Enabling industrial energy benchmarking

Process-level energy end-use, key performance indicators, and efficiency potential

Elias Andersson

Linköping Studies in Science and Technology
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Abstract

One of the greatest challenges of our time is global climate change. A key strategy for mitigating the emission of greenhouse gases is the improvement of energy efficiency. Manufacturing industry stands for a large share of global energy end-use but has yet to achieve its full energy efficiency potential. A barrier to untapping this potential is the lack of detailed data on industrial energy end-use at the process level, preventing the development of sound, bottom-up energy key performance indicators (KPIs). This hampers the ability to create a profound strategy for improving industrial energy efficiency because it is not known in which end-use processes the largest energy efficiency potential is to be found. Increasing knowledge about energy end-use at the process level also increases the possibility for energy comparisons, i.e. benchmarking, at the process level.

This thesis aimed to investigate how to further enable industrial energy benchmarking at the process level, primarily for the pulp and paper and wood industries. Relevant benchmarking requires that data on energy end-use is collected using a common, harmonized categorization of processes and that joint energy KPIs are applied. Therefore, suggestions for standardized categorizations of end-use processes were investigated for the studied industries.

Based on the calculations, and under the assumptions made in this thesis for estimating the energy efficiency potential of end-use processes, diversity was found between industries around which type of processes have the largest efficiency potential. It also emerged that, due to the lack of detailed data about energy end-use and lack of information about energy efficiency measures, processes accounting for a significant share of the energy efficiency potential in the wood industry risk being overlooked. It is not certain that current energy policies are sufficient to reach the full potential identified. The lack of information about energy end-use and energy efficiency measures implies that neither industrial actors nor policy-makers are able to develop thorough energy strategies or roadmaps for improved energy efficiency.

While the outcomes of this thesis show that a large share of Swedish pulp and paper mills carry out energy benchmarking to some degree, energy managers emphasized that benchmarking in this particular industry is difficult because it requires a deep understanding of the industry's heterogenous and integrated processes. This thesis proposes a widened perspective on energy benchmarking and its role in industrial energy management; namely, also considering the process of how energy KPIs are implemented within in-house energy management. A process that enhances energy management includes the continuous monitoring, visualization, and revision of KPIs. In this thesis, a method is developed that encourages the bottom-up implementation of energy KPIs in the pulp and paper industry, which further enables industrial energy benchmarking.

Sammanfattning

En av vår tids största utmaningar är den globala klimatförändringen. En viktig strategi för att minska utsläppen av växthusgaser är att förbättra energieffektiviteten. Tillverkande industri står för en stor del av den globala energianvändningen och har fortfarande en potential för energieffektivisering som inte utnyttjats. Ett hinder mot att uppnå potentialen är bristen på detaljerad information om energianvändningen i industrins processer. Detta försvårar också för utveckling av relevanta energinyckeltal baserade på enskilda processers energianvändning. Vidare hindrar detta möjligheten för en djupgående strategi för hur man kan förbättra energieffektiviteten i tillverkande industri eftersom det inte är känt inom vilka processer som den största potentialen för energieffektivisering finns. Genom att öka kunskapen om energianvändning ökar också möjligheten att jämföra energiprestandan mellan företag, det vill säga benchmarking, på processnivå.

Denna avhandling syftade till att undersöka hur man ytterligare kan möjliggöra industriell benchmarking av energieffektivitet på processnivå, med fokus på massa- och pappersindustrin och trävaruindustrin. För relevant benchmarking krävs att energianvändningsdata sammanställs efter en gemensam och harmoniserad kategorisering av industriella processer. Det är också nödvändigt att använda sig av gemensamma energinyckeltal. Därför undersöktes i avhandlingen möjligheter till standardiserade kategoriseringar av energianvändande processer för de studerade industrierna.

Baserat på de antaganden som gjordes för att uppskatta potentialen för energieffektivisering visades att det fanns en diversitet mellan branscher för vilken typ av processer som har störst potential. Det framkom också att bristen på information om energieffektiviseringsåtgärder riskerar medföra att processer med stor potential i trävaruindustrin förbises. Det är vidare inte säkert att existerande styrmedel är tillräckliga för att uppnå hela potentialen för energieffektivisering. Bristen på information om energianvändning på processnivå och effektiviseringsåtgärder innebär att varken industriella aktörer eller beslutsfattare kan utveckla välgrundade energistrategier eller färdplaner för ökad energieffektivitet.

Även om resultaten från denna avhandling visade att en stor andel av de svenska massa- och pappersbruken praktiserar någon typ av benchmarking av energieffektivitet, betonade energimanagers att benchmarking är svårt att genomföra eftersom det kräver en djup förståelse av branschens processer. Därför föreslås ett bredare perspektiv av energibenchmarking och dess roll i energiledningsarbetet som också inkluderar processen i hur energinyckeltal implementeras. För en framgångsrik implementeringsprocess är det viktigt med kontinuerlig uppföljning, visualisering och revidering av energinyckeltalen. I den här avhandlingen har en metod utvecklats för implementering av energinyckeltal i massa- och pappersindustrin baserat på en bottom-up-approach.

"The only limits to adventure are the limits of your imagination"

*Scrooge McDuck from *The Life and Times of Scrooge McDuck* by Don Rosa.*

List of papers

This thesis is based on the following papers:

- I. **Andersson, E.**, Arfwidsson, O., Thollander, P., 2018. Benchmarking energy performance of industrial small and medium-sized enterprises using an energy efficiency index: Results based on an energy audit policy program. *Journal of Cleaner Production*, 182, 883–895.
- II. **Andersson, E.**, Karlsson, M., Thollander, P., Paramonova, S., 2018. Energy end-use and efficiency potentials among Swedish industrial small and medium-sized enterprises – A dataset analysis from the national energy audit program. *Renewable and Sustainable Energy Reviews*, 93, 165–177.
- III. **Andersson, E.**, Nehler, T., 2018. Energy management in Swedish pulp and paper industry – benchmarking and non-energy benefits (3-093-18), in: *ECEEE Industrial Summer Study*. pp. 313–322.
- IV. **Andersson, E.**, Thollander, P., 2019. Key performance indicators for energy management in the Swedish pulp and paper industry. *Energy Strategy Reviews*, 24, 229-235.
- V. Johnsson, S., **Andersson, E.**, Thollander, P., Karlsson, M., 2019. A study of the energy end-use and greenhouse gas emissions in Swedish wood industry. *Energy*, 187, 115919.
- VI. **Andersson, E.**, Dernegård, H., Karlsson, M., Thollander, P. How to implement energy performance indicators for successful energy management practices in kraft pulp mills: A bottom-up approach. (*Submitted for publication*)

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Finally, my deepest gratitude now and always to Jesus for all You have done.

Abbreviations

BAT	Best available technology
CSC	Conservation supply curve
CCE	Cost of conserved energy
DEA	Data envelopment analysis
EEI	Energy efficiency index
$EEI_{total,j}$	Total energy efficiency index for a site j
$EEI_{weighted,j}$	Total weighted energy efficiency index for a site j
EKL	Act on energy audits in large companies
EnPI	Energy performance indicator
EU	European Union
IEA	International Energy Agency
IAC	US Department of Energy's Industrial Assessment Centers' database
ISO	International Organization for Standardization
KPI	Key performance indicator
$KPI_{i,j}$	Key performance indicator for process i at site j
$KPI_{ref,i}$	Average value of key performance indicator for process i of the studied companies
LTAs	Long-term agreements
MPI	Malmquist Productivity Index
NACE	Statistical classification of economic activities in the European Community
PFE	Program for improving energy efficiency in energy-intensive industries
$PS_{i,j}$	The percentage of total energy end-use of process i at site j
RISE	The Research Institutes of Sweden
SEA	Swedish Energy Agency
SEAP	Swedish Energy Audit Program
SEAS	Swedish Energy Audit Support for SMEs
SEC	Specific energy use
SFA	Stochastic frontier analysis
SME	Small and medium-sized enterprise
SNI	Swedish Standard Industrial Classification
STIND	Energistatistik för industrin [Energy statistics for the industry]

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1. Introduction

This chapter first presents the introduction to this thesis. The introduction is followed by the aim and research questions, scope and delimitations, and appended papers and co-author statements. The chapter ends with a description of my research journey.

The mitigation of global climate change is one of the greatest challenges of our time and actions to reduce greenhouse gas emissions in energy end-use sectors are necessary. Manufacturing industry accounts for about a third of final global energy end-use (IEA, 2019). This fraction is even higher in Sweden and it is therefore an important sector for the pursuit of the Swedish target of net zero emissions of greenhouse gases by 2045 (Government Offices of Sweden, 2017). One key approach to the reduction of anthropogenic greenhouse gas emissions in the industry sector is to make improvements in energy efficiency (IPCC, 2014).

The technical energy efficiency potential of the major industrial sectors in the EU is assessed to be about 20–23 % of final energy use by 2050 (Chan and Kantamaneni, 2015). The headline target for energy efficiency improvement in the EU is set higher than that, at 32.5 % by 2030 (European Commission, 2018). At the same time, previous studies have argued that barriers to implementing economically feasible energy efficiency measures pose the risk that an identified potential will not be reached (Hirst and Brown, 1990). This is denominated the *energy efficiency gap* (Jaffe and Stavins, 1994).

Estimated energy efficiency potential in general focuses on the installation of new, more efficient technology. The potential is argued to be larger if the management of energy is also considered, introducing the *energy management gap*, which consists of barriers to energy management practices (Backlund et al., 2012). Energy management practices were estimated by Paramonova et al. (2015) to account for at least 35 % of the total deployed energy efficiency potential in energy-intensive industry in Sweden. Thus, in order to achieve the full energy efficiency potential, both technical measures and energy management need to be considered.

The implementation of industrial energy management have been investigated in various studies (cf. Sivill et al., 2013; Stenqvist et al., 2011; Thollander and Ottosson, 2010), and in a sound review of the concept by Schulze et al. (2016). A subset of successful energy management practices consists of defining accurate energy key performance indicators (KPIs) and carrying out energy benchmarking (cf. Johansson and Thollander, 2018; Ke et al., 2013).

Energy benchmarking for industry is the process of comparing the energy performance of industrial plants (Worrell and Price, 2006). It uses defined energy KPIs and can be carried out at different aggregated levels. The EU benchmarking program, ODYSSEE-MURE (2017), provides energy indicators for different sectors in EU Member States, allowing for the benchmarking of e.g. the pulp and paper industry between countries. While this may determine the overall potential for energy efficiency

improvement of a sector, a more detailed benchmarking at the process level can provide information about where the actual energy saving potential is found (Ke et al., 2013). Process level benchmarking is therefore potentially valuable for both industrial actors and policy-makers.

Energy benchmarking at the process level is preceded by the categorization of energy end-use processes and the selection of energy KPIs. A common, standardized categorization of production processes in different industries is yet to be fully operationalized. The non-existence of a commonly used categorization of production processes (Thollander et al., 2015), and the absence of structured energy data collection at a detailed level (Sommarin et al., 2014), means that access to high quality, harmonized, and granulated national energy data is scarce.

Thus, the possibilities for energy benchmarking at a detailed level are limited. Indeed, it has been emphasized that industry currently lacks relevant process-level energy KPIs (Bunse et al., 2011; May et al., 2015). To enable energy benchmarking at the process level for a certain industry, first harmonized categorizations of industrial end-use processes need to be defined, then energy KPIs need to be developed.

1.1 Aim and research questions

The aim of this thesis is to further enable industrial energy benchmarking at the process level. This aim is studied from the perspectives of energy managers and policy-makers, and has been broken down into the following research questions:

- 1) How can a standardized categorization of production processes be developed for the allocation of energy end-use in a manufacturing industry?
- 2) How can industrial energy end-use processes with large energy efficiency potential at a national level be identified?
- 3) What are the opportunities and challenges of industrial energy benchmarking?
- 4) What are the currently applied energy key performance indicators, and what is their improvement potential from the perspective of industrial energy management?

The appended papers' relation to the research questions is presented in Table 1.

Table 1: Overview of which research questions each of the thesis papers is addressing. RQ = Research question.

Paper	RQ 1	RQ 2	RQ 3	RQ 4
I	X	X	X	
II	X	X		
III			X	
IV				X
V	X	X		X
VI	X			X

1.2 Scope and delimitations

The two primarily studied industries in this thesis are the *manufacturers of wood and of products of wood*, and *manufacturers of pulp and paper products*, from here on denominated the *wood industry* and the *pulp and paper industry*. In terms of industrial

energy end-use, the pulp and paper industry is the largest in Sweden (SEA, 2019a), and the third largest in the EU (Eurostat, 2020). Furthermore, the wood industry accounts for a significant share of industrial energy end-use in the EU (Eurostat, 2020), but is even more prevalent in Sweden where it is the fourth largest industry (SEA, 2019a). Therefore, it was of interest to study how energy benchmarking at a process level can be further enabled within these industries in order to enhance the identification of energy efficiency potential.

To a lesser extent, *manufacturers of food products* and *manufacturers of metal products* are studied, from here on denominated the *food industry* and the *metal industry*¹. The metal and food industries are studied for reasons of comparison with the wood industry. For research question 2, the estimation of energy-saving potential in industrial end-use processes, only the wood, food, and metal industries are covered, and not the pulp and paper industry.

The context of study is consistent throughout the thesis, i.e. all the studied cases are located in Sweden, and the data used for analysis is derived from Swedish industry. As the aim of this thesis regards process-level benchmarking, a bottom-up approach is adopted. This means that, for example, the estimation of the energy efficiency potential at a national level is based on energy end-use data of industrial processes. In this thesis, “process level” refers to individual production steps (e.g. sawing, drying) or auxiliary systems/support processes (e.g. lighting, ventilation). Furthermore, due to the bottom-up approach, the contribution to top-down energy indicators is limited.

The manufacturing industry is an intricate study object, due, among other factors, to the high complexity of the technologies used in production processes, and the heterogeneity of end-products and materials used. If a fair benchmarking between companies’ energy performance is to be carried out, an in-depth understanding of these factors is needed. It is important to note that this thesis does not present a complete method for benchmarking but is rather a contribution towards how to further enable energy benchmarking.

As regards energy KPIs that account for influencing factors in a benchmarking practice, it is difficult to adhere to all these factors. One reason is that a lot of the data needed for the inclusion of such factors is either not collected by the companies or is confidential. In this thesis, no measurements have been carried out to investigate the impact of influencing factors on a certain energy KPI, instead, the focus has been on method development on how to implement energy KPIs for successful industrial energy management.

In Paper III, the non-energy benefits of energy management are studied, and in Paper V, the allocation of greenhouse gas emissions at the process level is carried out, but as these are not critical to the aim and research questions of this thesis, they are not addressed further in the following chapters.

¹In this thesis, the studied industries are defined as the following classification of economic activities in accordance with NACE Rev. 2: Divisions 10, 16, 17, and 25.

1.3 Appended papers and co-author statements

- I. **Andersson, E.**, Arfwidsson, O., Thollander, P., 2018. Benchmarking energy performance of industrial small and medium-sized enterprises using an energy efficiency index: Results based on an energy audit policy program. *Journal of Cleaner Production*, 182, 883–895.

This paper presents a new method of benchmarking using an energy efficiency index (EEI). The index makes it possible to benchmark the energy performance at either site level or process level. It can be used by both energy managers at manufacturing companies and organizations with an auditing role. In this study, interviews were made with governmental and industrial actors to develop the EEI, and data from energy audit reports from 11 sawmills were used to test it. The paper is developed from my master's thesis, which I wrote in a shared effort with Oskar Arfwidsson. I developed the master's thesis into the scientific paper. Patrik Thollander provided the initial idea, commented, and supervised during the entire process.

- II. **Andersson, E.**, Karlsson, M., Thollander, P., Paramonova, S., 2018. Energy end-use and efficiency potentials among Swedish industrial small and medium-sized enterprises – A dataset analysis from the national energy audit program. *Renewable and Sustainable Energy Reviews*, 93, 165–177.

This paper presents energy data from the Swedish energy audit program allocated to both support and production processes. A previously developed categorization of processes, the unit process concept, was applied. Conservation supply curves (CSC) of real energy efficiency measures are also presented. Magnus Karlsson, Patrik Thollander and Svetlana Paramonova developed the idea for this paper. A first draft was written by a master's student, under the supervision of the three mentioned authors. I continued the unfinished first draft, refined the method and results, and finished writing the paper. I continued to work with the reviewers' comments under the supervision of Magnus Karlsson and Patrik Thollander.

- III. **Andersson, E.**, Nehler, T., 2018. Energy management in Swedish pulp and paper industry – benchmarking and non-energy benefits (3-093-18), in: *ECEEE Industrial Summer Study*, pp. 313–322.

This conference paper investigated the Swedish pulp and paper mills' current practices of energy benchmarking and the identified non-energy benefits from working with energy management. The data collection included a questionnaire sent to all Swedish mills, as well as qualitative interviews. The interviews only addressed energy benchmarking. The paper was written together with Therese Nehler in a shared effort. Therese Nehler was responsible for writing the introduction section, the theoretical background on energy management and non-energy benefits, and the results section on non-energy benefits. Therese Nehler also conducted the analysis of non-energy benefits. I was responsible for writing the background on energy efficiency benchmarking, the method section, and the results on energy performance benchmarking. We commented and provided input on each other's parts of the paper. We wrote the concluding discussion together.

- IV. **Andersson, E.**, Thollander, P., 2019. Key performance indicators for energy management in the Swedish pulp and paper industry. *Energy Strategy Reviews*, 24, 229–235.

This paper studies the current level of implementation and operationalization of energy KPIs in the Swedish pulp and paper industry. It also investigates drivers for and barriers to the energy performance measurement and development of energy KPIs. I collected the data for the paper through a questionnaire (the same questionnaire as for paper III), together with qualitative interviews conducted at a few mills (the same interviews as for paper III). Patrik Thollander supervised, commented, and reviewed the study continuously.

- V. Johnsson, S., **Andersson, E.**, Thollander, P., Karlsson, M., 2019. A study of the energy end-use and greenhouse gas emissions in Swedish wood industry. *Energy*, 187, 115919.

This paper presents a study of the energy end-use and greenhouse gas emissions at the process level in the wood industry. The data used is drawn from 14 energy audit reports. In addition, an analysis of energy efficiency measurements and their cost-efficiency is made through the calculation of CSCs. I co-wrote this paper in a shared effort together with Simon Johnsson. Patrik Thollander and Magnus Karlsson were both involved in developing the idea and continuously supervised and commented during the progress of the paper.

- VI. **Andersson, E.**, Dernegård, H., Karlsson, M., Thollander, P. How to implement energy performance indicators for successful energy management practices in kraft pulp mills: A bottom-up approach. (*Submitted for publication*)

This paper aims to present a novel and harmonized categorization of processes for the pulp and paper industry and a model for developing in-house energy KPIs for the energy management system. A case study methodology is applied for this, including interviews and workshops with actors in the industry. Magnus Karlsson had the main responsibility for planning the workshops, and I commented on this plan. I contributed with the idea of the paper and wrote the first draft. All authors commented on and contributed to the revisions of the paper.

1.4 Other publications

- i. **Andersson, E.**, Arfwidsson, O., Bergstrand, V., Thollander, P., 2017. A study of the comparability of energy audit program evaluations. *Journal of Cleaner Production*, 142, 2133–2139.
- ii. Nilsson, E., **Andersson, E.**, Rohdin, P., Thollander, P., 2018. Benchmarking of space heating demand for a sample of foundries in Nordic climate, in: *ECEEE Industrial Summer Study*. pp. 345–352.
- iii. Trianni, A., Cagno, E., Bertolotti, M., Thollander, P., **Andersson, E.**, 2019. Energy management: A practice-based assessment model. *Applied Energy*, 235, 1614–1636.

- iv. Lawrence, A., Nehler, T., **Andersson, E.**, Karlsson, M., Thollander, P. 2019. Drivers, barriers and success factors for energy management in the Swedish pulp and paper industry. *Journal of Cleaner Production*, 223, 67–82.

1.5 Research journey

During my PhD studies at the Division of Energy Systems at Linköping University, I have been involved in three different research projects. The scope and aim of each project has differed. This has in turn influenced the content of the appended papers in this thesis. Figure 1 shows the chronological timeline of the research projects and the output of papers.

Figure 1: A timeline overview of the research projects and the papers produced for this thesis. The background color of a paper refers to the research project within which the paper was substantially carried out. However, there are no distinct boundaries as the research projects' methods and findings have influenced each other.

Prior to the start of my PhD studies, I was involved in the research project *Categorization for benchmarking of industrial SME's energy-using processes and efficiency*. I undertook my master's thesis together with Oskar Arfwidsson within this project, which was later developed into Paper I. The other researchers in the project had been working on a similar study as my master's thesis, but with a different approach. I finalized that study and it turned into Paper II of this thesis. Both papers used data from the Swedish Energy Audit Policy Program (SEAP), which consists of data from energy audits on companies. One central part of both studies was the allocation of energy end-use into separate production processes by using the audit reports. In Paper II, the unit process concept was applied, which has the same taxonomy for all industries (it is further explained in Section 4.5). In Paper I, a previously developed categorization of processes for the wood industry was used. In both papers, it was possible to allocate energy end-use by using the categorization of processes.

The results presented in Papers I and II led to a continuation of the investigation on benchmarking possibilities in the research project *Energy management in the Swedish pulp and paper industry – barriers, drivers and general success factors*. Since the context

was the pulp and paper industry, which has a complex set of production processes, the approach selected was to address challenges and possibilities of energy benchmarking. This included the level of maturity of the development and implementation of energy KPIs in the industry. This was investigated through a questionnaire, conducted together with two other members of the research group: Akvile Lawrence and Therese Nehler. The questionnaire also included questions on themes other than energy KPIs, benchmarking, and non-energy benefits, which provided data for other papers not appended to this thesis. In parallel with the questionnaire, several semi-structured interviews were carried out. The interviews were arranged by another member of the research group: Josefine Rasmussen. Josefine Rasmussen and I carried out the interviews together. The interviews also included sections on other energy management activities that were used by Josefine Rasmussen in other publications. Papers III and IV were the outcomes of the research project that are appended to this thesis.

In 2017, a new research project named *Carbonstruct* was designed. In the first research project I was involved in, the energy end-use was allocated to production processes. In *Carbonstruct*, we wanted to expand the scope to include the largest manufacturing industries in Sweden. We had not previously allocated the energy end-use for different energy carriers, which was also something that would improve the analysis; for example, by enabling the potential of allocating greenhouse gas emissions at the process level. The idea for *Carbonstruct* was to develop and suggest industry-specific categorizations of production processes. Within this scope, the categorization used for the wood industry in Paper I was refined and validated. This led to Paper V, this time using energy audit reports carried out by the same company which, due to its long experience in the field, compiled high-quality and stringent reports². This study was carried out together with Simon Johnsson. Through this study, we achieved a further validated categorization of production processes in the wood industry.

During *Carbonstruct*, I was invited to join another research project being carried out at a large company group within the Swedish pulp and paper industry. That project aimed to develop energy KPIs for in-house energy management, thus proving to be highly relevant to *Carbonstruct*. A few workshops were held. A categorization of production processes was first developed, followed by a method for how to develop relevant energy KPIs (along with a list of suggested indicators). This led to the creation of Paper VI.

² Note that a few of these energy audit reports overlap with the reports used for data collection in Paper III. However, the whole set of reports differed.

2. Industrial energy efficiency and energy management

This chapter starts by defining the relevant energy concepts, followed by giving the background of industrial energy end-use and efficiency potential. In addition, relevant Swedish policies for the industrial energy system are presented. The rebound effect, industrial energy management, international standards, and classifications of economic activities are also covered.

2.1 Definitions of energy-related concepts and terms

Several energy-related expressions are used interchangeably, e.g. *energy consumption* and *energy use*. Even though the term *energy consumption* is widely accepted in the scientific literature, it is technically incorrect. According to the first law of thermodynamics, energy can neither be created nor destroyed, it can only change form (Çengel et al., 2008). In this thesis, the term *energy use* refers to the amount of mechanical, thermal, and electrical energy that is supplied to a process or system.

Energy efficiency is defined in the Energy Efficiency Directive (2012/27/EU) as “*the ratio of output of performance, service, goods or energy, to input of energy*” (European Commission, 2012). This is the definition applied in this thesis.

Energy efficiency improvements are achieved by reducing energy use while maintaining the output or by maintaining the energy use while increasing the output, by means of technological, behavioral or economic changes (European Commission, 2009). Improved energy efficiency can also be achieved when both energy use and the output of services increases, as long as the increase in output is larger (cf. Pérez-Lombard et al., 2013). The same is true when both energy use and the output of services decreases, as long as energy use decreases more. The Energy Efficiency Directive (2012/27/EU) defines improvement in energy efficiency as “*an increase in energy end-use efficiency as a result of technological, behavioral and/or economic changes*” (European Commission, 2012). The inclusion of behavioral changes implies that non-investment measures are also considered to be improvements in energy efficiency. In that sense, the full energy efficiency potential is not only achieved by investments in new energy-efficient technology, but also through efficient management (cf. Backlund et al., 2012; Paramonova et al., 2015).

In contrast to energy efficiency improvements, *energy savings* is an absolute figure while energy efficiency is based on a ratio. “Savings” refers to a reduction in the use of a resource, and “energy savings” is therefore the result of a reduction in the use of energy (Pérez-Lombard et al., 2013). Energy savings is thus not the same as energy efficiency improvement. Energy efficiency improvements might lead to energy savings, unchanged

energy use, or increased energy use. The latter is known as the “rebound effect” and is discussed further in Section 2.5.

The term *energy conservation* refers to an action in which energy use is reduced. At the same time, it implies a reduction in the amount or quality of service provided (Pérez-Lombard et al., 2013). In relation to energy efficiency, it is possible to distinguish three typical cases of energy conservation (Pérez-Lombard et al., 2013):

- 1) Energy is saved at the same rate as the output is decreased, which results in unchanged energy efficiency
- 2) Energy use is reduced at a higher rate than service output, leading to an improvement in energy efficiency
- 3) Energy use is reduced at a lower rate than service output, leading to decreased energy efficiency.

Energy performance is defined as the “measurable results related to energy efficiency, energy use and energy consumption” (ISO, 2018). Energy efficiency is dependent on one type of energy input (total energy end-use, or divided into energy carrier such as heat, fossil fuel, electricity etc.) and an output, forming a ratio. Consequently, energy performance is the outcome of the energy efficiency, but possibly of other measurable results as well, such as absolute energy use. The energy performance can be measured against energy targets or objectives, as stated by the organization (ISO, 2018).

2.2 Industrial energy end-use and efficiency potential

The manufacturing industry accounts for a large share of the energy end-use in the EU-27 (Eurostat, 2020) and in Sweden (SEA, 2019a). Figure 2 shows the amount and share of energy end-use of the industrial sector in comparison to the residential and services sector and the transport sector.

Figure 2: Final energy end-use for the sectors Residential and services, Industry, and Transport in Sweden and in the EU-27 (own calculations based on Eurostat, 2020; SEA, 2019a).

The final energy end-use of each manufacturing industry in the EU-27 and in Sweden is shown in Figure 3. The industries studied in this thesis, pulp and paper, wood, metal, and food, account for a significant share of industrial energy use internationally, but even more so in Sweden. In the context of the EU and Sweden, these industries are important sub-sectors for improved energy efficiency in order to reach the 32.5 % energy efficiency target.

*Other industries include transport equipment (89 TWh), mining and quarrying (44 TWh), and textile and leather (43 TWh).

Figure 3: Final energy end-use for the manufacturing industries in Sweden and the EU-27. Note that the classifications of industries differ between the diagrams, and what sectors are defined as industry. The industries addressed in this thesis are colored, while the other industries outside of the scope of this thesis are in grey (own calculations based on Eurostat, 2020; SEA, 2019a).

Statistics Sweden, on behalf of the Swedish Energy Agency, collects data on industrial energy end-use, which is presented on an annual basis. The statistics are divided into energy use for different energy carriers and industries (SEA, 2019a). It is possible to derive energy data at a more detailed level than that which is readily available on the Swedish Energy Agency's website, but it must be ordered from Statistics Sweden and carries an administrative cost. Statistics Sweden collects data on electricity use, fuel use, and use of heat (e.g. bought and self-produced) down to the workplace level (Nyström et al., 2008).

However, energy data is marked as confidential if it is too detailed so that individual workplaces or companies are not possible to identify.

A project commissioned by the Swedish Energy Agency, Energistatistik för industrin (STIND), aimed to improve the energy statistics of the manufacturing industry in Sweden. The first phase of STIND stated the preconditions and the current procedures of industrial energy data compilation, stating that beyond the energy balances given by the Swedish Energy Agency, some data on energy use is collected by the Swedish Environmental Protection Agency and the Swedish Tax Agency (Nyström et al., 2008). As well as government authorities, some industry associations carry out energy data collection.

The second phase of STIND focused on developing a protocol for energy balances adapted for the manufacturing industry (Borg et al., 2009). An important driver for STIND was to increase knowledge about energy end-use in order to conduct bottom-up analyses, which in turn facilitate the development of energy KPIs at different levels (Borg et al., 2009). This was deemed valuable both for supporting the counties' administrative boards in governing activities and for industrial energy benchmarking.

2.2.1 Processes and energy efficiency potential in the pulp and paper industry

Annual pulp production in Sweden is about 12 million tonnes, of which about 40 % is sold on the market (SFI, 2019a). Paper and paperboard production in Sweden is about 10 million tonnes, the majority of which is exported (SFI, 2019b). The production of paper begins with logs being debarked and disintegrated into wood chips. In the subsequent step, pulping, the goal is to separate the fibers of the wood chips, which is achieved through either mechanical or chemical means. In mechanical pulping, fibers are separated by mechanical energy in refiners (wood chips being defibrated between metal refiner discs) or grinders (by logs being pressed against a rotating grinder stone) (European Commission, 2015). Chemical pulping uses chemicals in a liquor to separate the fibers. Before the papermaking process, the pulp is cleaned, potentially bleached and, if it is to be sold on the market, dried. In an integrated pulp and paper mill, drying the pulp is not necessary. The pulp is diluted with water and sprinkled onto a continuously moving horizontal fabric, forming paper by removing the water. Surface treatments of the paper can be applied depending on the desired properties of the final product.

The International Energy Agency (IEA, 2007) estimated about 13 years ago that the total energy saving potential for the pulp and paper industry was 15–18 %. This estimate was based on a technical approach. In absolute figures, this would amount to about 360–420 TWh annually. A similar figure is found in a future scenario for the EU, where a bottom-up evaluation of cost-effective technologies shows a 14 %, or 60 TWh annually, energy saving potential between the years 2015 and 2050 (Moya and Pavel, 2018). Also for the EU, and for the same timeline, Chan and Kantamaneni (2015) projected a technical saving potential of 17 % in relation to a business-as-usual scenario for the pulp and paper industry. A thorough study on the pulp and paper industry in Germany estimated the fuel saving potential to 21% and the electricity potential to 16% (Fleiter et al., 2012a).

In relation to other industries, the estimated absolute saving potential for the pulp and paper industry in IEA member countries is smaller than for others such as the chemical and petrochemical, iron and steel, and cement industries, but larger than for aluminum and other industries that manufacture metals (IEA, 2007). In percentage terms, only the cement industry has a significantly higher energy efficiency potential.

2.2.2 Processes, energy use, and energy efficiency potential in the wood industry

Sawmills constitute a large fraction of the total energy end-use of the wood industry. The production line in a sawmill starts with debarking the timber, followed by sawing, drying and any potential finishing treatments, such as planing, before packing of the end-products. From the disintegration processes (e.g. debarking and sawing), by-products in the form of wood chips and sawdust are created. Naturally, biomass accounts for a large share of the wood industry's total energy end-use, about 61 % in Sweden (SEA, 2019a). Electricity accounts for about 24 % and fossil fuels for 5 %. The remaining share includes energy carriers such as waterborne energy (e.g. from district heating).

The drying kiln usually accounts for the largest share of energy end-use in a sawmill. The purpose of the process is to remove water from the lumber to reach a desired moisture content, usually in the range of 8 to 16 % (Swedish Wood, 2019). Different technologies for drying exist, the two most common in Sweden being progressive kilns and batch kilns (Andersson et al., 2011). In a progressive kiln, the lumber is transported through the kiln, passing through several drying zones, while in a batch kiln the air state changes following a drying scheme for each batch of lumber. The energy use and lead time differ between these types of kiln and are useful for different types of drying conditions (Anderson and Westerlund, 2014).

Given that, globally, the wood industry is smaller than the pulp and paper industry (in terms of energy end-use), studies focusing on the energy efficiency potential of this industry are scarce. A few examples are the following: The Research Institutes of Sweden (RISE) carried out a project jointly with the sawmill industry in Sweden with the aim of demonstrating that it is possible to achieve a reduction of 20 % in energy use (Andersson et al., 2011). In this project, the best available technologies (BAT) for each production step in sawmills were reviewed and their implementation potential evaluated (Andersson et al., 2011). Anderson and Westerlund (2014) studied the drying systems in sawmills and found the energy saving potential (for biomass) in Sweden to be about 0.33 TWh/year for heat exchanger technology, 5.56 TWh/year for mechanical heat pumps, and 3.44 TWh/year for an open absorption system. However, all the measures also imply an increase in electricity use. A case study on the drying of pine lumber by Szwedzka et al. (2016) showed a reduction potential of 6.9 kWh per m³ dried. Cristóvão et al. (2013) investigated energy efficiency potential of different sawing techniques. However, to the author's knowledge, prior to this thesis no study has coherently considered the entire wood industry within a national (or larger) context and its energy efficiency potential.

2.3 The energy efficiency gap and the energy management gap

In a perfect market, according to market economic theory, a number of prerequisites exist: Buyers and sellers can freely exchange assets, sellers and consumers maximize benefits and minimize costs, consumers and businesses have full information about market prices, and there are no transaction costs (Thollander et al., 2020). If one of these prerequisites is not perceived to function fully, it is regarded as a market failure or a market barrier (Thollander et al., 2020). Market barriers may lead to otherwise cost-effective energy efficiency measures remaining unimplemented, meaning that there is a gap between the optimal level of energy efficiency and the actual level. This gap is known as the *energy efficiency gap* (Jaffe and Stavins, 1994). Consequently, there is an unutilized potential consisting of non-implemented energy efficiency measures (Hirst and Brown, 1990).

Barriers to energy efficiency measures have been widely studied in the context of the manufacturing industry (cf. Arens et al., 2017; Thollander and Ottosson, 2008; Trianni and Cagno, 2012).

A market failure, for example, information asymmetries or imperfections, may justify policy interventions (Thollander and Palm, 2013). A market barrier, on the other hand, given that it is not a market failure, does not in itself justify such intervention. However, as noted by Thollander et al. (2020), the European Energy Efficiency Directive removes this distinction, meaning that not only market failures but also market barriers might be addressed by governmental policy programs (European Commission, 2012).

Previous research has also emphasized the importance of an extended systems perspective on energy efficiency. Backlund et al. (2012) introduced the idea of an *energy management gap*, which complements the perception of the energy efficiency gap. This implies that the energy efficiency potential also consists of the management of energy. Energy management practices are multifaceted and extend beyond a purely technical approach to include skills related to engineering, management, and housekeeping (Kannan and Boie, 2003). Paramonova et al. (2015) estimated that the potential of energy management accounts for at least 35 % of the total realized energy efficiency potential in energy-intensive industry. Barriers specific to energy management have scarcely been studied, with two exceptions being Lawrence et al. (2019a) and Sa et al. (2017).

2.4 Energy policies in Swedish manufacturing industry

Energy efficiency policies can be categorized according to four different approaches (Thollander et al., 2020):

- *Administrative policies* – e.g. regulations, management, or performance standards
- *Economic policies* – e.g. subsidies or taxes
- *Information policies* – e.g. voluntary guidelines or training
- *Research and development* – e.g. driving technological development.

The first three types of policy focus on removing the market barriers or market failures to energy efficiency (Thollander et al., 2020). Policy programs are often a combination of the above approaches. Voluntary agreements, or long-term agreements (LTAs), i.e. a policy where government authorities and industry sectors jointly set energy efficiency targets, are argued to be one of the most effective instruments for energy efficiency improvement (Bertoldi, 2001). An LTA policy in the Netherlands set a target of a 19 % decrease in energy intensity which, on average, was achieved (Farla and Blok, 2002). Energy audits are sometimes included in voluntary agreements as key elements, either as a mandatory part of the program or as a voluntary addition (Price and Lu, 2011).

Energy efficiency policies that are relevant to Swedish manufacturing industry, but not further described as they are outside the scope of this thesis, are (Thollander et al., 2020):

- Energy taxes (including a tax on electricity)
- Carbon dioxide taxes
- EU Emissions Trading Scheme
- Electricity certificate system
- The energy efficiency networks program for SMEs.

The following five energy efficiency policies are, or have been, relevant to Swedish industry, and are further described below (Thollander et al., 2020):

- The Swedish Program for Improving Energy Efficiency in Energy Intensive Industries
- The Act on energy audits for large companies
- The Swedish energy audit policy program
- Energy Audit Support for SMEs
- The Swedish Environmental Code.

All of these five policies, except for the Swedish Environmental Code, specifically include energy auditing as an important element. However, it is also sometimes required that energy audits are submitted to the auditing public authority by the company under audit within the operationalization of the Swedish Environmental Code.

The Swedish Program for Improving Energy Efficiency in Energy Intensive Industries (PFE) was initiated in 2004, with two subsequent five-year periods; thus, the program ended in 2014. It was designed as a voluntary agreement, allowing energy-intensive companies to receive an exemption from the electricity tax of 0.5 euro/MWh (SEA, 2016). In return, the participating companies had to: (1) implement and certify an energy management system³, (2) carry out a thorough energy audit, (3) implement cost-effective energy efficiency measures (for electricity), and (4) implement routines to consider energy in procurements. Evaluating the first five-year period, Stenqvist and Nilsson (2012) emphasize that energy management activities through the implementation of an energy management system have been important for the success of the PFE. In line with this, after analyzing PFE data, Paramonova et al. (2015) stressed the importance of including energy management practices in policy design.

Following the PFE, and to fulfil the requirements set by the Energy Efficiency Directive (2012/27/EU)⁴ (European Commission, 2012), the Act on energy audits for large companies (EKL) (2014:266) came into force in 2014. The purpose of EKL is to improve energy efficiency in large enterprises⁵ and requires companies to carry out an energy audit, and identify and present cost-effective measurements (SEA, 2019b). The reported energy end-use is divided into three categories: *buildings*, *transport*, and *processes*. There is no requirement to implement or report the measures identified. The energy audit is to be made every fourth year, and should be carried out either by a certified energy auditor or within the company if it has a certified environmental management system or energy management system (SEA, 2019b).

With SMEs particularly in mind, the SEAP ran between 2010 and 2014 (Lublin and Lock, 2013). It was designed primarily for companies with an annual energy use of more than 500 MWh, which could apply for a subsidy covering half the cost of an energy audit up to 30,000 SEK (Lublin and Lock, 2013). While mainly targeting SMEs, larger companies could apply for the subsidy if they could justify the need for financial support of an energy audit, but not if they were already participating in the PFE (Paramonova and Thollander, 2016a). Companies with multiple sites could participate in the program and

³ According to the European standard EN 16001 or the international standard ISO 50001, which later replaced the European standard.

⁴ Note that a new, amending directive (2018/2002) updated the policy framework (European Commission, 2018).

⁵ The definition of large enterprises is companies with at least 250 employees and an annual turnover of more than €50 million or a balance sheet of more than €43 million per year.

target one site, but they could only receive the subsidy once (Backlund and Thollander, 2015). The energy balance and the proposed energy efficiency measures were to be submitted to the Swedish Energy Agency along with the energy audit report.

The SEAP was followed by the Swedish Energy Audit Support for SMEs (SEAS). Similar to the SEAP, the SEAS provided a subsidy for up to half the cost of an energy audit. However, this now covered costs up to 50,000 SEK (SEA, 2019c). The SEAS ended in 2019.

The Environmental Code (SFS 1998:808) placed demands on both operators' own knowledge of their energy use and their use of the BAT. This includes the responsibility of companies to be aware of where energy is used and what possibilities exist to reduce energy use and improve energy efficiency (Environmental Collaboration Sweden, 2015). The BAT should always be applied if it is economically and technologically feasible (Environmental Collaboration Sweden, 2015). Implementing the Environmental Code as a regulatory policy for energy efficiency requirements is usually a lengthy process (Johansson et al., 2007). There are, however, cases of rulings based on the Environmental Code where actual figures have been set on such parameters as a pulp mill's maximum permitted use of heat (Swedish Environmental Protection Agency, 2019), and a paper mill's maximum permitted use of electricity and heat (Swedish Environmental Protection Agency, 2020). In both cases, the maximum allowed energy use was stated as an annual average linked to the amount of pulp/paper produced. There is yet to be an evaluation of the impact of the Environmental Code as a regulatory policy, but it will likely gather increasing importance (Thollander et al., 2020). In relation to this, supporting documents for authorities with an auditing role (i.e. municipalities, county administrative boards, and central government agencies) have been drawn up to further include energy issues during audit visits (Environmental Collaboration Sweden, 2015), and on how to improve the energy efficiency in support processes (SEA, 2017).

The European Commission provides BAT reference documents⁶ for manufacturing industries containing the currently used techniques, BAT, and emerging techniques for each specific sector (European Commission, 2019). One BAT reference document has been drawn up for general techniques of energy efficiency improvements that are relevant to multiple industries, e.g., lighting, drying, and heat recovery (European Commission, 2009). Furthermore, there are BAT reference documents that provide information about BAT to individual industries such as the manufacture of pulp, paper and board (European Commission, 2015). These BAT reference documents function as guidance documents for authorities with an auditing role. The Swedish Environmental Protection Agency (2018) has provided supporting documents on how to use the BAT reference document at audit visits.

2.5 The rebound effect

There is an existing notion that improved energy efficiency might not result in reduced energy use. This effect is known as *the rebound effect* (sometimes also *the takeback effect*). In brief, it addresses the issue that improvements in energy efficiency lead to lower prices for a service or product, thereby making it more affordable. An initial decrease in energy use would therefore be followed by an increase due to this. In the worst case, the increase in energy use is even higher than the initial energy saving. Thus, improving energy

⁶ Best available technology reference documents are sometimes abbreviated to BREFs.

efficiency could lead to increased greenhouse gas emissions and is therefore not a relevant strategy for public policies aiming to combat global climate change, as argued by Herring (2006). From a climate-change perspective, the key issue is the magnitude of the rebound effect (IEA, 2005).

The rebound effect can be divided into a direct rebound effect, an indirect rebound effect and economy-wide effects. Employees being less concerned about turning off the lights after a switch to more energy-efficient lighting, thus neglecting part of the energy saving potential of the measure, is considered a direct rebound effect. An indirect rebound effect is a secondary effect that results from the impact but lies beyond the energy service, e.g. increased demand for other services (Greening et al., 2000). If changes in the entire economy, e.g. changes in consumption patterns, are considered after energy efficiency improvements, it relates to the macro effects – or economy-wide effects. The two latter types of rebound effect are difficult to measure. Nonetheless, studies of the rebound effect for different end-users were reviewed by Greening et al. (2000), who estimated the long-term direct rebound effect for industrial processes to be 0–20 %. Furthermore, it can be argued that the rebound effect within a country tends to decline over time due to saturation and the increased quality of energy services (IEA, 2005).

2.6 Industrial energy management

An early contribution to the concept of energy management considers the “housekeeping” element through the improvement of an organization’s operating practices (O’Callaghan and Probert, 1977). Since then, energy management has been considered in many research studies. A thorough review was conducted by Schulze et al. (2016), showing that studies of energy management have attracted increased interest in recent years. Based on their review, Schulze et al. (2016) suggested the following definition of energy management:

Energy management comprises the systematic activities, procedures and routines within an industrial company including the elements strategy/planning, implementation/operation, controlling, organization and culture and involving both production and support processes, which aim to continuously reduce the company’s energy consumption and its related energy costs.

This definition of energy management provided by Schulze et al. (2016) is applied in this thesis. It presents five aggregated dimensions, which in turn comprise a total of 30 different practices. Overarching studies of industrial companies’ implementation and adoption of energy management practices have been carried out (cf. Abdelaziz et al., 2011; Brunke et al., 2014; Stenqvist et al., 2011; Thollander and Ottosson, 2010), as well as a study of single energy management practices and their relation to the overall work with energy management (Trianni et al., 2019). Energy benchmarking is considered an energy management practice, and as such, the information provided by a benchmarking practice should function as feedback for the energy strategy and the operations in a company (Schulze et al., 2016).

The management of energy has not been considered a core activity for energy-intensive industry (Thollander and Ottosson, 2010). However, energy management has attracted increased attention, due to rising energy costs and the requirements of energy policies. It is important to note that energy management should be considered distinct

from an energy management system, which is rather a tool to assist in the energy management of an organization (Thollander and Palm, 2013). The two different concepts are often mixed, both in industry and in research papers.

The largest energy efficiency potential consists of the combined implementation of energy efficient technology and successful energy management (Thollander and Palm, 2015). Following this line of thought, Johansson and Thollander (2018) outline a number of factors for successful energy management, including top-management support, a long-term energy strategy, and clear energy KPIs. These success factors have also been used as a framework in a case study of a manufacturing company (Sannö et al., 2019).

In order for manufacturing companies to excel in energy management, adequate knowledge of the distribution of energy across the various processes is necessary. Creating an energy balance could therefore be considered a first step in comprehensive energy management; for example, through an energy audit (Schulze et al., 2016). Establishing an energy balance provides an overview of which processes take up the largest share of energy use for different energy carriers. This indicates where the largest energy costs are. Another major part of an energy audit is to suggest adequate measures for improved energy efficiency (Thollander et al., 2020). High quality energy audits are important to increase the implementation rate of measures (Fleiter et al., 2012b). Energy efficiency measures should, at the very least, present the amount of energy saved, the investment cost, and pay-off time. Based on the proposed measures, a prioritization of where energy management efforts should be focused can be made.

The need for supporting activities in energy management has led to several tools, such as the energy management standard ISO 50001 (ISO, 2018). Other initiatives that facilitate energy management include the development of energy databases consisting of real energy efficiency measures, e.g. the US Department of Energy's Industrial Assessment Centers' database (IAC) (cf. Anderson and Newell, 2004), the SEAP database (cf. Blomqvist and Thollander, 2015)⁷, or the Nordic Energy Audit Database (NEA, 2020).

For successful industrial energy management, a number of factors have been identified as important, including commitment from top management (Thollander and Palm, 2013). This is highly ranked as a driving force for energy management in the pulp and paper industry (Lawrence et al., 2019a). In studies of the drivers of energy efficiency investments, people with real ambition have been shown to be an important behavioral and organizational driver for positive decision-making about improvements in energy efficiency (Thollander and Ottosson, 2008). Drivers and the success of energy management might differ between companies with different characteristics, such as industry and size. Large enterprises with mature energy management are more likely to include both energy and process personnel, while the main drivers for SMEs are the skills and personal motivation of the energy manager (Cooremans and Schönenberger, 2019).

2.7 ISO and European Standards

The International Organization for Standardization (ISO) develops international standards to ensure that certain criteria are met, such as specifications and guidelines (ISO, 2019). There are some standards that relate to energy efficiency and energy management in organizations, some of specific relevance to this thesis. The standard for energy management systems, ISO 50001, places a number of requirements on an

⁷ In the paper by Blomqvist and Thollander (Blomqvist and Thollander, 2015), SEAP is abbreviated EKC.

organization for it to receive its certification, including the establishment of an energy baseline with developed energy performance indicators (ISO, 2018). To assist organizations with the development and implementation of these energy performance indicators, the ISO 50006 standard provides guidance for the establishment, use and maintenance of such indicators (ISO, 2017).

The European Standard EN 16231 provides a methodology for energy efficiency benchmarking (Swedish Standards Institute, 2012). The guidelines are of a more general character, addressing how to collect and analyze energy data and its content is not directed towards sector-specific benchmarks.

2.8 Statistical classification of economic activities

The European Union has developed a classification of economic activities (NACE)⁸ that serves as a framework for how to categorize an economic activity, i.e. when resources (capital goods, labor, etc.) produce goods or services (European Commission, 2008). The NACE provides a uniform base for the reporting of statistics, such as energy use. The framework is structured as follows (European Commission, 2008):

- Economic activities are divided into different section (letters), e.g. “C” stands for “Manufacturing”.
- Each section is divided into different divisions. Section “C” includes the divisions 10–33, where for example “17” stands for “Manufacture of paper and paper products”.
- Each division is divided into groups; e.g. “17.1” stands for “Manufacture of pulp, paper and paperboard”.
- Each group is divided into classes; e.g. “17.11” stands for “Manufacture of pulp”.

If a company could be considered as being classified into more than one of the NACE categories, the activity that represents more than half of the company’s value added should be selected (European Commission, 2008). If no activity accounts for more than half of the value added, then the selection of classification should be based according to the following prioritization: section, division, group, and class, for each step following the principle of highest share of value added. For a complete list of the NACE rev. 2 classifications, please see European Commission (2008).

The Swedish Standard Industrial Classification (SNI) is coherent with the European standard but goes into further detail using five-digit codes. For instance, pulp manufacturers are divided into three different types: mechanical or semi-chemical pulp, sulphate pulp, and sulphite pulp (Statistics Sweden, 2007). For a complete list of SNI codes, please see Statistics Sweden (2007).

⁸ From the French title “Nomenclature générale des Activités économiques dans les Communautés Européennes”.

3. Industrial energy benchmarking

This chapter provides a description of industrial energy benchmarking from the two perspectives of policy makers and manufacturing companies. This is followed by a presentation of energy key performance indicators' relation to benchmarking and a systems perspective on benchmarking.

According to the definition by the international standard on energy benchmarking, EN 16231, the concept of benchmarking is the “*process of collecting, analysing and relating performance data of comparable activities with the purpose of evaluating and comparing performance between or within entities*” (Swedish Standards Institute, 2012). Another description is that a reference system is used to estimate the energy performance of a defined system (Ke et al., 2013). The central purposes of energy benchmarking practices are to act as a driver for improvement and indicate areas where efforts will be most effective (Eggleston, 2015).

Many research studies have carried out energy benchmarking using different benchmarking methods and at different level of details. Table 2 presents an overview of research studies' aggregated level and applied method of benchmarking in the industrial context. Furthermore, energy benchmark values are available for the pulp and paper industry (cf. CIPEC, 2008; Kramer et al., 2009; Laurijssen et al., 2013; Rogers et al., 2018).

Table 2: Research studies' aggregated levels of energy benchmarking and their applied method. Key for method: SEC = Specific Energy Use, DEA = Data Envelopment Analysis, MPI = Malmquist Productivity Index, SFA = Stochastic Frontier Analysis. (Revised from Paper I)

Study	Multi-national level	National and regional level	Facility level	Process level
(Morfeldt and Silveira, 2014)	SEC, DEA+MPI			
(Saygin et al., 2011)	SEC	SEC		
(Xu et al., 2009)		SEC		SEC
(Meyers et al., 2016)		SEC		
(Bernard and Côté, 2005)		Other		
(Han et al., 2014)		DEA+MPI		
(Xue et al., 2015)		DEA+MPI		
(Azadeh et al., 2007)		DEA, other		
(Worrell and Price, 2006)			SEC	SEC
(Hasanbeigi et al., 2012)			SEC	
(Boyd, 2017)			Other	
(Oh and Hildreth, 2014)			DEA+SFA	
(Aguirre et al., 2011)			DEA	
(Blomberg et al., 2012)			DEA	
(Nouri et al., 2013)			DEA	
(Önüt and Soner, 2007)			DEA	
(Ke et al., 2013)				SEC
(Laurijssen et al., 2013)				SEC
(Spiering et al., 2015)				SEC
(Giacone and Mancò, 2012)				Other
(Mateos-Espejel et al., 2011)				Other

3.1 Energy benchmarking from the perspective of policy makers

Aggregated energy efficiency indicators are necessary for the understanding of energy use patterns and energy efficiency improvements in industrial sectors at a national level. The analysis of such indicators should therefore help decision-makers to relate the energy efficiency to energy efficiency policies and provide a basis for tailoring future policies and programs (Eichhammer and Mannsbart, 1997). In that sense, it is also necessary for an indicator to not only represent progress in energy efficiency, but also connect to policy targets and instruments (Abeelen et al., 2019). An accurate policy design also requires that the energy efficiency potential within industrial sectors is identified through high-quality energy end-use data and energy benchmarking (Saygin et al., 2011). However, a precise analysis is often hampered by the limited availability and reliability of data (Eichhammer and Mannsbart, 1997). As a consequence, the choice of metric for an energy efficiency indicator is based on the data available (Abeelen et al., 2019).

The benchmarks for a sector could be used to negotiate with the companies in a voluntary agreement policy, by setting targets based on the benchmark that are agreed upon by the companies (Worrell and Price, 2006). However, for such a procedure to work, the availability and quality of data need to be improved (IEA, 2007; Saygin et al., 2011). A database with a harmonized categorization of energy end-use processes would therefore provide a helpful tool for decision-makers (Blomqvist and Thollander, 2015). To enhance a sector-wide comparison of energy efficiency, the establishment of a database should be preceded by agreement upon important elements that otherwise hinder the coherent allocation of energy end-use, such as boundary definitions (Tanaka, 2008).

3.1.1 Methodological issues with comparing aggregated energy indicators

Aggregated energy indicators at a national or sectoral level are affected by factors that are not necessarily linked to energy efficiency performance. These are called structural effects. The structural differences include quality of input resources, the share of different products manufactured and the diversity of products (IEA, 2007). Phylipsen et al. (1997) elaborated on this and defined the structure of a sector as being determined as either a *mix of products* or a *mix of activities*. Depending on which definition is applied to a sector, the performance of energy efficiency differs. The mix of products focuses on the different end-products manufactured in an industry, and two different processes that produce the same product will be subject to a difference in energy efficiency (Phylipsen et al., 1997). If a mix of activities is used as a definition, two different products will be considered part of the structure of the sector. In the pulp and paper industry, the mix of products is determined by such factors as the share of printing paper and newspaper or, for the input of material, the share of virgin pulp or waste paper (Phylipsen et al., 1997). The mix of activities in the pulp and paper industry considers the different techniques of separating wood fibers, through mechanical or chemical pulping (Phylipsen et al., 1997). A structural effect might shift over time into an actual energy efficiency difference, as progress in technology leads to not compromising on the quality of an end-product (Eichhammer and Mannsbart, 1997).

Other issues when developing energy indicators involve the availability of energy data. In many cases, the available data is of an aggregated nature, due to lack of structure, poor commitment in data collection, and for confidentiality reasons (IEA, 2007). Also, in

order to achieve a consistent cross-country analysis, it is necessary that countries use the same boundaries for the developed energy indicators (IEA, 2007).

3.2 Energy benchmarking from the perspective of manufacturing companies

The benefits of energy benchmarking for manufacturing companies are multiple, including finding areas in need of improvement, the potential for improvement, motivation for change, and increased learning. A few different approaches to benchmarking can be used. The main distinction is between internal and external benchmarking. Internal (or longitudinal) benchmarking refers to the comparison of energy end-use with a reference value from an earlier point in time at one specific site, and external benchmarking involves comparison with others, such as a company's peers (Peterson and Belt, 2009).

A methodology for collecting and analyzing energy data and carrying out comparisons of organizations' energy efficiency is presented in the standard on energy efficiency benchmarking (EN 16231) (Swedish Standards Institute, 2012). It is, however, difficult to generate a fair and relevant benchmarking, especially for heterogeneous manufacturing industries. Thus, it is argued that energy benchmarking is not suitable for certain circumstances and should primarily focus on comparing similar industrial processes and products (IEA, 2007). Studies that apply a process level approach have been successfully carried out, often in collaboration with industrial actors (Boyd, 2017; Laurijssen et al., 2013).

At a disaggregated level of benchmarking, most research studies address one specific industry, e.g., cheese manufacturing (Xu et al., 2009), the paper industry (Laurijssen et al., 2013), or mechanical engineering (Spiering et al., 2015). There are also benchmarking tools available for several industries. ENERGY STAR, based in the USA, allows an industrial plant to estimate its energy performance against its peers by using plant-level energy use, material use, and productive activities (Boyd et al., 2008). A Swedish benchmarking tool, "Nyckeltalsdatabasen ENIG", compared manufacturing companies' energy performance for a number of KPIs (SWEREA, 2017), but is no longer running. The available benchmarking tools are still limited in their use because they only cover parts of the industrial sector and mostly focus on the plant level rather than the process level.

In the context of industrial SMEs, the need for an energy benchmarking tool has been identified (Kimura et al., 2015). For SMEs, benchmarking should be kept easy to use and simple to understand, while at the same time generating relevant outcomes. Simple performance indicators, such as the commonly used SEC, are easy to apply to an entire manufacturing plant. However, simple performance indicators might not always prove relevant to a benchmark. Due to this delicate balance between relevance and simplicity, creating a relevant benchmarking tool for industrial SMEs is not an easy task.

3.3 Energy key performance indicators

A basic purpose of an energy KPI is to estimate the level of energy efficiency and it serves to facilitate the user's analysis and decision-making. This takes place in self-analysis and monitoring as well as in comparing the energy efficiency of activities and installations (European Commission, 2009). KPIs are also the basis for establishing energy targets, which can be either physical, volume, or economic targets (Rietbergen and Blok, 2010).

Energy KPIs are a central part of an energy management system. The ISO 50001 standard requires the application and monitoring of energy performance indicators (ISO, 2018). These indicators are to be regularly reviewed. ISO 50006, which acts as a supporting standard to ISO 50001 for developing energy KPIs, categorizes indicators into different levels (ISO, 2017). This is similar to the categorization of Sommarin et al. (2014), in which KPIs are categorized as overall figures, support-process-specific figures, or production-process-specific figures.

In a benchmarking practice, the choice of KPI should account for diverging factors between the entities being compared to enable a fair benchmark. Sometimes a distinction is made between economic indicators, denominated *energy intensity*, and physical indicators, denominated *energy efficiency* (Bunse et al., 2011; International Energy Agency, 2014b).

Specific energy use (SEC)⁹ is a commonly used indicator for measuring energy efficiency and is applied at different levels of aggregation (see Table 2). SEC is calculated as (European Commission, 2009):

$$SEC = \frac{\text{Energy used}}{\text{Products produced}} \quad (\text{Eq. 1})$$

SEC has been subjected to critique for its limitations in capturing the energy efficiency of an industrial sector (Morfeldt and Silveira, 2014). Lawrence et al. (2019b) raises a number of concerns when comparing SEC from different studies, such as lack of clarity in boundary definition, uncertainty in the quality of data used, and unexplained assumptions. If SEC is used to determine an industrial sector and a variety of products are included, Rietbergen and Blok (2010) suggest that the average value of SEC for different products can instead be weighted into an EEI. EEI is a dimensionless indicator, and in its simplest form is calculated as (European Commission, 2009):

$$EEI_{i,j} = \frac{SEC_{ref}}{SEC} \quad (\text{Eq. 2})$$

Where SEC_{ref} is the reference value. The reference value can be, for example, the best available technique or the industry's best practice¹⁰. If the average SEC is not available for an industry, one approach can be to calculate the EEI, where the final energy-end use of the industry is related to best practices in that industry (cf. Saygin et al., 2011). It is also possible to use EEI to compare different type of indicators, as done by Morfeldt and Silveira (2014). The use of multiple energy efficiency indices can enhance the evaluation of energy efficiency improvements within industrial sectors (cf. Zuberi et al., 2020).

3.4 The systems perspective of energy benchmarking

Churchman (1968) states that systems consist of a set of components that work together towards a common goal. For example, a pulp mill's function is to produce a commodity that

⁹ The abbreviation *SEC* is employed because the indicator is commonly known as *specific energy consumption*, but the phrase *specific energy use* is applied in this thesis in accordance with the first law of thermodynamics.

¹⁰ For example, Philipsen et al. (1997) distinguish three types of "best practice" for the reference SEC: "Best practice observed", which refers to the lowest SEC of plants in full operation, "Best practical means", which refers to the lowest SEC that it is possible to achieve with technology at a reasonable cost, and "Best available technology", which refers to the lowest SEC that it is possible to achieve with proven technology.

is suitable for manufacturing paper. While the function of all pulp mills remains the same, the means by which it is achieved, i.e. what the production processes are and how they are operated etc., may differ.

Depending on the scope, the aggregated level of benchmark, and the system boundaries, the degree of complexity will differ. Boulding (1956) suggests arranging theoretical systems into a hierarchy of complexity, consisting of 11 levels, ranging from the least complex level of a static structure to the most complex level of interactions between individuals. The lower levels include the static and dynamic relationship as well as predictable motions between the components of a system. In the context of benchmarking, the lower-end system of complexity is the comparison of equipment or a single production unit.

An example of a single production unit could be a kiln for drying of wood. If the boundaries are set at the walls of the kiln, and the inlet and outlet respectively, this would be a system of less complex level in the taxonomy of Boulding (1956): A simple dynamic system, because it is mainly constituted of predetermined motions. However, the improvement in the efficiency of a lower-end system risks becoming a sub-optimization of the larger system (Churchman, 1968).

Examples of more aggregated levels of benchmarking are entire facilities or end-products. As soon as the system boundary of the benchmarked entity is increased from a single piece of equipment to include the entire industrial plant, a lot more factors need to be accounted for. The components of the system include not only the equipment, but also the users of that equipment, culture, organizational policies and strategies, relationships between management and operating personnel, relationships between humans within a division or a smaller group, etc., all affecting the outcome of an energy KPI.

4. Methodology

This chapter presents the methodology used to further enable process level energy benchmarking. It starts with an overview of the research designs and thereafter a description of each method and how it has been used in the thesis's appended papers.

4.1 Research design

The stated aim of this thesis was to further enable industrial energy benchmarking at the process level for the studied industries. To address this aim, both qualitative and quantitative methods were used. An overview of the methods used related to the research questions is presented in Table 3.

Table 3: Methods used to respond to the research questions of this thesis. CSCs = Conservation supply curves

Research question	Database analysis	Interviews	Questionnaires	CSCs	Case study design
1. How can a standardized categorization of production processes be developed for the allocation of energy end-use in a manufacturing industry?	X	X			X
2. How can industrial energy end-use processes with large energy efficiency potential at a national level be identified?	X			X	
3. What are the opportunities and challenges of industrial energy benchmarking?		X	X		
4. What are the currently applied energy key performance indicators, and what is their improvement potential from the perspective of industrial energy management?		X	X		X

The procedure to address the research questions for the studied industries was as follows: Firstly, suggestions for how to develop a harmonized categorization of end-use processes were put forward for the studied industries. Interviews, case studies, and analysis of energy data from a database were the methods to develop this categorization of processes. To validate the categorizations, the energy end-use of companies was allocated into the suggested categorization using the database. Secondly, the energy efficiency potentials of end-use processes were estimated, both by creating an energy efficiency index (EEI) using data from the SEAP, and by constructing CSCs. Thirdly, the challenges and driving forces for companies to carry out benchmarking were investigated through interviews and questionnaires. Lastly, the energy KPIs currently used by industrial companies were

mapped and suggestions for improvements were given, using interviews, questionnaires, and case studies.

For the wood industry, all four steps of this procedure were carried out. The unit process concept was used in Paper II to allocate energy end-use in the wood, food, and metal industries, using the dataset from the SEAP. A second categorization of end-use processes, developed for sawmills, was developed prior to this thesis by Olsson et al. (2011) and was used in Paper I of this thesis. The categorization for sawmills was revised in Paper V to cover the entire wood industry, i.e., also including further refining processes of sawn goods, this time using a case study design. To estimate the energy saving potential of end-use processes in the wood industry, CSCs were calculated in Papers II and V. In Paper I, a tool for energy benchmarking was developed. This tool was based on an EEI and functions as another approach to identifying energy saving potentials in comparison to CSCs. For Papers I and II, the energy database from the SEAP was used.

For the pulp and paper industry, three of the four steps of the above-described procedure, leaving out estimation of the energy efficiency potential, were investigated. Both the categorization of processes and development of energy KPIs were studied using a case study approach. To determine the current use of energy KPIs in the industry, a questionnaire was sent out to the pulp and paper mills. The challenges and benefits of energy benchmarking cover the entire industry, thus including different types of mills (e.g., chemical pulp, mechanical pulp). For the development of a harmonized categorization of processes, the study was limited to manufacturer of sulphate pulp, from here on denominated kraft pulp mills (Paper VI).

4.2 Case study design

Case study design is a commonly used approach for the field of industrial energy efficiency. Cagno et al. (2015) made an exploratory study through a multiple case study of 30 foundries in Italy, studying the link between innovations and energy efficiency. Thollander and Ottosson (2010) also conducted a multiple case study studying energy management practices in energy-intensive industries in Sweden. Trianni et al. (2013) used a case study design to investigate small and medium-sized enterprises in the metal manufacturing sector to study barriers to energy efficiency measures.

Case study research is helpful when an in-depth understanding of a current phenomenon is desired (Yin, 2014). Furthermore, for some research questions, a case study design can be suitable if the case being studied functions as a representative case for the context in which it operates (Bryman, 2008). A case study design generally rests upon an inductive approach, i.e., that theory is generated from the data collection and the analysis (Bryman, 2008). Examples of sources of evidence in a case study are participant-observation and interviews (Yin, 2014).

A downside of case study design is its lack of generalizability, thus limiting its value for other cases outside the studied cases (Bryman, 2008). An approach advocated by Yin (2014) is instead to make an analytical generalization, i.e., to relate the case study's findings to previously conducted research studies. Yin (2014) also points out that the lessons learned from a case study might very well be applicable to a variety of situations, not just cases similar to those studied. An important factor when evaluating case study research is the consideration of alternative perspectives, i.e. whether rival explanations have been discussed (Yin, 2014).

Given the complexity of industrial energy end-use processes, case study research was deemed to be a suitable method to investigate how harmonized categorizations of end-use processes can be developed, as well as how to develop and implement energy KPIs for energy management.

4.2.1 Case study application in the papers

Paper V uses a case study design in which energy audit reports from 14 wood industry companies were used as a basis for data collection. The energy audit reports were carried out between 2010 and 2018 and conducted by the same audit company. The reports were used to further refine the categorization of production processes (developed by Olsson et al. (2011), as used in Paper I), and subsequently to divide the energy end-use into the refined categorization. This was done for four energy carriers: electricity, district heating, fossil fuels, and biofuels. The suggested categorization of processes was validated with personnel at a Swedish sawmill. In addition, an interview with an expert in the field was carried out to investigate the improvement potential of energy KPIs in sawmills.

Energy-intensive industries face various difficulties, including how to develop relevant energy KPIs and how to understand the variables affecting them (Sivill et al., 2013). Paper VI was conducted as a case study design in which the studied object, a company group of pulp manufacturers, ran a project with the purpose of improving the in-house energy management. Defining relevant energy KPIs was a central part of this project. The case study spanned the course of four workshops, in which personnel with energy responsibilities from the company group's kraft pulp mills and personnel from an external consultant company participated. During the workshops, firstly a categorization of processes to harmonize energy end-use data was developed, followed by defining energy KPIs based on the categorization of processes. From this case study, a model for energy KPI development for in-house energy management based on the suggested taxonomy was developed.

4.3 Interviews

Interviews as a data collection method in research studies can take different forms. Three common forms are the structured interview, the semi-structured interview, and the open interview. Structured interviews are most commonly used in quantitative research, while semi-structured interviews and open interviews are mainly perceived as qualitative methods. Interviews can be the sole data collection method in a research design (an interview study), or they can be used within a case study, where they constitute an essential source of evidence (Yin, 2014). For the latter, the interviews are often carried out as semi-structured or open interviews.

How evidence from interviews contributes to a research study is largely dependent on how interviews are perceived as a scientific method. This relates to prevailing notions on knowledge, epistemology, i.e. what knowledge is, and how it is obtained (Kvale and Brinkmann, 2009). A pragmatic notion to qualitative interviews, i.e. that language and knowledge are tools for understanding reality, entails that the interview is a process of collecting and constructing knowledge (Kvale and Brinkmann, 2009). It includes both the kind of knowledge that is identified objectively from an interviewed person and the

knowledge that is constructed in the interaction between the interviewer and the interviewee.

Qualitative interviews are a form of craftsmanship, which the interviewer learns by practicing the craft (Kvale and Brinkmann, 2009). Kvale and Brinkmann (2009) claim that the best way to improve the skills of a craft is through discipleship in a practice-based community. Thus, to learn the art of qualitative interviewing, one should preferably be part of a research group and join more experienced researchers in the act of interviewing. Activities undertaken within such a community can include, for example, to observe other interviewers, and to get feedback on one's own conducted interviews from more experienced interviewers.

Objections to the qualitative interview as a valid scientific method include claims that it is dependent upon subjective impressions and that the results are not generalizable due to the low number of data points (Kvale and Brinkmann, 2009). To strengthen the quality of semi-structured interviews, Kvale and Brinkmann (2009) emphasize, among other things, the researcher's ability to control, question and interpret the results, as well as the potential for translating knowledge from one specific context to another while accounting for the social aspects characterizing each respective context. When qualitative interviews are part of a case study research, evidence from the interviews is preferably confirmed with information from other sources (Yin, 2014).

Previous studies that have used qualitative interviews are, for example, Sivill et al. (2013) to identify research needs in energy performance measurements, and May et al. (2015), who suggest a method for developing energy KPIs. Given that a bottom-up approach to define a harmonized categorization of processes and developing energy KPIs is used in this thesis, qualitative interviews were deemed to be a suitable method. To investigate which energy KPIs to use for in-house energy management, and how to incorporate these into benchmarking practices, it is necessary to understand the underlying parameters affecting the outcome of KPIs.

4.3.1 Application of interviews in the papers

Interviews were used in Papers I, III and IV, as well as in part of the case study design in Paper V. An EEI was developed in Paper I, and the interviews served to elicit input on how to successfully carry out energy benchmarking. Six semi-structured interviews were carried out in total. Five of these were with representatives from the following government agencies: The County Administrative Boards of Östergötland and Dalarna, the Swedish Environmental Protection Agency, and the Swedish Energy Agency. One interview was conducted with an energy audit company. The interviews addressed the possibilities and difficulties of energy benchmarking and provided input for the development of the EEI. The data collection through interviews in Paper I was complemented with an analysis of energy data from the SEAP, as discussed in Section 4.5.1.

The interviews carried out in Papers III and IV were complemented with a questionnaire (see Section 4.4.1); thus, these studies were designed as a mixed-methods approach. Using a mixed method design can provide a stronger pattern of evidence (Yin, 2014). Previous research that has used a mixed methods approach is, e.g., Brunke et al. (2014), where the quantitative aspects of the research questions were addressed using a questionnaire, while the questions of more qualitative nature were investigated via interviews. In this thesis, the interviewees in Papers III and IV were personnel at pulp and paper mills with energy responsibilities (e.g. energy manager, production engineer).

Similar to Paper I, the interviews were semi-structured. The interviews considered both energy benchmarking and energy KPIs; thus, data was collected for both Paper III and Paper IV. 11 interviews at six different mills were conducted, in person or over the telephone. The selected companies represented non-integrated pulp mills and integrated pulp and paper mills, as well as mechanical pulp and sulphate pulp.

4.4 Questionnaires

Questionnaires are in many ways similar to face-to-face interviews or telephone interviews, but with the distinction that the interviewee responds to questions without the presence of an interviewer (Trost and Hultåker, 2016). One advantage of questionnaires over structured interviews is that it eliminates the potential effect that the interviewer might have on the respondent's answer, for example due to gender or social background (Bryman, 2008). The downsides of using a questionnaire include that it does not allow for follow-up questions to encourage the respondents to develop their answer (Bryman, 2008).

Important aspects of constructing a questionnaire were considered in this thesis, for example, the way in which questions are formulated, where double questions, leading questions and the use of negatives in questions were avoided (Bryman, 2008).

A questionnaire is suitable for investigating respondents' attitudes to statements through such approaches as Likert scales (Bryman, 2008). In the questionnaire developed in this thesis, a large part consisted of Likert-scale questions and closed questions with both single and multiple-choice answer options. Only a few open questions were included to allow for clarification for certain questions.

4.4.1 *Application of questionnaires in the papers*

In this thesis, two of the papers were based on a questionnaire for data collection (Papers III and IV). The population studied, Swedish pulp and paper mills, consisted of 50 mills at the time of the study (March to September 2017). Given this small population, the questionnaire was sent to all mills. In the field of industrial energy efficiency, studies usually target smaller groups, to which a questionnaire is distributed, often less than a hundred (cf. Brunke et al., 2014; Cooremans, 2012; Rohdin et al., 2007). When reaching out to the mills, someone with responsibility for energy issues was contacted, who then had to decide the most appropriate respondent (usually the energy manager). The respondents were given the choice to either fill in the questionnaire by themselves or over the telephone as a structured interview.

Of the 50 mills, 28 complete responses were received, resulting in a response rate of 56 %. This is perceived as acceptable according to Trost and Hultåker (2016). It is also similar to the response rates for other studies carried out in the field of industrial energy efficiency, e.g. the steel industry (Brunke et al., 2014) and the pulp and paper industry (Thollander and Ottosson, 2010). In detail, 46 % of the paper mills responded, 30 % of the pulp mills, and 74 % of the integrated pulp and paper mills (which is also the largest group in absolute numbers).

4.5 Swedish energy audit policy program database

The SEAP database consists of reports from the energy audits carried out at the participating companies, a dataset of the companies' energy end-use and energy efficiency measures, and basic information about the companies, such as building area and classification of economic activity. The energy end-use was allocated on the following support processes, based on the categorization of processes developed by Söderström (1996), and further refined by (Thollander et al., 2012):

- Administration
- Compressed air
- Hot tap water
- Internal transport
- Lighting
- Pumping
- Space cooling
- Space heating
- Steam
- Ventilation

All energy used in production processes was allocated into one category in the SEAP database.

Each energy efficiency measure was categorized by the end-use process to which it related, as well as a general description being given of the measure. For production processes, these descriptions were:

- Conversion to another energy carrier
- Increase efficiency of the process
- Power regulation of the processes
- Reduce stand-by losses
- Switch to energy-efficient motors
- Other.

In the first years of the program, there was no template for the energy audit reports. Therefore, the extents to which energy end-use, measurements, energy efficiency measures etc. were described in the reports differed. The energy efficiency measures in the SEAP database have been subjected to thorough quality control, as described in Blomqvist and Thollander (2015).

Over 700 companies were included in the database, 31 classified as wood companies (SNI 16), 27 as food companies (SNI 10), and 79 as metal companies (SNI 25).

4.5.1 Use of the Swedish energy audit policy program database in the papers

An analysis of energy use from the SEAP database was undertaken in Papers I and II. In Paper I, sawmills were studied. The energy end-use of production processes were allocated into the suggested categorization of processes by using the energy audit reports. The depth to which the energy balance was presented in the energy audit reports differed. Therefore, not all the energy audit reports of the sawmills participating in the SEAP could be used

for the purposes of Paper I. Furthermore, some of the companies classified as SNI 16 were manufacturers of products of wood and not sawmills. Out of the 31 companies classified as SNI 16 and participating in SEAP, 11 were used. An EEI was created based on the energy end-use. A classification of the energy efficiency measures, following the categorization of production processes, was carried out in order to estimate the energy efficiency potential.

Similarly to Paper I, Paper II also allocated the energy end-use of production processes into the suggested categorization of processes. For this study, the unit process concept as defined by Söderström (1996) was used to categorize energy end-use. The unit processes concept defines a generic categorization of support processes (as presented in Section 4.5) and of production processes that is intended for use across different types of manufacturing industries. Hence, the same categorization of processes was used for all three industries studied (manufacturers of wood, food, and metal). The unit process concept defines the following categories for production processes:

- Coating
- Cooling/Freezing
- Disintegrating
- Disjointing
- Drying
- Heating
- Jointing
- Melting
- Mixing
- Molding
- Packing
- Other.

The energy efficiency measures in the SEAP database were used to calculate CSCs, as described in Section 4.6.

4.6 Conservation supply curves

CSCs are used as a bottom-up method for estimating the technological energy efficiency potential of an industrial sector. It was first developed for the residential sector, as introduced by Meier et al. (1982). The method allows for a comparison of different measures. Decision-makers can utilize the outcome of CSCs by evaluating the annual energy savings and reductions in greenhouse gas emissions for different policy scenarios (Hasanbeigi et al., 2010).

CSCs have been applied in a number of industries in different regions, e.g. the cement industry (Hasanbeigi et al., 2010; Morrow et al., 2014; Worrell et al., 2000), the pulp and paper industry (Fleiter et al., 2012a), and the iron and steel industry (Brunke and Blesl, 2014; Li and Zhu, 2014; Worrell et al., 2003). Similar curves have also been calculated as energy efficiency cost curves (Bhadbhade et al., 2019; Zuberi and Patel, 2017).

It is beneficial to combine CSCs with benchmarks to further enhance the analysis of the potential energy savings (Njoku et al., 2017). Benchmarking enables an assessment of

the energy efficiency potential, and CSCs allow for the economic assessment of energy efficiency measures (Tesema and Worrell, 2015).

The method of constructing CSCs is outlined in Hasanbeigi et al. (2010) and Tesema and Worrell (2015), among others. CSC diagrams show the cost of conserved energy (CCE) of measures on the y-axis and the energy savings potential on the x-axis. In the diagram, the measures are presented in order of CCE, starting with those with the lowest CCE. The CCE is calculated as follows:

$$CCE = \frac{\text{Annualized capital cost} + \text{Annual change in operation and maintenance costs}}{\text{Annual energy savings}} \quad (\text{Eq. 3})$$

The annualized capital cost is the function of the discount rate and lifetime of a measure according to:

$$\text{Annualized capital cost} = \text{Investment cost of measure} \cdot \left(\frac{d}{1 - (1+d)^{-n}} \right) \quad (\text{Eq. 4})$$

While CSCs provide a clear overview of which measures are most cost-effective to achieve energy savings, the method also has some limitations. A few of the most important issues are addressed by Fleiter et al. (2009):

- *Input values*, which include the quality of data, discrepancies in discount rates used (among industrial companies and society), and lifetime of measures.
- *Decisions in methodology*, including considering the average values of inputs instead of a heterogenous reality and non-monetary costs.
- *Shortcomings in methodology*, including failing to consider interactions of conservation options and the rebound effect.

Even with these deficiencies, CSCs are helpful for decision-makers because they are easy to comprehend. However, the methodological assumptions and their implication for the results should be transparent when the information is used for developing policy instruments.

4.6.1 Application of conservation supply curves in the papers

In this thesis, real energy efficiency measures derived from energy audit reports are used for the calculation of CSCs. For these calculations, the term “conservation” is not perceived as defined in section 2.1, but rather as “energy savings”. However, conservation is the commonly used term in the literature for this method.

CSCs are used in Papers II and V to estimate the energy efficiency potential. Two approaches are used for constructing the CSCs. The first (Paper II) distinguishes between classifications of measures. The second (Paper V) follows the developed categorization of end-use processes and constructs CSCs that illustrate the energy efficiency potential of different processes.

In Paper II, where data from the SEAP was used, energy efficiency measures for production processes were considered for the calculation of CSCs. These measures were classified in the database according to type of measure, as described in Section 4.5. Information about investment cost, annual energy savings of the measures, and year of implementation (or if it was not planned to be implemented) was also present. The

measures did not consider the type of energy carrier saved, only the total amount of energy saved. The energy efficiency measures were therefore further categorized into whether electricity or fuel was saved. CSCs were calculated for electricity and for fuel, separately. Both the average CCE for each type of measure and the CCE for individual measures were calculated for the studied industries.

In Paper V, the energy efficiency measures found in the studied energy audit reports were categorized according to the end-use process and the type of energy they regarded. The following energy carriers were considered: electricity, district heating, biofuels, and fossil fuels. However, no measures were found for fossil fuels. The average CCE of all measures for a given process and energy carrier were used in the calculation of CSCs. The energy saving potential was aggregated to a national level under the assumption that the measures would be present at the same rate for all companies in the entire wood industry as they were for the studied set of companies.

In both approaches the discount rate was estimated to 7 %, also called social discount rate (Tesema and Worrell, 2015). Usually, a low discount rate is justifiable for society, while the discount rates for individual companies are usually higher due to the higher risks they face (Fleiter et al., 2009). For the lifetime of measures, it was estimated that the technological measures had a lifetime of 12 years, and the managerial measures a lifetime of five years, based on Backlund and Thollander (2015). Furthermore, no information was available on the annual change in operation and maintenance cost and was therefore assumed to zero.

5. Results and analysis

This chapter presents the main findings of the appended papers. First, the results from the categorization of production processes are presented, followed by energy saving potential, the opportunities and challenges of energy benchmarking, and the investigation of energy key performance indicators.

5.1 Categorization and energy use of industrial production processes

Research question 1:

How can a standardized categorization of production processes be developed for the allocation of energy end-use in a manufacturing industry?

5.1.1 The unit process concept applied to the wood, food, and metal industries

Based on a generic structure, the unit process concept serves to achieve a uniform treatment when analyzing the energy use of an industrial plant (Söderström, 1996). Using the dataset from the SEAP, the unit process concept was applied to the wood, food, and metal industries (Figure 4).

Which unit processes are the most prominent differs between the studied industries. *Molding* is the largest unit process in the metal industry, while for the wood and food industries it is *drying*. *Drying*, however, accounts for a much larger share of energy end-use in the wood industry than in the food industry. This illustrates the importance of dividing energy end-use into a more detailed categorization than only one sole category for production processes.

Figure 4 also reveals that a large share of the energy end-use was not possible to categorize into a process. In fact, over half of the energy end-use in the food industry is allocated in the category *other / not possible to categorize*. One reason for this is the method applied in Paper II, i.e. that the energy data and energy audit reports did not initially have the purpose of making such a division of the energy end-use. It is difficult to do this in retrospect.

Furthermore, the unit process concept, while perfectly viable for support processes, risks being too abstract for manufacturing companies to apply to their production processes, suggesting that a more practical categorization of the industries' production processes is desirable. In light of this, the application of a categorization of processes specifically tailored to the wood industry was investigated in Papers I and V.

Figure 4: The categorization of production processes according to the unit process concept and the studied industries' share of energy end-use in each of these unit processes. The processes with the highest share of energy end-use are colored to facilitate the interpretation of the diagram. The light grey bar represents multiple unit processes that were too small to show in the diagram. (Revised from Paper II)

5.1.2 A categorization of production processes for the wood industry

Olsson et al. (2011) developed a categorization of production processes in sawmills in collaboration with the industry. The same categorization was used in this thesis, together with the division of support processes from the unit process concept. This was applied to energy end-use data from the SEAP (Table 4).

Table 4: The categorization of production processes, as derived from Olsson et al. (2011) and of support processes with the average energy end-use of the 11 studied sawmills. The percentage of the total average energy end-use is rounded to the nearest whole number. For drying, the energy end-use was divided into heat and electricity use. (Revised from Paper I)

Support processes	Average energy end-use	
Space heating	2,024 MWh/year	(7%)
Internal transport	1,693 MWh/year	(6%)
Other	516 MWh/year	(2%)
Compressed air	395 MWh/year	(1%)
Lighting	251 MWh/year	(1%)
Ventilation	230 MWh/year	(1%)
Administration	69 MWh/year	(0%)
Space cooling	40 MWh/year	(0%)
Hot tap water	20 MWh/year	(0%)
Production processes	Average value	
Drying (heat)	18,821 MWh/year	(65%)
Drying (electricity)	2,990 MWh/year	(10%)
De-barking and sawing	1,155 MWh/year	(4%)
Other production processes	583 MWh/year	(2%)
Regrading	185 MWh/year	(1%)
Log sorting	162 MWh/year	(1%)
Total energy end-use for all processes	29,134 MWh/year	(100%)

The *drying of wood* accounts for the largest share of energy end-use in sawmills, amounting to about 75% when considering both heat and electricity. *Space heating*, *internal transport*, and *de-barking and sawing* also account for a significant share of the energy end-use. For the studied sawmills, over 80 % of the energy end-use is found in production processes.

The categorization of processes used in Table 4 was further refined in Paper V, also including companies that manufacture products out of wood, as shown in Figure 5.

Figure 5: The taxonomy developed for the wood industry (revised from Paper V).

From the studied energy audit reports (Paper V), it became evident that a large share of energy was used to remove sawdust from workspaces. This was generally done through ventilation shafts. The energy used for this purpose could be allocated to the support processes *ventilation* or *internal transport*. However, due to its large share of energy end-use and its connection to production, it was allocated into a separate production process, *process ventilation*. It should be noted that the residues, such as sawdust, might also be removed using another type of technique than through ventilation, e.g. by a screwing motion. An alternative denomination of the category *process ventilation* could therefore be *transportation of by-products*.

The amount of energy end-use of each energy carrier for the studied companies is shown in Figure 6a, and the share of each energy carrier used in the production processes is shown in Figure 6b.

Figure 6: The amount of energy end-use for each energy carrier for the studied set of companies (a) and the share of energy end-use for each production process, for different energy carriers (b). The share of energy end-use in support processes is presented as a whole. C16.1 refers to sawmills, and C16.2 refers to manufacturers of products of wood. (Revised from Paper V)

Similarly to the results in Table 4, *drying of wood* accounts for the largest share of energy end-use. Besides drying of wood, electricity is used to a large extent in *further processing*, i.e. production processes of the manufacture of products of wood. Also, *process ventilation* for manufacturers of products of wood accounts for a notable share of electricity use. Given that the studied companies operate in a cold climate, a large amount of energy use in *process ventilation* also means that a lot of heated indoor air is removed from the facility if the heat is not recovered. In turn, this means that high energy use in *process ventilation* also results in higher energy use for *space heating*. Only a small share, about 4 %, of the energy end-use was allocated to the category *other* (see Paper V).

5.1.3 A categorization of production processes for kraft pulp mills

The developed categorization of processes for kraft pulp mills is based on three different levels of detail. The first level considers the entire mill, the second level addresses systems and flows, and the third level regards specific end-use processes. This structure is harmonized with the three levels that are suggested for energy KPI development in ISO 50006 (ISO, 2017). The suggested categorization is shown in Table 5.

Table 5: The three levels of production processes in a kraft pulp mill (results from Paper VI).

Mill - level 1	Systems and flows - level 2	Processes - level 3
Kraft pulp mill	Chemical recovery system	Reception and storage of wood
	Pulp washing system	Debarking, wood chipping and screening
	Water content in pulp suspension	Cooking
	Secondary heat system	Screening and washing
	Process water/steam flow	Oxygen delignification
		Bleaching
		Post screening
		Pulp drying
		Pulp flash drying
		Evaporation
		Recovery boiler
		Turbine
		Causticising
		Lime reburning
		Boiler
		Sawmill
		Other processes

In Table 5, each category of processes listed under level 2 contains several categories of the processes listed under level 3. Some of these categories overlap. Table 6 shows which processes at level three are included in each of the systems and flows at level 2.

Table 6: Overview of the suggested taxonomy of production processes in a kraft pulp mill (results from Paper VI).

Chemical recovery system	Pulp washing system	Fiberline/Water content in pulp suspension	Secondary heat system	Process water/steam flow
Cooking	Cooking	Cooking	Sawmill	Sawmill
Evaporation	Screening and washing	Screening and washing	Debarking, wood chipping and screening	Cooking
Recovery boiler	Oxygen delignification	Oxygen delignification	Oxygen delignification	Oxygen delignification
Causticising	Bleaching	Bleaching	Bleaching	Bleaching
Lime reburning		Post screening	Post screening	Pulp drying
		Pulp drying	Pulp drying	Evaporation
		Pulp flash drying	Evaporation	Recovery boiler
			Other processes	Turbine
				Boiler
				Other processes

By including the second level in the suggested categorization of processes for kraft pulp mills, a new systems approach is created, in comparison to what categorizations usually provide (e.g. the BAT reference documents). Implementing energy KPIs for a specific system according to level 2 in Table 5 allows for an additional, explanatory element of the energy performance to be included for that same system or flow.

5.2 Energy efficiency potential and energy efficiency measures

Research question 2:

How can industrial energy end-use processes with large energy efficiency potential at a national level be identified?

The first approach to identify the energy efficiency potential was to create CSCs based on the type of measures presented in Section 4.5. The CSCs for electricity and fuel are shown in Figure 7 and Figure 8. The wood, food, and metal industries are covered simultaneously.

The CCE differs not only between type of energy efficiency measure, but also between industries. For example, the CCEs for *increased efficiency of processes* (ID 3) are similar between the wood industry and the food industry, but notably lower for the metal industry. *Power regulation of the processes* (ID 1) has the lowest CCE for the wood industry, while for the metal industry it is *reduced stand-by losses* (ID 2).

Figure 7: Average electricity conservation supply curves for the production processes in the wood, food, and metal industries. The cost of conserved electricity is the average value of cost of conserved electricity for all EEMs in each ID. Codes for IDs: 1 = Power regulation of the processes, 2 = Reduce stand-by losses, 3 = Increase efficiency of the process, 4 = Conversion to another energy carrier, 5 = Switch to energy-efficient motors, 20 = Other. (Revised from Paper II)

The total electricity savings potential of the production processes for all three industries is about 10,400 MWh/year (both non-implemented and implemented measures). If only considering implemented measures, the electricity savings are about 6,300 MWh/year. Considering all the suggested energy efficiency measures for production processes for electricity in each industry separately, the average electricity savings potential is about 140 MWh/company in the wood industry, 40 MWh/company in the food industry, and 65 MWh/company in the metal industry. If this is aggregated to the entire Swedish industries, only including SMEs and assuming the same average efficiency potential in all companies, the electricity savings potential in production processes is 156 GWh in the Swedish wood industry, 42 GWh in the food industry, and 158 GWh in the metal industry¹¹. The electricity efficiency potential in the wood industry corresponds to about 8% of the industry's total electricity use (SEA, 2019a).

The differences in type of measure, cost of measure, and amount of energy saved from each type of measure, as shown by the CSCs, reflect the heterogeneity of these industries. For example, a possible distinction between industries is that an industry is more or less characterized by companies with a continuous manufacturing. Power regulation is more prevalent in such cases (e.g. the wood industry), while a larger potential to reduce stand-by losses arises in industries where batches of material are processed at certain points in time (e.g. the metal industry).

Of the three industries studied in Paper II, the greatest fuel savings potential was found in the wood industry. Sawmills have a large use of wood chips, which are received as a by-product from the production processes. These chips are usually burned in a boiler

¹¹ These figures assume that the average energy efficiency potential is recurrent in all SMEs within a particular SNI code. The average energy efficiency potential is multiplied by the number of workplaces for the year 2015, as provided by Statistics Sweden (2019). The number of companies included in a few SNI codes was not obtainable for confidentiality reasons. The size of the workplaces is based on turnover: "small" is less than €10 million, "medium" is less than €50 million, and "large" is over €50 million.

for heating purposes. A lot of the fuel efficiency potential related to *increased efficiency of the process* (ID 3) was indeed found in the process drying of wood.

The total fuel savings potential in the production processes for all three industries is about 32,000 MWh/year (both non-implemented and implemented measures), with implemented measures accounting for 19,000 MWh/year. Considering all the suggested energy efficiency measures that considered fuel in each industry, the average efficiency potential is about 880 MWh/company in the wood industry, 140 MWh/company in the food industry, and 20 MWh/company in the metal industry. Aggregating this to the entire Swedish industries, only considering SMEs, similar to the procedure for electricity, the fuel savings potential is about 980 GWh in the Swedish wood industry, 150 GWh in the food industry, and 50 GWh in the metal industry. Even though the aggregated figures only consider SMEs, the fuel savings for the wood industry of almost 1 TWh is about 12 % of the industry's total energy end-use, or 21 % of the wood industry's total biomass end-use (SEA, 2019a). This means that the total energy efficiency potential for the wood industry (considering electricity and fuel savings jointly) is about 14% (SEA, 2019a).

Figure 8: Average fuel conservation supply curves for the production processes in the wood, food, and metal industries. The cost of conserved energy is the average value of the cost of conserved energy for all EEMs in each ID. Codes for IDs: 1 = Power regulation of the processes, 2 = Reduce stand-by losses, 3 = Increase efficiency of the process, 4 = Conversion to another energy carrier, 5 = Switch to energy-efficient motors, 20 = Other. (Revised from Paper II)

Besides type of energy saved, notable differences between Figure 7 and Figure 8 are the larger total amount of energy efficiency potential found in fuel and more measures with lower CCE in Figure 8. It is not possible to directly compare the CCE since the prices of electricity and fuels differ.

The figures for the three industries studied in Paper II are relevant for discerning the type of measure for production processes. The measures in Figure 7 and Figure 8 do not reveal which production processes that are affected by the measures. In Paper V, studying the wood industry, a second approach was used where energy efficiency measures were classified according to the categorization of end-use processes in the wood industry (as presented in Section 5.1.2). The energy efficiency measures were divided into the same

energy carriers as the energy end-use were allocated on. Figure 9 shows the CSCs aggregated to the entire wood industry¹².

The total amount of energy savings for all energy efficiency measures and energy carriers jointly is 1,100 GWh. This corresponds to about 13 % of the final energy end-use in the Swedish wood industry (SEA, 2019a). The electricity savings from the energy efficiency measures are about 280 GWh, or 15 % of the industry's total electricity use (SEA, 2019a). The largest electricity efficiency potential is found in the processes *compressed air*, *lighting*, and *process ventilation* (for manufacturers of products of wood). Two thirds of the electricity savings are found in these three processes.

The energy efficiency potential for district heating is found mainly in space heating and secondly in the drying of wood. It should be noted that district heating savings from measures in the drying of wood process stems from one sawmill. While the use of district heating in the drying of wood process is possible, it has limitations in, for example, the supply temperature being too low or sawmills not being connected to a district heating network. Due to these specific prerequisites for district heating to be a viable option, and the low number of sawmills studied, the energy efficiency potential of district heating is likely to be overestimated.

The largest biofuel efficiency potential is found in the *drying of wood*. This is the single largest process regarding energy efficiency potential, which was expected because the drying of wood accounts for about 75% of the total energy end-use in sawmills. In addition, *space heating* also has a significant energy efficiency potential for biofuels.

Figure 9: The energy efficiency potential for each support and production process. C16.1 refers to sawmills, and C16.2 refers to manufacturers of products of wood. The figures cover the entire wood industry in Sweden, based on the assumption that the energy efficiency measures given for the studied companies are representative at a national level. (Revised from Paper V)

¹² No energy efficiency measures that saved fossil fuels were given, therefore, this energy carrier is not present in Figure 9.

5.3 Benchmarking practices: opportunities and challenges

Research question 3:

What are the opportunities and challenges of industrial energy benchmarking?

5.3.1 Energy benchmarking in the Swedish wood industry

To investigate energy benchmarking possibilities in the wood industry, the approach selected was to develop an energy efficiency index (EEI) based on energy end-use data from sawmills participating in the SEAP. The method developed for calculating an EEI uses a bottom-up approach and enables comparisons at the process level as well as for the entire mill. For a process, the EEI was calculated as follows:

$$EEI_{i,j} = \frac{KPI_{i,j}}{KPI_{ref,i}} \quad (\text{Eq. 5})$$

Where $EEI_{i,j}$ is the resulting index for process i at plant j and $KPI_{i,j}$ is the value of the selected indicator of process i at plant j . In this thesis, $KPI_{ref,i}$ was selected as being the average value of KPI of the included companies.

To calculate the total EEI of a plant j , the following equation was used:

$$EEI_{total,j} = \sum_{i=1}^n PS_{i,j} \cdot EEI_{i,j} \quad (\text{Eq. 6})$$

Where n is the total number of processes included in the EEI, and $PS_{i,j}$ is each process's percentage of the plant's total energy end-use. For example, if space heating uses 100 MWh annually in a plant where the total energy end-use of all processes is 1,000 MWh, $PS_{space\ heating,j}$ would be 10 %. Processes using a higher share of a company's energy end-use therefore impact upon the EEI for the entire mill to a larger extent than processes with a lower share of the energy use. The inclusion of this term distinguishes the EEI developed in this thesis from other EEIs, e.g. Worrell and Price (2006).

In this thesis, the total EEI for the plants is balanced so that the average indexed value becomes 1 using the following equation:

$$EEI_{weighted,j} = EEI_{total,j} \cdot \left(\frac{m}{\sum_{j=1}^m EEI_{total,j}} \right) \quad (\text{Eq. 7})$$

Where m is the total number of companies included in the study.

The selected KPIs for the support processes and production processes of the categorization of processes employed are shown in Table 7. Note that the categorization of production processes is based on the first version of the categorization developed for sawmills, described in Table 4 in Section 5.1.2.

Table 7: The selected energy key performance indicators for each support and production process (revised from Paper I).

Support processes	KPI	Production processes	KPI
Space heating	kWh/m ² A _{temp}	Log sorting	kWh/m ³ sawn goods
Lighting	kWh/m ²	De-barking and sawing	kWh/m ³ sawn goods
Ventilation	kWh/m ² A _{temp}	Drying (electricity)	kWh/m ³ sawn goods
Administration	kWh/employee	Drying (heat)	kWh/m ³ sawn goods
Space cooling	kWh/m ² A _{temp}	Regrading	kWh/m ³ sawn goods
Hot tap water	kWh/m ³ sawn goods	Other production processes	kWh/m ³ sawn goods
Compressed air	kWh/m ³ sawn goods		
Internal transport	kWh/m ³ sawn goods		
Other	kWh/m ³ sawn goods		

Figure 10 and Figure 11 show the resulting EEI for support processes and production processes of the studied companies, respectively.

Figure 10: The resulting values of the energy efficiency index for the support processes of the studied companies. A low value of the index indicates that the company is performing well for that specific process in comparison to the other companies included in the benchmark, while a high value indicates that a company is performing poorly. (Revised from Paper I)

Figure 11: The resulting values of the energy efficiency index for the production processes in the studied set of companies. A low value of the index indicates that the company is performing well for that specific process in comparison to the other companies included in the benchmark, while a high value indicates that a company is performing poorly. (Revised from Paper I)

It is possible to derive the companies' ranking for each of the processes (Figure 10 and Figure 11). A lower value of the EEI implies that the company ranks better in that process than the other companies included in the benchmark. For example, Companies F and G have low value of the EEI for lighting, indicating that they are performing well in this process (Figure 10). Another example is that companies A, H, and I rank well in regrading, while Company C performs poorly in this process (Figure 11).

The EEI allows for guidance for an individual company in its energy management, i.e. indicating in which processes energy efficiency improvement projects should be carried out. However, a high value of the EEI only indicates that a company is a poor performer of that process, it does not necessary mean that the process accounts for a large share of energy use. Therefore, to further deepen the analysis, a company can relate the indexed values for each process to the share of energy use. Figure 12 shows the outcome of this for Company E.

Figure 12: The indexed values for process level in relation to their share of energy end-use for Company E (revised from Paper I).

The index value for *compressed air* ranked poorly for the company shown in Figure 12, but at the same time only accounts for about 7 % of the company's energy end-use. This means that *compressed air* might not have a large energy efficiency potential compared to other processes. It might therefore be better to focus on improvements in the processes *Drying (electricity)* or *De-barking and sawing* which, while receiving a lower EEI than *compressed air*, account for a larger share of the company's energy end-use.

The above example exemplifies how the EEI can be applied as a tool by an industrial company. Other actors that might make use of the index are the Swedish municipalities, county administrative boards, the Swedish Energy Agency, and the Swedish Environmental Protection Agency, e.g. when formulating energy targets or as a guiding tool in their governing activities. The EEI could also be useful for energy auditors, who are not always able to acquire in-depth knowledge of specific processes, and process-level benchmarking can complement energy audits in how to identify energy efficiency potentials (Ke et al., 2013).

5.3.2 Energy benchmarking in the Swedish pulp and paper industry

In Paper III, the pulp and paper mills' perceived value of energy benchmarking was explored. The most important benefits and difficulties identified from the interviews are presented in Table 8.

Table 8: The main factors derived from the interviews and a selection of quotes (revised from Paper III).

Challenges experienced with energy benchmarking	
Main factors	Selected quotes
Heterogeneity	<i>'We absolutely do not want people to start comparing different things without understanding why it appears like it does.'</i> <i>'Every mill is unique in its set of processes.'</i> <i>'If you do not know how the numbers are derived, they [the numbers] do not say anything. You have to go into detail to be able to say something.'</i>
Different taxonomies	<i>'We all used our own terminology [...] and it was not comparable.'</i>
Process integrations	<i>'A mill is often very integrated, so it is hard.'</i> <i>'We may have chosen to integrate differently internally than how a reference [mill] has.'</i>
Benefits experienced from energy benchmarking	
Main factors	Selected quotes
Creates incentives for further investigations	<i>'You have to start to contemplate why it appears the way it does.'</i> <i>'The greatest benefit is when you come down to a detailed level, a chain of "why" questions.'</i>
A positioning in relation to peers	<i>'It is always good to know where you stand in comparison to competitors [...] and that is a driver for everyone, I believe.'</i> <i>'Is it in-line with the rest of the world?'</i>

The two most frequently mentioned benefits boil down to the facilitation of setting the energy strategy: How do we perform compared to our peers, and where do we perform worse? To compare the energy performance of a pulp or paper mill, a simple benchmark, e.g. SEC for the entire mill, does not provide sufficient information. The indicator used for this is usually energy use for a specific amount of pulp or paper produced. Every mill is unique in its set of processes, which makes it difficult to compare the entire facility. Additionally, the integration of processes is another complicating factor.

Despite the difficulties of energy benchmarking in the pulp and paper industry, the vast majority of Swedish mills do practice it. Thus, energy benchmarking is considered to be important for the mills as they are undertaking it – only two of the responding mills do not practice any type of energy benchmarking. Figure 13a shows that the most common type of benchmarking was between mills within the same company group, 64 % of the mills practice this. The second most common, internal historical benchmarking, is practiced by 54 % of the mills, followed by external benchmarking with BAT, which is practiced by 37 %.

It should be noted that, for mills that do not have other pulp or paper mills in their company group, external benchmarking within the company group is not possible. The least frequently practiced type of benchmarking is external energy benchmarking outside the company group, which is only carried out by 21 %. One reason for this might be that they prefer not to share energy data with mills outside the company group. This barrier is likely to be smaller for mills sharing within a company group. One solution is for an independent third party to manage the energy benchmarking program, without disclosing sensitive information.

Another element of energy benchmarking that was studied was the level of detail at which it was carried out. Three levels of detail were defined: single equipment, single processes, and entire mills. Figure 13b shows that the single most common level of energy benchmarking in the Swedish pulp and paper industry is the process level, with 71 % of mills carrying out benchmarking at this level. This is even more prominent among integrated pulp and paper mills: 17 out of 19 mills carry out process-level benchmarking. At the same time, only three non-integrated mills out of nine practice this level of benchmarking. The second most common level of benchmarking, the entire mill, is practiced by 39 % of the mills.

Figure 13: The types of energy benchmarking (a) and the levels of detail of benchmarking (b) practiced by Swedish pulp and paper mills (revised from Paper III).

Figure 14 shows how the pulp and paper mills perceived the value of different types of energy benchmarking. Notably, the most commonly practiced type of energy benchmarking is not the one that is perceived as most valuable. Instead, internal energy benchmarking is deemed to provide the most important information. The benefits of internal benchmarking are that many of the barriers, in particular the three challenges mentioned in Table 8, do not apply to this type of benchmarking. At the same time, the outcome is less useful than if external benchmarking is successfully carried out.

Figure 14: The pulp and paper mills' perceived value of different types of energy benchmarking. A Likert-type scale was used in the questionnaire, ranging from 1 (not relevant at all) to 5 (highly relevant). The standard deviation is shown. (Revised from Paper III)

5.4 Energy key performance indicators

Research question 4:

What are the currently applied energy key performance indicators, and what is their improvement potential from the perspective of industrial energy management?

5.4.1 Energy key performance indicators in the wood industry

A common energy KPI in the wood industry is energy use by amount of sawn goods. Benchmarking values are attainable from the literature (cf. Ananias et al., 2012; Anderson and Westerlund, 2014; Szwedzka et al., 2016). Drying technologies are also covered in the BAT reference document on energy efficiency (European Commission, 2009).

In Paper V, the energy data for the sawmills included in the studied cases enabled the calculating of simple energy KPIs. The indicator SEC was applied, where energy use of single processes was divided by the total amount of goods produced by the sawmill. Table 9 shows the average and the range of the figures for electricity and fuel.

Table 9: Energy key performance indicators for the studied cases. The process categories follow the categorization presented in Figure 5. (Revised from Paper V)

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		
De-barking and 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

Many of the values in Table 9 are similar to the figures presented by Anderson and Westerlund (2014), e.g., for drying of wood, but the categorization differs. Drying of wood accounts for almost all the heat as well as about half of the electricity used by the production processes in sawmills.

When validating the categorization of processes at a Swedish sawmill, the possibilities to improve the energy KPIs currently used were discussed. Monitoring an indicator that is based on the moisture content of wood, such as thermal energy use by amount of water removed, for example, would be an improvement to the currently monitored indicators. A way to measure this is to weigh the wood batch before and after drying. To date, in order to achieve satisfactory moisture content, the wood is dried “too much” rather than “too little”.

A list of exemplary energy KPIs to monitor in the wood industry is presented in Table 10. These indicators are based on the entire sawmill as well as the two processes of *sawing* and *drying of wood*.

Table 10: List of suggested energy KPIs to monitor for the sawmill, as well as examples of explanatory indicators/parameters affecting the outcome of the indicator (results from Paper V).

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

5.4.2 Energy key performance indicators in the pulp and paper industry

In Paper IV, the degree of implementation of energy KPIs in pulp and paper mills was investigated. Table 11 shows the percentage of responding mills that monitor different types of energy KPIs at three different levels of detail.

Table 11: Percentage of pulp and paper mills monitoring five different types of energy key performance indicators at three different levels of detail (results from Paper IV).

Level of detail of monitoring	Electricity use/tonne	Steam use/tonne	Energy cost/tonne	Added value/tonne	Uptime
For the entire mill	75%	64%	46%	11%	43%
For a production line or department	71%	64%	25%	11%	89%
For single processes	32%	18%	7%	7%	29%

Most Swedish pulp and paper mills monitor SEC for electricity and for fuel at the entire mill or department. All mills monitor electricity use by amount of pulp produced for at least one level of detail, and only three mills do not monitor steam use at any level of detail. The single most commonly monitored indicator and level of detail is uptime for a production line, which highlights the importance of keeping production running.

Economic indicators, i.e. energy costs or added value by amount of pulp produced, are not monitored to the same degree as SEC among pulp and paper mills. About half of the mills have implemented the indicator energy cost by amount of pulp produced for the entire mill, while using added value is rare.

In addition to the type of energy KPIs monitored, how the indicators were communicated and visualized among the pulp and paper mills was also studied. The most common form of communication was by using the intranet (64 %) and through meetings (54 %). Other communication activities, such as mail or newsletter, were rarer (11 %). The frequency of visualization, and for which groups, is shown in Figure 15.

Figure 15: Number of mills visualizing energy KPIs for different groups, as well as the frequency of visualization (results from Paper IV).

Regardless of personnel group, the most common frequency of visualization in the pulp and paper mills was monthly. The mills that have a continuous visualization of energy KPIs are either non-integrated pulp mills or integrated mills. All non-integrated paper mills visualized energy KPIs either on a monthly basis or not at all.

The drivers for and the barriers to developing and implementing energy KPIs among pulp and paper mills were also investigated in Paper IV (Figure 16 and Figure 17). The most important driver is to monitor the energy end-use, followed by energy targets, the evaluation of energy efficiency measures, and the identification of energy efficiency potential. Notably, the energy management system only places as the fifth most important driver, even though the ISO 50001 standard states that energy KPIs should be continuously monitored and revised. One reason for this not being ranked higher might be that the guidelines are of a general nature, which might not specifically facilitate the development of energy KPIs in the pulp and paper sector. Another explanation could be that the currently implemented energy KPIs are perceived as sufficient.

The results from an open question in the questionnaire about the drivers for energy KPI development show that monitoring energy efficiency and energy end-use were important, similar to the top ranked driver in Figure 16. Other reasons mentioned were to receive input on how to reduce energy costs, to observe trends, and identify deviations in production.

Figure 16: Drivers for the development and application of energy key performance indicators (revised from Paper IV).

It is notable that the BAT reference document is ranked as the lowest driver for energy KPI implementation. This indicates that the figures found on energy use need to be improved. The BAT reference document itself states that future revisions of the document should improve the quality and comparability of data and collect energy use data using a harmonized method (European Commission, 2015).

Figure 17 shows that *lack of resources* was ranked as the most important barrier. Similar barriers (*lack of time* and *lack of access to capital*) have previously been ranked high in a study of the pulp and paper industry, but for barriers to energy efficiency investments (Thollander and Ottosson, 2008). For energy-intensive industry, Sivill et al. (2013) found that *lack of skills* and *lack of resources* were challenging to energy performance measurements.

Given that the barrier *lack of relevant KPIs* was ranked low, but the improvement potential of energy KPI implementation is large in the pulp and paper industry (see Paper IV), two possible explanations arise: (1) Energy managers are either satisfied with the currently monitored KPIs, or (2) find it better to develop them internally within the mill. If the latter, more resources need to be allocated to the development and implementation of energy KPIs since *lack of resources* is the highest-ranked barrier.

Figure 17: Barriers to the development and application of energy key performance indicators (revised from Paper IV).

One way to facilitate the development of energy KPIs and diminish the effect of lack of resources is to use guidelines or tools. The ISO 50006 standard provides guidelines for energy managers to implement energy KPIs to comply with the statements in ISO 50001. However, ISO 50006 addresses all industries and therefore takes a general approach. In Paper VI, a model for energy KPI development specific for kraft pulp mills was created (Figure 18).

The model for energy KPI development is based on a workshop process, during which the categorization of production processes (as presented in section 5.1.3) is applied. The workshops should preferably include representatives from all groups of personnel that will be using the energy KPIs. The workshop is the starting activity for defining the energy KPIs to be used at different levels of detail, i.e., processes, systems and flows, and the entire mill. The indicators were classified as one of two types. The first type was termed *descriptive indicators*, which provide the result of a metric and the energy performance of, for example, a process. A common descriptive indicator is SEC. To allow for further analysis of the energy performance and to identify factors that impact upon the outcome of the descriptive indicators, defining a second type of indicator is needed: *explanatory indicators* (Step 3b in Figure 18). Defining both types of indicators enhances successful energy management. It also needs to be clarified that the outcome of a descriptive indicator of a process might be affected by explanatory indicators found in other processes.

To illustrate this, the evaporation unit in a kraft pulp mill can act as an example. A strict technological focus on improvement of the steam demand in *evaporation* could imply investment in an additional evaporation stage. This would decrease the use of steam in the evaporation. A more management-oriented approach, however, could be to focus on reducing the water content of the black liquor that enters the evaporation stage. This could be done by using less washing water in the process *pulp washing*. Assuming that pulp quality is sustained, this would result in less water needing to be evaporated, consequently reducing steam use in the evaporation more than investing in an additional evaporation stage.

Another step in the model is to define the normal state of the mill (Step 3a in Figure 18), that is, to determine the ranges of values of the defined energy KPIs within which the mill normally operates. This has to be determined for a number of specific sets of inputs and outputs. If a deviation from normal operation occurs, the indicators (explanatory and descriptive) facilitate the analysis of identifying the cause of the deviation.

Step 4 in the model consists of monitoring the defined energy KPIs. This follows the continuous improvement element of ISO standards, meaning that the energy KPIs are regularly reviewed and revised.

Figure 18: The model for developing and implementing energy KPIs in relation to the international standards for energy management system (ISO 50001) and energy performance indicators (EnPIs) development (ISO 50006). (Revised from Paper VI)

6. Concluding discussion

This chapter begins with a synthesis of the outcome of the thesis. This is followed by a discussion on the implications for industry and policy. Subsequently, the main contributions of this thesis are presented. The chapter ends with suggestions for further research.

6.1 General approach to categorizing energy end-use processes and developing energy key performance indicators

Scientific articles, official reports, energy databases and energy policies adopt different approaches for energy benchmarking, energy end-use allocation, and energy KPI implementation. Figure 19 shows a model for describing these different approaches, revised from Arfwidsson and Andersson (2016).

Figure 19: Model for categorizing energy end-use processes and the level of detail of categorizations and energy KPI implementations (revised from Arfwidsson and Andersson, 2016).

The SEAP, and later on the SEAS, which mainly targeted SMEs, required the reporting of energy end-use at the level of detail of different support processes, such as ventilation, space heating etc., but considered the energy use of production processes as a whole. This reporting, based on energy audits, was conducted once for participating companies, and was thus a snapshot of the energy use during a specific year for each company. In

comparison, EKL requires large companies in Sweden to conduct an energy audit every fourth year; however, the reporting of energy end-use is divided into a less detailed categorization: *Buildings*, *transport*, and *processes*. Internationally, energy policy programs differ in how energy end-use is categorized (Thollander et al., 2015). The annual energy balance for manufacturing industry in Sweden is based on companies reporting the energy end-use of different energy carriers, but for the entire facility.

If a standardized way of categorizing the energy end-use of manufacturing industries were put in place, it would open up better opportunities for the comparison of energy efficiency and the evaluation of energy policy programs, something that has already been advocated by Paramonova (2016) and Thollander et al. (2015). Therefore, ways in which a standardized categorization of end-use processes could be used across EU Member States to support decision-makers at both the national and EU levels should be explored.

That said, the value of available energy end-use data needs to be weighed against the effort required to collect it. This means that, for the annual reporting of energy use in official statistics, it might be sufficient for industrial SMEs to report at a less detailed level, e.g., dividing energy use into support and production processes as two categories (corresponding to level 2 in Figure 19). However, within an energy audit policy program, such as the SEAP, a more detailed level of categorizing energy end-use should be expected. While different support processes should be part of such categorization, the results of this thesis also show that energy use in production processes for the wood industry account for a major share of the total energy end-use. It was also possible to allocate the energy use into individual process steps, and the same is probably true of other manufacturing industries as well.

In energy-intensive industries, the share of energy end-use in production processes is generally larger than for non-energy-intensive industries. A categorization of processes for energy-intensive industries should preferably be divided into different production processes, which is currently not done in the EKL. The suggested categorization of production processes in kraft pulp mills is based on an explorative case study and its applicability as a standardized categorization should be further explored, as well as a standardized categorization of other energy-intensive industries.

There is also a need for a broadened perspective regarding energy benchmarking and the implementation of energy KPIs within industrial energy management. Successful energy management is likely to be achieved in different ways depending on the characteristics of the industrial sector. The appropriate level of detail and frequency with which to monitor energy KPIs within a manufacturing company should be explored further, but taking the industries studied in this thesis as examples: Energy benchmarking in the wood industry is preferably carried out at the process level, but companies might lack the resources to collect data on a continuous basis. However, within the scope of an energy audit policy program, detailed data can establish a benchmark at one point in time, which provides valuable information for decision-makers about how to develop roadmaps for reaching energy targets. On the other hand, continuous monitoring of energy KPIs for in-house energy management in the wood industry could sufficiently be carried out at a facility level.

While energy benchmarking in the pulp and paper industry is difficult even when a bottom-up approach is used, a standardized categorization of processes could further enable the possibilities of benchmarking in this industry. It should be noted that, even though energy benchmarking might not be fully correct or fair, it is still an indication of the energy performance of mills and facilitates the formulation of energy policies and energy strategies. One approach that could be further explored is to benchmark the mills'

monitored energy KPIs, and the frequency of their visualization, because this is also an indication of the level of success of the energy management (cf. Trianni et al., 2019).

For example, the importance of visualizing relevant energy KPIs was shown in an energy management program carried out at a company that manufactures construction equipment, where it was found that visualizing different plants' progress in reaching a joint energy target was an important factor to a successful program because it created a sense of inclusiveness (Sannö et al., 2019). Similar procedures could be adopted in company groups in the pulp and paper industry or the wood industry.

6.2 Implications for industry

Previous research on industrial energy benchmarking has used several different methods, mainly at an aggregate level, i.e. either at the sector or national level. There is still an industrial knowledge gap for process-level energy benchmarking (Bunse et al., 2011; Sivill et al., 2013). This thesis's suggested approach for how to develop a standardized categorization of energy end-use processes further improves the possibilities of process-level energy benchmarking. If energy end-use data were widely collected based on such a standardized categorization, this would enable nationwide benchmarking rather than individual benchmarking projects with limited scope.

In this thesis, a categorization of the production processes in the wood industry was refined and tested. The results show that only a small share of the energy end-use, about 4 %, was allocated into the category *other*. This is one indication that the method used to develop a categorization of processes is a viable procedure. Future energy audits and energy measurements should also be able to use the same categorization of processes to allocate energy end-use. However, the results were limited to a number of case studies using energy audit reports from Swedish mills, therefore, the categorization would benefit from further validation with industrial actors and, preferably, subsequently adopted in national energy policy programs.

Developing a categorization of end-use processes for the pulp and paper industry is a complex procedure due to the industry's heterogeneity, why successful energy benchmarking might prove difficult to carry out. Still, the body of literature shows multiple examples of energy benchmarking at a process level in the pulp and paper industry, both in reports (cf. CIPEC, 2008; Francis et al., 2002; Kramer et al., 2009; Martin et al., 2000) and scientific papers (cf. Fleiter et al., 2012; Laurijssen et al., 2013; Rogers et al., 2018). Given the interest of benchmark values, it should be of relevance to further enable process-level energy benchmarking in the pulp and paper industry. The method used in this thesis to develop a categorization of processes in the kraft pulp industry could be applied on other sub-sectors as well.

A substantial energy efficiency potential has previously been estimated for both the Swedish wood industry (Anderson and Westerlund, 2014) and the European pulp and paper industry (Moya and Pavel, 2018). To untap the full potential, approaches that also consider energy management practices are needed. Previous research has shown that energy management plays an important role in energy-intensive industries (Paramonova et al., 2015). One way to improve the energy management in pulp and paper mills is to implement energy KPIs at a more detailed level. If this part of the ISO 50001 standard was more emphasized, e.g. by top management, and connected with benchmarking practices, it would enhance the understanding of energy managers, operators and other

personnel of their processes and assist them in finding additional ways to improve energy efficiency.

The results of this thesis regarding energy efficiency potential in the wood industry show that the largest electricity savings are not found in the process with the largest electricity use (*drying of wood*), but in the processes *compressed air*, *lighting*, and *process ventilation*. Previous research on the energy efficiency potential of *lighting* has been carried out (cf. Backlund and Thollander, 2015; Thollander et al., 2007) as well as on *compressed air* (cf. McKane and Hasanbeigi, 2011; Salvatori et al., 2018). The energy efficiency potential of *process ventilation* in manufacturing industry has not, however, to the author's knowledge, received the same attention. The findings of this thesis show that it accounts for a significant share of the electricity efficiency potential in the wood industry and should not be overlooked by energy auditors, policy-makers, or manufacturing companies.

To reach the EU's energy efficiency target, it is necessary to raise awareness of which processes has the largest share of the energy efficiency potential, which is not necessarily the processes with the largest share of energy end-use. It has previously been shown in the context of industrial SMEs that energy audits do not consider in detail all improvement areas for energy efficiency (Paramonova and Thollander, 2016a). The quality of energy audits differs, due to aspects such as the experience of the auditor and their knowledge of specific energy end-use processes (Paper I). An auditor is more likely to have knowledge about support processes, such as space heating and lighting, than production processes specific to a particular industrial sub-sector. This implies that the identified energy efficiency potential could be larger for production processes if the energy auditor had a deeper understanding of these processes as well. In addition, if non-technological measures, such as lean management, were also considered, the potential could be even larger.

A thorough understanding of production processes is even more critical in large and energy-intensive industries. Additionally, the quality of energy audits might also affect the level of implementation of energy efficiency measures (Fleiter et al., 2012b). This implies, as stated by Paramonova and Thollander (2016b), that energy auditors need supporting tools and that an energy audit is only the first step in continuous energy management. Further means of energy management activities enable the answering of the more specific question: where is the largest potential for energy cost reductions? In contrast to simply knowing where the largest energy costs are, knowing where the largest potential for energy efficiency is to be found will facilitate energy managers to direct efforts towards where they are most rewarding. Or, from the energy policy-maker's perspective: how can cost-efficient energy efficiency policy instruments be designed that target the processes with the highest potentials?

Applying further methods (e.g. CSCs or energy benchmarking) is therefore an important way of estimating the energy efficiency potential of end-use processes. In this thesis, CSCs were created that estimated the energy efficiency potential in the Swedish wood industry to about 14%. The energy efficiency target for 2030 for the EU is 32.5 % (European Commission, 2018). The discrepancy between the potential estimated in this thesis and the target potential emphasizes the importance of disaggregating energy efficiency potential to (at least) industry level, both for target setting and for drawing a roadmap for how to reach the set goals. It should be noted, however, that the potential in this thesis might be underestimated because it is based on assumptions and on a limited number of companies, as well as only considering the technological potential and not managerial measures. Other shortcomings in the method used (CSCs) for estimating the

energy efficiency potential include not considering how energy efficiency measures affect each other and neglecting the learning effects. Nevertheless, how large the energy efficiency potential is, and the means that are necessary to reach it, must be determined in order for a clear policy-setting and energy strategy to be possible for each EU member state and for the EU as a whole.

6.3 Energy policy implications

From a policy perspective, successful bottom-up energy benchmarking has been carried out in other EU Member States, for example the Netherlands, where a voluntary agreement allowed energy data to be accessible at the process level (Laurijssen et al., 2013). Governing agencies could apply this in the Swedish context as well. It has previously been carried out in e.g. the SEAP. However, since the reporting of energy data in the EKL is limited to the categories *buildings*, *transport*, and *processes*, a more granulated categorization is necessary if the data availability at the process level in energy-intensive industry is to be improved.

One way to sharply implement energy benchmarking from a policy perspective, building on experience from the PFE, is that tax exemptions could be provided, with the requirement that participating companies comply with a set of benchmarking values. This would require an improvement in the currently available benchmarking values, including the figures given in BAT reference documents, which was ranked as a low driver for energy KPI development among pulp and paper mills (Paper IV). In fact, the next review of the pulp and paper BAT reference document is suggested to collect data on energy use following a harmonized methodology (European Commission, 2015).

Other potential venues to further enable process-level energy benchmarking would be to settle agreements between peers in order to overcome the issue of data confidentiality. This is otherwise a large obstacle in benchmarking practices (Paper III). Energy efficiency networks have been perceived by companies as a valuable context for learning how to reduce energy costs (Paramonova and Thollander, 2016b), and energy benchmarking could be a tool for enhancing this even further.

One energy policy in Sweden that has attracted increased attention recently is energy supervision according to the Swedish Environmental Code, of which the use of BAT is an essential part. Because the BAT reference documents serve as guiding documents in the supervision, this becomes difficult regarding energy performance given the lack of available BAT figures for the pulp and paper industry, as noted by the Swedish Environmental Protection Agency (2018). Following a standardized categorization of processes is one way to improve the BAT energy efficiency figures at the process level. On the other hand, a technological focus might risk selecting a less energy efficient route, as discussed in Paper VI. An alternative path for supervision is to instead benchmark energy management practices (cf. Trianni et al., 2019). The results of this thesis show that the best-performing pulp and paper mills regarding energy KPI implementation monitor the KPIs at process level and revise them monthly (Paper IV). Supervision under the Environmental Code could follow up how mills implement and visualize energy KPIs in their businesses.

For the wood industry and other industries, it is not likely that they will need to be as rigorous as pulp and paper mills in the frequency and level of detail at which energy KPIs are monitored. In line with this, and following the model in Section 6.1, there should be nuances in the requirements set by the authorities regarding the level of detail of

energy KPIs and the frequency with which they are monitored, depending on the type of industry. This also includes assessing the work process of how energy KPIs are implemented. Important aspects of how a manufacturing company is working with energy KPI implementation are, for example, the level of detail and the frequency of monitoring, visualization, and revision.

6.4 Contributions

By categorizing bottom-up energy end-use at the process level, this thesis contributes to further enable industrial energy benchmarking. The method for developing a standardized categorization of processes and energy KPIs in manufacturing industries is a main outcome. This method widens the perspective on energy benchmarking and its role in industrial energy management, implying that it is not only relevant that a certain energy KPI is monitored, but also how a company is working with implementing energy KPIs, including visualization, monitoring, and the revision of indicators. A bottom-up approach to energy KPI implementation enhances successful industrial energy management and, consequently, industrial energy efficiency. This widened perspective can also improve how governmental actors carry out their auditing role within energy policies.

6.5 Further research

Further research should aim to validate the method for creating a standardized categorization of processes and to develop harmonized categorizations of processes for other manufacturing industries not covered in this thesis. This possibly entails a large improvement in identifying energy efficiency potentials and might also enhance the development of BAT reference documents.

Since external benchmarking allows for better possibilities than internal benchmarking to identify the energy efficiency potential, further research should also strive to improve energy KPIs at the process level for external benchmarking purposes. The suggested method for energy KPI development could be applied for this by also including actors from government authorities in the process. Ways to adopt visualization of energy KPIs within e.g. energy efficiency networks, or other policy instruments, could also be explored.

It is also recommended to further validate the developed energy efficiency index (EEI). A larger set of harmonized energy end-use data is needed in order to establish the usefulness of the EEI as an energy benchmarking tool. The EEI should also be applied to other manufacturing industries. With further validation, it could possibly be used by industrial companies within industry associations or energy efficiency networks. The EEI could also be of interest to decision-makers as a guiding tool in policy instruments, such as the Swedish Environmental Code.

Finally, further research should investigate the possibilities to adopt process-level energy benchmarking in policy instruments, and how to effectively and fairly use benchmark values in policy programs.

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