency improvements and material substitution. Resource efficiency can also have a significant impact on reducing process CO_2 emissions.

3.4 The 2021 *Industrial Decarbonisation Strategy* (IDS)

3.4.1 The General Framework of the IDS

The UK Government published its new *Industrial Decarbonisation Strategy* (IDS) in March 2021 (HMG, 2021a). This elaborated on the proposals originally found in the *10-Point Plan*. Thus, it targeted cutting industrial GHG emissions by *two-thirds* by 2035 against a baseline of 2018, and by at least 90% by 2050 (HMG, 2021a; Kennedy, 2021; Doyle, 2021). The latter reduction target contrasts with that proposed by the *Climate Change Committee* (CCC, 2020), who recommended a cut in industrial emissions of 90% by 2040 (Doyle, 2021). In addition, to aims to capture at least 3 $MtCO_{2e}$ from industry *per year* by 2030 (HMG, 2021a; Kennedy,

Table 1. 'Manufacturing and construction' residual GHG emissions and abatement options associated with major industrial processes in 2050 ($MtCO_{2e}$)

Major Industrial Processes	**Residual GHG Emissions and Abatement Options**							
	Residual emissions	CCS	Electrification	Hydrogen	BECCS	Other	Energy efficiency	Resource efficiency & material substitution
Boiler / steam	0.37	2.72	2.88	4.74	0.07	0.00	1.67	0.96
Furnace	0.36	3.35	3.62	0.63	0.52	0.00	0.74	2.25
Generators & CHP	0.70	0.00	3.09	3.16	0.06	0.00	1.08	0.54
Machinery	0.34	0.00	1.91	4.60	0.00	0.00	0.06	0.03
Process CO_2	0.33	2.87	0.00	0.00	0.00	0.00	0.15	2.27
Kiln	0.10	0.00	0.01	0.74	1.59	0.00	0.08	2.17
Dryer	0.04	0.00	0.96	0.36	0.00	0.00	0.33	0.18
Oven	0.00	0.00	0.92	0.12	0.00	0.00	0.21	0.10
Methane venting & flaring	0.27	0.00	0.00	0.00	0.00	0.33	0.05	0.16
Other	0.29	0	0	0	0	0	0.03	0.02

Scenario: The UK *Climate Change Committee's 'Balanced Net Zero'* Transition Pathway.

Abbreviations: BECCS – biomass energy with CCS; CCS – carbon capture and storage; CHP – combined heat and power; CO_2 – carbon dioxide; GHG – greenhouse gas.

Source: Adapted from CCC (2020).

2021; Doyle, 2021), rising to 8-14 $MtCO_{2e}$ by 2050. Currently, GHG emissions from industry account for about 14% of total UK emissions. The IDS therefore holds out a vision of enabling a better, more competitive, and greener future for UK manufacturing and construction (HMG, 2021a; Kennedy, 2021). It suggests a funding stream of £1 billion (bn) to aid these cuts in emissions, and support for the creation of 80,000 jobs over the next 30 years. Investment will be channelled towards new low-carbon, efficient technologies and infrastructure. However, opposition political parties claim that there is no new cash – only the reallocation of funds already announced – and that the IDS lacks urgency and ambition compared to other industrialised countries. Nevertheless, it would encourage fuel switching, so that about 20 TWh *per year* of low-carbon power would be adopted within industry by 2030 from fuels such as H_2, bioenergy and renewable electricity replacing fossil fuels (HMG, 2021a; Doyle, 2021). According to the IDS, low-carbon H_2 could be consumed as an alternative fuel at a rate of 10-16 TWh *per year* by 2030, rising to 86 TWh by 2050. [The UK Government indicated that it would publish a subsequent '*UK Hydrogen Strategy*' later in 2021 (discussed in Section 5.2 below) that might indicate how this may be made up in terms of 'blue' or 'green' (or electrolytic) H_2 shares (as described in Section 2.3 above).] The IDS proposes the development of new and improved product standards, as well as co-ordinated action to use public procurement as a means of creating a demand for 'green' industrial products. Energy and resource efficiency – building on ideas around the notion of a *Circular Economy* (see Section 2.2 above) – are seen as playing a key role in reducing industrial GHG emissions in the 2020s. A 'carbon pricing tool', or penalty price, would be used to nudge firms towards the adoption of clean technologies. In addition, the UK Government will evaluate the impact of the new EU *carbon border adjustment mechanism* (CBAM) on the UK. This is a tariff, or import mechanism, intended to reduce 'carbon leakage' and protect domestic industry from foreign competition in countries that have a weaker carbon pricing system, i.e., without again "pushing emissions and business abroad". The IDS will also supports a '*Just Transition*' in the industrial sector in order to encourage workers to migrate from high-carbon to low-carbon jobs (HMG, 2021a; Doyle, 2021). Businesses would be assisted in upskilling and retraining their employees.

3.4.2 Support for Industrial Decarbonisation Clusters

Cluster regions of industrial activities in the UK have been identified as onshore networks linked to CO_2 storage sites under both the North Sea and the North East part of the Irish Sea (Cooper and Hammond, 2018). The UK distribution of these CO_2 point sources and their associated CCUS cluster regions are again shown in Fig. 4 (Griffin *et al.*, 2018a). They are principally along the east coast of Britain adjacent to depleted oil and gas fields in the North Sea: the Firth of Forth in Scotland, Teesside in the North East of England, and the Humber and Thames Estuaries on the East Coast of England. As part of the IDS, the *UK Research and Innovation* (UKRI) has allocated £171 M funding across nine major projects (HMG, 2021a; Kennedy, 2021). These industrial decarbonisation clusters are a principal component of the UKRI's *Industrial Strategy Change Fund* (ISCF). They include the *Net Zero Teesside* and *Zero Carbon Humber* (ZCH) projects in the North East of England, and *NECCUS* at Grangemouth (Firth of Forth) on the east coast of Scotland (another route to CCUS, along with the production of hydrogen at scale); see once again Fig. 4 (Griffin *et al.*, 2018a). The ZCH project seeks to facilitate shared trans-regional dual supply pipelines for both low-carbon H_2 and captured CO_2 emissions. This would create one of the world's first net-zero industrial clusters by 2040 led by 12 leading companies and organisations across the Humber region. Its anchor development is the proposed *Hydrogen to Humber* (H2H) Saltend scheme led by *Equinor* (formerly *Statoil*; Norwegian state-owned multi-national energy company) that plans to establish the world's largest so-called 'blue' H_2 production plant with CO_2 capture at the Saltend Chemicals Park. The *H2H Saltend* project will be the starting point for a CO_2 and H_2

pipeline network developed by *National Grid Ventures*, connecting EI industrial sites throughout the region. It would therefore offer businesses the option to directly capture their CO_2 emissions or fuel-switch to hydrogen. All captured CO_2 will be compressed at *Centrica Storage's* Easington site, and stored under the southern North Sea using offshore infrastructure shared with the Teesside industrial cluster (see again Fig. 4). The cluster could potentially facilitate the conversion of the *British Steel* works at Scunthorpe to H_2 firing (Griffin and Hammond, 2021); thereby providing them with the potential to reduce the carbon intensity of their operations. The main industrial area in Wales (and one of the largest agglomerations in the UK) includes the *Tata Steel* integrated steelworks at Port Talbot on its South Coast. However, Cooper and Hammond (2018) observed that there is not an appropriate CO_2 storage locations in its vicinity, i.e., beneath the Bristol Channel. Shipping is therefore likely to be used for transporting CO_2 from the planned *South Wales Industrial Cluster* (SWIC), perhaps to Liverpool Bay (on Merseyside) in order to be integrated into the proposed *HyNet North West* combined hydrogen/CCUS pipeline network. Unfortunately, most of the H_2 projects funded in the UKRI ISCF industrial decarbonisation cluster deployment competition involved 'blue hydrogen' production, and not the more innovative 'green hydrogen' developments that greatly reduces the generation of CO_2 emissions (see Section 2.3 above). Three offshore CO_2 storage sites in the North East and North West of England and Scotland make up the full portfolio of ISCF industrial cluster projects.

3.4.3 Decarbonising the Cement and Steel Sectors

The steel and cement sectors are significant emitters of greenhouse gases (see again Fig. 3). In this regard, the IDS suggests that the UK Government would examine ways to halt emissions from ore-based steel-making by 2035 as recommended by the *Climate Change Committee* (CCC, 2020; Doyle, 2021). The latter body additionally proposed that cement production should reach near-zero by 2040. Both these goals represent very considerable challenges that risk deindustrialisation, if implemented. The IDS observes that decarbonising the two large-scale blast furnaces at Port Talbot and Scunthorpe would be required for such a 'green steel' making transition pathway (Griffin and Hammond, 2021). Wisely, the UK Government proposes to take a 'technology neutral' approach, and would not rule out the possibility of retaining steel production using coking coal together with CCUS (HMG, 2021a; Doyle, 2021). Nevertheless, a reconstituted *UK Steel Council* will examine the implications of the CCC targets for ore-based steel-making (HMG, 2021a; Kennedy, 2021). This body consists of representatives from the six major steel companies in the UK with *UK Steel* (the industry's trade association), trade unions and the Devolved Administrations in attendance. The UK Government has made a commitment within the IDS to develop a £250 M public sector 'clean steel fund' that would come into operation around 2023 (HMG, 2021a; Doyle, 2021). This has been criticised by opposition political parties and environmental groups, who believe that multi-billion pound support for a transition to clean steel is required, e.g., in line with competitor industrialised nations like Germany.

In the context of the cement sector, the IDS expressed a willingness to explore various decarbonisation options (HMG, 2021a; Doyle, 2021), such as those described by Griffin *et al.* (2016). Cement production sites in Britain are not located near to the identified industrial clusters (see Fig. 4), and that would make the sector difficult to couple with CCUS facilities. Nevertheless, the IDS indicates that the UK Government will collaborate with the *Mineral Products Association* (MPA – the trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar and silica sand industries) in order to evaluate decarbonisation options for dispersed sites. Likewise, it would support product innovation towards novel low energy, low CO_2 cements (Griffin *et al.*, 2016). In the wider context of the built environment, the IDS commits the Government to providing £932 M in public support for nearly 430 individual low-carbon projects directed at local authority buildings, schools and hospitals. New rules will also be introduced for improve the performance of the largest commercial and industrial buildings across England and Wales aimed at saving 2 $MtCO_2$ *per year*. In addition, public funding will be used to support the development of low-carbon heating systems, such as energy efficiency measures, e.g., thermal insulation, LED lighting, and heat pumps. The pre-existing *Infrastructure Delivery Taskforce* will be renamed '*Project Speed*' to create a land use planning system fit for a new generation of low-carbon infrastructure (HMG, 2021a; Kennedy, 2021).

4. SUBSEQUENT UK POLICY DEVELOPMENTS

4.1 The COP26 Context

A rush by the UK Government to broaden their policy framework in terms of climate change mitigation and adaptation arose because it was the host of the 26th United Nations (UN) Climate Change *Conference of the Parties* (COP26) held in Glasgow over 1 – 12 November 2021. This was organised in partnership with the Italy, whose Government hosted a pre-COP Summit and related preparatory events (such as a youth conference) in Milan over 30 September – 2 October 2021. In this context, the UK Government wished to exhibit leadership and greater ambition ahead of COP26 in order to stimulate other participants (countries and other organisations) to take significant steps to secure their own pathways towards net zero GHG emissions, or so-called 'carbon neutrality', by 2050. Thus, in order to flush out their policy landscape they issued a new '*UK Hydrogen Strategy*' on 17 August 2021 (HMG, 2021b) and a '*Net Zero Strategy*' embracing all sectors of the economy on 19 October 2021 (HMG, 2021c). Environmental activists regarded this timing as being rather late given the nearness to the COP26 meeting, but these developments were nonetheless generally welcomed.

4.2 The 2021 *UK Hydrogen Strategy*

A comprehensive, first-ever UK hydrogen (H_2) strategy was flagged as early as the *10-Point Plan* document and the follow-on *IDS*. The British Government saw the launch of this strategy as key to its plans to "build back better" (HMG, 2021b) with a cleaner, greener energy system. Low-carbon H_2 was seen as a potential means of replacing high-carbon fuels and decarbonising some of the vital, albeit hard-to-abate, industrial sectors. The strategy confirms the ambition to secure an infrastructure that can support 5 GW of low carbon H_2 at scale by 2030 as set out in the *10-Point Plan* (see Sections 2.3 and 3.2 above); saving carbon (driving towards the *Sixth Carbon Budget* and 2050 net zero target), generating economic growth, and creating 9,000 'good quality' jobs. This would require a rapid ramp up of production over the forthcoming decade. The UK Government argued that the country was well positioned because of its geology, existing pipeline infrastructure, and technical know-how. Nevertheless, it will need new market and regulatory frameworks, as well as improved awareness and buy-in from potential H_2 users. The strategy envisages significant research and innovation in order to accelerate cost reduction and technology deployment; thereby effectively kick-starting a new industry. Linked analysis suggested that 20-35% of total energy requirements in the UK could be H_2-based by 2050, when potentially 100,000 jobs would have been created.

The new *UK Hydrogen Strategy* (HMG, 2021b) was widely welcomed by industrial companies in the sector, particularly its economy-wide and whole-systems approach. It had set out a number of subsequent consultations: on the preferred H_2 business model, the design of a £240 million *Net Zero Hydrogen Fund*, and a *UK Low Carbon Hydrogen Standard*. Again, the potential industrial partners expressed a willingness to engage in this process. There was some criticism from clean technology advocates and climate change campaigners for the emphasis on blue H_2 from SMR that was viewed as undermining the net zero challenge. In reality, the strategy took a 'twin track' approach embracing electrolytic (green) H_2 (Newborough and Cooley, 2020; 2021), in addition to blue H_2, although the detail would not be provided until later in 2022. Recently Howarth and Jacobson (2021) found that GHG emissions from blue H_2 was quite high; being only 18-25% less than grey H_2 (see Section 2.3 above) on a life-cycle basis, taking account of both CO_2 emissions and fugitive methane emissions. The balance between blue and green H_2 over the period to 2050 is not clearly spelt out in the strategy document (HMG, 2021b). These processes are both currently expensive and CCUS to generate blue H_2 is not yet in place at scale within the UK (but see the discussion in Section 2.3 above). Indeed, climate campaign groups believe that a reliance on blue H_2 could lock the UK into decades of North Sea gas production or a dependence on gas imports.

4.3 The 2021 UK *Net Zero Strategy* – Industrial Aspects

The 368-page *Net Zero Strategy* (NZS) (HMG, 2021c) builds on the Prime Minister's *10-Point Plan* for a '*Green Industrial Revolution*', and illustrates how the UK Government aims to meet the commitments set out in the earlier document (see Section 3.2 above). This NZS asserts that overall, the costs of action on climate change outweigh the costs of inaction (HMG, 2021c; Hawkes, 2021). It describes the interventions implicit in the strategy across all sectors of the British economy, based on a whole-systems approach. The analysis was underpinned by target-compliant 'indicative delivery pathways' for each sector of the economy out to 2037 with three routes to net zero, based on electrification, hydrogen and innovation. Implications for industry are the principal topic considered here. That indicated a target drop in industrial GHG emissions of 63-76% by 2035; roughly in line with that envisaged in the IDS (see Section 3.4 above). The NZS focused on the need for the UK Government to work with businesses to ensure deep cost reductions in low-carbon technologies through "fair carbon pricing" (HMG, 2021c) that would support up to 54,000 jobs by 2030. In order to 'build back greener' in line with net zero goals, the NZS seeks to attract inward investment, future-proof industrial sectors, and generate high-wage, high-skill jobs. The strategy aims to improve energy efficiency, demand-side measures [product labelling, the transparency of embodied emissions data (see, for example, Hammond and Jones, 2008; 2011), regulatory standards, and public and private procurement] and resource efficiency (or CE interventions), while growing new industries around renewable energy, low-carbon H_2, and CCUS (via a £1 bn *CCS Infrastructure Fund*). These will be integrated into industrial clusters (as depicted in Fig. 4); referred to as '*SuperPlaces*' (HMG, 2021c). It recognises that dispersed sites accounts for about half of industrial emissions in the UK. Accelerated decarbonisation might be achieved through industrial heat pumps for low temperature processes (like pasteurisation in food and drink manufacturing) and electrification of off-gas grid sites. A decision on the future of H_2 in the gas grid is a key infrastructure decision that the UK Government intends to take by 2026 (HMG, 2021c). Funding for *Mini-Cluster Industrial Decarbonisation Plans* could be announced in the early 2020s. In an ICE infrastructure blog, Hawkes (2021) suggests that the NZS provides "clear signals to the private sector about the direction of travel and where opportunities lie in the years ahead". Nevertheless, he recognised that there are gaps in the policy, including lack of details on specific CO_2 savings from the various proposed interventions and how they would be funded.

A long-term economic review of the transition to net zero was published by HM Treasury (HMT, 2021), alongside the NZS, that examined the key issues and trade-offs it raised. This noted that it would have significant fiscal impacts and place pressures on the public finances. Tax revenues will be eroded from fossil fuel related activities, including the *Vehicle Excise Duty* (VED) and fuel duties, leaving a potential deficit amounting to of £37 bn in 2019-20 (HMT, 2021; Hawkes, 2021). Road pricing might be one way of making good on this shortfall. Indeed, Hawkes (2021) observed that the ICE had previously argued for a 'pay as you go' (PAYG) road pricing model, and that public polling had indicated a willingness to see such a scheme replace both VED and other fuel duties. HM Treasury (2021) contended that the 'polluter pays principle' (Hammond, 2004) would prohibit the UK Government from passing costs on to future taxpayers rather than those who cause climate change. £26 bn of public funds would support green plans with a further £60 bn expected from the private sector (HMG, 2021c). The Prime Minister noted in his foreword to the NZS that nearly £6 bn in overseas investment had been received in the ten months since the publication of his *10-Point Plan*. HM Treasury (HMT, 2021), while highlighting the risk of imposing green taxes in pushing businesses abroad (see Section 2.3 above).

In their customary role of monitoring progress towards reducing UK GHG emissions and achieving 'carbon budgets' or targets, the *Committee on Climate Change* (CCC) undertook an independent assessment of the NZS (CCC, 2021). They welcomed the strategy as setting out, for the first time, how the UK Government would deliver on its 2050 net zero, as well as their interim target of a 75% GHG reduction by 2035 against a 1990 baseline (or 63% relative to 2019). The CCC viewed the 63-76% reduction target by 2035 (from 2019) as ambitious (CCC, 2021; Hakimian, 2021). They saw the *UK Emissions Trading Scheme* (UK ETS) that came into being on 1 January 2021 as a credible and key policy lever, although energy and carbon pricing reforms would be required for manufacturers not included in the scheme. The CCC noted that the NZS '*Balanced Pathway*' contains about £1.5 bn of private and public incentives for fuel switching and CCS in the period up to the end of 2024, which are likely to be further incentivised by the UK ETS (CCC, 2021). However, they felt there was a lack of detail in the NZS on both electrification and resource efficiency within industry (CCC, 2021; Hakimian, 2021). Ways of managing 'carbon leakage', such as maintaining tariffs or pursuing conditional market access [like *Carbon Border Adjustment Mechanisms* (CBAMs)] (HMG, 2021c), will need to be complimented by the development of measurement standards, e.g., based on the use of eco or carbon intensities (CCC, 2021).

5. CONCLUDING REMARKS

The UK contributed a little below 1% to annual global GHG emissions in 2018 [excluding land use change and forestry (LUCF)], whilst China emitted 26%, the USA 13%, the rest of the *European Union* (EU-27) 8%, India 7%, the Russia Federation 5%, Japan 3%, and Brazil 2% (updated from Hammond, 2019). Consequently, in order to mitigate climate change, the focus on reducing emissions requires action principally by these major emitter nations and regions. Alternatively, it can be argued that responsibility rests on those that have made the bulk of GHG emissions on a historic timescale. Such cumulative CO_2 emissions from fossil fuels and cement emitted over the period 1750-2018 (i.e., roughly since the start of the *Industrial Revolution* in the UK), again excluding LUCF, have led to the USA contributing 26%, which is nearly twice as much as China (14%). The EU-27 have emitted 18% historically, Russia 7%, the UK 5%, Japan 4%, and India 3% (updated from Hammond, 2019). Many of the larger annual emitters today, such as India and Brazil, are not therefore particularly significant in a historic context. Likewise, *per capita* GHG emissions in regional terms are sometimes used as part of an ethical argument over the responsibility for climate change: North America 13 tCO_2 *per capita*, Europe and the Middle East both about 8 tCO_2, Asia 4 tCO_2, South America 3 tCO_2, and Africa only 1 tCO_2. The global average is around 4.8 tCO_2 *per capita* (Hammond, 2019). It has therefore been suggested on a 'climate justice' or moral basis that the large *per capita* emitter industrialized countries should contract or reduce their GHG emissions, while that of the less developed nations are permitted to rise allowing economic growth in those countries (RCEP, 2000).

Notwithstanding the relatively modest annual GHG emissions from the UK, the British Government introduced a bold, legally-binding target of reducing the nation's GHG emissions overall to net-zero by 2050 in the amended *Climate Change Act* (CCA, 2019), i.e., balancing emissions with CO_2 removal, or achieving 'carbon neutrality'. In essence, this is an ethical argument without practical consequences for the Earth's climate. If the UK could stop emitting '*greenhouse gases*' immediately, it would have negligible impact on global warming. That is because the country only releases ~1% of the total annual world GHG budget presently and climate change is principally influenced by emissions discharged over the preceding century or so: the notional residence time of CO_2 in the atmosphere [see Section 1.1 above (Archer and Brovkin, 2008; Griffin and Hammond, 2021)]. Nevertheless, the UK Government was anxious to show global leadership on climate change mitigation in the run-up to the *United Nations Climate Change Summit* (COP26) that it hosted, in partnership with Italy, in Glasgow (Scotland) over 1-12 November 2021. The financial 'costs' of tackling the British contribution to global warming, and the associated lifestyle changes, will fall primarily on the ordinary citizens of the UK: 'the man and woman in the street' [classically, albeit endearingly, termed *The Common People* (by Cole and Postgate, 1949) or, in German, the *decent* ('Anständigen') *people* (see Clay, 2020)]. Consequently, the British Government and the Devolved Administrations need to be clear (or 'straight') with their citizens about the moral basis for its climate change actions going forward.

The industrial sector in the UK accounts for 19% of primary energy equivalent consumption in 2019 (BEIS, 2020b) and a corresponding 14% of 'greenhouse gases' (GHGs) (BEIS, 2020c). Prospects for reducing industrial energy demand and associated GHG emissions in British industry has consequently been evaluated here, although the lessons learned are applicable across much of the industrialised world. This sector embraces both *energy-intensive* (EI) and *non-energy-intensive* (NEI) industrial sub-sectors (see Fig. 2). The so-called *Foundation Industries* (FI) produce a significant share of the overall industrial GHG emissions in the UK, e.g., iron and steel (around 25% - Griffin and Hammond, 2019), chemicals (19% - Griffin *et al.*, 2018a), cement (8% - Griffin *et al.*, 2014; 2016), pulp and paper (6% - Griffin *et al.*, 2018b), and glass (3% - Griffin *et al.*, 2021): see again Fig. 1. In order to meet the UK Government's net zero target by 2050, both fossil fuel and process GHG emissions will need to be significantly reduced over this timeframe. The recently published *Industrial Decarbonisation Strategy* (IDS) (HMG, 2021a) has therefore been critically evaluated. Its policy content has been compared with the latest recommendations of the UK Government's independent *Climate Change Committee* (CCC), as well as drawing on lessons from the techno-economic assessments published by the author and his collaborators for a number of key FI (Griffin *et al.*, 2014; 2016; 2018a; 2018b; 2021; Griffin and Hammond, 2019; 2021). Overall, the IDS has been welcomed by industry, NGOs and several 'green' groups, but it received some criticism for many "reheated pledges", little new funding, and investment levels that are projected to be significantly lower than equivalent programmes in, for example, France and Germany. However, the UK Government has wisely taken a 'technology neutral' approach to the possibility of retaining steel production using coking coal together with CCUS. That is against the recommendation of the CCC to halt emissions from ore-based steel making by 2035 (CCC, 2020). Deep decarbonisation of the steel production in the latter way might well result in 'deindustrialisation' of the sector, i.e., "pushing emissions and business abroad", and thereby leaving large-scale blast furnaces as 'stranded assets' (Griffin and Hammond, 2021). The UK Government's legally-binding 2050 net zero emissions target (i.e., 100% abatement) applies across the economy as a whole (CCA, 2019; CCC, 2019a; 2019b), but the use of 'negative emissions' technologies (Kruger and Darton, 2013; Solano Rodriguez *et al.*, 2017; Gough *et al.*, 2018a; Griffin *et al.*, 2018a; 2018b) in some sectors will provide the opportunity for variation between different end-use energy demand sectors and various industries (CCC, 2018a). There are a number of hard-to-abate industrial sectors, particularly amongst the FI, that may need to take advantage of this 'headroom' in achieving net zero emissions (Griffin and Hammond, 2021): the steel industry is certainly one of those.

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