Citation for published version:
Rogers, JG, Cooper, SJ & Norman, JB 2018, 'Uses of industrial energy benchmarking with reference to the pulp and paper industries', Renewable & Sustainable Energy Reviews, vol. 95, pp. 23-37.
https://doi.org/10.1016/j.rser.2018.06.019

DOI:
10.1016/j.rser.2018.06.019

Publication date:
2018

Document Version
Peer reviewed version

Link to publication

Uses of industrial energy benchmarking with reference to the pulp and paper industries

John G Rogers, Samuel J G Cooper, Jonathan B Norman

Abstract

Plant operators and policy makers frequently use energy benchmarking to assess the potential for reducing energy consumption from industrial plants. As benchmarking studies require considerable resources and the cooperation of plant operators it is tempting to try to merge or compare data from different studies. This paper reviews published benchmarks and energy-saving estimates from the paper and pulp industries to explore how comparable data from independent studies are. A literature review was conducted which identified that benchmarks were either produced through a top-down process using annual production and fuel consumption data or through a bottom-up process from process-level data. It was concluded that top-down benchmarks are useful in measuring national trends but are of little value to individual plants. For common process such as Kraft pulp production it is possible to compare values from different studies but only if sufficient information is given in the original studies to confirm that their scope is identical. However, it is unlikely that improvement rates in energy use can be inferred from the difference between studies that use different sources, as the degree of disagreement between contemporary studies is of the same order as the identified potential energy savings. Benchmarking studies were found to provide good summaries of potential technological improvements although there is some inconsistency in estimations of potential impacts.

Keywords

Paper and pulp industry; Energy benchmarking; comparisons of industry benchmarks, energy saving technology in paper making

1 Introduction

Energy Benchmarking is the process of comparing the performance of a plant with that of a similar plant or its own performance at an earlier time. It is an important tool to help identify potential energy savings. Benchmarking studies can be influential in the setting of policies, regulations and targets. The benchmarking process can be useful in highlighting where improvements can be made and in the case of temporal benchmarking identify the need for, or effectiveness of, maintenance work [1-4]. Benchmarks can be produced through a top-down approach using annually reported energy-use and production data or through a bottom-up approach using plant level energy-audit and production data. The top-down approach is useful for estimating national trends and assessing the impact of policies. The bottom-up approach is useful for comparing the performance of specific plants. Bottom-up studies need the participation of the major mills within the geographic areas being considered and entail considerable effort from the plant operational staff. Top-down studies use commercially sensitive production and cost data. Both approaches require significant commitment from the participant organisations. As such they represent a considerable investment. As an alternative to conducting a new benchmarking exercise it would be useful to be able to compare studies from different geographic locations and earlier time periods as an aid in assessing regional differences or progress in reducing energy consumption. Examples where benchmark studies of the same industry are compared appear to be missing from the literature. This paper examines when benchmarks from different sources can be compared and the value of comparing them.

This study is based on published academic literature and official reports. These documents used a mixture of original benchmark surveys, updated benchmark surveys and stakeholder consultations. A single industrial sector was chosen for the current study to bring focus and clarity to the approach, whilst acting as an exemplar for the wider questions concerning the value of benchmarking.

The paper and pulp industry was selected for the detailed analysis of benchmarks because it is an established global industry and a major energy consumer. As a sector it has the third highest carbon intensity (measured as t CO_{2e} per £k GVA) of any industry [5], with energy representing an average of 16% of the industry's costs [6,7]. This means there is a significant incentive for companies to examine their energy use and take part in benchmarking studies. The processes involved in paper production are well documented in the literature and described in Appendix 1.

Studies were identified that are representative of the type of benchmarking studies available. These are reviewed in Section 2. Four studies were selected for detailed comparison and are discussed in Section 3. Given the amount of data included in the selected studies it was decided to put the results of the comparison into three appendices. Appendix 2 aligns the product descriptions used in different studies. Appendix 3 lists the specific energy demands for electricity and steam converted into GJ per dry-tonne of paper. Appendix 4 identifies the Best Available Technology (BAT) and emerging technologies from the wider range of studies. The detailed comparison highlights the importance of having identical process boundaries and product definitions when comparing benchmarks. The identification of BAT and emerging technologies are comparable across studies but estimations of their potential impact differ between studies.

As the focus of this paper is on energy benchmarking, it is not intended to provide a comprehensive review of the literature on the potential for energy efficiency improvements in the paper and pulp industry. Recent reviews of emerging technology have been published [2, 8]. Several of the benchmarking studies also include assessments of emerging technology and these are discussed in Sections 3.4 and 3.5.

2 Published benchmarks in the paper and pulp industry

The reviewed benchmark studies have been grouped by geographic regions.

2.1 Global Benchmarks

The Ernest Orlando Lawrence Berkeley National Laboratory produced a report titled 'World Best Practice Energy Intensity Values for Selected Industrial Sectors' for the US Department of Energy [9]. This report used survey data for the pulp and paper industry [10-12]. The report provides separate figures for electricity use, energy used for steam generation, total energy used, and primary energy used for several products from both separate and integrated mills. As the report's purpose is to give BAT values, the ranges of reported specific energy values are not given. Data from the report are used by the Institute for Industrial Productivity (IIP) in order to provide benchmarks for some energy intensive industries on their web site[1].

The International Energy Agency (IEA) published a report on 'Energy Technology Transition for Industry' [13], this report covers specific energy consumption data for industries in different countries and estimates the potential scope for improvement. It acknowledges that there are inconsistencies in the way that countries report the use of Black Liquor (a by-product of the widely used Kraft sulphate chemical pulping process) and industrial combined heat and power generation (CHP). Consequently, they relied on national energy and trade data to produce national average specific energy requirements rather than the reported specific energy consumption of plants within each country. The report summarises BAT benchmarks for electricity and heat use for different processes provided in other work [10, 14-16].

In 2016 the IEA published a report on Energy Efficiency Indicators for member countries [17]. It used a top-down approach and adopts MJ/$\$_{US}$ to measure energy intensity. Although this gives an indication of the economic value generated per unit of energy it gives little indication of actual energy use as it can be influenced by changes in currency exchange rates and product mix as well as improvements in energy efficiency. An Energy Efficiency Index (EEI) for different countries can be calculated by comparing the aggregated energy use for a sector within a country with that which would be required by the 10% least energy intensive plant in the country to achieve the same production [18]. EEIs have been used to estimate the potential energy

[1] http://ietd.iipnetwork.org/content/pulp-and-paper#benchmark

savings achievable by improving energy efficiency by using data from [13] (discussed above) to calculate the EEIs for the paper and pulp sectors [18].

2.2 North American Benchmarks

The US Department of Energy commissioned ‘Energy Bandwidth’ reports into the potential for energy-efficiency improvements in different sectors. These studies assess the energy demand for the following classifications: Current Technology (CT), using median data from survey return; State of the Art (SOA), using the latest commercially implemented technology; Practical Minimum (PM), which includes identified potential improvements from other studies; and Thermodynamic Minimum (TM), which gives absolute minimum values from the laws of thermodynamics. The TM estimate is used as a baseline to estimate savings. The original study into the pulp and paper industries was carried out in 2006 [19]. This was updated in 2015 [20]. These reports cover a range of products and feedstocks. They give data for individual processes and products rather than complete mills. Losses associated with on-site electricity generation, and steam supply are covered in separate sections of the reports.

The US Environmental Protection Agency ran a series of energy reduction programs under the “Energy Star” initiative [4, 21]. The paper and pulp industries were covered by one such study [22]. An Energy Performance Index (EPI) was used rather than specific energy consumption. The EPI uses a formula that relates energy use to the specific production process, product made, and feedstocks used. The coefficients used in this formula are arrived at by regression analysis from confidential survey data. The computed value of energy demand is then compared with the actual value to produce an Energy Performance Score with 100 representing the score of the most efficient plant. This approach has the advantage that it can deal with mills that make more than one grade of product. However, the use of the EPI prevents a direct comparison with other studies as it does not allow energy use or emissions to be calculated.

Natural Resource Canada (NRC) published a benchmarking report in 2006 [23]. It gives detailed breakdowns of the energy use for each production phase taken from Canadian mills giving the energy consumption for the 25th percentile, median, 75th percentile and figures for “modern” mills to reflect the latest developments. The report gives values for specific electricity and thermal energy consumption.

2.3 European Benchmarking

The EU Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control) requires the preparation of ‘Best Available Techniques Reference Documents’ to be produced for industrial sectors. Several studies have used the 2001 version of this document [10], which was revised in 2015 [24]. These reports contain data on energy use, emissions and BAT. They use specific energy figures for different feedstocks taken from a 2007 survey of German mills [25], which reported on the range of energy used in existing plants. BAT values were calculated using a bottom-up approach utilising proven leading technology. The document also gives an assessment of emerging technologies in pulp and paper manufacturing.

The European Emission Trading System (EU ETS) is a cap and trade industrial emissions reduction scheme. It only covers direct emissions i.e. those that occur from the processes carried out onsite and onsite combustion of fuels. It excludes emissions that arise from the generation of grid electricity or the production of fuels. Under the scheme, installations that could lose business to competitors who are in countries that are not members of the scheme are given free allowances equivalent to the emissions that would be emitted by the least polluting 10% of plants in the same sector. Benchmarking has been used to identify the least polluting 10% of plants [5, 26, 27]. The EU ETS covers site-level emissions, so it is not possible to calculate the energy use for individual processes from these data.

The Climate Strategy research organisation produced a status report on the European pulp and paper industry in 2016 [28]. This report used benchmark data from Best Available Techniques (BAT) Reference Document [24], World Best Practice Energy Intensity Values for Selected Industrial Sectors [9] and a 2013 paper reporting on a primary energy benchmarking study on the Dutch paper industry [29]. The free allowances offered by different emission cap and trade schemes [30-32] are also compared in this report.

Intelligent Energy Europe published a report based on an analysis of the ODYSSEE and MURE Databases [33]. Decomposition analysis was used to extract the impact of energy efficiency measures from the simple trend in energy use and emissions across the economies of several European countries. The report includes data on complete industrial sectors for each country but does not give any production data or specific energy values.

2.4 UK Benchmarks

The UK Climate Change Agreements (CCA) are industry-wide agreements which commit industries to reduce those emissions that are not covered by the EU ETS in return for tax concessions [34, 35]. CCAs can report in terms of actual energy use, greenhouse gas emissions (GHG), specific energy use or specific GHG emissions (i.e. per unit of production). The progress reports associated with CCAs could be considered to give a high-level emissions benchmark for the industry but the exclusion of emissions included in the EU ETS means that submissions made under both schemes would need to be combined in order to give a complete picture of a site's performance.

Various UK government departments have commissioned benchmarking exercises. The Department for Environment, Food and Rural Affairs (DEFRA) produced a report on the sustainability of the UK paper industry in 2012 [36]. It is basically a desktop review and uses energy benchmarks from the 2001 edition of the Integrated Pollution Prevention and Control (IPPC) Reference Document on Best Available Techniques in the Pulp and Paper Industry [10]. The Department of Energy and Climate Change (DECC) and the Department for Business, Innovation and Skills commissioned several consultancies to produce an 'Industrial Decarbonisation And Energy Efficiency Roadmaps To 2050 – Pulp And Paper Pathways to Decarbonisation in 2050' [37]. This uses data from the Carbon Trust [38] and Intelligent Energy Europe [33] to estimate current energy use and carbon emissions. They modelled varying level of adoption of energy savings technology to calculate the corresponding emission reductions. The degrees of implementation for each technology was arrived at after discussions with industrial stakeholders. The report and its appendix contain a good summary of potential improvements, but it does not give a breakdown at a product level.

In 2013, the UK Energy Research Centre (UKERC) commissioned the development of the "Useable Energy Database" to give a publicly available database of the energy used by the five largest energy-consuming sectors of UK industry and estimates of the cost of applying energy efficiency measures. The data for the paper and pulp sector came from an industry source and although it was subdivided by plant areas, it was also aggregated to give national totals. An accompanying report and conference paper have been published [39, 40]. The Carbon Trust carried out a study into the potential for emissions reduction in the UK paper industry [38]. This was based on company returns made under the sector's CCAs and work with UK paper mills [34, 35]. The report provides a table of specific energy for different grades of paper reported by the manufacturers for 2008. The Carbon Trust estimated that on average the UK industry used 38% more energy than would be expected from the Technical Association of the Pulp and Paper Industry standard (TAPPI TIP 0404–63– Paper Machine Energy Conservation standard, 2006 revision).

2.5 Other major producers

China is now the largest paper manufacture in the world [41]. However, it has a very low level of forest reserve and relies on recycled material, non-wood fibres (straw and bamboo) and imported pulp.

The China Sustainable Energy Program commissioned a report into potential for improvements in energy efficiency in the Chinese paper and pulp industry, from the Ernest Orlando Lawrence Laboratory [42]. This report does not include detailed benchmarking data, and any national benchmarks may have limited use as the industry is undergoing major restructuring with many older plants being closed. However, under the 11th five-year plan (2005 – 2010) the primary energy intensity of pulp production fell from 16.1 to 13.2 GJ/t and that for paper fell from 24.3 to 19.9 GJ/t. The 12th five-year plan includes an energy reduction target of 20%. The low level of virgin pulp production means that most plants use pulp from recycling or imported pulp and use coal-fired boilers with the larger plants using CHP technology. This means that the CO_2 emissions from Chinese paper manufacture are higher than those in North America or Europe which mainly use gas-fired CHP plants or fuel derived from biomass.

In their 2015 paper, Peng et. al [43] consider the trend in specific energy use by the pulp and paper industry in China based on annual fuel use and production data. These were compared with similar data from other countries to assess the rate of modernisation of the Chinese industry. They identify policies and technologies that have helped China match the efficiency levels of the developed world. Related work was published in 2016 [44], however its main focus was on CO_2 emissions reduction rather than reduction in energy use.

India's demand for paper is growing at 7-8% a year. A descriptive report on best practice in the Indian paper industry [45] gives examples for specific plant items that can be adopted but does not contain any plant-level or product data. Although much of this report relates to coal-fired CHP plants it also covers best practice in water use and forestry. The report is part of a programme to raise the performance of the industry to match the performance of modern plants in the rest of the world. This programme includes a voluntary target of reducing the specific energy intensity of Indian paper mills by 1-5% a year.

In 2010 Brazil was the world's fourth largest pulp producer and 10th largest paper producer. Its industry has been rapidly expanding over the last 40 years. The energy efficiency of its paper and pulp sector was analysed for the period 1979 to 2009 by Fracaro et al. [46] who used decomposition analysis to isolate improvements resulting from increased energy efficiency from those due to structural change and increases in activity. Fracaro et al. used product-weighted energy-efficiency indicators using reference values from 1997 [47]. These were compared to equivalent indicators for the Canadian, American, Finish and Swedish industries over the same period.

3 Analysis

This section looks at the comparability of different benchmark studies. Energy benchmarks are expressed in terms of either primary energy (fuel) or energy vectors (electricity, steam, direct heating, fuel). In situations where a significant amount of the energy consumption is provided by electricity from the public supply, a comparison of the primary energy consumption of different plants can reveal more about the relative efficiencies of the electricity supply grids than the efficiencies of the plants being considered. Consequently, this analysis concentrates on benchmarks that report separately on electricity and heat use. It is reasonable to expect that energy requirements will be dependent on the feedstock used and the grade of product produced, consequently only studies that include this information can be compared. It is evident from Section 2 that benchmarking reports frequently use data from previous studies. Comparison of data from two such studies will naturally result in an agreement, so it was decided to compare studied that use original data. The following studies use original survey data and so were selected for detailed comparison: the IEA report by Worrell et al. [9], Jacobs [19] (which is the basis of the US Bandwidth studies), Blum et al. [25] (which is the basis of the EU IPPC BAT document [24]) and the Natural Resource Canada (NRC) report [23]. Throughout this section and its associated figures and appendices these reports will be identified by the principal authors' names.

The four reports identified above use different units. These have been converted to a common unit (GJ per air dried metric tonne) to enable their findings to be compared. The reports use regional systems of product classifications, these are compared in Appendix 2. The specific energy requirements from the four reports are reproduced in Appendix 3. There are a considerable number of gaps in the tables in Appendix 3. This is because the studies concentrate on the processes and products made in specific regions and they omit processes with negligible output in their region. Table A3.1 shows that the energy used to pulp wood varies with technology, this will be discussed in Section 3.3. There is also considerable variation in the energy demand for different grades of product.

3.1 Comparison between studies

Only two products are included in all four reports. These are non-integrated wood-free covered paper (CEPI classification 232000) and Kraft pulping (CEPI classification 922100) (i.e. chemical / sulphate Kraft). The Specific energy requirement for non-integrated wood-free coated paper from the different reports is shown in Figure 1. The reports indicate that they have a consistent scope of supply for this product. The distribution of values across the reports has a standard deviation of 10% for electricity and 11% for heat.

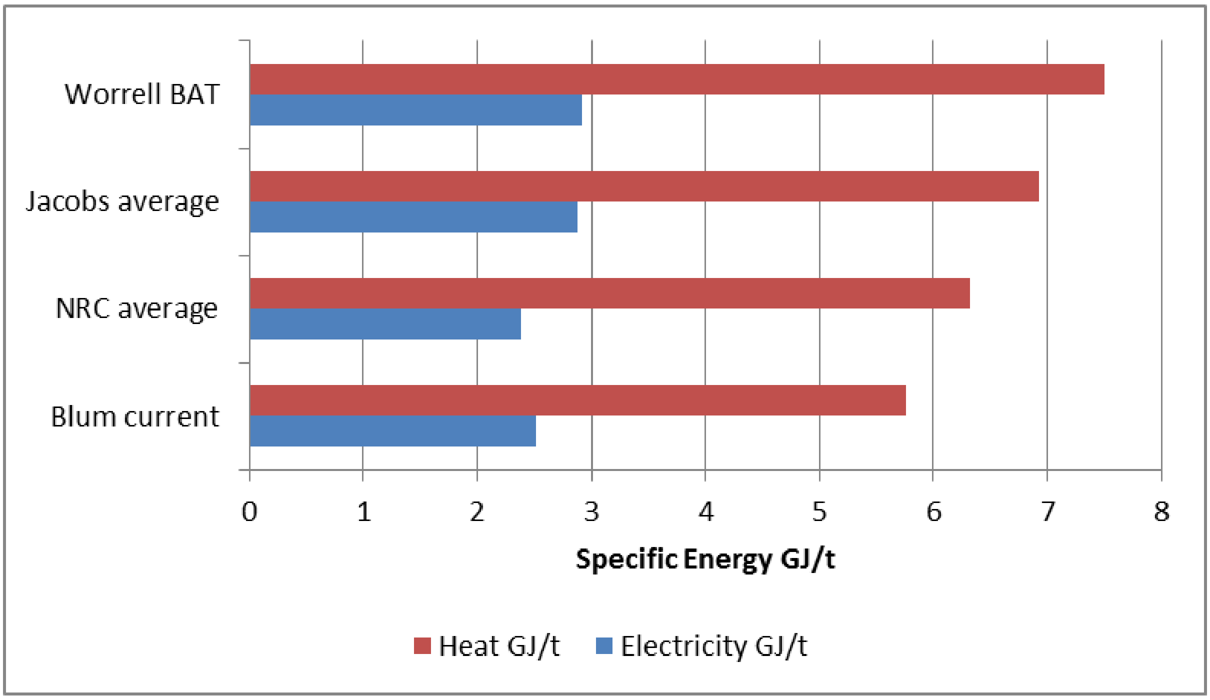

Fig 1. Specific energy requirement for non-integrated wood-free coated paper

The specific energy requirements for standalone Kraft pulping mills are plotted in Figure 2.

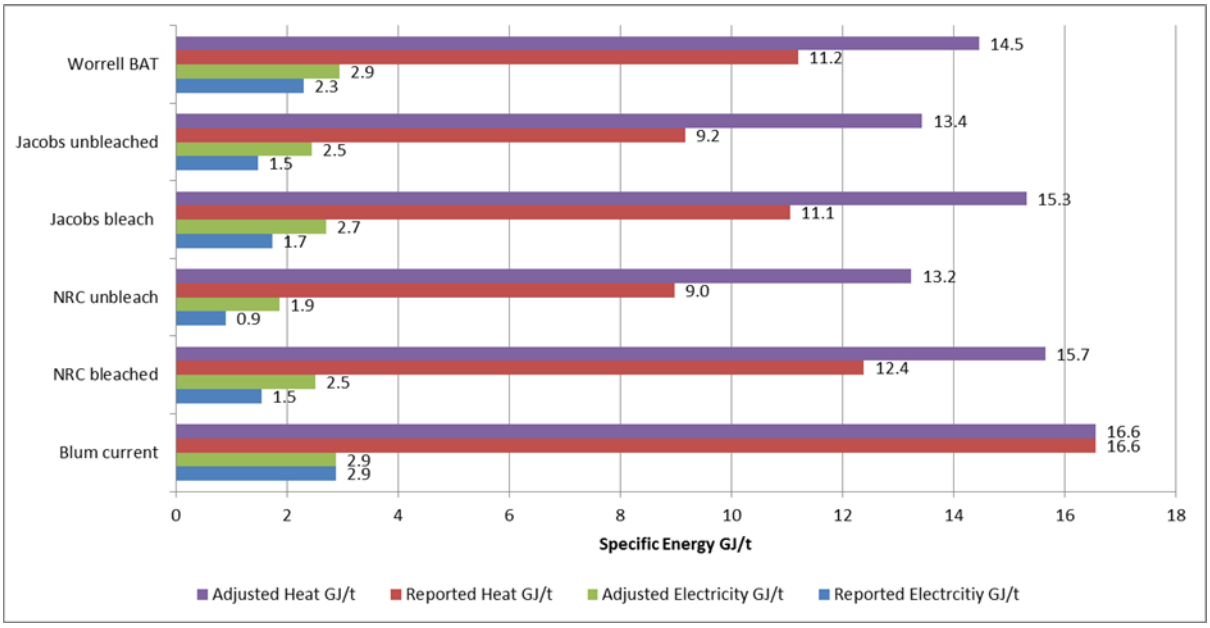

Fig. 2. Specific energy requirement in Kraft pulping mills

Although there appears to be a wide spread in the reported values, there are differences in the scope of the studies. Standalone pulp mills produce “market pulp” which is dried before transport; the energy for this is included in Blum's whole mill data but excluded in the other studies. To balance the scope the energy requirement for drying market pulp from Blum have been added to the other studies. The NRC and Jacobs reports give separate estimates for the water- and effluent-treatment plants associated with the mill whereas Blum and Worrell include these loads in their estimates. The energy requirements of water- and effluent-treatment plant provided by NRC and Jacobs have been added to the reported values from these reports to give the "Adjusted Values" in Figure 2. This scope adjustment causes the standard deviation between the values from the four studies to fall from 38% to 15% for electricity and from 24% to 9% for heat.

Jacobs and NRC give separate estimates for unbleached and bleached pulp. These are relatively consistent. The adjusted heat value from Worrell falls between these estimates but Worrell does not state whether the pulp is bleached, unbleached or a mixture (over the course of a year, a mill could produce both bleached and unbleached pulp for different customers). Blum gives a range of values for current consumption with electricity for the Kraft process ranging from 2.5 to 2.9 GJ/t and heat ranging from 13.7 to 18.4 GJ/t. This is similar to the spread of values between reports shown in Figure 2.

Comparing Figures 1 and 2 there would appear to be no evidence of any of the reports consistently reporting higher energy demand than the others but there are insufficient data to prove this.

3.2 Process benchmarking

All four studies include energy use subdivided by processes. Descriptions of the individual processes are given in Appendix 1. All the reports highlight that expert judgment has had to be used to overcome limitations in measuring regimes in some mills and that process boundaries are not necessarily consistent between plants. Jacobs includes the energy consumption of individual processes for average integrated writing and printing paper, linear board and newsprint production, these are shown in Figure 3.

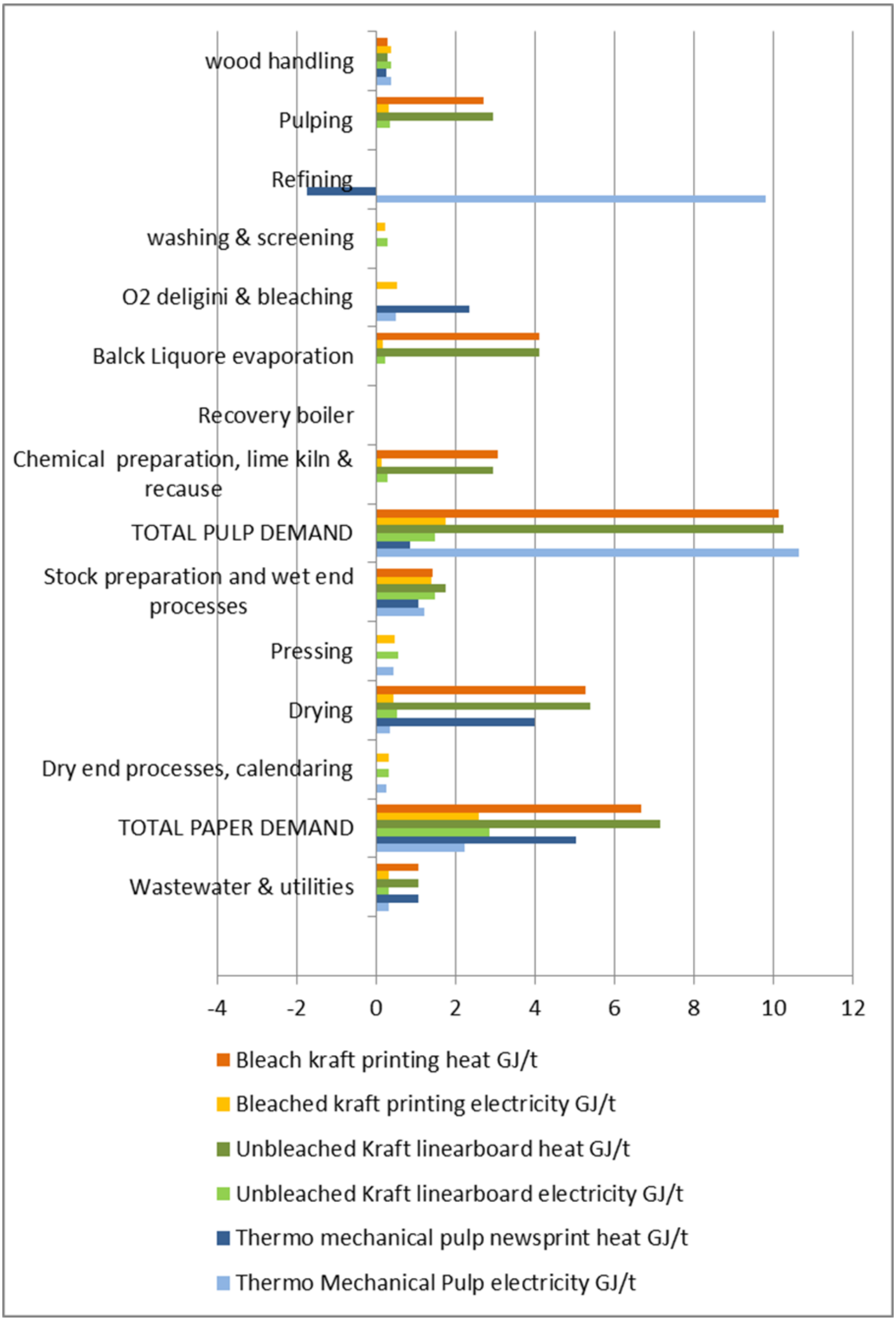

Fig. 3. Process energy requirements for integrated paper mills using Kraft or Thermomechanical pulping

The refining of thermomechanical pulp causes the pulp to heat up. This heat can be extracted for use as process heat in the papermaking process. This extracted heat is shown as a negative heat consumption for this process. Figure 3 shows that the processes that consume the most energy are pulp production and paper drying. Pulp production is discussed in Section 3.3. The difference in the drying load reflects the different weight of the product and the amount of coatings added to it. The total energy requirement is the sum of the individual requirements of the processes needed to produce the finished product. The differences in energy requirement between the products produced in non-integrated mills are shown in Figure 4 (also see Appendix 3, Table A3.1).

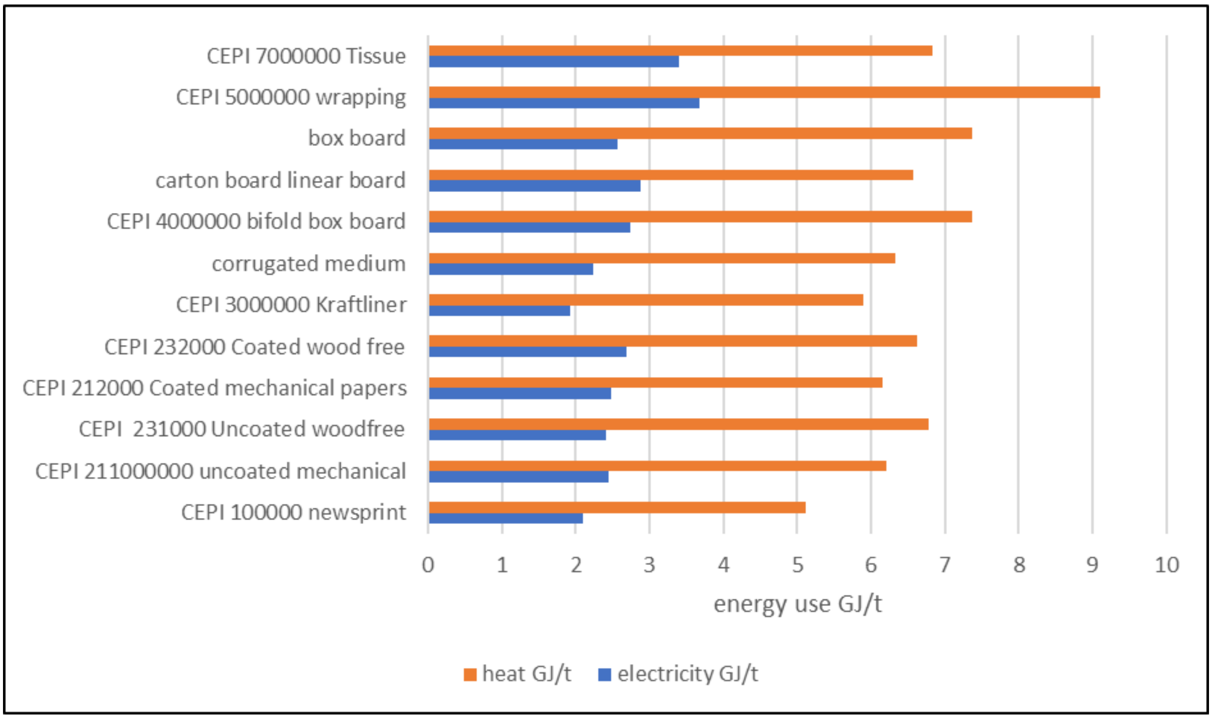

Fig.4. Process energy requirements for different grades of product produced by non-integrated mills.

The unweighted average of all the product grades shown in Figure 4 is 2.63 GJ/t electricity and 6.69 GJ/t heat with standard deviations of 19% and 15% respectively. It is noticeable that the CEPI 5000000 wrapping paper has a considerably higher heat demands than the other grades. If this is treated as an outlier and removed from the calculation, the averages become 2.53 GJ/t electricity and 6.48 GJ/t heat with standard deviations of 16% and 10%.

3.3 Impact of pulping technology

The major commercial pulping techniques have very different energy demands. These are shown in Figure 5.

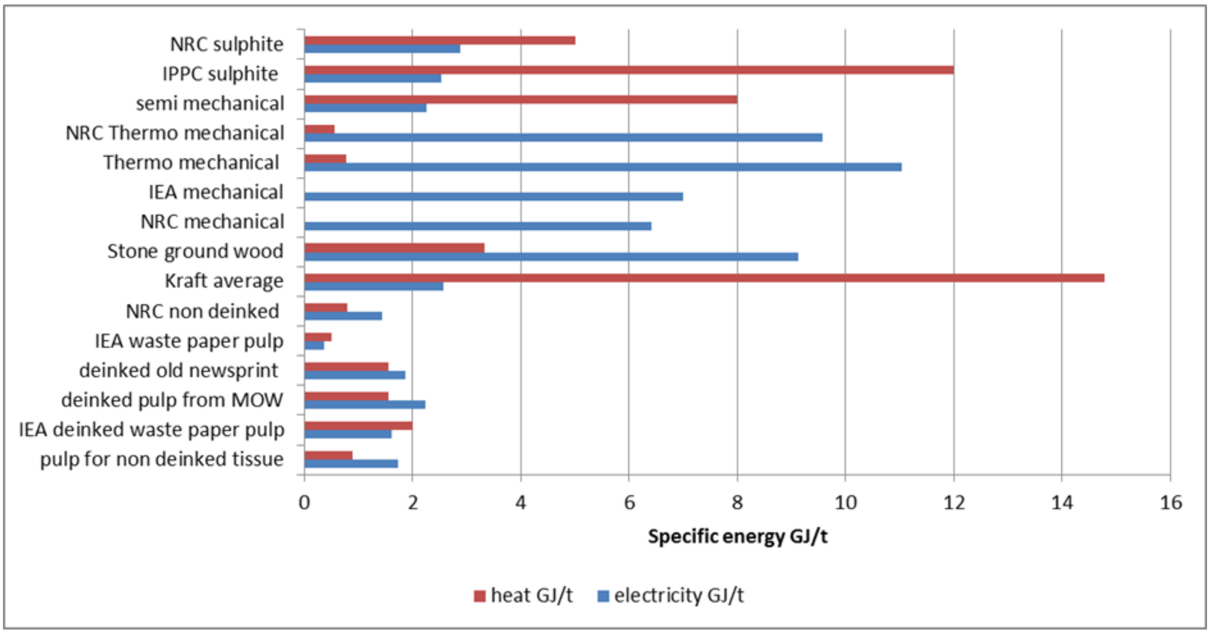

Fig. 5. Energy requirements of different pulping technologies

All the data for Figure 5 are taken from Jacobs [19] unless otherwise stated. The IEA data are taken from [14], IPPC from [24] and NRC from [23]. The Kraft average is the arithmetic average of the adjusted values in Figure 2. There appears to be a wide discrepancy between the heat input for sulphite pulping between the NRC and IPPC reports. The IPPC BAT reference document [24] gives the thermal requirement for bleached sulphate pulping as being between 7.5 and 16.5 GJ/t depending on the need to dry the pulp and the range of by-products produced. The NRC data are for unbleached pulp which is likely to require less energy than bleached pulp as shown in Figure 5. It is worth noting that sulphite pulping is a legacy technology which only produces 2% of the world's pulp [7] and these data may come from a limited number of old plants. The Jacobs Stone Ground Wood (SGW) estimate appears inconsistent with the IEA and NRC estimates for mechanical pulping (which would encompass SGW). Pure mechanical pulping does not involve any heating (normally waste heat is recovered from the process) so there would appear to be something unusual in the Jacobs value. Jacobs reports that the SGW process is only used to produce 1.6% of US pulp so these data may have come from a few mills producing a specialist market pulp; in which case, the associated heat demand may be needed to dry the pulp for transport.

Producing recycled pulp requires less energy than pulping virgin timber, but there is a wide range of reported values. The recycling process involves: rehydrating, refining (to get a consistent pulp), cleaning to remove fillers and coatings, and deinking to remove ink and glues. As these processes remove unwanted material their energy requirements are dependent on the quality of the material being recycled and the required purity of the pulp.

3.4 Comparing BAT values

When comparing current or average benchmarking data it could be expected that while results may differ between regions, due to regional variation in the age and size profiles of mills, there should be agreement on the best available technology (BAT) between contemporary studies. However, the data shown in Figures 6 and 7 appear to show the opposite; the range of values is higher amongst the BAT values than in the reported current or average energy demand data.

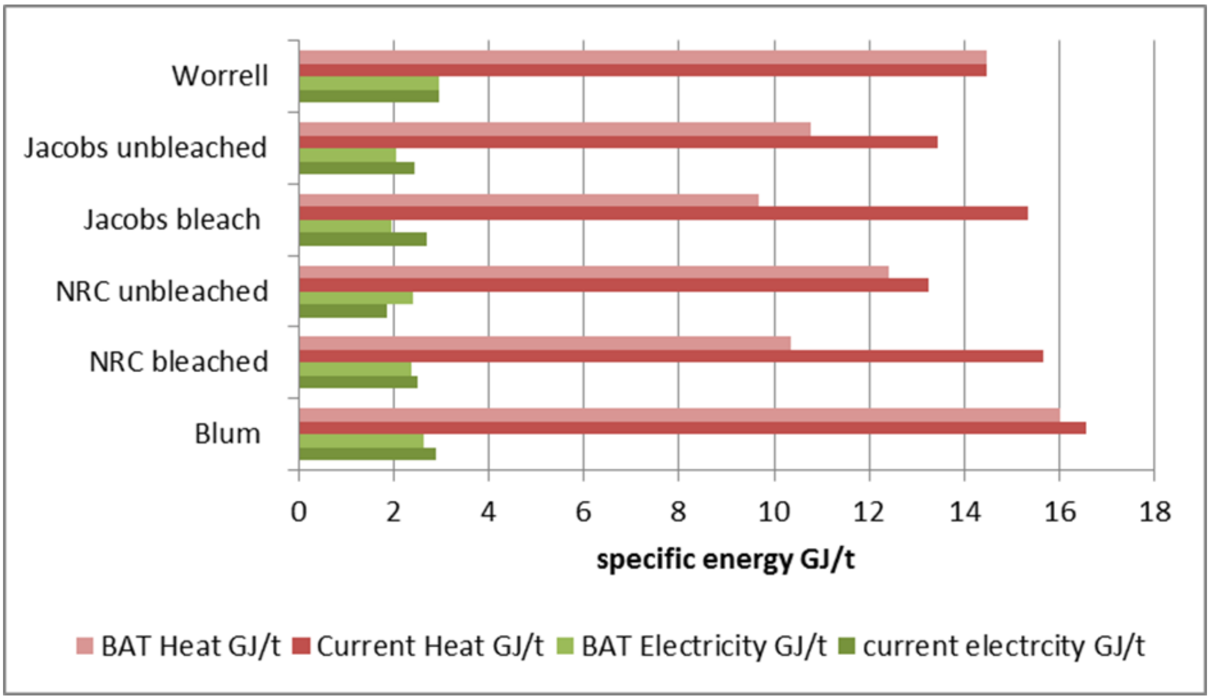

Fig. 6. Comparisons of current and BAT values for Kraft pulping

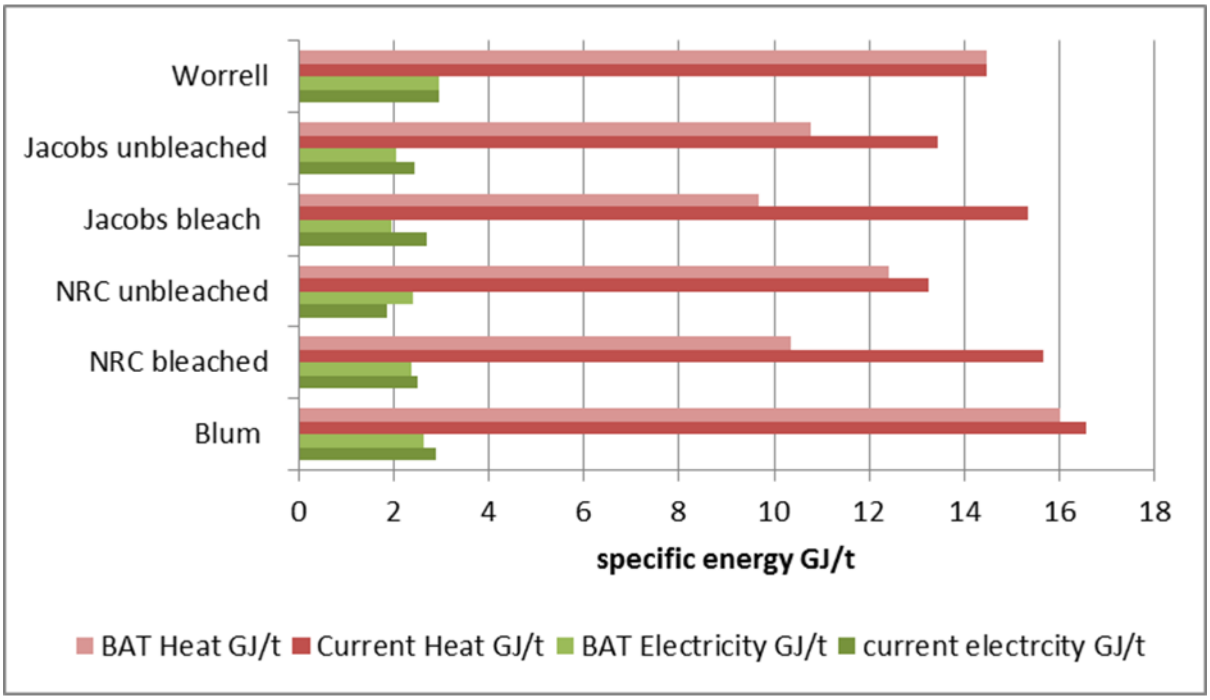

Fig. 7. Comparisons of current and BAT values for non-integrated wood-free coated paper mills

Although there is limited agreement of what the BAT energy requirements are there is some consensus on the approaches needed to achieve it. There is insufficient space in this paper to carry out a detailed review of BAT measures which would take a separate paper to cover fully. BAT technologies and practices are identified in many of the benchmarking publications [8, 20, 23, 25, 29, 42, 48]. These have been summarised in Table 1. Although there is a lot of commonality between the reports, some measures are only covered in some of the reports. The measures have been grouped into categories that reflect the ease with which they can be retrofitted / implemented in an existing mill.

Table 1. Identified BAT measures

Good operating practices	System wide generic modifications	Plant item specific modification
Instigate energy management systems.	Use high efficiency electric motors, pumps and agitators.	Use unrecyclable organic waste and residuals in boilers for process heating.
Shut down plant at the end of production run and any items that are not needed for the grade of product being produced.	Use frequency invertors for fan, compressor and pump control.	Use excess heat for sludge drying and black liquor concentration where applicable.
Operate headbox within design flow ranges.	Match motors power to loads.	Install high efficiency screening and refining technology.
Optimise vacuum systems to balance steam penetration, sheet temperature and air infiltration.	Use low energy lighting.	Use high consistency pulps (higher solids hence less drying).
Carrying out regular leak checks on compressed air and service steam systems.	Insulate steam and condensate pipes.	Improve moisture profile to allow maximum possible moisture content at the reel.
Maintain plant so that it works as designed rather than just keep going.	Implement modern control schemes that optimise energy use.	Use high performance felts.
Run compressed air and service steam systems at the minimum required pressure.	Use CHP for steam generation.	Install shoe presses.
Optimise operation of existing refining plants.	Maximise heat recovery.	Minimise re-wet in press section.
Avoid steam venting during normal operation.	Use Low pressure steam in place of high pressure steam where possible.	Use recovered heat to raise temperature of process and wash water. Use LP or vented steam for steam boxes and showers to increase sheet temperature and improve exit dryness (reduces viscosity hence improves efficiency of mechanical pressing).
	Automate warm up, shut down and break recovery response to minimise steam losses.	Raise hood dew point temperature in dryer to reduce air flow and improve heat recovery.
	Monitor press performance - water flows, fabric permeability, moisture, temperature (probably need updated instrumentation and Supervisory Control And Data Acquisition system).	User thermo-compressors to enhance cascade operation of drying cylinders.
	Avoid tanks where possible and design for continuous flows, this reduces stop start losses and the need for slurry agitation.	Use energy efficient vacuum systems for dewatering, consider turbo-compressors in place of vacuum pumps for high vacuum duties and fans or blowers in place of vacuum pumps for low vacuum applications.
	Avoid over agitation, use variable or two speed agitators to reduce level of agitations and consider zone agitation where complete mixing is not needed.	Provide water/air separation ahead of vacuum pump and reduce pressure loss in suction and discharge ducting of vacuum system.
		Graduate vacuum down the table to reduce drag and provide good sheet consolidation.
		Optimise differential pressures for condensate evacuation and blow through flows.
		Maximise condensate recovery and flash steam recovery.

Some of these measures can be implemented by revising operational practices, but others need to be implemented during plant overhauls and are dependent on new investment capital being available. All these items have been considered to be cost effective in some circumstances by at least one study, so it should be expected that they will be adopted as plant is refurbished. The extent of savings does depend on the state of current practice; Blum estimates savings of 4 – 25% depending on the process and product [25], where Jacobs estimates the savings as 7 – 45% [19].

3.5 Innovations

Several studies have discussed innovations that are in the development stage and these are listed in Appendix 4. Two of the studies [20, 38] discuss innovations that are currently under development while the others [49, 50] are more concerned with those in the concept phase. The US bandwidth study [20] gives estimates of practical minimum (PM) energy requirements based on concepts that have been proven at a laboratory or prototype scale and are in the process of development to an industrial scale. The techniques they identified are shown in Table A4.1. Although listed as an emerging technology, prototype gas-fired drum driers were demonstrated in 2004 [51] and condebelts in 1998 [52] which indicates that there are either technical limitations to their use or that the economic conditions have not been favourable for their wider adoption. UK industrial stakeholders said that condebelts were not considered to be viable in the UK in interviews with The Carbon Trust [38].

The Confederation of European Paper Industries has produced a road map for the industry to become a low carbon bio-economy by 2050. They recognised that this could not be achieved with existing technology. They set up two teams of experts drawn from across the sector (i.e. researchers, scientists, manufacturers, suppliers and industry representatives) to come up with possible innovations. The ideas from the two teams were then assessed by an expert jury [49]. The top eight suggestions are shown in Table A4.2. An earlier European collaborative project called ECOTARGET investigated innovations to reduce energy use, wood consumption, fresh water consumption and waste in the European paper industry [50]. They concentrated on five areas shown in Table A4.3.

As part of their study The Carbon Trust [38] conducted some qualitative research with stakeholders to critique emerging innovations and their findings are reproduced in Table A4.4. The Carbon Trust research focused on UK industry. There are no Kraft pulp mills in the UK so some of the techniques listed in Tables A4.1 – A4.3 do not appear in Table A4.4. Table A4.4 also includes some items that are identified as BAT in other studies.

By their nature it is not possible to fully quantify the impact of any innovation and savings from innovations in different areas may not be cumulative. However there appear to be several developments that could reduce energy requirements for some products by 25%.

4 Conclusions

4.1 Types of benchmarks published

The publications reviewed in Section 2 revealed a wide range of benchmarks, ranging from ones covering national industries to individual plants. Energy use was reported in terms of primary energy or energy vectors. This limited the amount of direct comparisons that could be made between studies. However, if the conversion efficiencies for electricity, heat and steam generation are known it is possible to calculate the primary energy requirement from the energy vector consumption data.

Electricity generated from wind, solar or hydro-electric sources is frequently considered as primary energy. Consequently, an increase in the use of these renewable sources will reduce the primary energy demand of a process that uses electricity without any improvement in the energy consumption of the process.

It is clear from Section 2 that several of the benchmark studies relied on data from previously published studies. Although they may be presenting the data from a different perspective they cannot be considered as independent data sources.

4.2 Can energy benchmarks be compared?

Appendix 3 compares specific energy requirements from four studies. The results for two products that are covered in all four studies are plotted in Figures 1 and 2. These show that the reported energy requirements are of a similar order but that they are not close enough to be considered the same. Consequently, in the case of the studies considered, the results cannot be combined. These differences may be due to genuine differences in the performance of the plants, scoping issues within the studies or measurement uncertainties. The issue of scoping was discussed in Section 3.1. In theory, provided the boundaries of the benchmarks being compared are well defined and the energy consumption is split down into plant processes, it is possible to adjust the outputs of two studies with different scopes to allow them to be compared.

Energy supplies are normally measured at the plant boundary. A study carried out by Natural Resources Canada [23] found that there was a discrepancy between the energy supplied or generated on site and the accumulation of the individual measured loads. On average the discrepancy was 2.5% for electricity and 5.7% for steam. These discrepancies are due to instrumentation uncertainties, differences in the times data was recorded, and unaccounted system losses (steam leaks, electrical transformer losses). If there are a significant number of mills making the same product in a study the effect of these errors may average out, but in cases where there are only a few mills this cannot be relied on. Even after scope adjustment, the differences between specific energy requirements for identical processes in Figures 1 and 2 are greater than the expected measurement uncertainties. This implies that there are in fact differences in energy usage in paper-making in different countries.

Energy Efficiency Indicators are useful to assess the relative performance of national industries or mills that produce a range of products. For the pulp and paper sector, the IEA define the energy efficiency indicator by Equation 1:

$$EEI = \frac{\sum_0^i (Q_i\, SEC_i)}{Annual\_energy\_use} \qquad \text{Equation 1.}$$

Where Q_i is the annual production of product i and SEC_i is the specific energy consumption for product i from a BAT reference plant [3]. The advantage of this method is that it can be used to compare plants where only the annual production and energy consumption are known. The index can be calculated in terms of electricity use, heat use or emissions depending on the information available and the area of concern. Care must be taken to ensure that losses associated with onsite electricity generation are handled consistently between for the site (or country) being considered and the BAT benchmark. It should be possible to calculate EEIs for plants with a known specific energy benchmark. One advantage of EEIs is that by using the annual energy use it captures all the non-production energy losses. Care needs to be taken when comparing energy-use data from plants that generate some of their own electricity and those that purchase all their electricity from the public supply in order to ensure that conversion losses are handled in a consistent way.

4.3 Comparing energy requirements of different products

Although one would expect energy use to vary with the grade of product being produced the variation across products shown in Figure 4 was not that much more than the variation between studies, as shown in Figures 1 and 2. This implies that simple benchmarks based on annual production and energy usage may be only slightly less accurate than more detailed studies.

4.4 Comparison of BAT values

As BAT is defined as the best available technology plants in similar climatic zones using BAT technology should have identical energy use (although the best economically available technology will vary between countries). So, it is surprising that there was not closer agreement between BAT values in Figures 6 and 7. Appendix 3 Table A3.3 contains reported estimates of the potential savings that could be obtained by using BAT technology on different products. This shows a wide difference in estimated savings between the reports. This may in part be due to different estimations of the potential for applying a particular innovation in different national industries. Some studies use whole plant BAT figures from the best performing mills while other estimate them from hypothetical mills employing the BAT technology for each individual process. The second approach will yield a lower value but risk underestimating operational losses. There may well be reluctance on the part of operators of high performance plants to make energy use data available to public studies; this will result in a higher BAT value being assumed. Appendix 4 Table A4.4 gives an indication of the interest that the UK paper industry has in some BAT technologies, which in some cases is considerably less than the proponents of the technologies assume.

The use of ‘Practical Minimums’ and ‘Thermodynamic Minimums’ in the US bandwidth studies [19, 20] may give a better indication of the potential for savings than BAT as these do not rely on reported performance. The innovations discussed in Section 3.5 indicate that there are several options for reducing energy use beyond current BAT values.

4.5 Energy use and greenhouse gas emissions

In many industries, greenhouse gas (GHG) emissions are governed by energy use. But as explained in Appendix 1, efficient paper mills that use the Kraft pulping process produce sufficient co-product fuel (Black Liquor and bark) to power the plant. As these fuels are derived from biomass they can be considered carbon neutral (provided that the timber used is sustainably sourced). Recycled pulp is produced in mills that use fossil fuels. These frequently use CHP plants with high energy-utilisation rates but many mills in India and China use coal-fired CHP plants which have high GHG emissions. This leads to the surprising conclusion that using virgin pulp causes less GHG emissions than using recycled pulp. Given that there are clear resource benefits in using recycled pulp, ways of reducing the GHG emissions in the re-pulping process merit further investigation.

5 Acknowledgments

This research was financed as part of the Centre for Industrial Energy, Materials and Products (CIE-MAP) a UK industrial energy demand reduction centre funded by the Engineering and Physical Sciences Research Council (EPSRC) grant EP/N022645/1. The authors would like to thank the editor and reviewers for their helpful comments and perseverance thoughout the publishing process.

6 References

[1] Bunse K., Vodicka M., Schönsleben P., Brülhart M., Frank O. Ernst., 2011, Integrating energy efficiency performance in production management - gap analysis between industrial needs and scientific literature, Journal of Cleaner Production 19 (2011) 667-679

[2] Sun C., Williamson M., 1999. Industrial Energy Use Benchmarking. 1999 ACEEE Summer Study on Energy Efficiency in Industry Proceedings. Downloaded from: http://aceee.org/files/proceedings/1999/data/papers/SS99_Panel1_Paper68.pdf

[3] Ke J., Price L., McNeil M., Zheng Khanna N, Zhou N.,2013, Analysis and practices of energy benchmarking for industry from the perspective of systems engineering, Energy 54 (2013) 32-44

[4] Boyd G., Dutrow E., Tunnessen W., 2008, The evolution of the ENERGY STAR® energy performance indicator for benchmarking industrial plant manufacturing energy use, Journal of Cleaner Production, Volume 16, Issue 6, April 2008, Pages 709-715.

[5] Vivid Economics with Ecofys, 2013, Carbon leakage prospects under Phase III of the EU ETS, London: Department of Energy and Climate Change (DECC)

[6] Confederation of European Paper Industries (CEPI), 2014, Pulp and Paper Industry Definitions and Concepts. Downloaded from: http://www.cepi.org/system/files/public/documents/publications/statistics/2014/FINAL%20CEPI%20Definitions%20and%20Concepts_0.pdf

[7] Sixta, H, ed. (2006). Handbook of pulp. Winheim, Germany: Wiley-VCH. p. 9. ISBN 3-527-30997-7.

[8] Abdelaziz A.E., R. Saidur R.. Mekhilef S., 2011, A review on energy saving strategies in industrial sector, Renewable and Sustainable Energy Reviews 15 (2011) 150–168

[9] Worrell E., Price L., Neelis M., Galitsky C., Zhou Nan, 2008, World Best Practice Energy Intensity Values for Selected Industrial Sectors, Ernest Orlando Lawrence Berkeley National Laboratory report LBNL-62806 REV

[10] IPPC, 2001. Reference Document on Best Available Techniques in the Pulp and Paper Industries. Integrated Pollution Prevention & Control. Brussels / Sevilla: European Commission

[11] Francis, D. W., Towers M. T., Browne T. C., 2002. Energy Cost Reduction in the Pulp and Paper Industry: An Energy Benchmarking Perspective. Ottawa: NRCan.

[12] Karlsson, M., 2005. The Dutch Innovation Transition, Small/Large Paper/Board Machine Concepts, Automation. Presentation at Meeting of the Royal Netherlands Paper and Board Industry Association (VNP), Beekbergen, The Netherlands, February 23rd, 2005.

[13] International Energy Agency 2009, Energy Technology Transition for Industry, Paris: IEA Publications, ISBN 978-92-64-06858-2

[14] International Energy Agency, 2007 Tracking Industrial Energy Efficiency and CO2 Emissions, Paris: IEA Publications. ISBN: 978-92-64-03016-9

[15] Martin et al, 2001, Opportunities to improve energy efficiency in the US pulp and paper industries, Lawrence Berkeley National Laboratory, Berkley California

[16] Finnish Forestry Industries Federation, 2002, Possibilities of reducing CO2 emissions in Finish Forest Industries, Helsinki

[17] Quadrella R, 2016, Energy Efficiency Indicators Highlights, International Energy Agency, Paris, Downloaded from: www.iea.org

[18] Saygin D., Worrell E., Patela M. K., Gielen D. J.,2011, Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries, Energy 36 (2011) 6661- 6673

[19] Jacobs, Institute of Paper Science and Technology, 2006, Pulp and Paper Industry Energy Bandwidth Study, American Institute of Chemical Engineers (AIChE) report for Department of Energy's Industrial Technologies Program, Project Number: 16CX8700

[20] Miller T., Kramer C., Fisher A., 2015, Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing, report prepared for DOE / EERE's Advanced Manufacturing Office by Energetics Incorporated, DOE/EE-123. Downloaded from: http://www.energy.gov/sites/prod/files/2015/08/f26/pulp_and_paper_bandwidth_report.pdf

[21] EPA,2015, Reducing Greenhouse Gas Emissions by Advancing Industrial Energy Efficiency, US Environmental Protection Agency Energy Star program document 430-R-15-006

[22] Boyd G. A., Yi Fang Guo,2012, Development of Energy Star® Energy Performance Indicators for Pulp, Paper, And Paperboard Mills. Downloaded from:

www.energystar.gov/buildings/tools-and-resources/development-performance-based-industrial-energy-efficiency-indicator-5

[23] Natural Resource Canada, 2006, Benchmarking Energy Use In Canadian Pulp And Paper Mills, ISBN 0-662-69589-5 Downloaded from: www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/pdf/industrial/technical-info/benchmarking/pulp-paper/pdf/benchmark-pulp-paper-e.pdf

[24] Suhr M., Klein G., Kourti I., Gonzalo M. R., Roudier G. G. S., Sancho L. S., 2015, Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board, Industrial Emissions Directive 2010/75/EU European Commission report prepared by Joint Research Centre Institute for Prospective Technological Studies Integrated Pollution Prevention and control report JRC95678, EUR 27235 EN, ISBN 978-92-79-48167-3 (PDF), ISSN 1831-9424 (online), doi:10.2791/370629 Luxembourg: Publications Office of the European Union, 2015

[25] Blum O., Maur B., Öller H., 2007, Revision Of Best Available Technique Reference Document For The Pulp & Paper Industry, Report Nr. 2 Use Of Energy Saving Techniques. Umwett Bundes Amt Munich Commissioned by Federal Environmental Agency Germany (UBA Germany), Dessau, TU Darmstadt - Fachgebiet Papierfabrikation und Mechanische Verfahrenstechnik, Downloaded from: www.dehst.de/SharedDocs?Downloads/Archiv?BVT_UBA_Papier-Zellstoff.pdf

[26] The European Commission, 2011, Determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council.

[27] Ecofys, 2009, Methodology for the free allocation of emission allowances in the EU ETS post 2012 Sector report for the pulp and paper industry, European Commission Study Contract: 07.0307/2008/515770/ETU/C2 Ecofys project Number: PECSNL082164

[28] Roth S., Zetterberg L, Acworth W., Kangas H.,L.,Neuhoff K.,Zipperer V.,2016, The pulp and paper overview paper Sector analysis for the Climate Strategies Project on Inclusion of Consumption in Carbon Pricing, Report produced by Climate Strategies, Downloaded from: www.climatestrategies.org

[29] Laurijssen J., Faaij A., Worrell E., 2013, Benchmarking energy use in the paper industry: a benchmarking study on process unit level, Energy Efficiency (2013) 6:49–63, DOI 10.1007/s12053-012-9163-9

[30] Neelis M., Worrell E., Mueller N., Angelini T., Creme C.,r, Schleich J., Eichhammer W., 2009, Developing Benchmarking Criteria For CO2 Emissions prepared by Ecofys and The Fraunhofer Institute for Systems and Innovation research, Ecofys project number: PECSGB073248 for the European Commission Service contract ENV.C.4/SER/2007/0059

[31] Australian Government (2012) Establishing the eligibility of emissions-intensive, trade-exposed activities under the Jobs and Competitiveness Program and Renewable Energy Target.

[32] CARB, California Air Resources Board, (2011) Cap-and-Trade Regulation: July 2011, Appendix B: Development of Product Benchmarks for Allowance Allocation.

[33] Eichhammer W, 2012, Monitoring energy efficiency trends and policies in the EU - Lessons from the Odyssee Mure Project. Intelligent Energy Europe. Downloaded from: http://www.odyssee-mure.eu/publications/br/synthesis-energy-efficiency-trends-policies.pdf

[34] Huddleston J., 2004, Climate Change Agreements Results Of The First Target Period Assessment, Future Energy Solutions report 01838/1 AEA Technology plc

[35] Ekins P., Etheridge B.,2006, The environmental and economic impacts of the UK climate change agreements, Energy Policy 34 (2006) 2071–2086

[36] DEFRA. 2015, Project WR1210 – How can paper be made more sustainable?

[37] WSP Parsons Brinckerhoff, 2015, INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAPS TO 2050 – PULP AND PAPER Pathways to Decarbonisation in 2050

[38] Carbon Trust, 2011. Industrial Energy Efficiency Accelerator - Guide to the paper sector. CTG059

[39] Griffin P., Hammond G., Norman J., 2013, Industrial Energy Use from a bottom up perspective: developing the Usable Energy Database (Beta Version), REF UKERC/WP/ED/2013/002 Downloaded from: data.ukedc.rl.ac.uk/simplebrowse/edc/efficiency/industry/EnergyConsumption accessed April 2016

[40] Griffin, P.W., G.P. Hammond and J.B. Norman, 2017. 'Industrial decarbonisation of the pulp and paper sector: A UK perspective', Proc. 4th Sustainable Thermal Energy Management (*SusTEM2017*) International Conference, Alkmaar, The Netherlands, 28-30 June, 183-192.

[41] Confederation of European Paper Industries (CEPI), 2015, Key Statistics 2014 EUROPEAN PULP AND PAPER INDUSTRY. Downloaded from: http://www.cepi.org/system/files/public/documents/publications/statistics/2015/Key%20Statistics%202014%20FINAL.pdf

[42] Kong L., Hasanbeigi A., Price L., Liu H., 2013, Analysis of Energy-Efficiency Opportunities for the Pulp and Paper Industry in China, Ernest Orlando Lawrence Berkeley National Laboratory report LBNL-6107E

[43] Peng L, Zeng X , Wang Y, Hong G, 2015, Analysis of energy efficiency and carbon dioxide reduction in the Chinese pulp and paper industry, Energy Policy 80(2015)65–75.

[44] Wang Y, Yang X, Sun M, Lei Mac L, Li X , Shi L, 2016, Estimating carbon emissions from the pulp and paper industry: A case study, Applied Energy 184 (2016) 779–789

[45] Confederation of Indian Industries (CII),2008, National Best Practices Manual Pulp & Paper Industry - Making Indian Pulp & Paper Industry World Class, Published by Confederation of Indian Industry, CII – Sohrabji Godrej Green Business Centre, Survey # 64, Kothaguda Post, R R District, Hyderabad – 500 032, India.

[46] Fracaro G., Vakkilainen E., Hamaguchi M., Samuel Nelson Melegari de Souza S. N.,2012, Energy Efficiency in the Brazilian Pulp and Paper Industry , Energies 2012, 5, 3550-3572; doi:10.3390/en5093550

[47] Farla J., Blok K., Schipper L., 1997, Energy efficiency developments in the pulp and paper industry - A cross-country comparison using physical production data, Energy Policy, Vol. 25, Nos. 7-9, pp. 745-758,

[48] Hua-Wei Chen, Chung-Hsuan Hsu, Gui-Bing Hong, 2012, The case study of energy flow analysis and strategy in pulp and paper industry, Energy Policy 43 (2012) 448–455.

[49] Confederation of European Paper Industries (CEPI,2013), Two Team Project Report Unfold the future. Downloaded from: http://www.cepi.org/node/16891

[50] Ottestam C, 2009, New and innovative processes for radical changes in the European pulp & paper industry, Publishable Final activity STFI-Packforsk report ECOTARGET 500345

[51] Chudnovsky Y., Kozlov A.,Sherrow L., 2004, Laboratory Development of a High Capacity Gas-Fired Paper Dryer Final Technical Report, Gas Technology Institute report TGTI/DOE/SMP/GRI-61134/80042/30797

[52] Lehtinen J.,1998, Condebelt Board And Paper Drying, Drying Technology, 16:6, 1047-1073, DOI: 10.1080/07373939808917453

[53] Gavrilescu D., 2008, ENERGY FROM BIOMASS IN PULP AND PAPER MILLS, Environmental Engineering and Management Journal 7 (2008), 5, 537-546

[54] Briggs, D. G.,1994, Forest products measurements and conversion factors: with special emphasis on the U.S. Pacific Northwest. University of Washington. Institute of Forest Resources, report no. 75. TS806.P33B75 1994674'.0212-dc20 94-18965. Available at: http://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_book.asp

[55] Skogs Industrierna The Swedish Forest Industries. Downloaded from: http://www.forestindustries.se/documentation/statistics_ppt_files/international/global-paper-production-by-grade 14 July 2016

[56] Schaefer K, 2015, Outlook for the World Paper Grade Pulp Market, RISI, Inc. Downloaded from: www.cepi.org/system/files/.../EuropeanPaperWeek2015/Schaeffer%20-%20RISI.pdf

1 Appendix 1: Background to the paper and pulp industry

1.1 Basic process

Although a small amount is made from no-wood pulps (grasses or bamboo) most paper is made from wood pulp. Pulp can be produced by several different processes.

1.1.1 Recycled paper

The proportion of pulp produced from recycled paper has increased from 44% in 2004 to 57% in 2014 [41]. Recycled paper and board is rehydrated and mixed to a smooth pulp in a refining stage. Inks, glues and non-fibre solids (stapes etc.) are removed by a multi-stage aeration and flocculation process known as deinking. Deinked pulp often needs to be bleached to make good-quality paper.

1.1.2 Virgin wood pulp

It is not always practical to recycle paper for reasons such as hygiene, use in long-life products (electrical insulation and books), use as cigarette paper or being too small to collect etc. There are also losses from the recycling process due to fibre damage, removal of filler material and contaminates. These are reported to be between 4% to 9% for cardboard and 32% to 46% for deinked office paper [53]. Consequently, even if the demand for paper stabilised, the paper industry will always need a supply of virgin wood pulp.

Globally, 80% of virgin wood pulp is produced by the Sulphate (or Kraft) chemical pulping process where woodchips are heated in a pressure vessel in sodium hydroxide cooking liquor (soda pulp) or a mixture of sodium hydroxide and sodium sulphide cooking liquors. This dissolves the lignin in the wood leaving the cellulose fibres. The lignin is recovered as 'black liquor' and used as a boiler fuel. The pulping chemicals are recovered and re-causticized with lime for reuse in the process. Kraft pulp has long fibres which means that it produces paper with high strength. The rest of virgin pulp is produced by either Mechanical grinding; Thermo-mechanical (TMP), where woodchips are softened in hot water before mechanical pulping; Chemi-Thermomechanical (CTMP), a development of TMP where the chips are chemically pre-treated before pulping; or Sulphite pulping, a chemical process where woodchips are cooked in a pressure vessel in the presence of a bisulphite cooking liquor. Mechanical pulping produces shorter fibres than Kraft pulping so the resulting paper is not as strong. However, as the lignin fibres are also included in the pulp, yield per tonne of timber can be double that of Kraft pulping [54]. As with recycled pulp, virgin pulps are frequently bleached before being used for paper making. Pulp can be used on site in an integrated paper mill or dried and sold as market pulp.

Paper is made by depositing a slurry of fibres and water onto a traveling mesh conveyor (or wire). The water is then removed by gravity, mechanical pressure, suction and heating. The dried paper is then wound onto a reel. Fillers can be added to the slurry to reduce the need for fibres and coating can be applied to the dried paper to improve its surface quality. Coatings are applied as solutions and need a secondary dryer stage. The finished paper can be buffed in a process known as calendaring to smooth the finished surface. Comprehensive explanations of these process can be found elsewhere [6, 24].

The paper making process does not inherently emit greenhouse gasses, and the widespread use of black liquor and CHP plants reduces the emission of GHG from energy production. Consequently, although energy intensive, the paper industry is not normally considered to be carbon intensive. However, as electricity grids become decarbonised, fossil fuel-fired CHP plants will be considered as high-carbon sources of electricity. There is also likely to be a considerable increase in demand for biomass as a low-carbon energy source so there are strong incentives for the industry to minimise its energy use.

1.2 The Global Industry

The global demand for paper and board was 406 Mt in 2014, split between the following product categories: newsprint (6%), printing and writing (26%), tissue (8%), corrugated material (38%), paperboard and packaging (14%) and other paper (8%).

The market continues to grow at around 6 Mt a year; however, this growth is not spread evenly across all product grades. Demand for newsprint and graphic paper (including printing and writing) is falling or plateauing while that for packaging and sanitary tissue is increasing [55, 56]. Paper and wood pulp are globally traded either directly or indirectly as part of the trade of boxed goods.

2 Appendix 2: Correspondence between product descriptions

There does not appear to be a consistent terminology for describing paper and pulp products across the literature. This appendix identifies the classifications that the authors consider to be equivalent.

Table A2.1 Correspondence between paper and pulp product classifications

EU ETS product benchmark	CEPI title	CEPI description	NAICS last 6 dig	description
Newsprint	CEPI 100000 newsprint	paper mainly used for printing newspapers	322122	newsprint
Uncoated fine paper	CEPI 211000000 Uncoated mechanical	paper suitable for printing or other graphic purposes where less than 90% of the fibre furnish consists of chemical pulp fibres		
Uncoated fine paper	CEPI 231000 Uncoated woodfree	paper suitable for printing or other graphic purposes, where at least 90% of the fibre furnish consists of chemical pulp fibres.	3221213	Uncoated freesheet paper (containing not more than 10 percent mechanical fibre)
Coated fine paper	CEPI 212000 Coated mechanical papers CEPI 232000 Coated wood free	all paper suitable for printing or other graphic purposes and coated on one or both sides with minerals such as china clay (kaolin), calcium carbonate, etc.	3221211	Clay-coated printing and converting paper
Testliner and fluting Coated carton board	CEPI 3000000 Case materials	papers and boards mainly used in the manufacture of corrugated board. Included are kraftliner, testliner, semi-chemical fluting, and waste-based fluting (Wellenstoff). Also known as containerboard, corrugated case materials, cardboard, linerboard or corrugating medium.	3221301 3221305	Unbleached kraft packaging and industrial converting paperboard (80 percent or more virgin woodpulp): Semi chemical paperboard, including corrugating medium (75 percent or more virgin woodpulp)
Uncoated carton board	CEPI 4000000 Carton board	made from virgin and/or recovered fibres, mainly used in cartons for consumer products. Also known as solid board, folding box board, boxboard or carrier board.	3221303 3221307	Bleached packaging and industrial converting paperboard (80 percent or more virgin bleached woodpulp) Recycled paperboard
	CEPI 5000000 Wrappings (up to 125 g/m2)	papers whose main use is wrapping or packaging made from any combination of virgin or recovered fibres, bleached or unbleached. Included are sack kraft, other wrapping krafts, sulphite and grease-proof papers	3221219	Unbleached kraft (not less than 80 percent) packaging and industrial converting paper
	CEPI 6000000 Other papers mainly for packaging purposes	this category embraces all paper and board mainly for packaging purposes other than those listed above.	322121A	Packaging and industrial converting paper, except unbleached kraft
Tissue	CEPI 7000000 Sanitary and Household	This covers a wide range of tissue and other hygienic papers for use in households or commercial and industrial premises.	322121N 322121G	Sanitary tissue paper products, made in paper mills Tissue paper and other machine-creped paper
	CEPI 8000000 Other paper and board	includes cigarette papers and filter papers, as well as gypsum liners and special papers for waxing, insulating, roofing, asphalting, and other specific applications or treatments.	322121E 322121C	Construction paper Special industrial paper, except specialty packaging, including absorbent,

	battery separator, electrical papers, etc.

3 Appendix 3: Comparison of current energy use from different benchmarks

The data from the individual benchmarks have been converted to consistent units so that they can be compared. No study covered all the product classifications. Worrell reports a negative value of the heat load of thermo-mechanical pulping; this signifies that the mechanical pulping generates more heat than is required for the process and that some of this heat can be exported for use as process heat by other processes.

Table A3.1 Specific energy use for current mills

	Blum		**Worrell**		**Jacobs**		**NRC**	
pulp mills	Electricity	Heat	Electricity	Heat	Electricity	Heat	Electricity	Heat
CEPI title	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t
CEPI 923000 mechanical					9.13	3.33	6.41	0.00
CEPI 923400 thermo mechanical			7.88	-1.30	11.04	0.78	9.58	0.56
CEPI 921000 semi chemical					2.26	7.99		
CEPI 922200 Sulphite			2.52	16.00			2.87	5.00
CEPI 922100 Chemical - Sulphate (or kraft)	2.88	16.56	2.30	11.20	1.94	11.28	1.55	12.4
kraft bleached hardwood					1.74	11.06		
Kraft unbleached					1.49	9.17		
recovered pulp			1.19	0.30			1.24	0.11
old corrugated cardboard					1.49	0.84		
Mix office waste non deinked tissue					1.74	0.88		
MOW deinked					2.23	1.55		
old newsprint					1.86	1.55	1.44	0.80
market pulp steam dry					0.64	3.26	0.55	4.59
wet lap							0.26	
conversion							0.31	
non integrated paper mills								
CEPI title								
CEPI 100000 newsprint			2.05	5.10	2.23	4.88	2.03	5.36
CEPI 211000000 uncoated mechanical							2.44	6.21
CEPI 231000 Uncoated woodfree	2.52	6.84	2.30	6.70				
CEPI 212000 Coated mechanical papers					2.48	6.15		
CEPI 232000 Coated wood free	2.52	5.76	2.92	7.50	2.88	6.93	2.39	6.32
CEPI 3000000 Kraftliner			1.93	5.90				
corrugated medium					2.23	6.32		
CEPI 4000000 bifold box board					2.73	7.37		

carton board linear board			2.88	6.70	2.86	6.43		
box board					2.56	7.37		
CEPI 5000000 wrapping							3.68	9.10
CEPI 7000000 Tissue	3.6	7.2	3.60	6.90	2.98	6.40		
TAD tissue	9	21.6						
CEPI 8000000								
Other paper and board								
integrated paper mills								
CEPI title								
CEPI 100000 newsprint								
newsprint TMP			7.92	-1.30				
CEPI 211000 Uncoated mechanical	4.68	5.04						
uncoated sulfite			4.32	18.00				
CEPI 231000 Uncoated woodfree			4.32	14.00				
CEPI 212000 Coated mechanical papers	5.76	5.76						
CEPI 232000								
coated sulfite			5.40	17.00				
CEPI 5000000			3.6	14.00				
RCF non deinked packaging[2]	1.44	5.04						
RCF deinked graphic paper	3.96	4.68						
RCF deinked board	1.8	5.76						
board non deinked RFC			3.24	8.00				
newsprint deinked RCF			3.60	4.00				
tissue deinked RFC	4.68	9	4.32	7.00				
waste water & utilities					0.33	1.00	0.10	0.00
effluent activated sludge	0.0144	0.0288					0.18	0.00
general buildings	0.072	0.108					0.05	0.04

[2] RCF is recycled cellulose fibres

Table A3.2 Specific savings using BAT technology

	Blum		Worrell		Jacobs		NRC	
pulp mills	Electricity	Heat	Electricity	Heat	Electricity	Heat	Electricity	Heat
CEPI title	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t	GJ/t
CEPI 923000 mechanical					8.53	3.16	5.94	
CEPI 923400 thermo mechanical			7.88	-1.30	8.35	0.61	9.81	
CEPI 921000 semi chemical					2.11	5.27		
CEPI 922200 Sulphite			2.52	16.00	0.00	0.00	0.94	4.11
CEPI 922100 Chemical - Sulphate (or kraft)	2.628	16.002	2.30	11.20	1.45	8.15	1.26	6.8
kraft bleached hardwood					1.39	7.25		
Kraft unbleached					1.08	6.49		
recovered pulp			1.19	0.30			0.92	0
old corrugated cardboard					0.82	0.63	0.00	0
Mix office waste non deinked tissue					1.39	0.63	0.00	0
MOW deinked					1.89	1.40	0.00	0
old newsprint					1.58	1.40	0.00	0
market pulp steam dry					0.64	2.66	0.51	2.3
wet lap							0.24	0
conversion							0.21	0
non integrated paper mills							0.00	0
CEPI title								
CEPI 100000 newsprint			2.05	5.10	1.31	3.50	1.19	4.9
CEPI 211000000 uncoated mechanical							2.01	4.93
CEPI 231000 Uncoated woodfree	2.16	4.68	2.30	6.70				
CEPI 212000 Coated mechanical papers					2.22	4.68		
CEPI 232000 Coated wood free	2.16	4.32	2.92	7.50	2.00	4.03	1.98	5.1
CEPI 3000000 Kraftliner			1.93	5.90				
corrugated medium					2.05	3.59		
CEPI 4000000 bifold box board					1.89	3.24		
carton board linear board			2.88	6.70	1.89	3.24		
box board					1.42	4.56		

CEPI 5000000 wrapping							2.97	8.47
CEPI 7000000 Tissue	3.24	7.2	3.60	6.90	2.68	6.17		
TAD tissue								
CEPI 8000000								
Other paper and board								
integrated paper mills								
CEPI title								
CEPI 100000 newsprint TMP			7.92	-1.30				
CEPI 211000000Uncoated mechanical	3.3336	3.942						
uncoated sulfite			4.32	18.00				
CEPI 231000 Uncoated woodfree			4.32	14.00				
CEPI 212000 Coated mechanical papers	4.32	6.12						
CEPI 232000 coated sulfite			5.40	17.00				
CEPI 5000000			3.60	14.00				
RCF non deinked packaging								
RCF deinked graphic paper	1.08	3.96						
RCF deinked board	3.24	4.32						
board non deinked RFC	1.62	3.6	3.24	8.00				
newsprint deinked RCF			3.60	4.00				
tissue deinked RFC			4.32	7.00				
waste water & utilities							0.05	0
effluent activated sludge							0.11	0
general buildings							0.02	0.04

Table A3.3 Savings achievable using BAT technology

	Blum		Worrell		Jacobs		NRC	
pulp mills	Electricity	Heat	Electricity	Heat	Electricity	Heat	Electricity	Heat
CEPI title								
CEPI 923000 mechanical					6.6%	5.1%	7.3%	0.0%

CEPI 923400 thermo mechanical					24.4%	21.6%	-2.4%	100.0%
CEPI 921000 semi chemical					6.7%	34.1%	0.0%	0.0%
CEPI 922200 Sulphite							67.4%	17.8%
CEPI 922100 Chemical - Sulphate (or kraft)	8.8%	3.4%			25.0%	27.7%	16.1%	28.0%
kraft bleached hardwood					20.0%	34.5%	0.0%	0.0%
Kraft unbleached					27.7%	29.3%	0.0%	0.0%
recovered pulp							25.6%	100.0%
old corrugated cardboard					44.6%	25.0%		
Mix office waste non deinked tissue					19.8%	28.6%		
MOW deinked					15.4%	9.5%		
old newsprint					15.1%	9.5%		
market pulp steam dry					0.0%	18.4%	7.8%	49.9%
wet lap							5.6%	0.0%
conversion							33.3%	0.0%
non integrated paper mills								
CEPI title								
CEPI 100000 newsprint					41.2%	28.3%	41.6%	8.6%
CEPI 211000000 uncoated mechanical							17.6%	20.6%
CEPI 231000 Uncoated woodfree	14.3%	31.6%						
CEPI 212000 Coated mechanical papers					10.5%	24.0%		
CEPI 232000 Coated wood free	14.3%	25.0%			30.6%	41.8%	17.0%	19.3%
CEPI 3000000 Kraftliner								
corrugated medium					8.2%	43.2%		
CEPI 4000000 bifold box board					30.8%	56.0%		
carton board linear board					33.9%	49.6%		
box board					44.4%	38.1%		
CEPI 5000000 wrapping							19.3%	6.9%
CEPI 7000000 Tissue	10.0%	0.0%			10.2%	3.6%		
TAD tissue								
CEPI 8000000								

Other paper and board			
integrated paper mills			
CEPI title			
CEPI 100000 newsprint			
newsprint TMP			
CEPI 211000000Uncoated mechanical	28.8%	21.8%	
uncoated sulfite			
CEPI 231000 Uncoated woodfree			
CEPI 212000 Coated mechanical papers	25.0%	-6.3%	
CEPI 232000			
coated sulfite			
CEPI 5000000			
RCF non deinked packaging	25.0%	21.4%	
RCF deinked graphic paper	18.2%	7.7%	
RCF deinked board	10.0%	37.5%	
board non deinked RFC			
newsprint deinked RCF			
tissue deinked RFC	30.8%	20.0%	
waste water & utilities			52.3%
effluent activated sludge			35.1%
general buildings			63.9%

511

4 Appendix 4: Innovations

Table A4.1 Innovations reported in US bandwidth study

Technology	Description	Potential saving
Black liquor gasification	improve energy recovery by 10% increase electricity gen by 200-300%	
Direct green liquor utilisation	use 20%-30% of green liquor to pre-treat wood chips - reduces flow of green liquor to be treated and digester load	25% saving Kraft process
Membrane concentration of black liquor	use membrane to increase concentration of black liquor from 15% to 30%	evaporator heat load reduced by 37%
Dry Kraft Pulping	pre-soak woodchips with pulping solution, no additional solution is needed	30% reduction in heat load of Kraft process
Oxalic Acid pre-treatment for mechanical pulping	10 min soak reduces pulping power and improve pulp quality	25% reduction in mechanical pulping electricity
Condebelt drying	Web dried between heated and cooled steel belts rather than heated drum	37% heat reduction + 37% reduction is dryer electricity
new fibrous fillers	depends of filler improves performance of press	up to 25% saving in press and 40% heat saving in dryer
high consistency forming	low weight paper consistency up to 3%	8% reduction in paper machine electricity
pulse drying	pulse of hot air directed onto web for yankee and MG dryers or rollers for newsprint or paper	up to 60% saving on dryer energy
gas fired drum driers	dryer cylinders heated by internal gas burner rather than steam	10%-15% saving in dryer heat requirement
dry sheet forming	tissue paper formed from fibres suspended in turbulent air	50% less drying heat but 250kWh/t (30%) increase in electricity

Table A4.2 CIEP Two-team project innovation proposals

Technology	Description	Potential saving
Deep Eutectic Solvents	these are newly discovered natural solvent that are used by plants to survive water stress conditions by extractive chemicals from their own structure. This science is at an early stage of development, but it looks like DES solvents can be found for lignin and hemicellulose and probably cellulose. This opens up the possibility of chemically extracting cellulose from a wide range of biomass at low temperatures without milling.	up to 40% reduction in primary energy consumption and yield valuable bio chemical by-products.
Flash condensing with steam	dry fibre, filler, and chemicals are mixed into a turbulent steam flow which them passes into a condensing zone where the paper is formed in the condensing fog. The paper is formed with a 70% solid content.	needs less than 50% of the drying energy required by todays dryers.
Superheated Steam Drying	Use dry steam (steam that is at a temperature greater than the boiling point for the steam pressure) to remove the evaporated moisture from the paper in the dryer. The steam can then be used for steam forming or other processes. As the steam is at a higher temperature than the existing air more useful heat can be extracted. The high temperatures and pressures mean that machines operating on these principles will need to be remotely operated.	Energy savings of 25% are envisaged
Dry pulp for cureformed paper	Fibres are coated with a protective film than suspended in a viscous solution, after forming the viscous fluid is removed in a press and the paper is them cured. This process can be adapted to produce multi layered products in a single step	Energy savings estimated to be around 25%.
Supercritical CO_2	This can be used to freeze dry paper in place of conventional dryers. Supercritical CO_2 can also be used in the deinking and cleaning processes in recycled pulp	primary energy saving of up to 20%

Electrification	Use TMP as a flexible load for intermittent renewable electricity and high efficiency electrical drying techniques.	
Functional surface	Developments in formation and pulps could allow the same physical properties to be achieve with a reduce weight product	30% weight reduction possible
Toolbox	Basically uses multiple incremental developments in biochemical processing, advance forming and 3 D printing to provide evolving bio based products that replace many of the conventional paper products (and some new ones).	

Table A4.3 Areas for innovation investigated by STFI-Packfork

Area	Description	Potential saving
virgin fibre supply	Using enzymatic of wood chips before mechanical pulping or chemical pre-treatment before TMP pulping	energy savings 8% to 28% with enzymes, up to 25% with chemical but some pulp deterioration
Recovered paper sorting improved by new sensors	Sensors developed to help automate recycled feedstock sorting. Also work package also developed a single loop deinking plant.	deinking plant could save 16% of electricity and 30% of steam and 20% reduction in material loss when compared to a traditional plant
Furnish solution	The aim of this work package was to select fibres for particular grades of paper. This was done using enzyme treatment and improve fractionalisation techniques.	
Papermaking solutions	Stratified forming, producing a multi layered product by simultaneous stratified forming thus avoiding the need laminate and glue multi layered products.	Energy savings estimated as 16%.
Additives	starches were used to decrease build-up of organic substances in white water allowing lower bleed and fresh water makeup rates.	

Table A4.4 UK industry stakeholders interest in areas of innovation from The Carbon Trust 2011. Industrial Energy Efficiency Accelerator

Technology	Priority	Maturity	Comments
Stock Preparation			
Better segregation	low	medium	Possible partnering with Local Authorities to deliver non-comingled waste. Technically mature - innovation would be in systemic approach to problem.
Advanced conditioning (Enzymatic, chemical, etc.)	low	high	Regarded as generally adopted and thus current known advances need to diffuse before new ones developed
Pumping optimisation	med	medium	The individual elements of pumping optimisation (pump selection, motor selection, low friction coatings, impeller design, system layout, variable speed, controls etc.) are mature.
High consistency processing	Low	high	Can already take place at 15-20%
Online Fibre analysis (high frequency)	Low	medium	Demonstration in Canada, didn't create much interest in UK Industry
Recycled mineral fillers (RMF PCC)	low	low	Very little interest/discussion - felt that it was moving carbon emissions and not eliminating them.
Pulping Optimisation	high	medium	New pulpers are being introduced by manufacturers and hence could be considered as commercial technology
Wet end			
Use of other carrier liquids	Low		No interest, too immature

Advanced controls including moisture measurement	high	medium	Perhaps the most interest here (a common theme in all areas)
Dry forming	Low	low	Not much interest
Vacuum optimisation	high	medium	A lot of interest - this is as much about control of vacuum systems as it is about new technology in vacuum pumps
Advanced felts	low	medium	Not much interest but only because it is easy to do. Perhaps shouldn't be dismissed but made part of other project ideas
Press configuration	medium	medium	Hot pressing. Main issue here is difficulty and cost. There appears to be a limit on the maximum temperature possible in pressing - while higher temperatures reduce water viscosity and improve drainage they also have an impact on fibre strength.
Impulse Drying	high	low	Applying heat and pressure for dewatering before drying. Regarded as a good innovation but doubts expressed about performance of impulse dryers
Drying			
Advanced heat recovery (Heat pumps, Chemical heat transformers – upgrade waste heat)	low	medium	The main interest here is either to generate electricity from the waste heat or to upgrade the heat with a "heat amplifier".
Advanced heat recovery – better integration (reuse either in plant or outside)	low	medium	Could be stand alone as a PINCH software solution for the sector or as part of a new technology. Integration is also about linking paper industry with symbiotic industries (i.e. needing low grade heat) or with district heating.
Advanced controls	high	medium	Considerable interest in better humidity and mass flow control. Would facilitate operation with lower air flows and higher relative humidities at exhaust - this would upgrade quality of heat in exhaust stream (higher specific enthalpy). Sensor reliability in paper machine environments was considered a barrier
Hood segregation – air flow management	high	medium	Linked to above
Condebelt‖ dryers	low	low	Rejected - not considered as a viable future technology path
Other heat technologies (e.g. Microwave, IR, etc.)	medium	medium	Apply heat to web prior to dryer using IR - so dryer cylinders used for evaporation and not heating. Offset new carbon emissions for IR vs. reductions in steam consumption
Power			
Biogas from recycling wastes	low	high	Regarded as demonstrated; main industry interest is in partnering with 3rd party energy from waste operators, i.e. mass burn incineration with CHP.
Advanced predictive controllers for central energy plants	medium	medium	Good interest here again with a control project. Aylesford Newsprint have a neural net based system for their boiler
Steam accumulation	low	high	Linked with advanced controls – as a way of damping changes in the steam system
Steam system optimisation – cascade systems	low	high	Recovery and reuse of flash steam in the dryer sections

521