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Influences of material recycling on energy efficiency, Case: iron and steel industry & pulp and paper industry

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Abstract
Lately, attention has been drawn to the importance of material efficiency. Material recycling (use of secondary materials, i.e. recycled materials) seems to result in lower specific energy consumption in industrial production. This paper discusses the influences of material recycling on energy efficiency in the iron and steel industry and in the pulp and paper industry. The paper shows that the share of secondary production in the iron and steel industry and the utilisation rate of recovered paper in pulp and paper industry are important factors affecting the average specific energy consumption at the national level. One possible way to allocate the benefits of material recycling between primary and secondary production, discussed here, is allocation in the cascade over the whole life cycle of material use.

Keywords: Energy efficiency, recycling, specific energy consumption, process industry

1. Introduction

Manufacturing industry accounts for one third of global energy use [1] and 50% of Finnish final energy use [2], so reducing energy intensities and improving energy efficiency in industrial processes are important sustainable development objectives [3]. Improving of material efficiency by material recycling is seen as an important way of reducing the energy consumption and CO_2 emissions of industrial processes. For example, in the steel industry recycling is seen as the most promising solution to limit greenhouse gas emissions in the short term [4].

Energy efficiency is often defined as the ratio of energy input into a process to the useful output of the process. In energy-intensive industries, such as the iron and steel industry, the pulp and paper industry and the chemical industry, the useful output is typically measured as tons of product produced. Therefore, specific energy consumption (SEC) is the energy efficiency indicator most commonly used to measure energy efficiency in these industries. Sometimes, the terms 'energy intensity value' [5] or 'energy consumption intensity' [6] are used instead of SEC.

SEC can be used to analyse trends in energy efficiency in a manufacturing process, sector or even at the national level. Depending on the case, SEC can be calculated using either bottom-up or top-down methods. In top-down methods, the energy efficiency indicators are calculated from national statistics. The Odyssee project has used a top-down method to define energy efficiency indicators for the EU countries [7]. Besides analysing energy efficiency trends, Odyssee indicators can be used for international comparisons. Also, some international benchmarking studies on the energy efficiency performance of industrial sectors have been made [8, 9, 10, 11, 12]. Benchmarking studies are based on a comparison with the best performance data, i.e. best practices. The most recent 'best practice data' for selected industrial sectors has been collected by Worrell et al. [5].

Various factors other than the development of energy efficiency affect changes in the energy consumption of industrial processes [10]. For instance, differences in indicators between countries may reflect the difference in product mix, i.e. the structure of an industrial sector [3, 8, 11, 12, 13]. Therefore, special attention was paid to the structure of industrial production in the international benchmarking studies referred to here.

Karbuz [14] and Farla and Blok [11] emphasise the selection of appropriate data when energy efficiency indicators are used as a basis for international comparisons. Farla and Blok [11] concluded that the quality of the energy consumption data used largely determines the accuracy of the physical energy intensity indicators. The definition of system boundaries and self generation of electricity were mentioned, among others, as the main differences in energy consumption data from statistical sources.

The utilisation of recycled materials is a major factor affecting the product mix and energy consumption of the industrial sector. Life cycle assessments (LCAs) have been carried out and compared to assess the environmental impacts of recycling, especially in the pulp and paper industry [15, 16, 17]. The allocation of environmental loads, including energy consumption and CO_2 emissions, is one of the most important methodological problems to be tackled when carrying out the LCAs of a recycling process. Ekvall and Tillman [18] have analysed different allocation procedures that can be considered in open-loop recycling, i.e. in a recycling process that produces material or energy for use in more than one product.

The purpose of this paper is to analyse the effects of recycling on the energy efficiency of iron and steel production and pulp and paper production. The paper includes: 1) a statistical analysis of the effects of the utilisation of recovered materials on the average SEC at the national level in selected European countries and 2) a discussion on possible methodology to allocate the benefits of material recycling between primary and secondary production.

2. Utilisation of recycled materials in energy intensive industry

The European waste policy is based on the waste hierarchy, according to which waste production has primarily to be prevented or reduced, and secondly the waste has to be recovered by recycling or re-use or used as a source of energy [19]. In the steel industry and in the pulp and paper industry, recycled materials are mainly used as a substitute for primary materials.

2.1. Iron and steel industry

There are thousands of different types of steel with varying chemical compositions and microstructures [20]. However, there are only two main steel production routes: (1) the integrated steelmaking route, based on the blast furnace (BF) and the basic oxygen furnace (BOF) and (2) the electric arc furnace (EAF) route. The integrated steelmaking route uses primarily iron ore as a raw material and therefore it is referred to here as ‘primary production’. The EAF route is called ‘secondary production’ because it is based on the utilisation of recycled steel, also known as scrap. Most recycled steel is utilised by melting it in the EAF process, but small amounts of scrap (typically 10 to 25 per cent [21]) can also be used in the converters of the BOF process. Both production routes may be followed by advanced treatments, such as casting, hot and cold rolling and galvanising.

The use of recycled steel as a substitute for primary raw materials is an important factor reducing SEC and CO_2 emissions. Steel is a 100% recyclable material, and can be recycled without loss of properties. Based on the World Steel Association’s estimate, about 80% of post-consumer scrap steel is recycled [20]. In 2006, the amount of recycled steel was equal to about 37% of the crude steel produced that year [22]. There is insufficient recycled steel available to meet society's demand because of the long life cycles of steel products and increased demand for steel. For instance, buildings and bridges made with steel last 40 to 100 years, or even longer with proper maintenance [20]. Steel demand is expected to grow 3-5% per year worldwide. The growth is fastest in developing countries such as China, India and Russia, with an annual growth rate of 8-10% [20]. Therefore, regardless of increased steel recycling, also the primary production of steel will increase in the future. This will lead to increased energy consumption and CO_2 emissions from the steel industry.

Finland is a net exporter of steel products. Finland used 64% and 51% (in crude steel equivalents) of its crude steel production in 2007 and 2006, respectively [22].

2.2. Pulp and paper industry

In 2007, the recycling rate of paper, i.e. the percentage of recovered paper utilisation compared to total paper consumption, was 56.4% in the CEPI[1] countries. Because the CEPI countries export more paper than they import, the average utilisation rate, i.e. the percentage of recovered paper utilisation compared to total paper production, was lower, 48.4%. The utilisation rate was highest in Spain (84.6%) and lowest in Finland (5.1%). In Finland, the utilisation rate was low due to the high export rate: in 2007, Finland exported 19% and 92% of its pulp and paper production, respectively. However, the recycling rate of paper in Finland was 57.8%. [23]

The utilisation rate of recovered paper is the highest, up to 87-92%, in newsprint and case materials, but according to the EN 643 "European List of Standard Grades of Recovered Paper and Board", recovered paper can be used in 57 paper grades, including high grades.

Every time waste paper undergoes the process of recycling, the quality of its fibres is weakened. Therefore, the fibres can be recycled no more than 4–6 times [16] and it is always necessary to add virgin pulp to meet the demand and quality requirements of paper. The length of the life cycle varies a lot with the paper product: newsprint and packaging boards can be returned for recycling after a short time, but books may last decades or even centuries.

2.3 Energy consumption of primary and secondary production

Table 1 presents the world best practice energy intensity values for selected industrial products. As shown in Table 1, the energy consumption of secondary production is typically much lower than that of primary production. The only exception is newsprint production in the integrated pulp and paper mill, where primary production consumes less final energy than secondary production. The reason for this is that thermo-mechanical pulping (TMP) produces a significant amount of heat that can be recovered and utilised in paper drying. However, the primary energy consumption of recovered paper-based newsprint is much lower than that of wood-based (TMP) newsprint. This is due to fact that the production of thermo-mechanical pulp consumes a lot of electricity (in [5] the primary energy consumption of electricity is assumed to be 3.03 times the final energy consumption).

[1] CEPI (Confederation of European Paper Industries) countries include: Austria (AT), Belgium (BE), Czech Republic (CZ), Finland (FI), France (FR), Germany (DE), Hungary (HU), Italy (IT), The Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Slovak Republic (SK), Spain (ES), Sweden (SE), Switzerland (CH), United Kingdom (UK)

Table 1. Comparison of world best practice final energy intensity values (GJ/t) / primary energy intensity values (GJ/t) for primary and secondary production of selected industrial products [5].

	Primary production technology	Final energy / Primary energy*) GJ/t	Secondary production technology	Final energy / Primary energy*) GJ/t
Steel	Blast Furnace – Basic Oxygen Furnace – Thin slab casting	14.8 / 16.3	Scrap - Electric Arc Furnace – Thin slab casting	2.6 / 6.0
	Blast Furnace – Basic Oxygen Furnace – Continuous Casting and hot rolling (bars)	16.5 / 18.2	Scrap - Electric Arc Furnace – Continuous Casting and hot rolling (bars)	4.3 / 8.0
	Blast Furnace – Basic Oxygen Furnace – Continuous Casting and hot rolling (bars) + Cold rolling and finishing	18.0 / 20.6		
Pulp	Kraft pulp	11.1 / 11.0	Recovered paper pulp	1.5 / 3.9
Integrated pulp and paper	Wood-based (TMP) newsprint	6.6 / 22.7 **)	Recovered paper-based newsprint (de-inked)	7.6 / 14.9 **)
	Wood-based (50% TMP) board	11.8 / 28.6 **)	Recovered paper-based board (no de-inked)	11.2 / 17.8 **)

*) Primary energy includes electricity generation, transmission, and distribution losses of 67%.

**) Misprint found in Table 2.4.6 of [5] corrected.

3. Materials and methods

3.1. Statistical analysis: effects of recycling on specific energy consumption

In this study the energy consumption of national iron and steel sectors and pulp and paper sectors in selected European countries is analysed. EU countries having iron and steel production[2] as well as Norway (NO), Switzerland (CH) and Turkey (TR) are included in the analysis of the iron and steel sector. In the case of the pulp and paper sector, the CEPI countries are considered. Farla and Blok [11] stated that when international comparisons are made, the use of international sources of statistical data instead of national data sources is preferable because of uniform data collection based on uniform definitions. Therefore, international data sources are used in this study. Due to the most recent statistics available, the years 2006 and 2007 are considered here.

The average specific energy consumption (SEC) of each sector is calculated as follows:

$$SEC = \frac{energy\ used\ \ per\ sector}{products\ produced\ \ per\ sector} \tag{1}$$

where SEC is measured in GJ/t.

The calculation of country-specific SEC was based on the following annual energy consumption data for the iron and steel industry: (1) IEA[3] statistics [24]: total energy consumption for the iron and steel sector in Mtoes + total coal transformation in Mtoes (2) Eurostat statistics (1,000 toes) [25]: final energy consumption of all products for the iron and steel industry + transformation input in coke-oven plants of all products + transformation input in blast-furnace plants of all products - transformation output from coke-oven plants of all products - transformation output from blast-furnace plants of all products.

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[2] EU countries having iron and steel production include: Austria (AT), Belgium (BE), Czech Republic (CZ), Finland (FI), France (FR), Germany (DE), Greece (GR), Hungary (HU), Italy (IT), Luxembourg (LU), The Netherlands (NL), Poland (PL), Portugal (PT), Slovak Republic (SK), Spain (ES), Sweden (SE), United Kingdom (UK)

[3] International Energy Agency

For the pulp and paper industry the following annual energy consumption data was collected: (1) IEA statistics (Mtoes) [24]: total energy consumption for the paper, pulp and printing sector (2) Eurostat statistics (1000 toes) [25]: final energy consumption of all products for the paper and printing industry (3) CEPI statistics [23]: total primary energy consumption (fossil and non-fossil) per energy carrier in TJ + purchased electricity in GWh * 3.6. In the statistics the energy consumption of the printing industry is included in the pulp and paper sector. However, it is assumed here that the energy consumption of the printing industry is small compared to pulp and papermaking and therefore no serious error is made if these statistics are used for the pulp and paper industry.

The annual crude steel production and annual pulp and paper production were collected from the statistics of World Steel Association [22] and CEPI statistics [23], respectively. In this study, the production of end-products is used as a divider in Eq. 1. For the steel industry the annual crude steel production is used. However, for the pulp and paper industry the summarised production of paper and market pulp is used. Because, for example, the Odyssee indicators are calculated based on paper production only [7], this kind of sensitivity analysis is made here, too.

Because the definitions of different statistics differ to some extent, the comparison of SECs based on different statistical sources was made first. Then, the dependence of SEC on material recycling was analysed by using IEA energy consumption data for 2007. In the case of the steel industry, the ratio of secondary production to total crude steel production (R) is used as a measure of recycling. This ratio is calculated as follows:

$$R = \frac{production\ of\ secondary\ steel}{production\ of\ crude\ steel} \tag{2}$$

, where the production of secondary steel, i.e. production in electric furnaces, was collected by country from the statistics of World Steel Association [22]. National utilisation rates of recovered paper were obtained from the CEPI statistics [23]. National sector-specific SEC figures were presented as a function of recycling by using a similar kind of illustration as ADEME used for the steel industry [7].

3.2. Allocation of benefits between primary and secondary production

One possible way, presented by Ekvall and Tillman, to allocate part of the benefits of recycling to primary production is allocation in the cascade. In this study, the allocation is based on the consideration of primary material (m) still available at each recycling stage. The share of primary material available in each stage of recycling depends on the recycling rate (r), as presented in Fig. 1.

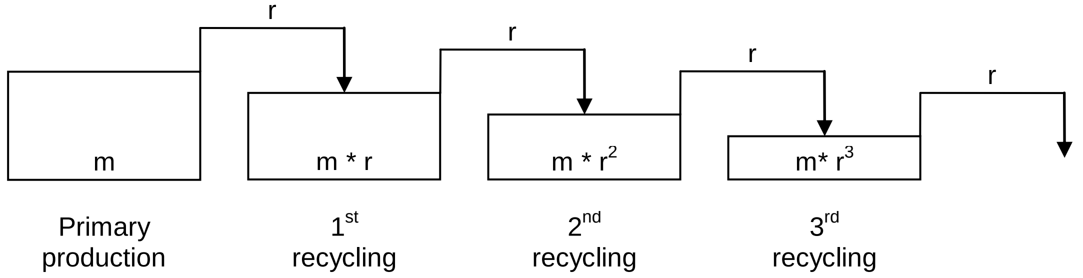


Figure 1. The share of primary material available in each stage of recycling.

For simplicity it is assumed that the recycling rate (r) is constant over the time, i.e. in each stage of recycling. Therefore, the share of material used in primary production reduces by factor r in each stage of recycling. Also, the energy consumption in every recycling stage is assumed to be constant (SEC_{sec}). The energy consumption allocation in the cascade is studied here so that part of the energy consumption of primary production is allocated to the following recycling stages according to the principle:

$$SEC' = \frac{m * SEC_{prim} + \sum_{n=1}^{i}(SEC_{sec} * m * r^n)}{m + \sum_{n=1}^{i}(m * r^n)} = \frac{SEC_{prim} + SEC_{sec} * \sum_{n=1}^{i}(r^n)}{1 + \sum_{n=1}^{i}(r^n)} \tag{3}$$

, where m is the mass of product produced (1 tonne), SEC_{prim} the specific energy consumption of primary production and SEC_{sec} the specific energy consumption of secondary production.

For closed loop recycling, such as the steel industry, material can be recycled forever without loss of properties. So, n in the summary formula can obtain values from 1 to ∞. However, paper can be recovered up to six times, so the maximum value n can obtain is i=6.
For closed loop recycling, Eq. (3) can be written as follows:

$$SEC' = \frac{SEC_{prim} + SEC_{sec} * (\frac{1}{1-r}) - 1}{\frac{1}{1-r}} = \frac{SEC_{prim} + SEC_{sec} * (Z-1)}{Z} \tag{4.a}$$

$$Z = \frac{1}{1-r} \tag{4.b}$$

4. Results

4.1. Statistical analysis: effects of recycling on specific energy consumption

4.1.1. Iron and steel industry

Fig. 2 shows the national crude steel production divided into primary and secondary production. There are big differences between countries in the shares of primary production based on virgin materials and secondary production based on recycled materials. For example, there is only primary production of steel in the Netherlands, Slovak Republic and Hungary. On the other hand, in Greece, Luxembourg, Norway, Portugal and Switzerland the production is based totally on secondary production. The share of secondary production is also high in Spain, Turkey and Italy.

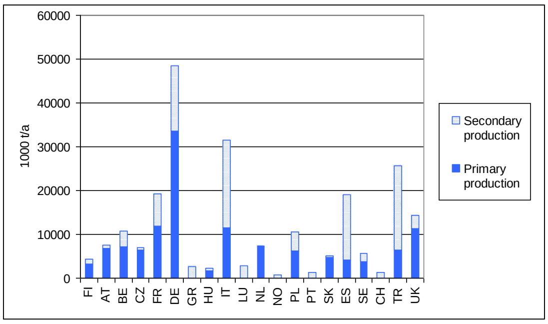


Figure 2. Crude steel production in 2007 [22].

The average SEC of the iron and steel sector in selected countries was calculated according to Eq. 1 (Fig. 3). There is no big difference in the SECs based on IEA and Eurostat statistics or between the years 2006 and 2007. The average SEC of the iron and steel sector in Norway is extremely high, and therefore it has not been included in the further analysis presented below.

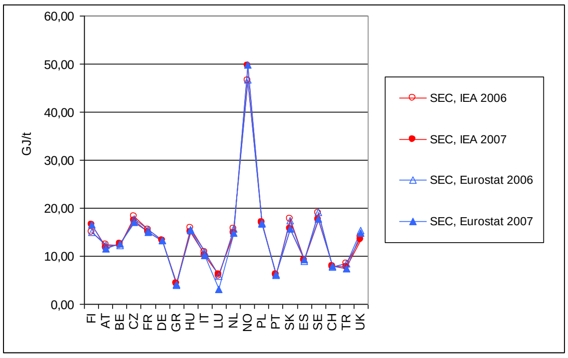
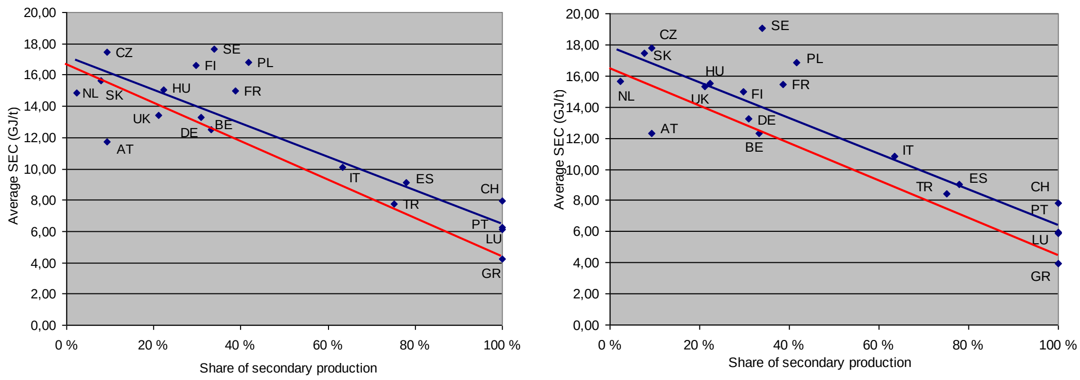


Figure 3. Comparison of SEC in the iron and steel industry [22, 24, 25].

Fig. 4 shows the average SEC of the iron and steel sector as a function of the share of secondary production in a similar way to that presented by ADEME [7]. The difference in the average SEC between countries can be partly explained by the production rates and quality of the end-products. So, some countries above the red line, such as Sweden and Finland, might produce highly processed products. In addition, the distance to the red line might show the potential for energy efficiency improvements. However, the accuracy of international statistics is not sufficient to make any conclusions on the energy efficiency of national iron and steel sectors. Fig. 4 shows that there is clear correlation between the average energy consumption and recycling. Based on the 2007 energy consumption data of IEA, the correlation is -0.86 (Fig 4.a). If different statistics and reporting year are used (Eurostat 2006), there might be differences in the average SEC in some cases. For example, in Sweden and Finland, the changes in production rates might have affected the average SEC. However, the position of each country is almost unchangeable and the correlation is the same -0.86 (Fig. 4.b).



The upper blue line in the figures shows the linear trend line of scattered points and the lower red line the theoretical curve between the world best practice final energy intensity values of primary production and secondary production (for continuous casting and hot rolling of bars).

a) b)

Figure 4. The influence of share of secondary production of steel on the average SEC a) based on IEA data for 2007 [24, 22] b) based on Eurostat data for 2006 [25, 22].

4.1.2. Pulp and paper industry

In Fig. 5 national pulp and paper production is shown. Pulp production is divided into integrated pulp production and market pulp production. In some countries with significant paper production, such as Germany, Italy, France, Spain and the UK, there is only minor pulp production or no pulp production at all. Therefore, paper production in those countries is mainly based on the utilisation of recovered paper. In Sweden, Finland and Norway, there is a lot of integrated pulp and paper production. In Sweden and Portugal, pulp production is higher than paper production, i.e. the share of market pulp production is high.

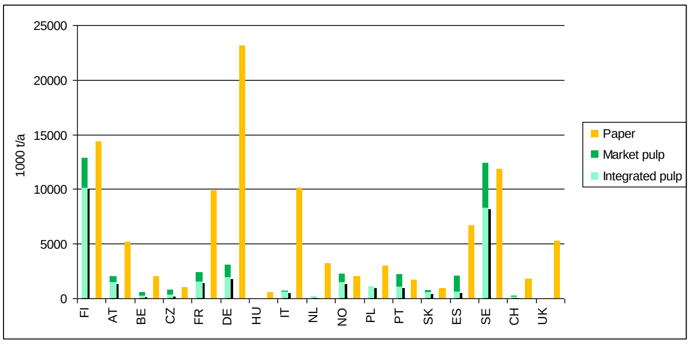
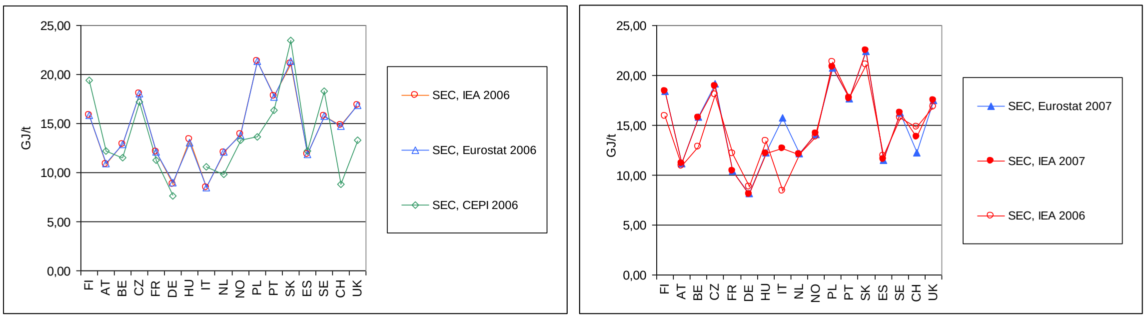


Figure 5. Pulp and paper production in 2007 [23].

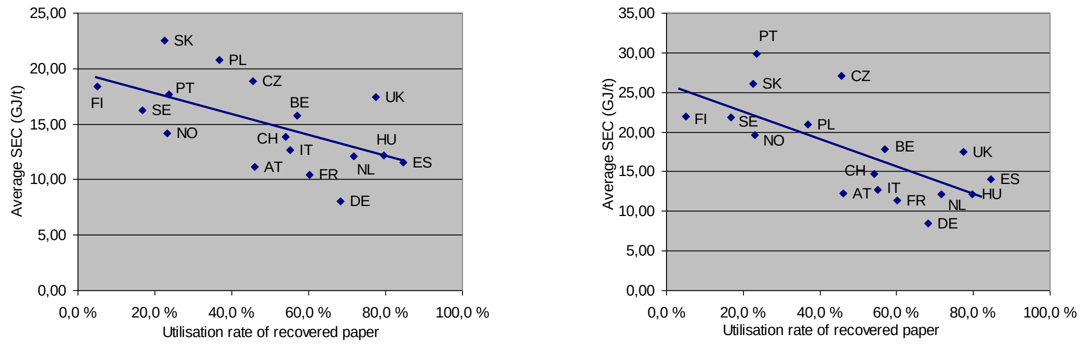
Fig. 6 shows the comparison of the average SEC in the pulp and paper industry. For the year 2006 three different statistics were available (Fig. 6.a). As in the iron and steel industry, IEA and Eurostat statistics do not differ a lot. However, the average SEC based on CEPI statistics differs from the other SEC values in some countries, e.g. Poland, Switzerland and the UK. There are also some differences in the Finnish and Swedish values. For example, in the IEA and Eurostat statistics 2006 for Finland, the industrial heat production has not been allocated to different industrial sectors. However, in the CEPI statistics and also in the IEA and Eurostat statistics 2007 for Finland the allocation has been made (Fig. 6.b), which increases the average SEC to some extent. So, by using the IEA statistics for 2007 in the further analysis this conflict can be avoided. Also, in the case of Italy, there are changes in the consideration of industrial heat production between different statistics and reporting years.



a) b)

Figure 6. Comparison of the average SEC in the pulp and paper industry [23, 24, 25].

Fig. 7 presents the average SEC of the pulp and paper sector as a function of the utilisation rate of recovered paper. In a similar way to the iron and steel industry, the difference in the average SEC can be explained partly by differences in the product mix and partly by the potential for energy efficiency improvements. When the average SEC is calculated with regard to the summarised production of paper and market pulp, the correlation between the utilisation of recovered paper and the average SEC is around -0.60 (Fig 7.a). The correlation is higher (-0,70) when the average SEC is calculated with regard to paper production (Fig. 7.b). If CEPI statistics [23] are used the correlation with regard to paper production is even higher (-0.78). The position of most countries with regard to the blue line is quite similar in both cases. However, Portugal with major exports of market pulp seems to have a very high average SEC if market pulp production is not taken into account in the SEC definition (Fig. 7.b). The consideration of market pulp production seems to be favourable for Sweden, too.



The blue line in the figure shows the linear trend line of scattered points.

a) b)

Figure 7. The influence of the utilisation rate of recovered paper on the average SEC a) the SEC calculated for paper and market pulp production [23, 24] b) the SEC calculated for paper production [23, 25].

4.2. Allocation of benefits between primary and secondary production

The allocation of benefits of material recycling is studied by using Eq. 3 and the world best practice energy intensity values (GJ/t) presented in Table 1 for primary and secondary production. So, the average SEC of recyclable material can be calculated.

For steel production, it is assumed that steel can be recycled forever. However, if a recycling rate of 80% is assumed [20] the recycling of the same tonne of primary steel reduces over time. As the number of recycling stages tends to the infinity, Eq. 4.b obtains the value 5 if the recycling rate is 80%. This means that in the end one tonne of primary steel can be used to produce 5 tonnes of steel products over the whole life cycle of the steel. For continuously cast and hot rolled steel bars, the allocation according to Eq. 4.a gives that the average SEC in primary stage and the following recycling stages is around 6.7 GJ/t and 10 GJ/t in final energy consumption and primary energy consumption, respectively. So, the energy saving due to recycling over the whole life cycle is four times the difference of the energy consumption of primary production and energy consumption of secondary production.

Paper can be recycled up to 6 times. If the recycling rate of paper, 56.4% [23], is used, the average SEC of newsprint production in the primary stage and the following six recycling stages is around 7.2 GJ/t and 18.4 GJ/t in final energy consumption and primary energy consumption, respectively. So, the average final energy consumption allocated to the primary stage would be higher than presented in Table 1. However, primary energy consumption would be lower. As explained earlier, newsprint production is an exceptional case due to the high heat production of TMP. For board production the figures are 11.5 GJ/t and 22.6 GJ/t in final energy consumption and primary energy consumption, respectively.

5. Discussion

The increased utilisation rate of recovered materials seems to result in lower specific energy consumption. The recyclability of industrial products differs from sector to sector. Usually, the recycling affects the raw material quality: e.g. in paper recycling the quality of the fibre is reduced and the fibre becomes shorter. These products can be recycled a limited number of times. However for some products, such as steel, the quality of the material remains almost unaffected. Also the length of the product life cycle may vary, depending on the industrial sector. A newspaper can be returned to recycling after a short time, whereas the steel used for construction is used for many years or decades. Whether the length of the product life cycle should be taken into account when the benefits of recycling are allocated is an interesting question not included in this study.

Life cycles of products are not usually considered when the SEC and CO_2 emissions of industrial production are monitored, and therefore these indicators do not take the recyclability of a product into account. For example, under the EU's emissions trading scheme (EU ETS), CO_2 emissions are monitored at the installation level, and therefore the installations that utilise recycled materials get the whole benefit from recycling in the form of reduced emissions of secondary production. Therefore, emissions trading promotes the use of recycled materials but gives no incentive to develop or produce recyclable products.

In this study only one way to allocate the benefits of recycling between primary and secondary production was analysed. The method used here would give an incentive to produce recyclable material. However, recovered materials should be cheaper than virgin raw materials to provide an incentive to their use.

When international comparisons of the SEC in industrial sectors are made, the utilisation rate of recovered materials should be taken into account. However, there might be other differences in the production mix, such as the quality of the end-products, between different countries. Therefore, the analysis made here does not necessarily say anything about the relative level of energy efficiency in the selected countries. More information on the accuracy of statistics and the reasons for statistical differences would be needed to compare the energy efficiency of industrial sectors between countries.

Benchmarking has been proposed as an option to allocate emission allowances to various industrial activities from 2013 onwards. The analysis presented here shows that the utilisation rate of recovered materials is one important aspect that should be taken in account in benchmarking. From the Finnish point of view, it should be noted that large exports of energy-intensive products weakens the availability of recycled materials for domestic markets. Therefore, the structural change towards secondary production is not easy and some part of the energy and CO_2 emission benefits of exported recyclable materials should be allocated to primary production.

6. Conclusion

The analysis presented here shows clearly that recycling of materials reduces national average specific energy consumption both in the iron and steel and in the pulp and paper industry. Therefore the energy efficiency indicators used should take the benefits of material recycling into account. That can be done by allocating the benefits of recycling to both primary and secondary production. When international benchmarking is done, the availability of recyclable material and its effects on the production mix should be taken into account.

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References

[1] IEA, Energy Technology Perspectives 2008, Scenarios & Strategies to 2050. OECD/IEA, Paris, 2008. pp.471-517.

[2] Statistics Finland, Final energy consumption by sector 2008, http://www.stat.fi/til/ehkh/2008/04/ehkh_2008_04_2009-03-24_kuv_017_en.html. Accessed on November 26, 2009.

[3] IAEA, Energy Indicators for Sustainable Development: Guidelines and Methodologies. Austria, 2005. pp. 52-54.

[4] Rynikiewicz, C., The climate change challenge and transitions for radical changes in the European steel industry, J. Cleaner Prod. 2008, 16: 781-789.

[5] Worrell, E., Neelis, M., Prie, L., Galitsky, C. & Zhou, N., World Best Practice Energy Intensity Values for Selected Industrial Sectors, Berkeley, CA, Lawrence Berkeley National Laboratory, 2008, 45 pp.

[6] IEA, Assessing measures of energy efficiency performance and their application in industry, IEA information paper, OECD/IEA, Paris 2008. 40 pp.

[7] ADEME, Evaluation and Monitoring of Energy Efficiency in the New EU Member Countries and the EU-25, Paris, 2007. xvi + 106 pp.

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

[9] Lehtilä, Antti, Savolainen, Ilkka & Tuhkanen, Sami. 1997. Indicators of CO_2 emissions and energy efficiency. Comparison of Finland with other countries. VTT Energy, Technical Research Centre of Finland. VTT Publications 328. Espoo, Finland. 80 pp. + app. 31 pp.

[10] Eichhammer, W. and Mannsbart, W., Industrial energy efficiency - Indicators for a European cross-country comparison of energy efficiency in the manufacturing industry. Energy policy 1997, Vol. 25, Nos. 7-9. pp. 759-772.

[11] Farla, J.C.M. and Blok, K., The quality of energy intensity indicators for international comparison in the iron and steel industry. Energy Policy 2001, 29 (7), 523-543.

[12] Phylipsen, D., Blok, K., Worrell, E. & de Beer, J., Benchmarking the energy efficiency of Dutch industry: an assessment of the expected effect on energy consumption and CO_2 emissions. Energy policy 2002, 30 (8), 663-679.

[13] Möllersten, K., Yan J. and Westermark K., Potential and cost-effectiveness of CO_2 reductions through energy measures in Swedish pulp and paper mills, Energy 2003, 28: 691-710.

[14] Karbuz, S., Achieving accurate international comparisons of manufacturing energy use data. Energy Policy 1998, 26 (12), 973-979.

[15] Ekvall, T., Key methodological issues for life cycle inventory analysis of paper recycling, J. Cleaner Prod. 1999, 7: 281-294.

[16] Schmidt, J. H., Holm, P., Merrild, A., Christensen, P., Life cycle assessment of the waste hierarchy – A Danish case study on waste paper. Waste Management 27 (2007), 1519-1530.

[17] Villanueva, A., Wenzel, H., Paper waste – Recycling, incineration or landfilling? A review of existing life cycle assessments. Waste Management 27 (2007), S29–S46.

[18] Ekvall, T. and Tillman, A-M., Open-Loop Recycling: Criteria for Allocation Procedures, Int. J. LCA 1997, 2 (3): 155-162.

[19] EC, Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste. Official Journal of European Union, L114 pp. 9-21.

[20] World Steel Association, 2008 Sustainability report of the world steel industry. 34 pp.

[21] Reinaud, J., Industrial Competitiveness under the European Union Emission Trading Scheme, IEA Information Paper, Paris, 2004.
[22] World Steel Association, Steel Statistical Yearbook 2008, Brussels, 2009. pp. 22-25 and 90.
[23] CEPI, European Pulp and Paper Industry, Annual Statistics 2007. 72 pp.
[24] IEA, Energy balances of OECD countries, 2009 edition, OECD/IEA, Paris, 2009. pp. II.1-151.
[25] Eurostat, European Commission, Energy balance sheets 2006-2007, 2009 edition, Luxembourg, 2009. pp. 267-523.