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Research Paper

Industrial decarbonisation of the pulp and paper sector: A UK perspective

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A B S T R A C T

The potential for reducing industrial energy demand and 'greenhouse gas' (GHG) emissions in the *Pulp and Paper* sector (hereinafter denoted as the *paper* industry) has been evaluated within a United Kingdom (UK) context, although the lessons learned are applicable across much of the industrialised world. This sector gives rise to about 6% of UK industrial GHG emissions resulting principally from fuel use (including that indirectly emitted because of electricity use). It can be characterised as being heterogeneous with a diverse range of product outputs (including banknotes, books, magazines, newspapers and packaging, such as corrugated paper and board), and sits roughly on the boundary between *energy-intensive* (EI) and *non-energy-intensive* (NEI) industrial sectors. This novel assessment was conducted in the context of the historical development of the *paper* sector, as well as its contemporary industrial structure. Some 70% of recovered or recycled fibre is employed to make *paper* products in the UK. Fuel use in *combined heat and power* (CHP) plant has been modelled in terms of so-called 'auto-generation'. Special care was taken not to 'double count' auto-generation and grid decarbonisation; so that the relative contributions of each have been accounted for separately. Most of the electricity generated via steam boilers or CHP is used within the sector, with only a small amount exported. Currently-available technologies will lead to further, short-term energy and GHG emissions savings in *paper* mills, but the prospects for the commercial exploitation of innovative technologies by mid-21st century is speculative. The possible role of bioenergy as a fuel resource going forward has also been appraised. Finally, a set of low-carbon UK 'technology roadmaps' for the *paper* sector out to 2050 have been developed and evaluated, based on various alternative scenarios. These yield transition pathways that represent forward projections which match short-term and long-term (2050) targets with specific technological solutions to help meet the key energy saving and decarbonisation goals. The content of these roadmaps were built up on the basis of the improvement potentials associated with different processes employed in the *paper* industry. Under a *Reasonable Action* scenario, the total GHG emissions from the sector are likely to fall over the period 1990–2050 by almost exactly an 80%; coincidentally matching GHG reduction targets established for the UK economy as a whole. However, the findings of this study indicate that the attainment of a significant decline in GHG emissions over the long-term will depends critically on the adoption of a small number of key technologies [e.g., energy efficiency and heat recovery techniques, bioenergy (with and without CHP), and the electrification of heat], alongside a decarbonisation of the electricity supply. The present roadmaps help identify the steps needed to be undertaken by developers, policy makers and other stakeholders in order to ensure the decarbonisation of the UK *paper* sector.

1. Introduction

1.1. Background

The industrial sector in the *United Kingdom of Great Britain and Northern Ireland* (UK) accounts for 17% of total final energy consumption [1] and a corresponding 20% of carbon emissions [2] in 2015. 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 (see Fig. 1 [3]). It is clear that the pulp and paper subsector (hereinafter denoted as the *paper* industry) as seen in Fig. 1 gives rise to the sixth highest industrial energy consumption in the UK; caused by a combination of drying/separation processes (40%), low temperature heating processes (28%), compressed air requirements (10%), space heating (8%) and electrical motors (6%) [3]. UK industry overall has been found to

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Nomenclature

Abbreviations

BAT	Best Available Technology
BCE	before the 'Common Era'
BGS	British Geological Survey
BPT	Best Practice Technology
CCA	Climate Change Agreements
CCL	Climate Change Levy
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CE	(in the) 'Common Era'
CEPI	Confederation of European Paper Industries
CHP	Combined Heat and Power
CPI	Confederation of Paper Industries (in the UK)
CT	(the UK) Carbon Trust
DECC	(the former UK) Department of Energy and Climate Change
DNO	Distribution Network Operator
DSF	Demand-Side Flexibility
DSP	Demand Side Participation
DSR	Demand Side Response
DUKES	Digest of United Kingdom Energy Statistics (annual)
ECN	Energy research Centre of the Netherlands
ECUK	Energy Consumption in the UK (DECC annual statistical publication)
EI	energy-intensive
EU	European Union
EU-ETS	EU Emissions Trading Scheme
GB	Great Britain
GHG	'greenhouse' gas
GOS	(the UK) Government Office of Science
H:P	heat-to-power ratio
I&C	industrial and commercial
ICT	information and communications technology
IEA	International Energy Agency
IOP	Index of Production (ONS statistical bulletin)
IPPC	Integrated Pollution Prevention and Control (EU regulatory data)
LA	Low Action (scenario)
NEI	non-energy-intensive
NG	natural gas
NP RES	'non-programmable' renewable energy sources
ONS	Office of National Statistics (for the UK)
ORC	organic Rankine cycle
PRODCOM	'Production Communautaire' (Community Production – EU statistical database)
PV	(solar) photovoltaic (power generators)
RA	Reasonable Action (scenario)
RA-CCS	Reasonable Action together with Carbon Capture & Storage (scenario)
RCUK	Research Councils UK
RT	Radical Transition (scenario)
SEC	specific energy consumption
SIC	(UK) Standard Industrial Classification
SRF	solid recovered fuel
UED	(the industrial) Usable Energy Database
UK	United Kingdom of Great Britain and Northern Ireland
UKERC	UK Energy Research Centre

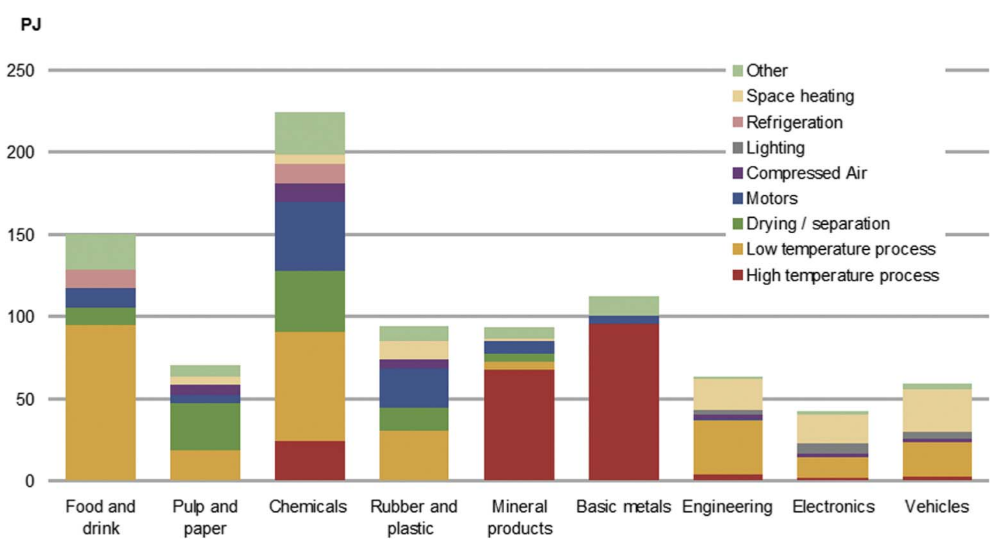

Fig. 1. Final UK energy demand by industrial subsector and end-use. *Source:* Norman [3].

consist of some 350 separate combinations of sub-sectors, devices and technologies [4,5]. Nevertheless, it is the only end-use energy demand sector in the UK that has experienced a significant fall of roughly 60% in final energy consumption over the period 1970–2015 [1]. This was in spite of a rise of over 40% in industrial output in value added terms. However, the aggregate reduction in energy intensity (MJ/£ of gross value added) fell by 38 per cent during 1990–2015 [1], 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 price mechanism [4,5]); *structural changes in industry* [a move away from *energy-intensive* (EI) industries towards *non-energy-intensive* (NEI) ones, including services [4,5]}; 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).

1.2. The issues considered

The present study builds on work by Dyer et al. [4], commissioned by the UK *Government Office of Science* (GOS), Hammond and Norman [6], and on a recent 'Advanced Review' by Griffin et al. [7]. In each case, a variety of assessment techniques for determining potential energy use and 'greenhouse gas' (GHG) reductions were discussed. Griffin et al. [7] then evaluated the wider UK industrial landscape with the aid of decomposition analysis [8] in order to identify the factors that have led to energy and carbon savings over recent decades. They consequently assessed the improvement potential in two sectors: 'Cement' and 'Food & Drink', which represent the EI and NEI industrial sectors respectively. Here the pulp and paper sector of UK industry is examined in terms of their energy use and GHG emissions, as well as its improvement potential. It can be characterised as being heterogeneous (having a diverse range of product outputs, including banknotes, books, magazines, newspapers and packaging, such as corrugated paper and board), and as sitting on the rough boundary between EI and NEI industries (see Fig. 2 [7]). [A high value in any of the measures shown in Fig. 2 suggests that a given sub-sector would be EI.] However, the *Confederation of Paper Industries* (CPI), the trade association, regards the industry as being EI. It accounts for some 6% of GHG emissions from UK industry as shown in Fig. 3 [7]. Notwithstanding the growth of electronic media, domestic consumers and businesses continue to make use of paper in all its many forms.

The opportunities and challenges to reducing industrial energy demand and *carbon dioxide equivalent* (CO_{2e}) emissions (carbon dioxide is the principal GHG [5]) in the British *paper* industry have been evaluated, although the lessons learned are applicable across much of the industrialised world. The data here has been largely extracted from an industrial *Usable Energy Database* (UED) that was produced for the *UK Energy Research Centre* (UKERC) [actually an academic community or network funded by the *Research Councils UK (RCUK) Energy Programme*] by the present authors (see Griffin et al. [7,9,10]). A set of industrial decarbonisation 'technology roadmaps' out to 2050 are finally reported, based on various alternative scenarios: named *Low Action* (LA), *Reasonable Action* (RA), *Reasonable Action including Carbon Capture and Storage (CCS)* [RA-CCS], and *Radical Transition* (RT) respectively. Such roadmaps represent future projections that match short-term (say out to 2035) and long-term (2050) targets with specific technological solutions to help meet the key energy saving and decarbonisation goals. Their contents were built up in the present study on the basis of the improvement potentials associated with various processes employed in the *paper* industry and embedded in the UED [7,9,10]. They help identify the steps needed to be made by industrialists, policy makers and other stakeholders in order to ensure the decarbonisation of the UK *paper* sector.

2. The pulp and paper sector

2.1. Historical development of the paper industry

The historical context in which the various industrial sectors are viewed has changed over time. Sir Neil Cossons (an industrial archaeologist and former Director of the *Science Museum* in London, 1986–2000), for example, placed the *paper* sector under the broad umbrella of 'The Chemical Industries' [11]. This was because (at least since the 1870s) pulp - from which paper is produced - had to be boiled, along with a variety of acid and alkaline reagents, in order to purify or remove contaminants. But it was Arabic science from about 3500 BCE, based largely in Egypt and the Near East, that led to what is now recognised as chemicals [12,13]: the early smelting of metals [especially copper, gold and mercury (or '*quicksilver*'), as well as alloys like bronze] gave rise to an understanding of the properties of their chemical compounds. The Egyptians had paper and ink with which to write [14]. They made paper from the pith of the papyrus reed, which was cut into strips and laid across each other at right angles, then pressed, dried, smoothed, and gummed together in order to form a roll. Ink was made from a lamp-black and gum solution, and their pens (used brush-wise at first, but later cut into quills) from rushes. Ancient Egypt had a monopoly on papyrus, but was obviously able to export it [14]. They had no need to resort to *cuneiform* writing [12]; first developed by the ancient Sumerians of Mesopotamia (c. 3500–3000 BCE). This term originally came from the Latin 'cuneus', whereby a wedge-shaped stylus was used to make impressions on a clay or similar surface. Egypt's hieroglyphic script meant that it provided a major stimulus to the spread of writing amongst its neighbours [14]; both to the east and west. Indeed, the Islamic civilisation was in direct contact with the Far East by the *Early Middle Ages* (6th to the 10th Century CE) [12]. The Arabic world imported from the east valuable materials (including high-quality steel, paper, porcelain and silk) and other elements of knowledge, such as the Indian system of mathematical notation (which is still known today as 'Arabic numerals') [14].

The fruits of Arabic science and technology progressively migrated across Europe. But the only significant advance made in the Ancient Greek and Roman civilisations in terms of writing was in the replacement of papyrus by parchment [14]. This parchment was made from untanned leather, with the best quality ('vellum') being made from the skin of a very young calf or kid [15]. It was worked and soaked in lime to get rid of dirt and large amounts of natural grease; dried on a stretching-frame; shaped with a knife; and then smoothed to produce a perfect writing-surface [14]. (In the UK, *Acts of Parliament* are still printed on vellum for archival purposes.) However, parchment was mainly replaced by paper; the earliest paper being referred to as 'cloth parchment'. The invention of printing with movable type by Johannes Gutenberg (the German blacksmith, goldsmith, printer and publisher; c. 1398–1468) [16] and the increasing demand for books ultimately led to the development of good quality paper from rag pulp [15]. It was in fact produced from various raw materials of a fibrous nature, not just rags from linen or cotton, but also from straw or wood [14,17]. Pulp was manufactured by pulverising such cellulosic ingredients, highly diluted with water, in order to disperse the fibres [11,14,16], and then pouring the resulting thick liquid pulp into sieves (or 'moulds') [15]. This would ensure that the fibre retained the necessary shape from which it could be sequentially pounded in a vat and dried [15,17]. The rectangular mould - a screen or tray with a fine wire screen surrounded by a wooden frame (or 'deckle') across the bottom [11] - was dipped into the vat and then held up to drain. In the 15th Century there were about 11 wires to the cm, but this was gradually increased to produce finer paper [12]. The paper on the bottom of the tray was then placed onto woollen felt [14], and constructed as a 'quire' of some 144 sheets and felts [17]; prior to going under a screw press. Sheets of pressed paper would be separated from the felts, and subsequently laid out on drying racks in the atmosphere; typically in a loft [11,15]. Additives, such as china clay or gypsum, were mixed with the pulp to provide 'filling' and gloss, thereby improving the quality of the finished paper for artwork or illustrations [11,14,15]. Thus, by the age of the English literary writer Dr. Samuel Johnson (1709–1784) printing was already 300 years old and, from the perspective of the user (in contrast to the maker), the printed book was not fundamentally different from books today [14]. In 1700 there were around 100 paper mills in England; over half were in the South East (clustered around London), and the rest quite widely spread [17]. By this time water power was often used at paper mills to drive the machinery that pounded the rags into pulp [17]. A good supply of pure water was also essential for mixing with the rags.

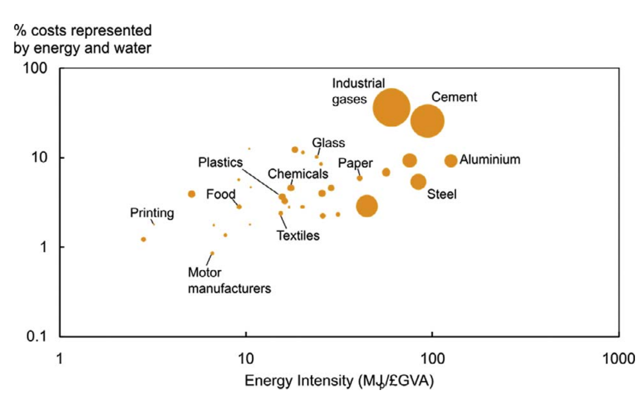

Fig. 2. Primary energy intensity, percentage of costs represented by energy and water, and mean primary energy use per enterprise (reflected by the area of the data points). *Source:* adapted from Griffin et al. [7].

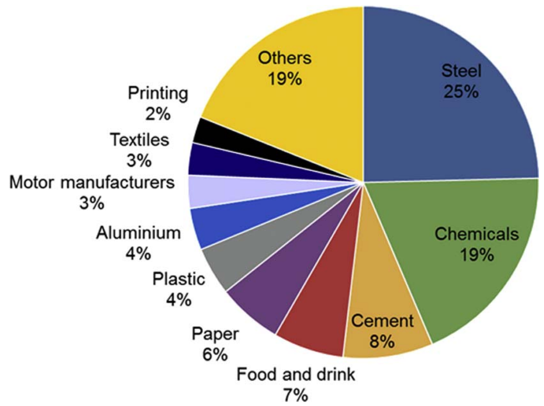

Fig. 3. *Greenhouse gas* (GHG) emissions from UK industry. Source: adapted from Griffin et al. [7].

Significant innovations in paper-making accompanied the so-called *Industrial Revolution* in the UK from about 1760 CE onwards [11,14,15] accompanying, for example, the discovery of ways of bulk-producing acids and alkalis. Such developments came about from a fusion of empirical 'rules of thumb' with the basic sciences [12]. The first steam engine to drive a paper mill was installed at Wilmington near Hull in about 1786, and there were several steam-powered mills located in various parts of Britain by 1815 [17]. Machines to make paper on an endless 'web' (similar to that patented by John Gamble in 1801) were built by the London inventor and engineer Bryan Donkin [17] in 1804 in order to replace the earlier batch type of process [11]. Pulp was poured onto a moving web (belt or cylindrical drum) from which it was drawn out as a continuous sheet, and then dried on rollers [15]. Variants of this design were installed by Henry and Sealy Fourdrinier in paper mills that continuously produced paper or board at Two Waters and Frogmore in Hertfordshire, and at St Neots in Huntingdonshire (see Fig. 4 [18]). Donkin subsequently developed a rotating type bed that came into practice in 1813 [17], and which further increased the speed of printing [14]. A dramatic rise in the reading public in the latter half of the 19th Century led to a significant increase in the consumption of paper, even before the excise duty was abolished in 1861 [14]. The provision of the first municipal libraries in Britain around 1850 generated interest in books and, after the newspaper tax was repealed (in 1855), the number of newspapers trebled in forty years [14]. This demand could not be met from linen and cotton rags and straw, and *Esparto* grass from Spain and North Africa began to be imported [14]. However, the real solution to this problem was the use of wood-pulp, which progressively replaced rags with cellulose fibre from coniferous trees [11,14]. The pulp was initially prepared by using grindstones immersed in water containing ready-cut logs. But this did not remove detrimental resin and other impurities, and from 1873 onwards chemical wood-pulp was employed by boiling wood chips with soda or sulphite solutions. This provided most of the input material for the great rolls needed by the emergent newspaper industry [14].

2.2. Structure of the modern pulp and paper sector

A modern paper-making machine is usually an enhanced version of the *Fourdrinier* type [11] (see again Fig. 4), which uses a specially woven plastic fabric mesh conveyor belt that is often several hundred metres long. The proportion of the machine involved in removing water from the web either by drainage or steam represents over 90% of the total length [11]. The speed at which paper, and more particularly multi-layer boards can be produced is determined by the rate at which the water can be removed from the webs [11]. An innovative development in the early 1960 s was the 'Inverform' machine in which water is removed under gravity from below and with the aid of a vacuum box from above the webs [11]. This paper-making device can be used for the manufacture of single or multi-ply grades of paper, and is capable of extremely high operating speeds. The contemporary *paper* industry is a relatively high technology sector that takes full advantage to modern developments in electronics and *Information and Communications Technology* (ICT), such as for the automatic control and monitoring of paper-making plants [19]. Wood-pulp for the British industry is now typically produced from resources obtained via the timber industries in Canada and Scandinavia, as well as from Scotland [15]. The UK *paper* sector has continued to innovate and has invested heavily, for example, in a modern newsprint machine (producing 400,000 tonnes of newsprint per year) and £300 M in a state-of-the-art containerboard machine to produce lightweight paper [19].

The consumption of paper and board products in the UK amounted to just over 10.5 Mt in 2010 (the baseline year for the present study) according to the national trade association: the *Confederation of Paper Industries* (CPI) [20]. There was a modest decline of some 2% per annum thereafter. Corrugated paper demand corresponded to around 2.15 Mt in 2010, which has risen modestly in recent years (to ~2.3 Mt in 2015) [20]. These demands were met with the aid of 3.8 Mt of recovered or recycled paper in the base year. Indigenous production of paper and board was about 4.3 Mt in 2010 from just over 50 paper mills of varying sizes and specialisms [20] (having ~9000 employees). Parent reel tissue production was only around 730 kt. These mills utilised 1.1 Mt of wood-pulp (0.9 Mt from indigenous sources and 0.2 Mt imported), as well as sawmill residues, like wood chips [20]. Timber extracted in the UK for pulp and paper production amounts to less than 5%, and comes typically via virgin wood fibre from sustainably managed and certified forests [19]. Recovered paper has steadily increased since the 1950 s [19] to the current level of 3.75 Mt. Indeed, the British *paper* industry has a recycling rate of ~80% (collected from both households and businesses), which is the highest of any material. However, there are constraints on the quantity of paper fibre that can be recycled [19]. Around only 19% is not recyclable, because (i) it increasingly degrades as it is goes through successive recycling phases (up to about a maximum of 7 times, although in Europe it now stands at 3.4 cycles); (ii) it is kept embodied in artistic works, books, photographs or wall paper; or (iii) it disintegrates when used in the form of cigarette or sanitary papers [19]. The UK was a significant exporter of recovered paper amounting to some 4.3 Mt that went to China (~75%), the *European Union* (EU) (~14%), India (~5%), Indonesia (~3%), and the Rest of the World (~3%) [20]. This helps reduce 'carbon footprints' of paper-making elsewhere around the world.

Fuel consumption in the UK paper and board sector is dominated by boiler and *combined heat and power* (CHP) or co-generation plants for process electricity and steam production. Energy is required to drive machinery and to generate heat to dry the paper produced [19]. Fuel demands are mostly met by natural gas (NG), although biomass is increasingly being utilised and presently accounts for about 15% of sector

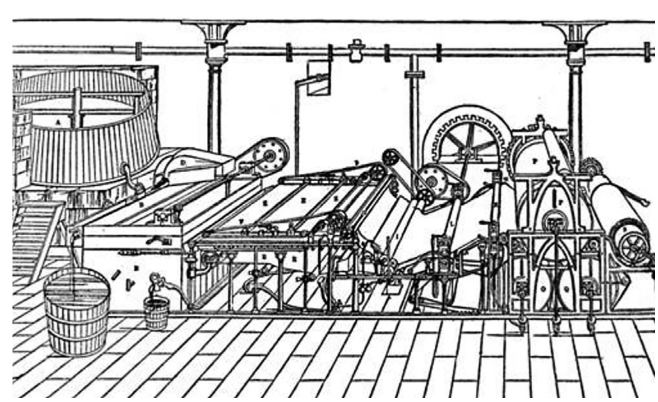

Fig. 4. The traditional Fourdrinier paper-making machine of the type built by Bryan Donkin. *Source:* adapted from the University of Michigan, 1920 [18].

fuel consumption. Paper is formed and dried from pulp, and finished into paper products. Just two mills were fully integrated pulp and paper operations. Final energy demand at typical mills is dominated by the dryer section in which steam-heated cylinders heat the paper fibres to around 100 °C [21]. The physical unit of production for the sector is *tonnes of paper and board* (tpb). UK sector energy demand in 2010 was 60 PJ; of which fuel demand was 53 PJ. Imported electricity was 8.5 PJ, whilst the corresponding power supplies exported was 1.5 PJ. The UK paper-making industry reduced its total energy consumption by 34% per tonne of paper made between 1990 and 2010 [19]. Production was 4.3 Mtpb in 2010; resulting in a direct *specific energy consumption* (SEC) of 12.2 GJ/tpb and primary SEC of about 19 GJ/tpb. Energy costs amount to about 30% of the total cost of paper-making [19]. Direct GHG emissions were some 2.3 $MtCO_2e$; a reduction of 42% over the period 1990–2010, due to investment in lower carbon energy sources [19]. The corresponding total emissions, including those attributable to net electricity, were 3.3 $MtCO_2e$. Large and complex paper mills typically take control of their energy supplies by building CHP plants that are more efficient than separate supply of electricity and heat, and reduce GHG emissions and generating costs [19]. A number of such CHP plants use biogenic (wood) waste, which is a renewable resource and gives rise to further reductions in GHG emissions. The UK paper sector is the largest user and producer of bioenergy in Europe [19].

3. Methods and materials

3.1. A Hybrid top-down/bottom-up approach

There are two broad ways to modelling the industrial sector [7]: top-down and bottom-up approaches, as illustrated in Fig. 5 (adapted and elaborated from those presented by Dyer et al. [21] and Griffin et al. [7]). A top-down approach splits industry into sub-sectors, usually based on available statistical data, and uses this data to determine energy use, output, energy intensity and other measures for which data is available. This approach has the advantage of covering a large proportion of energy demand, but it is limited by the level of disaggregation available from industry-wide statistical sources. Thus, the conclusions that can be drawn from such top-down studies are often only indicative in nature. In contrast, a bottom-up approach would typically focus on a single industrial sub-sector. Energy use can then be separated into lower order sub-sectors, processes or manufacturing plants. The data used for this type of bottom-up study typically comes from more specific information sources, such as trade associations, company reports, and case studies. Such a bottom-up study can therefore be useful in terms of presenting more accurate findings [22,23], although it will be limited in the breadth of its application.

An innovative hybrid approach was employed to develop the industrial *Usable Energy Database* (UED) [9,10], produced by the present authors for the whole of the UK industrial sector as part of the research programme of the *UK Energy Research Centre* (UKERC). Aspects of both top-down and bottom-up models were adopted, with detailed bottom-up studies set within a top-down framework. Using this novel approach would normally entail focusing on a number of sub-sectors for the bottom-up study [7], with the remainder of the sector being treated in a generic manner. Sub-sectors that use a large amount of energy are obviously prioritised for bottom-up studies. In additional, sub-sectors that use energy in a relatively homogeneous manner are easier to analyse, and this may also be considered when selecting appropriate sub-sectors. Sub-sectors that are not the subject of detailed bottom-up modelling require a focus on the potential reduction in emissions through widely used, 'cross-cutting' technologies can be useful [7,9,10].

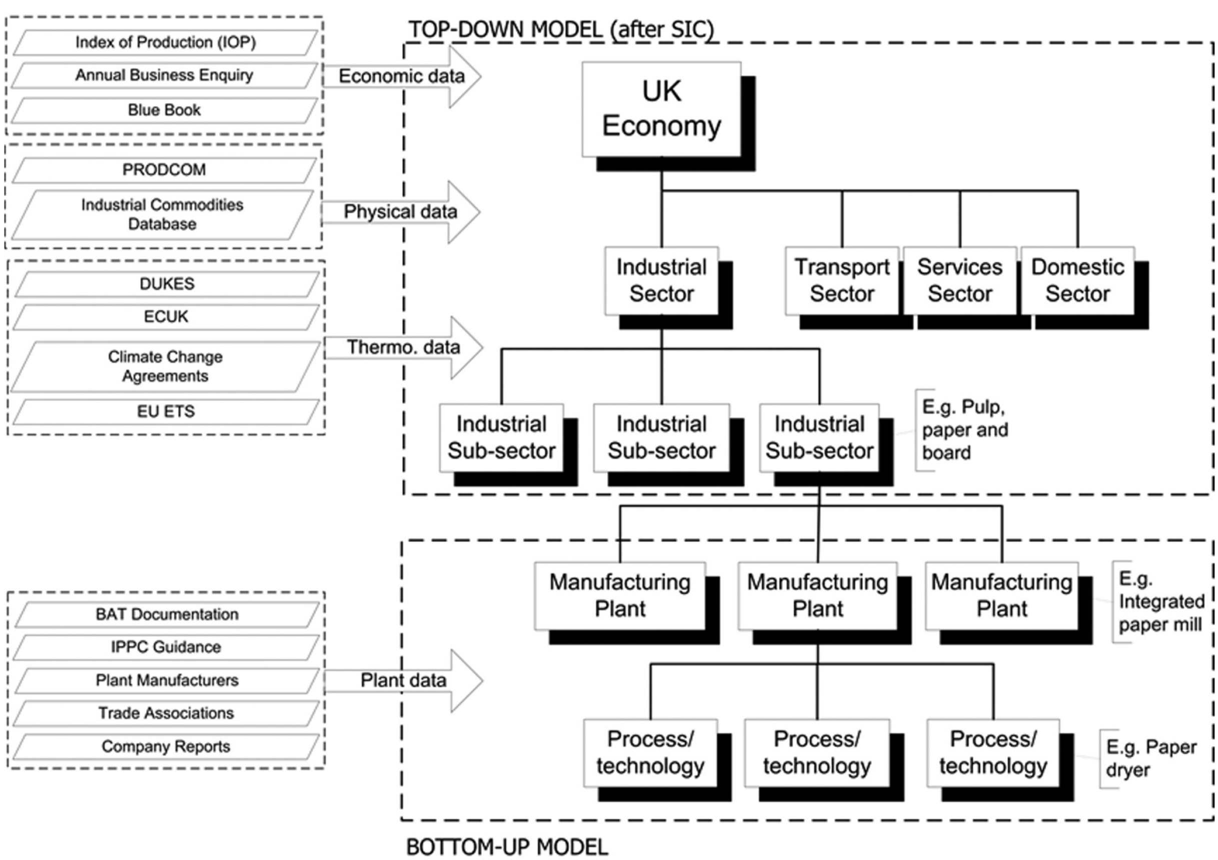

Fig. 5. Schematic representation of an integrated top-down and bottom-up modelling approach for the UK industrial sector. *Source:* elaborated from the diagrams presented in Dyer et al. [21] and Griffin et al. [7].

3.2. The baseline conditions

The energy inputs to the UED pulp and paper section were based on information from the trade association (David Morgan, CPI, private communication, 2013). This covers all paper mills (51 sites) in the UK (see the Sankey-type energy flow diagram presented in Fig. 6), but not the manufacture of "finished paper products" that use energy in a different manner. The information here covers the UK *Standard Industrial Classification* (SIC) Code (2007) 17.12 [24]. Their energy use covered around 50% of energy demand at the 3 digit SIC level (i.e., SIC 17.1 - *Manufacture of pulp, paper and paperboard)*, according to the UK Government's former *Department of Energy and Climate Change* (DECC) [25]. Output from these mills was taken from the information submitted by industrial companies as a requirement of *Climate Change Agreements* (CCA) and collated by AEA [26]; what is now the consultancy *Ricardo Energy & Environment*. CCA are voluntary agreements between UK industry and the UK Government's *Environment Agency* aimed at delivering reductions in energy use and GHG emissions. Operators receive a discount on the *Climate Change Levy* (CCL), effectively a tax on energy delivered to UK non-domestic users, of 90% on electricity bills and 65% on other qualifying input fuels. The CCA for the *paper* sector is administered by a wholly-owned subsidiary of the CPI [27]; the *Paper Sector Climate Change Management Co. Ltd.* Direct GHG emissions come under the remit of the *EU Emissions Trading Scheme* (EU-ETS). SEC data is reported for the *paper* sector for some 46 UK paper mills in 2015 [27]. The basis of this information was again confirmed by the CPI (David Morgan, CPI, private communication, 2013), although the energy demand differed slightly from that reported under the CCA, due to the inclusion of renewable energy sources (that is not reported under CCA). Economic output was taken from the UK Government's *Annual Business Survey* [28].

Fuel use by CHP plants was based on reported auto-generated electricity (again via David Morgan, CPI, private communication, 2013), and sector heat-to-power (H:P) ratio was calculated from the *Digest of United Kingdom Energy Statistics* (DUKES) [29]. Similarly, the overall efficiency of CHP was taken from DUKES. Information on exported electricity from CHP was given by the CPI (Morgan, 2013). The fuel used in producing this exported electricity was calculated based on information from DUKES [29]. The Sankey diagram (shown in Fig. 6) depicts the 2010 baseline division of energy inputs (fuels and primary electricity) against comparative outputs (associated with the core paper machines and ancillary processes). The thickness of the 'arrows', 'links', or 'lines' is proportional to the quantity of energy. The major role of CHP plants in providing both heat and power is illustrated as an intermediate node or process. Non-CHP fuel input is assumed to be used in steam systems, based on a report by the UK *Carbon Trust* (CT) [30]. The SEC of the various processes was then based on information adopted from that study [30], although they were scaled to match the total electricity demand reported by the CPI (Morgan, 2013). Using the same scaling factor for steam use yielded a boiler efficiency of 82%. This is high in comparison to the average for the industrial sector, but not unreasonably so.

3.3. Improvement potential

3.3.1. The overall context

Improvement potentials were initially extracted from the CT study [30], which particularly focuses on UK *paper* manufacturing rather than on the pulp sub-sector. This mainly covers short-term opportunities, and so was therefore supplemented by information from alternative (international) sources that cover opportunities that involve more major changes to the production process [21,31,32]. There may be some potential for greater use of the wastes from paper production as fuels, for example, and this was considered in the UED in terms of CHP gasification. However, there was insufficient technical information available to give greater consideration of this opportunity. Pulp production is comparatively small in the UK. The sector already uses both a substantial amount of recycling and imported pulp. Domestic pulp represents just ~6% of the sector input [30], with only two integrated mills in the UK that use mechanical pulping. They could technically convert to chemical pulping, and use the products produced (so-called 'black liquor') to become net zero GHG emitters. Thus, pulp production was not included in the UED.

3.3.2. Fuel switching - towards a bio-economy

The *Confederation of European Paper Industries* (CEPI) [33], a Brussels-based non-profit-making organisation representing the European pulp and paper industry, has recommended the further conversion of industrial installations to low or zero carbon energy use, particularly from renewable sources. 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 leads to 'negative emissions' when coupled to CCS facilities [34]. It has more recently been proposed in a Swedish context [35,36] to integrate a biorefinery with pulp and paper mills in order to produce high value chemical products [23] alongside conventional outputs. The UK Government's *UK and Global Bioenergy Resource Model* (an updated feedstock availability model) suggests that there is substantial quantities of indigenous biomass and biogenic waste available even accounting for the application of more stringent sustainability and land use criteria [37]. The total 2030 UK bioenergy resources might be equivalent to some 850–1120 PJ; with accessible resources of perhaps 580–672 PJ. But many industrial sectors will be competing for this resource alongside, for example, power generation. This is likely to, in any case, drive up biofuel prices. Nevertheless, the UK pulp and paper sector is already substantially invested in the use of biomass feedstock as both a raw material and fuel, although the CPI has advocated further government support for the expansion of UK agricultural land use for woody biomass. On-site residuals from *paper* production (such as 'black liquor, waste fibre, bark and fines) are used to generate a biogenic replacement (*syngas*) for natural gas via gasification. This can be obtained using a variety of feedstocks: *solid recovered fuel* (SRF), waste wood, and other waste materials. Unfortunately, in their stakeholder engagement with the UK Government, representatives of the *paper* industry (via the CPI)

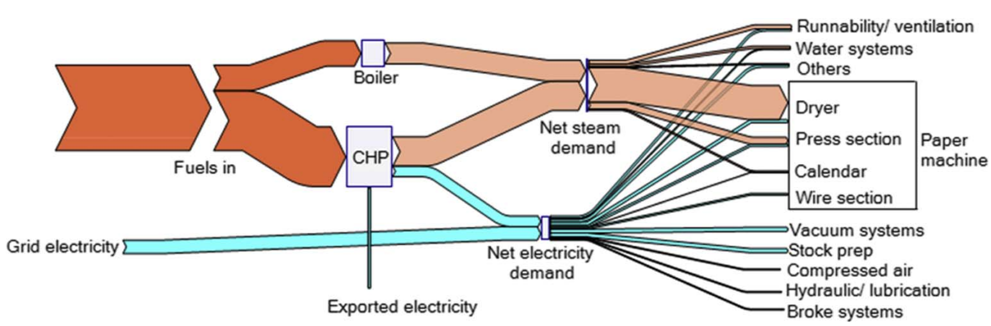

Fig. 6. Sankey energy flow diagram of the UK *Pulp and Paper* sector as modelled here; baseline data in 2010. *Source:* Griffin et al. [9].

noted that the costs of such gasification are high and rather unreliable. Presently all direct heat, around 13.5% of that is generated in the UK *paper* industry, is produced from the burning of NG. Some 2.2 TWh is produced from biofuels - constituting 23% of all fuels utilised in the sector. Indeed, the CPI have suggested to the UK Government that it could be a promising candidate for an above average share of biomass for electricity and heat (> 7% by 2030). That would be equivalent to a growth of biomass use of around 4% per annum, or some 22,000 tonnes of additional resource. According to the CPI, the main technological opportunities going forward are likely to be in the areas of CHP and, in the longer term, CCS. Residuals from paper-making can be employed as a new feedstock for low-quality paper, as a source of minerals, or else applied in the construction sector. A downside of paper waste utilisation is the production of ash from its incineration, which is contaminated with heavy metals from dyes, inks and surface treatments.

3.3.3. Energy efficiency and heat recovery

In meeting the twin challenges of climate change mitigation and energy security, the UK Government's *Carbon Plan* [38] set out a number of guiding principles. The first among them was to use less energy in the most cost-effective manner in industry as elsewhere. This central role for energy efficiency improvements were echoed at an international level by the *International Energy Agency* (IEA) [39], by the EU [40], and countries like Germany [41] and Sweden [42,43]. The IEA have attempted to capture the highest potential reduction in global emissions from efficiency measures in their clean energy pathways or roadmaps out to 2050 [39]. They argue that the cost savings accrued from reducing energy demand could outweigh additional costs by 2.5:1 and, after discounting future savings to present money with a 10% discount rate, save several trillion US dollars. The IEA suggest that the implementation of *Best Available Technologies* (BATs) - those that are proven technologies, but which may not yet be economically viable - could reduce energy consumption by 20% from current levels [39]. They argue that the BATs offer some of the most promising least-cost options for reducing energy consumption and GHG emissions in industry. But action is needed to invest in new facilities and to retrofit equipment that reach BAT levels, otherwise this capacity will be suboptimal and very costly to upgrade.

Energy efficiency measures have therefore been widely recommended for the pulp and paper sector and other industries [38–43]. Likewise heat recovery opportunities are seen as having a significant improvement potential [21,26,30–32]. In the UK, Hammond and Norman [6] employed a database of the heat demand, heat recovery potential and location of industrial sites involved in the EU-ETS to estimate the potential application of different heat recovery technologies. The options considered for recovering the heat were recovery for use on-site (using heat exchangers); upgrading the heat to a higher temperature (via heat pumps); conversion of the heat energy to fulfill a cooling demand (employing absorption chillers); conversion of heat to electricity (adopting *organic Rankine cycle* (ORC) devices; see also Chen et al. [44]); and transport of the heat to fulfill an off-site heat demand. Similarly, the *Energy research Centre of the Netherlands* (ECN) have examined the potential of modern industrial heat pumps that could generate steam up to 200 °C utilising waste heat [45], including a test cell programme related to the particular needs of the *paper* industry. The UK analysis by Hammond and Norman [6] provided an indicative assessment of the overall potential for the various technologies. The greatest potential for reusing surplus heat was found to be recovery at low temperatures (via heat exchangers), and in its conversion to electrical power (mostly utilising ORC technology [44]). Both these technologies exist in commercial applications, but are not well established. Support for their further development and installation could therefore increase their take-up. A broad analysis of this type, which investigates a large number of sites, cannot accurately identify all site-level opportunities. Nonetheless, the overall heat recoverable in the UK using a combination of these technologies was estimated at 52 PJ/yr, saving over 2.0 $MtCO_{2e}$/yr in comparison to supplying the energy outputs in a conventional manner [6]. A network and market for trading in heat, along with the wider use of district heating systems, could also open significant potential for exporting heat from industrial sites to other users. A range of *Best Practice Technologies* (BPTs) – those that represent the 'best' technologies, which are currently in use and therefore economically viable – for both energy efficiency improvements and heat recovery has been advocated for introduction into the pulp and paper sector in future [21,26,30–32].

3.3.4. Demand-side flexibility

Demand-side flexibility (DSF) is the ability to change electricity demand from an industrial plant or other user in response to an external signal from a power supplier [46,47]. 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 and has major advantages in the context of an energy infrastructure designed to meet occasional peak demands. This will be particularly important in the transition towards a low-carbon future. *Demand Side Participation* (DSP) concepts are mainly short-term (minutes to hours) [48], whereas flexibility is needed over several days or more. The rigid patterns of power supply based on life-long experience of fossil-fuelled supplies make such flexibility challenging, but are important to explore. Fully automated DSR concepts, such as 'smart' controllers for EV charging and heat-pumps, have been studied in some detail. *Industrial and commercial* (I&C) customers can benefit financially by offering 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 'System Operator' for the Great Britain (GB)). *Distribution Network Operators* (DNOs), who run and maintain regional distribution systems, can employ DSF to manage local network restrictions. This can reduce stress at peak times, support planned or unplanned network outages, and defer or avoid the need for network reinforcement [46]. In both cases, the operators are motivated by the growing share of so-called 'non-programmable' renewable energy sources (NP RES) on the network [49]. The contribution of DSF in GB electricity markets is currently small and mainly for grid balancing on a second-by-second basis. It is therefore a largely 'untapped' resource. DSF will inevitably be required in future in order to manage the system and market risks [38]. *Smart power* innovations - a combination of interconnectors, storage and demand flexibility (or DSR) - could generate £8 bn per year of savings; according to a report for the recently-established UK *National Infrastructure Commission* [50].

The *National Grid* (NG) in GB aims to address various barriers to customer participation, and is initially focusing on interacting with I&C customers [46]. Those customers who offer *demand-side flexibility* generally do so to reduce their electricity costs and generate new revenue streams, enabled by new ICT (e.g., metering and automation). But pilot demonstrations will be necessary in order to overcome the fears of some I&C customers that disturbances to their production processes might lead to reduced outputs or quality. Many such customers work with 'aggregators', because current DSR markets in the UK are seen as complex, or their volumes are too small to access DSF tools directly [46]. On-site or 'back-up' generation provides much of the DSF today [46]. Nevertheless, leveraging further on-site CHP or co-generation plants from the *paper* industry will enable the sector to interact more easily with the energy market [49]. The *Confederation of European Paper Industries* (CEPI) has suggested that mechanical pulping, an electro-intensive process, can be used for 'peak shaving' programmes [33]. It can react at reasonably short notice, ranging from as short as 15 min up to one hour, depending on the frequency and schedule of interruptions. In some European countries (e.g., Austria, Belgium and Norway), the *paper* industry is also involved in 'valley filling' programmes, whereby the whole production process is shifted to the night or to the weekends so as to optimise baseload electricity generation [49]. But, in the paper-making process, the flexibility margin is very small [49] and most of the energy required by the sector (steam and electricity) is generated on-site, therefore mostly 'off-grid'. Nevertheless, the widespread geographical distribution of paper mills across Europe would permit the cost-effective absorption of excess electricity from NP RES, substantially reducing the need for costly investments in grid extensions [49]. Policy makers, and actors in the energy sector more broadly, envisage that the scale and value of DSF is likely to grow in the future as part of a *smarter* system and with technological advances [4]. DSP will necessarily require the adoption of an appropriate regulatory framework, clear market roles, and a standardisation of processes to reduce transaction costs for aggregators.

3.3.5. Emerging and breakthrough technologies

Carbon sequestration from forestry and vegetation is an important part of the Earth's carbon cycle. Worldwide, carbon sequestration technologies capable of removing CO_2 from the flue gases of fossil fuel-fired power plants are now being investigated as a matter of some priority [26,32,51]. They are perhaps the key innovative technology in this area. The *paper* industry has long used biogenic process waste as an energy source, and over half of the energy utilised by the European industry is generated from biomass [52]. The UK industry, represented by the CPI [19], argues that paper production drives sustainable (and certified) forest growth. Here the IEA worked jointly with the '*Carbon Sequestration Leadership Forum*' and the '*Global CCS Institute*' [53]. They noted that the deployment of large-scale CCS demonstration projects is critical to the deployment of the technology. The IEA progress review [53] suggests that government and regional groups had made commitments to launch 19–43 such demonstrators by 2020. These developments were identified in the USA, the EU ("particularly the United Kingdom"), Canada and Australia. But the partners noted that implementation of such a programme would be challenging. The 2008 economic 'downturn', and the more recent *Eurozone* financial crisis, have both made the economic situation far more difficult in terms of potential public investments in large-scale energy projects of all kinds. If CCS facilities could be employed together with bioenergy, then it would give rise to 'carbon sinks' or 'negative emissions'. However, given the output produced and the size of sites this is considered by some to be unlikely to be realised [34], and have instead advocated *carbon capture and utilisation* (CCU) in order to use CO_2 to produce fuel, chemicals [23] and other materials [5]. The CEPI believe that other innovative (so-called 'disruptive') technologies could complement the GHG emissions reduction by some 3 $MtCO_{2e}$ in Europe by 2050 [33].

4. UK pulp and paper 'technology roadmaps' to a low carbon future by 2050

4.1. Background

A set of technology roadmaps have been developed in order to evaluate for the potential deployment of the identified paper sector technologies out to 2050. (Alternative modelling approaches have been adopted by the EU [54] and in the USA [55].) The extent of resource demand and GHG emissions reduction has been estimated here and projected forward. Such roadmaps represent future projections that match short-term (say out to 2035) and long-term (2050) targets with specific technological solutions to help meet key energy saving and decarbonisation goals. A bottom-up technology roadmap approach has been adopted, based on those that were initially used by Griffin et al. [7,23,56] to examine the impact of UK cement decarbonisation (for further details see Griffin [57]). Thus, their contents were built up on the basis of the improvement potentials associated with various processes employed in the *paper* industry and embedded in the UED [7,9,10].

4.2. Benchmark UK paper technology projections

The projected benchmark is affected by sector output, grid decarbonisation, and deployment of BPT/BAT. It is assumed that the GB grid will decarbonise by around 85% over the period 2010–2050. GHG emissions pathways of illustrative technology roadmaps for several of the smaller UK so-called energy intensive industrial sectors - pulp and

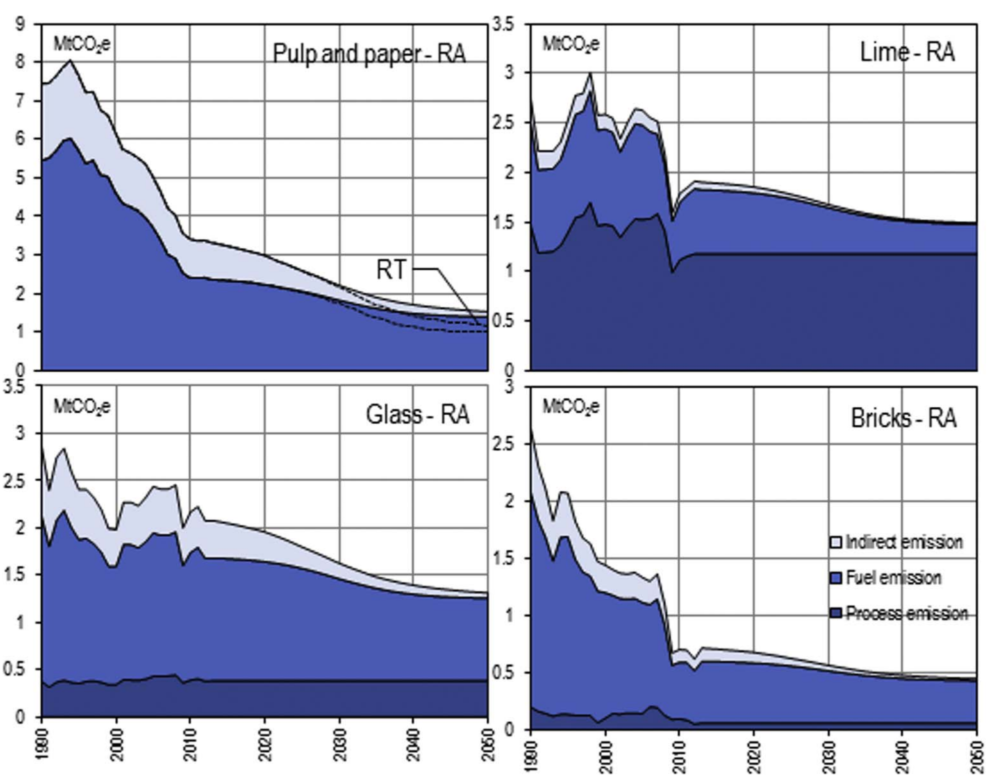

Fig. 7. *Greenhouse gas* (GHG) emissions splits of 2050 technology roadmaps of some UK energy-intensive industries under the *Reasonable Action* (RA) scenario: pulp and paper, lime, glass, and bricks. {The overall trend under a more *Radical Transition* (RT scenario) is also depicted.} *Source:* Griffin [47].

paper, lime, glass, and bricks - over the period 1990–2050 are illustrated in Fig. 7. None of these sectors were identified as having viable CCS opportunities, and only the *paper* sector was identified as being open to radical process transition. Also shown are the trajectories of relevant GHG emission targets and caps. It was estimated that EU-ETS legislation in 2010 covered 94% of direct GHG emissions from energy-intensive industry. These four industrial sectors were determined via the bottom-up assessment of the relationship between SEC and physical output. Physical output was first obtained or estimated for each sector. For bricks, output was determined by moving the 2010 tonnage reported for the CCA scheme *pro rata* with the trend in numbers of brick produced according to the *British Geological Survey* (BGS) [57–60]. Glass output trend was back-calculated from raw material process emission estimated for the UK GHG Inventory [61], which assumes emissive raw material demand in the vast majority of glass product types and mass output [62]. The same approach is applied to estimate the production trends for lime (and ammonia; see Griffin [57]). Efficiency improvements via CHP plant were not directly assessed here, due largely to uncertainty about the impact of fuel switching.

4.3. Scenario definition

The identified improvement technologies for the UK were incorporated into the *paper* technology roadmap framework through a series of scenarios. The baseline year for the framework was taken as 2010. Full details of the both the 2010 baseline and the BAT/BPT improvements can be found in the UKERC industrial UED [9,10]. Four future scenarios were devised in order to demonstrate this approach. The *paper* industry has been active in the area of technology roadmapping, particularly at the global level by the IEA [39], and ideas from such roadmaps were drawn on in constructing some of the scenarios detailed below [7,23,56,57]:-

- *Low Action* (LA). This scenario describes a path of only slight improvements. No further investment is presumed to be made in additional process technology improvements and efficiency is only improved incidentally through the replacement of industrial facilities.
- *Reasonable Action* (RA). All identified efficiency technologies are presumed to be installed by 2025, and retired equipment are replaced with best practice ones by 2030.
- *Reasonable Action including CCS* (RA-CCS). This scenario is based on RA, but includes the potential impact of CCS. Biomass co-firing with CCS may, of course, mitigate upstream emissions on a full life-cycle basis, due to potential ‘negative emissions’ [63]; something that will need careful examination in future studies.
- *Radical Transition* (RT). This scenario explores a boosted or radical version of the reasonable action (without CCS) scenario [57].

4.4. Alternative UK paper technology roadmaps

The various so-called ‘energy-intensive’ sectors considered include pulp and paper, lime, glass and bricks (with some reference given to the wider ceramics sector described by Griffin [57]). Background calculations and modelling are described there. For brick manufacture, present fuel mix was taken from a recent study by the *Carbon Trust* [60] and combined with the SEC reported for the sector CCA scheme [64]. SEC was linearly extrapolated to the level in 1980 as reported by Langley [65]. For glass, SEC was assumed to change with the trend in efficiency of glass furnaces reported by *British Glass* [66], which is likely to account for about 70% of sector energy demand. Fuel mix since 1990 is dominated by natural gas for both glass and bricks production, and was assumed to conform to the mix published by the UK *Office of National Statistics* (ONS) [67] for glass and other ceramic products (SIC 23.1–4 and 23.7–9). SEC of paper-making was backcasted linearly from the baseline (2010) to that reported in 1980, and fuel mix changes in renewable fuel requirements were informed by the CPI (David Morgan, CPI, private communication, 2013). It was not possible to extrapolate Lime SEC to an earlier time period, and so this was conservatively assumed to improve at a rate of 1% per annum from 1990 to the baseline date. The fuel mix was inferred from ONS data [67], which has stayed reasonably constant over the period, except for an increase in the use of waste fuels in recent years. Natural gas combustion is listed separately for ammonia production by the ONS, and this was used to represent energy demand for ammonia (see also Griffin et al. [23]).

GHG emission splits for the *Reasonable Action* (RA) roadmaps of

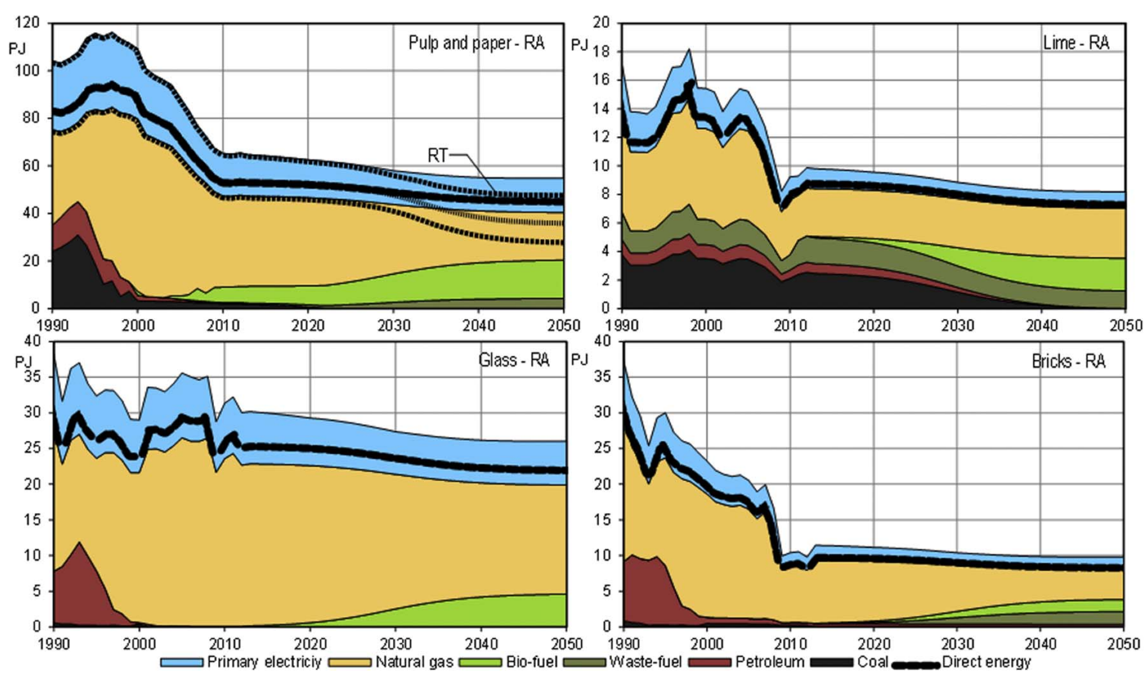

Fig. 8. Energy splits in the 2050 technology roadmaps of some UK energy-intensive industries under the *Reasonable Action* (RA) scenario: pulp and paper, lime, glass, and bricks. {The overall trend under a more *Radical Transition* (RT scenario) is also depicted.} *Source:* Griffin [47].

each of the energy-intensive industrial sectors modelled over the period 1990–2050 is depicted in Fig. 7. It can be seen that pulp and paper sector satisfies the 80% decarbonising target by 2050 compared to the emissions in 1990. This was established by both the UK Government for the economy overall [38], and by the CEPI for the European pulp and paper sector [33]. The CEPI believe it can be achieved alongside 50% more added value created by the industry. Fig. 7 indicates that, under the RA scenario, the total (fuel plus indirect) GHG emissions are likely to fall from about 7.5 $MtCO_{2e}$ in 1990 to 1.5 $MtCO_{2e}$ in 2050, i.e., coincidentally almost exactly an 80% reduction. The Radical Transition (RT) roadmap trend for pulp and paper is also shown in Fig. 7 for completeness, and displays an 85% fall. The associated energy splits are then displayed in Fig. 8. This suggests that, again under the RA scenario, natural gas is likely to contribute some 37% towards the total (fuel plus indirect) pulp and paper sectoral energy use by 2050, whilst biofuels and biogenic wastes similarly amount to 37%. Primary electricity [principally generated via nuclear power, onshore and offshore wind turbines, solar photovoltaic (PV) systems, and hydro-power] accounts for the remaining 26%. This is an energy mix with a much lower carbon content than the 2010 baseline made up of 56% NG, 28% primary electricity, 11% biofuels, and ~5% coal. With the application of a more *Radical Transition* (incorporated in the RT scenario), an energy saving of 56% is observed over 1990–2050 in comparison to that pertaining with just *Reasonable Action* (resulting from the RA scenario) of 47%. Energy demand for the *paper* industry remains fairly constant at about 55 PJ after 2030; only half that in 1990. Both the RA and RT scenarios presume a 15% process SEC improvement going forward. In the various energy-intensive industrial sectors illustrated in Fig. 8, the dramatic (negative) impact of the 2008 global 'financial crisis' on UK industry that resulted in a severe economic downturn or 'recession' can clearly be seen, particularly as reflected by the fall in energy consumption associated with construction-related artefacts and infrastructure projects (requiring the use of *Bricks* and *Lime*). That was due mainly to the decline in physical products from these sectors. The Sankey-type energy flow diagram shown above as Fig. 6 indicates the 2010 baseline division of inputs (fuels and primary electricity) to the UK *paper* industry against its outputs (the energy consumed by the paper machine and ancillary processes). The important role of CHP plants in providing both heat and power is depicted in Fig. 6 as an intermediate node or process between the 'arrows' or 'links' that represent the magnitude of the energy flows.

5. Concluding remarks

The potential for reducing industrial energy demand and 'greenhouse gas' (GHG) emissions in the *Pulp and Paper* sector has been evaluated within a UK context, although the lessons learned are applicable across much of the industrialised world. This sector gives rise to about 6% of UK industrial GHG emissions resulting principally from fuel use, as well as that indirectly emitted because of electricity use. It can be characterised as being heterogeneous with a wide range of product outputs (including banknotes, books, magazines, newspapers and packaging, e.g., fabricated from corrugated paper and board), and sits roughly on the boundary between energy-intensive (EI) and non-energy-intensive (NEI) industrial sectors as previously characterised by Griffin et al. [7] (see again Fig. 2). Some 70% of recovered or recycled fibre is employed to make *paper* products in the UK. Process energy requirements are dominated by a combination of drying/separation processes (40%), low temperature heating processes (28%), compressed air requirements (10%), space heating (8%) and electrical motors (6%) [3]. Fuel use in *combined heat and power* (CHP) plants has been modelled in terms of so-called 'auto-generation'. Special care was taken not to 'double count' auto-generation and grid decarbonisation; so that the relative contributions of each have been accounted for separately. Most of the electricity generated via steam boilers or CHP is used within the sector, with only a small amount exported. Currently-available technologies (BATs) will lead to further, short-term energy and GHG emissions savings in *paper* mills, but the prospects for the commercial exploitation of innovative technologies by mid-21st century is speculative. There are many non-technological barriers to the take-up of such technologies [7,22]. The possible role of bioenergy as a fuel resource going forward has also been appraised. Finally, UK roadmaps for the *paper* sector out to a low carbon future in 2050 have been evaluated. They exhibit quite large uncertainties, and the attainment of significant falls in GHG emissions over the long-term will depends critically on the adoption of a small number of key technologies [e.g., energy efficiency and heat recovery techniques, bioenergy (with and without CHP), and the electrification of heat], alongside a decarbonisation of the electricity supply. Thus, this novel technology assessment and associated roadmaps help identify the steps needed to be made by developers, policy makers and other stakeholders in order to ensure the decarbonisation of the UK *paper* industry.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.applthermaleng.2018.01.126.

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