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Energy savings and greenhouse gas mitigation potential in the Swedish wood industry

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ABSTRACT

Improving energy efficiency in industry is recognized as one of the most crucial actions for mitigating climate change. The lack of knowledge regarding energy end-use makes it difficult for companies to know in which processes the highest energy efficiency potential is located. Using a case study design, the paper provides a taxonomy for energy end-use and greenhouse gas (GHG) emissions on a process and energy carrier level. It can be seen that drying of wood is the largest energy using and GHG emitting process in the studied companies. The paper also investigates applied and potentially viable energy key performance indicators (KPIs). Suggestions for improving energy KPIs within the wood industry include separating figures for different wood varieties and different end-products and distinguishing between different drying kiln technologies. Finally, the paper presents the major energy saving and carbon mitigating measures by constructing conservation supply curves and marginal abatement cost curves. The energy saving potential found in the studied companies indicates that significant improvements might be achieved throughout the Swedish wood industry. Even though the scope of this paper is the Swedish wood industry, several of the findings are likely to be relevant in other countries with a prominent wood industry.

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1. Introduction

In 2016, the industrial sector accounted for 25% of the total energy use within the EU. In Sweden, the industrial sector's share of the final energy use is 38%, of which the wood industry accounts for 5% [1]. With a net export value of SEK 96 billion, the forest industry is the largest net exporting industry in Sweden [2].

Several studies have been undertaken concerning improved energy efficiency in the wood industry, which have shown a large energy saving potential [3–5]. Anderson and Westerlund [6] analyzed the impact of state-of-the-art heat recycling technologies on the most common drying schemes used in Swedish sawmills.

Having information about energy end-use (EEU) is crucial for knowing in which processes it may be most useful to implement energy efficiency measures (EEMs). A wide range of studies of different industries have analyzed the EEU on process level [7–9]. However, Thollander et al. [10] found that the bottom-up energy data for industrial small and medium-sized enterprises (SMEs) differs widely between countries, and call for a general taxonomy for structuring EEU data along with EEMs. Without this general taxonomy it is unlikely that EEMs and measures for greenhouse gas (GHG) mitigation will reach their full potential, due to not knowing in which processes the main potential is found, how far industry has come in terms of deployment and in which areas future energy policies are needed [10]. Andersson et al. [11] reviewed the EEU and energy efficiency potential among industrial SMEs participating in the SEAP using a unique categorization of production processes, highlighting the challenge of generalizing results without available bottom-up EEU data.

For EEMs, Fleiter et al. [12] suggested a classification scheme containing 12 attributes based on the relative advantages, technical contexts and information contexts. The scheme contributes a basis for identifying policies that can increase the rate of adoption for EEMs. Trianni et al. [13] also developed a classification scheme for EEMs. This classification scheme was based on 17 attributes and included structuring and sharing knowledge regarding EEMs. In addition, the scheme could serve as a structured basis for the analysis of drivers that policy-makers should conduct to promote industrial energy efficiency.

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For EU members, the Industrial Emissions Directive (IED, 2010/75/EU) states that information about best available techniques (BAT) shall be provided to relevant industries through reference documents. However, while many industries have a specific BAT reference document, the wood industry lacks one. On the other hand, the BAT reference document on energy efficiency addresses general technologies applicable to multiple industries, some of which might be relevant for wood industry companies [14]. In Sweden, policy programs that have addressed industrial energy efficiency improvement include the Swedish Energy Audit Policy Program (SEAP) and the Program for Improving Energy Efficiency in Energy Intensive Industries (PFE).

To be able to estimate the energy efficiency potential of the industry and make decisions on improvement measures, it is necessary to define relevant energy key performance indicators (KPIs). These include both aggregated indicators (i.e. sectoral, which facilitate decisions by policy makers) and disaggregated indicators (i.e. site or process level, which facilitate decisions for industrial actors and policy makers). There is a need within industries in general for energy KPIs at process and plant levels [15].

A number of technology reviews of different industries have been carried out (e.g. Refs. [16–20]). To the authors' knowledge, few comprehensive studies have been carried out for the wood industry, and additional studies that investigate energy efficiency technologies in the wood industry and their potential for implementation are therefore needed.

The aim of this paper is to provide a taxonomy for EEU and GHG emissions on a process level in the wood industry. Furthermore, this paper analyses what the major GHG mitigation measures are in the wood industry. Based on this, the following research questions are to be answered:

- Which processes in the Swedish wood industry have the highest energy use and the largest GHG emissions?
- What are currently applied and potentially viable energy key performance indicators in the wood industry?
- What are the major energy saving and GHG mitigation measures in the Swedish wood industry?

This paper is structured as a case study of the Swedish wood industry. The wood industry is defined as companies classified as C16 according to NACE rev. 2 [21], or, where applicable, companies where the main material used in production processes is manufactured wood (e.g. manufacturers of furniture made from wood). The study makes an important contribution to improving the understanding of which processes within the wood industry are the major energy users and GHG emitters. In addition, finding out where the greatest potential lies for energy efficiency and GHG mitigation is also highly relevant, and the paper also contributes to this. The outcome is highly relevant for policy makers in understanding the impacts of e.g. energy audit policy programs. Industrial companies will benefit from the results regarding both the energy efficiency potential and the implementation of energy KPIs. The paper is structured as follows: First, a review is carried out of the existing literature regarding EEU, GHG emissions and energy key performance indicators (KPIs) in the Swedish wood industry. Second, the method for data collection and categorization is described, followed by the results and analysis section which presents the findings of the study. Lastly, the paper ends with a discussion and conclusions.

2. Energy end-use, greenhouse gas emissions and key performance indicators in the wood industry

Statistics Sweden retrieves data on EEU for all industrial sectors, divided up into four different energy carriers (Table 1). Due to confidentiality, some data are missing, and the actual final EEU is thus larger.

To enable the allocation of EEU at a process level, Söderström [22] developed a generic taxonomy for support and production processes using the unit process concept. This taxonomy has been applied to the wood industry by Andersson et al. [11]. However, a large amount of the EEU for production processes could not be allocated. Another approach for dividing up the EEU of production processes in the wood industry was proposed by Andersson et al. [23]; using a model for sawmill production processes developed by Olsson et al. [24]. The model divides the sawmill production line into five different zones: log sorting, sawing, drying, regrading, and other production processes.

Studies of GHG emissions at a process level are yet to be carried out. However, life cycle analyses of wood products are more common. Murphy et al. [25] found that electricity use in Irish wood processing are the major cause of GHG emissions for e.g. sawn wood products, when considering biofuel to be carbon neutral. Diederichs [26] adopts a life-cycle perspective for the German sawmill industry and presents a monitoring approach covering GHG emissions, taking different end-products into account. While the outcome accounts for the product mix, it is not shown specifically which individual processes account for the largest GHG emissions.

The most commonly adopted energy KPI is the amount of energy use per m^3 of sawn goods (kWh/m^3) for an entire sawmill. This simple form of KPI is generally defined as the specific energy use[1] (SEC) [14]. SEC is generally useful as a measure of the energy efficiency of individual processes [27]. For the entire sawmill, SEC is easy to monitor and report since the needed data, energy supplied to the sawmill and the amount of produced goods, is usually available. This KPI is also applicable to individual production processes (cf. [6,23]. A variant of SEC involves deriving the amount of water removed from the wood (MJ/kg water), which is studied by Anderson and Westerlund [6]. There are ways to estimate the moisture content of wood packages, and efforts are carried out to improve these estimations (cf. [28]. However, there is currently no widespread practice for measuring the moisture content of wood among industrial companies.

3. Methodology

This paper is structured as a case study of the Swedish wood industry, inspired by Yin [29]. A supply chain perspective is applied, which begins with forestry, followed by sawmilling and processing wood, and ending with the final customer. The scope of this paper is the sawmills and the further processing of the dried wood. The bottom-up data of EEU and EEMs are collected from energy audit reports from 14 companies,[2] conducted between 2010 and 2018. The selected reports were all carried out by the same energy audit company. The coherence in the energy audit reports facilitated a more detailed analysis of the EEU data. The studied companies' statistical classification of economic activity (NACE rev. 2) is shown in Fig. 1.

[1] The common denomination is "*specific energy consumption*", but since energy cannot be consumed, in accordance with the law of conservation of energy, the term "*use*" is applied in this paper.

[2] Notably, one company was excluded from the selection of companies since the company was too unique in its production processes.

Table 1
Final energy end-use for the year 2015 divided up by different energy carriers for all Swedish companies under NACE 16 on a four-digit level, as derived from Statistics Sweden. For confidentiality reasons, some companies' energy use is not included (the cells marked "X"), and the actual final energy end-use is thus larger. This also applies to some of the other figures, since the Swedish classification is on a five-digit level (e.g. waterborne energy for the Swedish classification code 16232 is omitted).

NACE	Final energy end-use [GWh]	Renewable energy use [GWh]	Fossil fuel use [GWh]	Waterborne energy use [GWh]	Electricity use [GWh]	Number of workplaces[a]
16.10	6927	3249	317	1966	1362	585
16.21	348	210	X	X	113	38
16.22	133	X	2	X	60	13
16.23	433	185	23	49	158	442
16.24	80	33	13	5	29	97
16.29	919	656	1	11	158	90
Total	**8841**	**4334**	**356**	**2030**	**1879**	**1265**

[a] Workplace refers to addresses with e.g. a group of buildings where a company conducts business [43]. The number of companies is either equal to or less than number of workplaces.

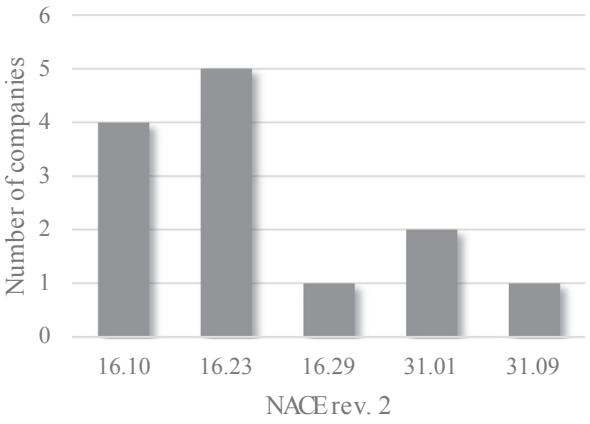

Fig. 1. Number of studied companies and their classification of economic activity.

3.1. Allocation of energy end-use

The EEU is categorized based on the following energy carriers: electricity, district heating, fossil fuels, and biofuels. To allocate the production processes within the sawmills, the categorization proposed by Olsson et al. [24] is used. For support processes, the taxonomy developed by Söderström [22] is used, as also found in Rosenqvist et al. [30]. Table 2 shows the categorization of sawmills' production processes, and the support processes for industry in general.

As the entire wood industry is studied in this paper, the categorization of production processes has to be expanded to include the wood industry companies belonging to NACE classifications other than 16.1. Therefore, the studied energy audit reports serve as a basis for defining an extended categorization of production processes for the wood industry.

The developed categorization of production processes for sawmills was validated with a process engineer and an expert in drying of wood, both employed at a large Swedish sawmill.

3.2. Energy key performance indicators in the wood industry

In line with the case study method, the sawmill – which is the object for the validation of the categorization – is also used as a case for identifying the energy KPIs currently applied in the industry. This is not comprehensive for the whole sector, but given that it is one of the three largest sawmills in Sweden (in terms of the amount of produced goods), it is likely to be one of the industry leaders in the maturity of energy management. The current state of implemented energy KPIs in the wood industry is also reviewed by an expert at a research institute with several years of experience of the wood industry. This further enables consideration for developing new energy KPIs in addition to the current set of energy KPIs normally used in the industry. Suggestions for such potential new indicators for implementation by companies, or for further research, are outlined in this paper.

Table 2
The categorization of production processes in sawmills, and for support processes for industry in general. The production processes are derived from Olsson et al. [24]; and the support processes from Söderström [22].

Support processes	Production processes	Included production sub-processes
Lighting	Log sorting	Intake of timber
Compressed air		Rough sorting
Ventilation		Storage of timber
Pumping	De-barking and sawing	Debarking
Space heating		Sawing
Cooling		Sorting and stacking
Hot tap water	Drying of wood	Drying (different types of kilns)
Internal transport	Regrading	Adjustment
Steam		Sorting
Administration		Wrapping and packaging
		Storage
	Boiler	Boiler
		Fuel drying
		Support equipment, e.g. flue gas fan, circulator pumps
	Other production processes	Planing
		Other production processes

3.3. Aggregation of energy end-use data and greenhouse gas emissions

The aggregation of EEU data is conducted as an analytical generalization as described by Yin [29]. The national EEU of each process is presented, assuming that the studied companies are representative of the Swedish wood industry. The aggregation of EEU is calculated by multiplying the share of each energy carrier used in each end-use process by the total EEU of the same energy carrier in the Swedish wood industry as given by Statistics Sweden. The GHG emissions for each process at a national level are calculated according to Equation (1).

$$\textit{Annual GHG emissions} = \textit{Annual energy use of an energy carrier in a unit process}\ (MWh) * \textit{Emission factor}\ (kgCO_{2eq}/MWh) \quad (1)$$

The emission factors used are shown in Table 3.[3] Depending on the applied system boundary, the emission factors for combustion of biofuels differ. If the GHG emissions from the combustion of biofuels are assumed to be reabsorbed by biomass regrowth, the emission factor can be considered 0 $kgCO_{2eq}$/MWh [32]. This is applied by e.g. Fleiter et al. [16]. However, if biomass is not used in a sustainable manner, it could be considered a limited resource on the market, and the emission factor would be higher [34]. Therefore, both approaches are adopted in this paper for the calculation of GHG emissions.

The GHG emissions from electricity are calculated based on both the marginal electricity perspective and the Nordic electricity mix. As the demand for electricity varies over time, electricity production needs to follow the demand variations. Marginal electricity is the most expensive electricity produced at a given time. As the electricity demand varies throughout the year, so too does the marginal production technology [35,36]. The most CO_2 intensive electricity production in the Nordic electricity system is coal condensing power plants, which are estimated to be price setting 70–75% of the time [37]. The emission factor for production of marginal electricity (940 $kgCO_{2eq}$/MWh) represents the average amount of GHG emissions per MWh of electricity produced in OECD member countries during the period 2011–2015 [32]. All the emission factors in this study take into account the efficiencies of the power plants. The electrical efficiencies for coal condensing plants are usually 35–45% [38], while heat-only plants have efficiencies of 80–95% [32].

The energy data from Statistics Sweden do not reveal the fuel composition of district heating and fossil fuels. To calculate the GHG emissions from district heating on a national level, an emission factor that represents the fuel mix on a national level is needed. The emission factor of 55.6 $kgCO_{2eq}$/MWh represents the most common district heating system in Sweden, which consists of a fuel mix including 89% biofuel, 10% oil and 1% electricity [31]. The emission factor for fossil fuels is derived by taking the mean of the emission factors from the fossil fuels used within the case companies based on the emission factors given by SEPA [44] (i.e. diesel and domestic heating oil).

Three different scenarios are adopted: Scenarios 1 and 2 are two different takes on Scope 2 used in the GHG Protocol Corporate Standard. Scope 2 includes both GHG emissions directly from owned or controlled sources, and emissions indirectly from the generation of purchased energy [39]. In this paper, scenario 1 considers biofuels an unlimited resource, and scenario 2 considers biofuels a limited resource. Scenario 3 in this paper corresponds to Scope 1 in the GHG Protocol Corporate Standard, which only takes direct emissions from owned or controlled sources into account [39].

[3] A number of assumptions are made in relation to the fuels in Table 2. Diesel is assumed to be used for all internal transportation that is powered by fossil fuels. The coal condensing plants are assumed to be using sub-bituminous coal. In this paper, biofuels are equivalent to wooden fuel since this is the only type of biofuel that has been identified in the studied companies. The emission factor for biofuels (as limited resource) is based on that if one plant starts to use biofuels, the marginal user of biofuels within the wood industry will have to use another fuel instead. In this study it is assumed that the marginal user of biofuel in the wood industry would use oil if biofuel wouldn't be available.

3.4. Conservation supply curves and marginal abatement curves

In order to derive the main GHG mitigation measures for the wood industry, conservation supply curves (CSC) with a process-level perspective are calculated. The concept of CSC was first developed for the household sector, but has since been applied to the industrial sector [40]. The CSCs in this paper are calculated as follows:

$$CCE = \frac{Annualized\ capital\ cost + Annual\ change\ in\ operation\ and\ management\ costs}{Annual\ energy\ savings} \quad (2)$$

where CCE is the cost of conserved energy, and annualized capital cost is:

$$Annualized\ capital\ cost = Investment\ cost\ of\ measure \cdot \left(\frac{d}{1-(1+d)^{-n}}\right) \quad (3)$$

where d is the discount rate and n is the lifetime of the measure. Due to a lack of information, the discount rate is assumed to be 7%. The lifetime of each measure that regards reduced stand-by losses is assumed to be 5 years, and for all other types of measures 12 years are assumed, similar to Andersson et al. [11] and Backlund and Thollander [41].

CSCs are also relevant for ranking GHG mitigation measures, i.e. CO_2 abatement curves [18]. To calculate the cost of GHG mitigation, the following equation is used in this paper:

$$Cost\ of\ GHG\ mitigation = \frac{Annualized\ capital\ cost + Annual\ change\ in\ operation\ and\ management\ costs}{Annual\ GHG\ mitigated}$$

The *annual CO_2 mitigated* is calculated by multiplying the annual energy savings of a measure by the emission factor for the type of energy carrier saved.

4. Results and analysis

4.1. Energy end-use at process level in the Swedish wood industry

Based on Olsson et al. [24] and Andersson et al. [11,23], a categorization of EEU processes for the wood industry is developed (Fig. 2). The categorization for sawmills (C16.1) follows Olsson et al. [24] and Andersson et al. [11,23] to a large degree. The

Table 3
The emission factors used for the energy carriers.

Energy carrier	Emission factor ($kgCO_{2eq}$/MWh)	Source
District heating	55.6	Engström et al. [31]
Biofuels (unlimited resource)	0	Fleiter et al. [16]
Biofuels (limited resource)	268.1	SEPA [44]
Fossil fuels	227.9	Own calculations based on SEPA [44]
Electricity (marginal production)	940.0	IEA [32]
Electricity (Nordic electricity mix)	131.2	IVL [33]

categorization is further developed in this paper by also including process ventilation in sawmills, due to its high share of the EEU. Process ventilation includes the transportation of sawdust. After regrading, further refining processes of wood are manifold and also account for a relatively small share of the EEU. Therefore, all different processes after regrading are considered as one category. For sawmills that have further refining processes, these are included in "Other production processes (C16.1)". For all remaining types of companies in the wood industry classified as C16.2 or other, these processes are categorized as "Further refining processes (C16.2)".[4] The reason for this approach is that further refining processes in a sawmill are not as relevant due to other much more energy-intensive processes, while in non-sawmill companies in the wood industry, these processes are generally the core processes. Process ventilation is also distinguished for companies classified as C16.2. Furthermore, for companies classified as C16.2, the EEU that the energy auditors asserted as belonging to production, but could not allocate to a specific production process, is categorized as "Other production processes (C16.2)".

Fig. 3 shows the share of EEU for each process and energy carrier. Early in the wood processing flow, the process with the largest share of EEU is *drying wood*, accounting for over 80% of the total EEU in C16.1. About 80% of this consists of biofuel. For production processes that relate to companies classified as C16.2 or similar, *further refining processing* and *process ventilation* account for a large share of the EEU.

The share of EEU for each support and production process poses some interesting points. For electricity, more than half of the end-use is allocated to the production processes, with *drying of wood* accounting for about 25% of all the electricity use. This is even more notable for the use of biofuels, where 74% of all biofuel is used in the process of *drying of wood*. On the other hand, district heating and fossil fuels are mainly used in the support processes, in particular *space heating* (for district heating) and *internal transport* (for fossil fuels). It should be noted that district heating is used in *drying of wood* by one of the studied companies, but is not necessarily widespread in the Swedish wood industry.

Assuming that the studied companies are representative of for the entire wood industry in Sweden, i.e. that the distribution of EEU is as shown in Fig. 3, the final EEU of the different energy carriers is as shown in Fig. 4.

For the studied companies in this paper, the majority of the fossil fuel is used in *internal transport*, e.g. for forklift trucks. Other EEU processes with potentially larger shares of the use of fossil fuel are *space heating* and *drying of wood*. Otherwise, it is notable that the largest share of EEU is found, as expected, in drying of wood and space heating. The processes differ in terms of energy carriers used, where a larger share of district heating is used in *space heating*, while electricity and biofuels account for a large share in *drying of wood*. For electricity, the largest EEU processes are (in descending order): *drying of wood*, *further refining processes*, *lighting*, *compressed air*, *process ventilation (C16.2)* and *sawing*.

4.2. Energy key performance indicators in the wood industry

KPIs for the total electricity and heat use of sawmill production and for each production process are presented in Table 4. Four of the studied companies are classified as C16.1 (see Fig. 1). The selected energy KPI is SEC for electricity and fuel/heat, using the

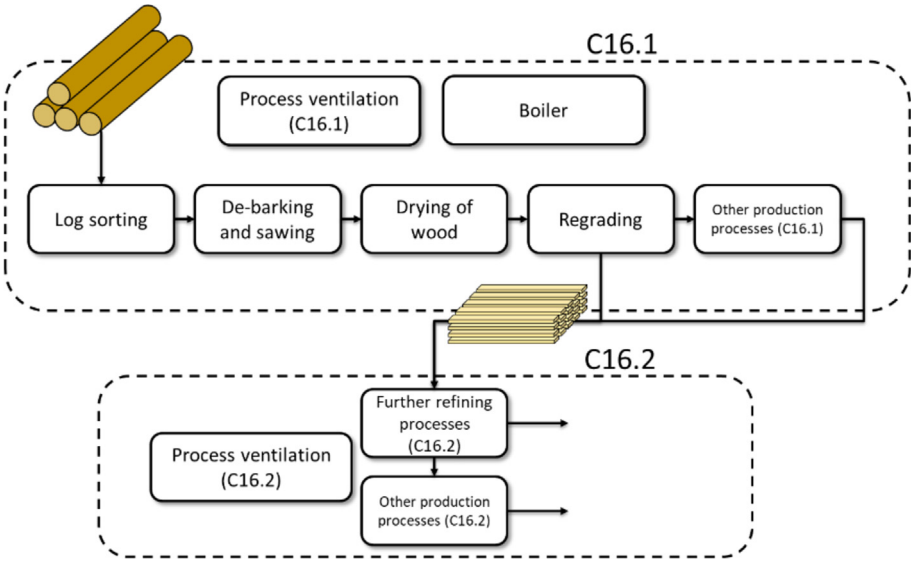

Fig. 2. The developed categorization of production processes for the wood industry.

[4] Examples of processes found in the energy audit reports for companies classified as C16.2 or similar are *sawing*, *planning*, *sizing*, *pressing*, *surface treatment*, *steam bending*, *chipping*, *milling*, and *finger joint*.

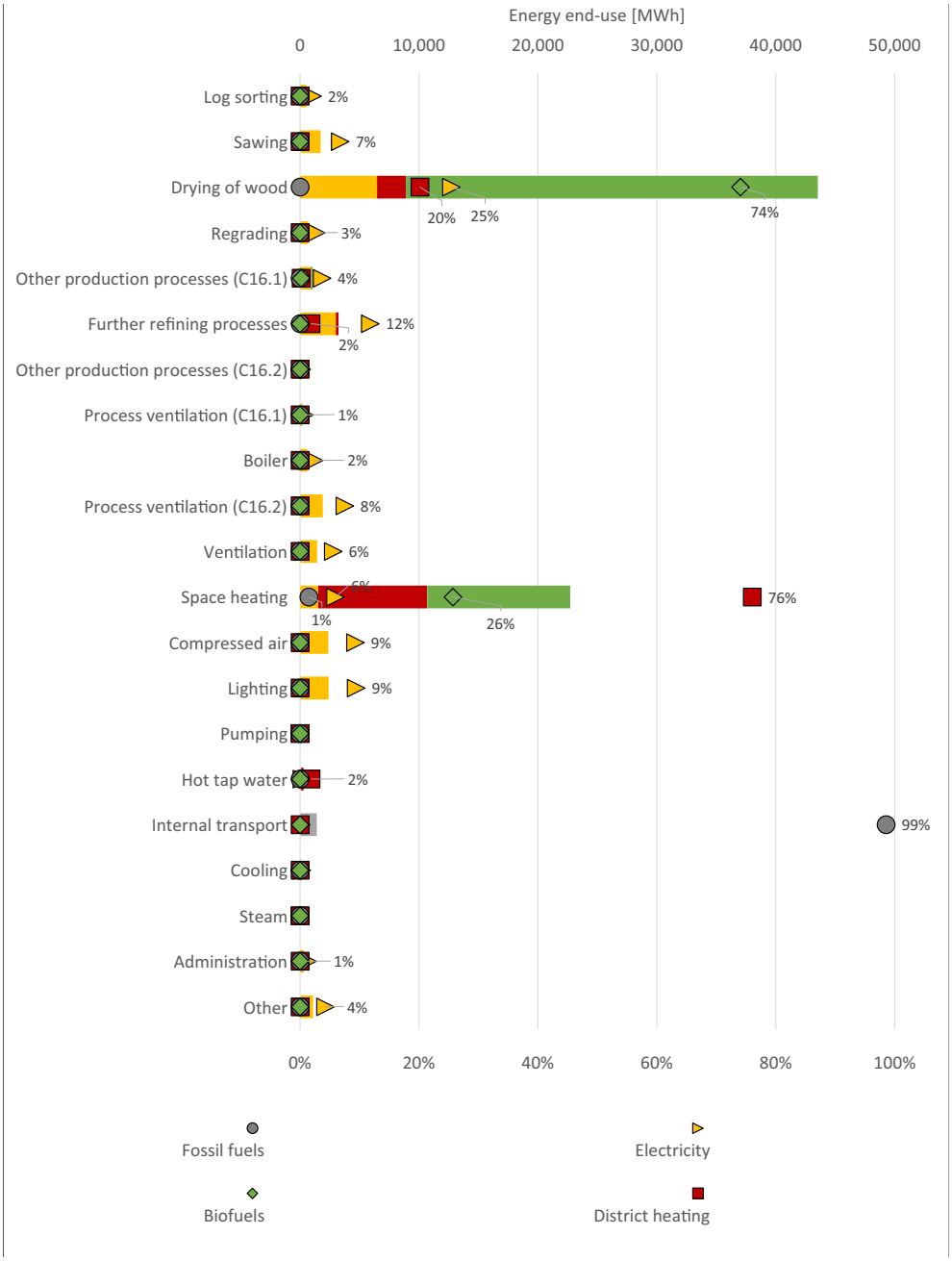

Fig. 3. The total amount and the percentage share of EEU for each support and production process for the studied set of companies.

total amount of the mill's produced sawn goods, and should be interpreted as simplified KPIs. The figures in Table 4 are similar to those found in Anderson and Westerlund [6]; but e.g. fuel/heat used for *drying of wood* is slightly lower in the set of companies studied in this paper, while the electricity use in *drying of wood* is slightly higher.

While SEC can be useful to measure the energy efficiency of a single process level [27], it has its limitations. For sawmill processes, and especially for drying of wood, there are a number of factors that affect the EEU as discussed by e.g. Andersson et al. [23]. For *drying of wood*, the major impact on energy use is the moisture content before the drier as well as the target moisture content. The moisture content for the input of wood is generally not defined; instead, an assumption is made. Given that the end-product needs to have the desired moisture content (e.g. 16% for exterior uses or 8% for floorboards), the wood is dried for too long rather than not long enough. An estimation of the moisture content (e.g. based on the basic density of wood) might provide a decent indication, but it is difficult to get an accurate result (cf. [28]). Measuring the weight of a sample of wood is another approach, e.g. by weighing it before and after being dried in a kiln. This is not commonly practiced to date. If the moisture content of the input wood to the drying kiln and outgoing wood from the drying kiln was determined, a potentially valuable supplementary KPI would be tracking the energy use per amount of water removed. This KPI would be able to track the actual efficiency of the process, as well as more accurately estimating the energy saving potential.

Regarding sawing, an additional energy KPI to monitor is the

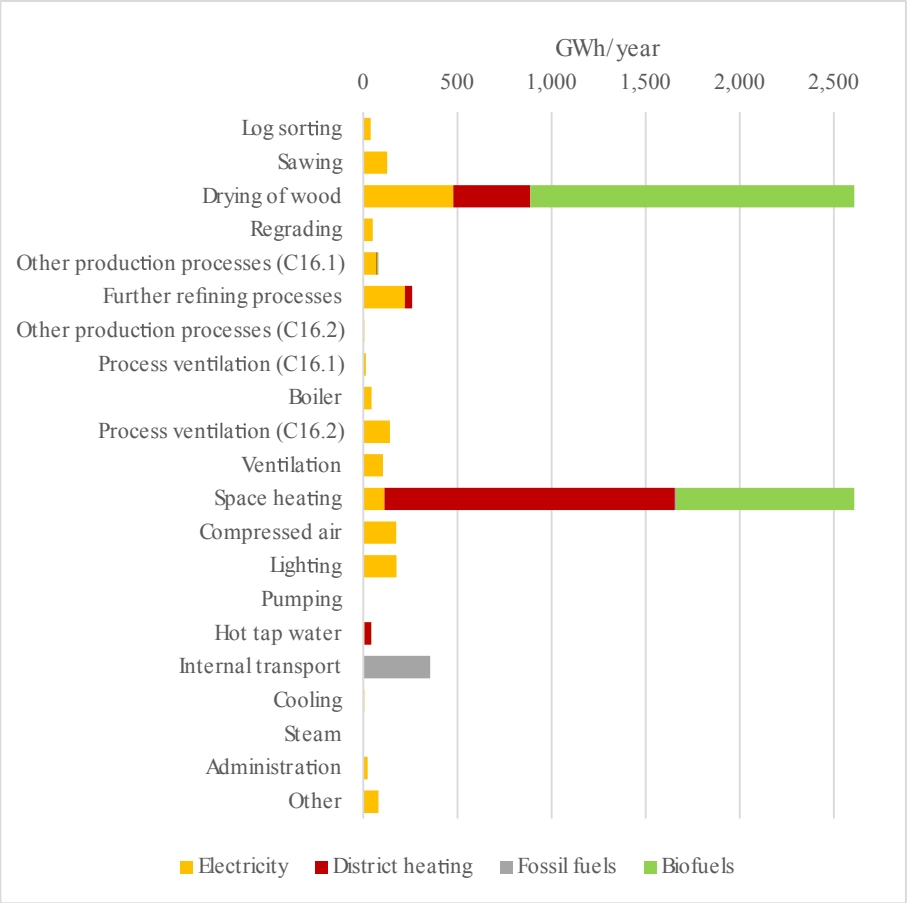

Fig. 4. The total final EEU in the Swedish wood industry divided up by support and production processes. This is based on data from Statistics Sweden, and assumes that the studied companies are representative of the entire wood industry. Note that the final EEU is larger in reality, since some data is missing due to confidentiality.

Table 4
The average and range of SEC for electricity for three of the four companies belonging to NACE 16.1 in the studied set of companies. While the annual energy end-use is allocated to each process, the amount of sawn goods is based on each sawmill's total amount produced during a year, as stated in the energy audit reports, i.e. not the amount that is actually processed in each step.

Process	$SEC_{electricity}$ [kWh/m^3 sawn goods]		$SEC_{fuel/heat}$ [kWh/m^3 sawn goods]	
	average	range	average	range
Log sorting	5	4–5		
Sawing	10	2–20		
Drying of wood	43	30–57	242	214–282
Regrading	4	2–5		
Other production processes	6	2–8	2	2
Process ventilation	2	2		
Boiler	6	3–8		
Total	**71**	**56–82**	**243**	**214–282**

electricity efficiency of the sawn logs. For one of the studied sawmills the number of processed logs was attainable, resulting in electricity use of 0.78 kWh/processed log for *sawing*, or 8.16 kWh/processed log for the entire mill.

Table 5 provides a list of suggested energy KPIs to monitor the energy efficiency of a sawmill for the entire mill and for the two most energy intensive processes (*sawing* and *drying of wood*). The KPIs for the entire sawmills are commonly monitored, although different end-products or raw materials used are not considered. Separate indicators for different products and raw materials would be an improvement to simply monitoring SEC for the entire mill. Most sawmills should have data for their different end-products and amounts produced annually, but in order to determine the energy efficiency (at mill level) for each product, the data have to be distributed on a daily or hourly basis (both energy use and product produced). To be able to apply an even more disaggregated approach, the energy use has to be measured at process level.

Table 5 also presents examples of explanatory indicators/parameters that affect the suggested energy KPIs. For example, availability is very important for both productivity and energy efficiency, and companies generally want to reduce the amount of downtime for production processes. In *sawing*, log gap and feed speed are also relevant for energy efficiency, as decreased log gap and increased feed speed would improve the energy efficiency of *sawing*. The most important parameter for *drying of wood* is, as already mentioned, the moisture content of wood before drying and the target moisture content. What also needs to be considered is the sapwood-heartwood ratio, which affects the moisture content. Heartwood generally has a much lower moisture content than sapwood.

4.3. Greenhouse gas emissions in wood industry processes

Assuming that the studied companies are representative of the entire wood industry in Sweden, the GHG emissions of each process for the Swedish wood industry would be as in Figs. 5 and 6. In scenario 1, *drying of wood* is the process that accounts for the largest GHG emissions (about 472 kton CO_{2eq}/year when applying

Table 5
Suggestions for energy KPIs to monitor in-house energy management in a sawmill for the entire mill as well as the two most energy intensive processes: sawing and drying of wood.

System boundary	Energy key performance indicator	Explanatory indicators/parameters
Sawmill	$SEC_{electricity}$ [$kWh_{electricity}/m^3$ produced goods] SEC_{fuel} [$MJ_{heat/fuel}/m^3$ produced goods]	Availability (h/h)
Sawing	Energy use by amount of sawn goods [$kWh_{electricity}/m^3$ sawn goods] Energy use per log processed [$kWh_{electricity}$/no. logs] Energy use by sawn area [$kWh_{electricity}/m^2$ timber]	Log gap [m] Energy use related to log gap [kWh/m] Feed speed [m/min] Temperature of logs [C] Yield [%]
Drying of wood	Thermal efficiency of drying [$MJ_{heat/fuel}/m^3$ dried wood] Electrical efficiency of drying [$kWh_{electricity}/m^3$ dried wood] Thermal energy use by amount of water removed [MJ_{heat}/kg water] Electrical efficiency by amount of water removed [$kWh_{electricity}$/kg water] Energy efficiency of kiln and product [$kWh_{kiln}/m^3_{product}$]	Moisture content of wood [%] Target moisture content [%] Amount of wood loaded into kiln [m^3] Sapwood-heartwood ratio

marginal electricity (ME) and about 86 kton CO_{2eq}/year when applying the Nordic electricity mix (NEM)). *Drying of wood* accounts for 27% of all GHG emissions related to electricity in scenarios 1 and 2.

In scenario 2, where biofuels are considered to be a limited resource, *drying of wood* is the largest GHG emitting process (1596 kton CO_{2eq}/year when ME is applied, and 1210 kton CO_{2eq}/year when NEM is applied), followed by *space heating* (582 kton CO_{2eq}/year when ME is applied, and 492 kton CO_{2eq}/year when NEM is applied). *Drying of wood* and *space heating* account for 100% of the GHG emissions related to biofuels.

In scenario 3, where only direct emissions from owned or controlled sources are taken into consideration, emissions from electricity and district heating are excluded since the emissions for these energy carriers happen at the utility plant. This means that only processes that use fossil fuels or biofuels emit GHG in scenario 3. Fossil fuels and biofuels are only used in three processes among the studied companies, namely drying of wood, internal transportation and space heating. *Drying of wood* emits 1124 kton CO_{2eq}/year in scenario 3, while *space heating* and *internal transport* emits 390 kton CO_{2eq}/year and 80 kton CO_{2eq}/year respectively. Regardless of which scenario is applied, drying of wood is by far the largest GHG emitting process.

In scenario 1, processes with high electricity use are the most prevalent GHG emitting processes. In scenarios 2 and 3, processes with high biofuel use are the most prevalent GHG emitting processes.

4.4. Energy efficiency measures and greenhouse gas mitigation measures

With the assumption that the studied companies are representative of the wood industry, and that their peers have the same level of EEMs, the total potential for the wood industry in Sweden would be as shown in Fig. 7. Each measure is categorized according to which EEU process it addresses (sawing, lighting etc.). The total energy saving potential is slightly over 1,100 GWh, or about 13% of the final EEU as given by Statistics Sweden. The largest amount of energy savings is found in *compressed air*, *lighting*, *process ventilation* (all electricity), *space heating* (district heating) and *drying of wood* (biofuels). The measures suggested by energy audit reports for *drying of wood* imply optimization of circulation air flow in the driers, pre-heating of air, additional insulation, and demand-controlled drying air flow. Notably, there are no suggestions for heat recovery technologies.

For *space heating*, recurrent EEMs regard turning off *process ventilation* or *ventilation*, installing frequency controllers for fans, and improving the technical characteristics of the buildings by e.g. adding insulation. For the first two measures, *space heating* is saved since heated air removed through the ventilation does not have to be replaced by the heating system. In many of the case companies, the use of heat recovery technologies was non-existent. The EEMs for *lighting* include installing more energy efficient lighting and motion detectors. For *compressed air*, EEMs regarded sealing off air leakages, turning off compressors or reducing compressor operating times, and reducing the pressure in the compressed air system.

Notably, *sawing* accounts for 7% of electricity use in the wood industry, but does not have a single proposed EEM. E.g. Andersson et al. [23] have mentioned this issue of energy auditors mainly focusing on the larger EEU processes and cross-sectoral technologies (i.e. support processes), since such knowledge is scalable to other sectors as well. This could also be an explanation why *further refining processes*, the production process accounting for the largest share of EEU for companies classified as C16.2, only has a small energy efficiency potential.

Also, there is a discrepancy where *pumping* has an energy saving potential even though none of the case companies have any EEU allocated to this process (Fig. 3). The EEU for pumping is likely to be small and not properly measured or calculated, and thus found in *Other* support *processes*, but the EEM proposed (one in total) still addresses pumping.

It is not possible to directly denote which processes have cost-effective EEMs, since the energy prices vary from company to company. Given that the electricity price level has been around EUR 50/MWh (about SEK 500/MWh) [42], most EEMs that regard electricity savings should be cost-efficient. For district heating, the prices vary depending on a company's district heating provider. The biofuel (i.e. bark and sawing residues) used in the sawmills is “free” since it is a by-product from the production processes. However, instead of using it within the company, the biofuel could be sold on the market, where the selling price would represent the cost for the company of burning it itself.

From a policy perspective, only 11 companies in the Swedish wood industry participated in the first phase of the Swedish Program for Improving Energy Efficiency in Energy Intensive Industries (PFE) with energy efficiency savings of 28.0 GWh/year. The 31 SMEs which participated in the Swedish energy audit policy program achieved energy savings of 19.4 GWh, only considering the implemented measures. Even if additional companies have carried out energy audits and implemented EEMs later on, it is likely that the energy efficiency potential in the wood industry is yet to be achieved.

The GHG mitigation potential is calculated for two scenarios using marginal abatement curves, and in both cases considering the entire wood industry. Fig. 8a shows the GHG mitigation potential

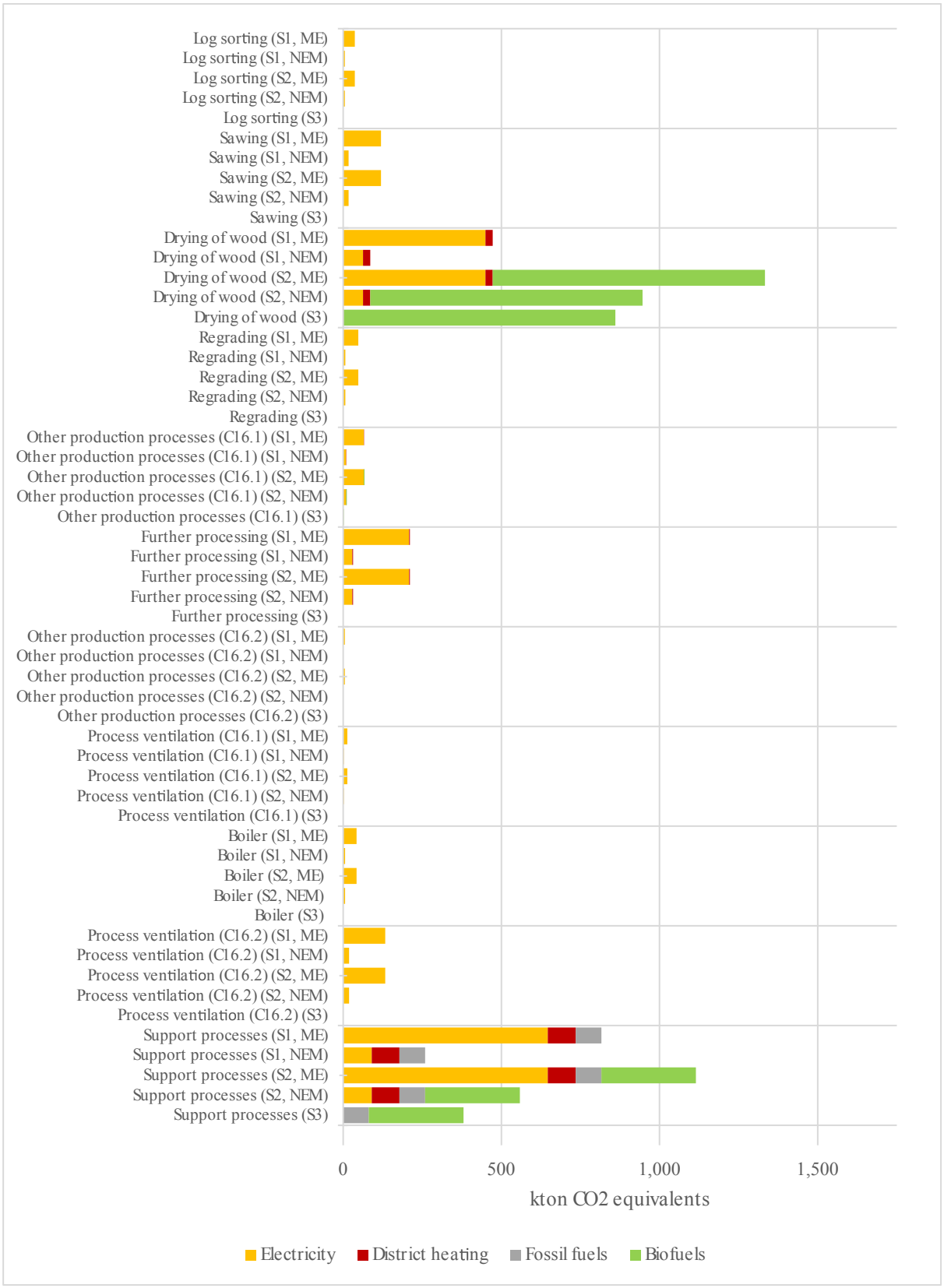

Fig. 5. The total national emissions of CO_{2eq} at process level for the Swedish wood industry for each production process, and for support processes jointly. This estimation of the CO_2 emissions for the entire industry is based on the assumption that the studied companies are representative of the entire wood industry. S1 = Scenario 1, S2 = Scenario 2, S3 = Scenario 3, ME = Marginal electricity, NEM = Nordic electricity mix.

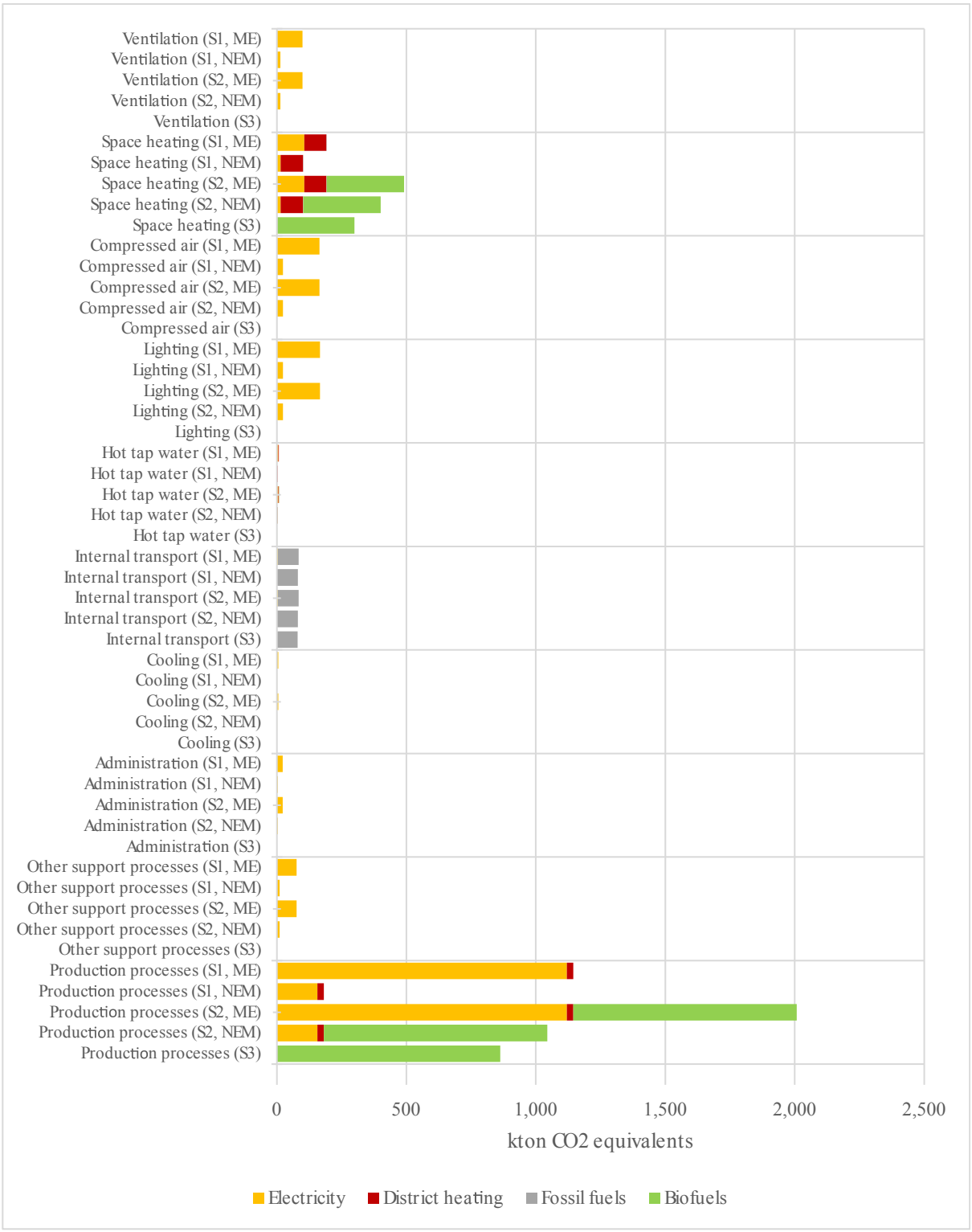

Fig. 6. The total national emissions of CO_{2eq} at process level for the Swedish wood industry for each support process, and for production processes jointly. This estimation of the CO_2 emissions for the entire industry is based on the assumption that the studied companies are representative of the entire wood industry. The processes "Steam" and "Pumping" have been omitted due to having 0 use of energy. S1 = Scenario 1, S2 = Scenario 2, S3 = Scenario 3, ME = Marginal electricity, NEM = Nordic electricity mix.

using the Nordic electricity mix and considering biofuel as a limited resource. In this case, *drying of wood* accounts for the largest mitigation potential nationally, at more than 100,000 ton CO_{2eq}. However, more cost-effective measures exist for the support processes *compressed air*, *ventilation*, and *hot tap water* as well as *regrading* and *further refining processes*.

Fig. 8b shows the national CO_2 mitigation potential if the marginal electricity perspective is applied where coal condensed power plants represent the margin of electricity generation. The most notable difference in comparison to Fig. 8a is that EEMs for

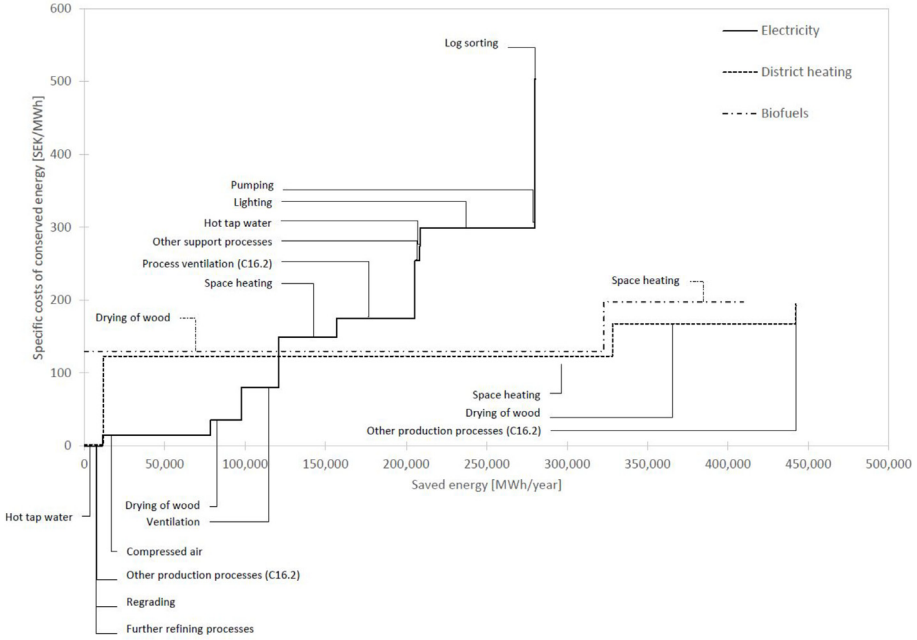

Fig. 7. The energy efficiency potential per process in the entire wood industry in Sweden, assuming that the EEMs given for the studied companies are representative at a national level. Companies classified as both C16.1 and C16.2 are considered in this diagram.

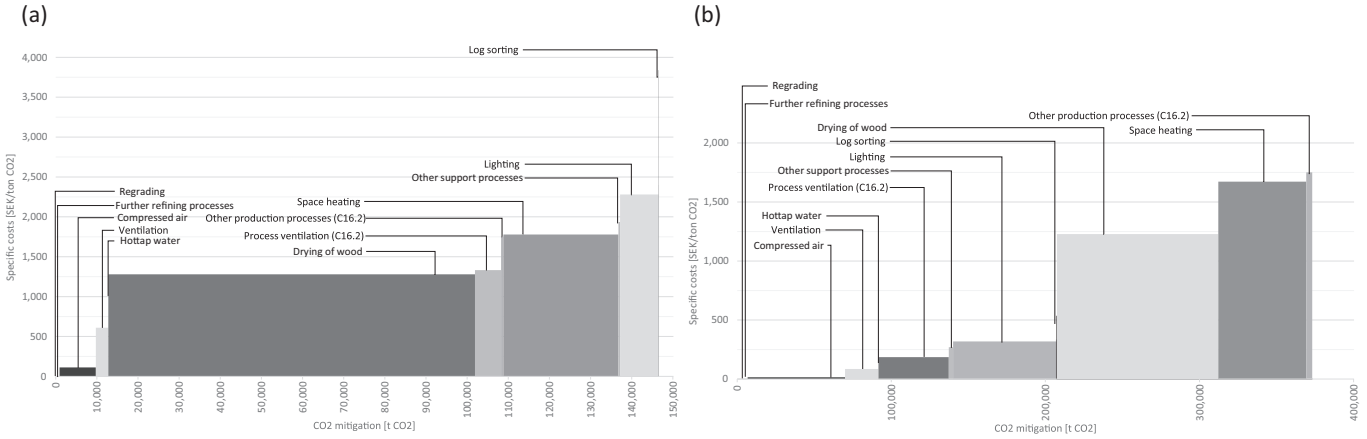

Fig. 8. National CO_2 mitigation potential assuming that the EEMs given in the energy audit reports are representative of the industry. Figure (a) shows the mitigation potential when assuming the Nordic electricity mix. Figure (b) shows the mitigation potential when assuming marginal electricity. Biofuel is considered a limited resource in both (a) and (b). Note that a few processes have a very small energy saving potential and are hard to visualize in the diagram. These are for (a) hot tap water (CCE = SEK 1059/ton CO_2) and log sorting (CCE = SEK 3838/ton CO_2). For (b), these are hot tap water (CCE = SEK 162/ton CO_2) and log sorting (CCE = SEK 536/ton CO_2). For both (a) and (b), pumping was omitted due to no mitigation potential.

additional end-use processes are more cost-efficient than the *drying of wood* process. This is true for *log sorting*, *process ventilation (C16.2)*, *other* support *processes*, and *lighting*, which also have a large CO_2 mitigation potential.

5. Discussion

5.1. Energy end-use, energy saving potential and systems perspective

When calculating GHG emissions, the two perspectives on biofuel provide distinct outcomes. If biofuel is considered carbon neutral, this paper shows that the high electricity use in EEU processes is a major contributor to GHG emissions in the wood industry, which is also noted by Murphy et al. [25]. However, if biofuel is considered a limited resource in the market, it is a larger contributor to GHG emissions in the wood industry, since every amount of biofuel used in a sawmill could potentially replace the use of fossil fuel elsewhere (cf. [34]).

If the system boundary are extended beyond the firms to also include the generation of district heating, this implies that, from a systems perspective, it would be better to replace other (fossil) fuels for district heating with residual biofuels from sawmills. In other words, instead of only using the generation of heat directly in a boiler at a sawmill, it would be beneficial to use the biofuel in a CHP plant for both electricity and heat generation. However, if excess heat is to be used in district heating, this is not possible if a sawmill is located where there is no district heating network. It

might also not be possible to replace all heat for drying with district heating alone, but part of the energy use for drying a mill could originate from district heating.

Regarding CSCs and EEMs, *sawing* of wood, which accounts for a significant proportion of the EEU in the production processes, did not received a single EEM from the energy auditors. There are a number of possible explanations for this: (1) the best available technology could already be implemented at the studied companies, (2) measures for this process were omitted due to being deemed cost-inefficient, or (3) the auditors did not possess sufficient knowledge of the process to suggest adequate EEMs. This has not been investigated within the current study, but could imply a knowledge gap where unidentified, and thus unexploited, energy efficiency potential exists.

What should be noted when analyzing the results of this paper is that when bottom-up energy data is aggregated to national sector level, the bottom-up data used includes companies that would not normally be considered part of the wood industry, i.e. division 16 of NACE rev. 2. Instead, three companies are part of the classification 31.01: Manufacture of office and shop furniture. These companies are partly included because of the applied supply chain perspective, but more importantly because of the possibility that a company classified as C16 might also have further value-adding processes that are part of another classification, e.g. C31.01.

Other uncertainties in this paper regard the applied method and available data. The energy audits consist of uncertainties in both the measurements and calculations of EEU. In the analysis of the energy audit reports, it is not always clear to which process some of EEU should be allocated, e.g. because specific names for processes are used by the audited company. For the aggregation of process level EEU data to a national level, the studied companies are most likely not representative of the entire wood industry. Therefore, the figures should be interpreted with great care. However, the total EEU of each energy carrier is provided by Statistics Sweden; it is the percentage of distribution to each EEU process that is based on the case companies. Therefore, the figures should provide valuable information for policy makers as an analytical generalization.

It must be added that, beside the fact that some of the national energy data is omitted by Statistics Sweden for confidentiality reasons, there is no extensive control of the quality of the data that is reported to the agency, which might result in other errors in the national data.

In order to get adequate energy data at national level for the wood industry in the long term, we advocate a longitudinal collection of energy data by government agencies, where the proposed categorization of end-use processes as developed in this study is applied for structuring the collection of data. Such a longitudinal study should include a thorough quality control of a limited, but statistically significant, sample of energy audits.

5.2. Energy key performance indicators for sawmills

It is evident that there is potential for improvement regarding the currently operational energy KPIs. A straightforward improvement of the KPIs would be to separate figures for different wood species and different end-products (structural effect called *mix of products*) and also distinguish between different drying kiln technologies (e.g. chamber dryer or continuous kiln, the structural effect known as *mix of processes*). In this case, the KPIs for these different scenarios are potentially more relevant in e.g. benchmarking practices, and is also more relevant for a company to follow its own improvement. This is because it is not necessarily the case that an improvement of a single KPI that does not account for the abovementioned factors reveals an actual improvement, i.e. it could be a result of a shift in end-product mix where there is e.g. an increase in products with higher moisture content. This would require continuous monitoring and measurement of EEU, preferably at a disaggregated level.

5.3. Policy implications

Information for industrial companies regarding the EEMs studied in this paper is lacking in the European Commission's best available technique (BAT) reference documents. Thus, there is a knowledge gap of potential EEMs for the wood industry, which is partly covered by the results in this paper. However, further research should aim to conduct an industry-wide investigation of the energy efficiency measures with their corresponding energy saving potential, both in Sweden and in the EU.

This implies a major policy implication, since the energy saving potential in certain EEU processes is large. Drying wood and process ventilation are two production processes in the wood industry that would benefit from a leap in technology. Relevant policies to achieve this could be, for example, investment support for energy efficient technologies applicable for these processes or innovation projects targeting these processes. Furthermore, given that the wood industry accounts for a large share of the industrial EEU in Sweden, and possibly also in other EU member states, the sector should be provided with a BAT reference document that covers not only cross-sector processes such as drying, but also processes specific to the wood industry. Information about best practice and best available techniques is currently lacking, and such benchmarking values would be beneficial not only for policy makers to estimate the energy efficiency potential, but also for individual wood companies.

6. Conclusions

This paper provides a taxonomy for EEU and GHG emissions on a process level in the wood industry, and analyses in which processes the major GHG mitigation measures are found in the Swedish wood industry. This is a novel approach which, to the authors' knowledge, has not earlier been carried out for the wood industry. A number of scientific papers have historically elaborated on energy savings and mitigation measures in the manufacturing industry (e.g. Refs. [11,16,17]). The novelty of this study and its major general contributions to the overall general scientific knowledge in the field are:

- A general taxonomy for the categorization of EEU and emissions of the processes in the wood industry is suggested.
- Currently applied energy KPIs and their magnitudes for the wood industry are presented.
- A novel proposal for new innovative energy KPIs is suggested.

Findings specific to the Swedish wood industry are:

- A state-of-the-art review of the EEU is presented, including current GHG emissions and actual mitigation measures.
- The major policy implications for Sweden are that the current policies are not sufficient for achieving the full energy efficiency potential.
- In line with the above, new policies are needed with a focus on processes and process-related technologies to reach the targets.

Even though the scope of this paper is the Swedish wood industry, many of the findings are likely to be applicable to other countries with a prominent wood industry. This regards the review of the technical energy efficiency potential at process level, as well as the categorization of processes and the energy KPIs.

Furthermore, even though Sweden has carried out energy audit policy programs, not all of the energy efficiency potential has been deployed. Energy audit policy programs alone are not enough to reach the targets set by the EU, which should be relevant for policy makers in other EU member states to consider.

Also, the categorization of processes and the energy KPIs are useful for both individual wood industrial companies and governing agencies. This is suggested as a subject for further research, where the developed categorization could be further validated and relevant energy KPIs in the management of energy in companies could be developed and applied.

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