Improved Energy Efficiency in the Aluminium Industry and its Supply Chains

Joakim Haraldsson

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Abstract

Energy is an essential resource in the daily lives of humans. However, the extraction and use of energy has an impact on the environment. The industrial sector accounts for a large share of the global final energy use and greenhouse gas (GHG) emissions. The largest source of industrial GHG emissions is energy use. The production and processing of aluminium is energy- and GHG-intensive, and uses significant amounts of fossil fuels and electricity. At the same time, the global demand for aluminium is predicted to rise significantly by the year 2050. Improved energy efficiency is one of the most important approaches for reducing industrial GHG emissions. Additionally, improved energy efficiency in industry is a competitive advantage for companies due to the cost reductions that energy efficiency improvements yield.

The aim of this thesis was to study improved energy efficiency in the individual companies and the entire supply chains of the aluminium industry. This included studying energy efficiency measures, potentials for energy efficiency improvements and energy savings, and which factors inhibit or drive the work to improve energy efficiency. The aim and the research questions were answered by conducting a literature review, focus groups, questionnaires and calculations of effects on primary energy use, GHG emissions, and energy and CO₂ costs.

This thesis identified several energy efficiency measures that can be implemented by the individual companies in the aluminium industry and the aluminium casting foundries. The individual companies have large potentials for improving their energy efficiency. Energy efficiency measures within the electrolysis process have significant effects on primary energy use, GHG emissions, and energy and CO₂ costs.

This thesis showed that joint work between the companies in the supply chains of the aluminium industry is needed in order to achieve further energy efficiency improvements compared to the companies only working on their own. The joint work between the companies in the supply chain is needed to avoid sub-optimisation of the total energy use throughout the entire supply chain. Better communication and closer collaboration between all the companies in the supply chain are two of the most important aspects of the joint work to improve energy efficiency. An energy audit for the entire supply chain could be conducted as a first step in the joint work between the companies in the supply chains. Another important aspect is to increase the use of secondary aluminium or remelted material waste rather than primary aluminium.

The companies in the Swedish aluminium industry and the aluminium casting foundries have come some way in their work to improve energy efficiency within their own facilities. However, the results in this thesis indicate that cost-effective technology and improved management can, in total, save 126–185 GWh/year in the Swedish aluminium industry and 8–15 GWh/year in the Swedish aluminium casting foundries.

This thesis identified several demands regarding economics, product quality and performance, and environment placed on the companies and products in the supply chains that affect energy use and work to improve energy efficiency. These demands can sometimes counteract each other, and some demands are more important to meet than improving energy efficiency. This implies that improving the energy efficiency of the supply chains as well as designing products so they are energy-efficient in their use phase can sometimes be difficult. The results in this thesis indicate that it would be beneficial if the companies reviewed these demands to see whether any of them could be changed.

Both the economic aspects and demands from customers and authorities were shown to be important drivers for improved energy efficiency in the supply chains. However, placing demands on energy-efficient production and a company's improved energy efficiency would require those placing the demands to have deeper knowledge compared to demanding green energy, for example. Requiring a company to implement an energy management system to ensure active work to improve energy efficiency would be easier for the customer than demanding a certain level of energy efficiency in the company's processes. Additionally, energy audits and demands on conducted energy audits could act as drivers for improved energy efficiency throughout the supply chains.

This thesis showed that the most important barriers to improved energy efficiency within the individual companies include different types of risks as well as the cost of production disruption, complex production processes and technology being inappropriate at the site. Similar to the supply chains, important drivers for improved energy efficiency within the individual companies were shown to be economic aspects and demands from customers and authorities. However, the factors that are most important for driving the work to improve energy efficiency within the individual companies include the access to and utilisation of knowledge within the company, corporate culture, a long-term energy strategy, networking within the sector, information from technology suppliers and energy audits.

Sammanfattning

Energi är en viktig resurs i människors dagliga liv, men utvinningen och användningen av energi påverkar miljön. Industrin står för en stor andel av den globala slutliga energianvändningen och de globala utsläppen av växthusgaser. Den största källan till industriella växthusgasutsläpp är energianvändning. Produktionen och bearbetningen av aluminium är energiintensiv och har stora utsläpp av växthusgaser och använder betydande mängder fossila bränslen och elektricitet. Samtidigt beräknas efterfrågan på aluminium öka avsevärt globalt till år 2050. Energieffektivisering är ett av de viktigaste medlen för att minska industriella växthusgasutsläpp. Dessutom är energieffektivisering inom industrin en konkurrensfördel för företagen på grund av de minskade kostnader som energieffektivisering medför.

Syftet med den här avhandlingen var att studera hur energianvändningen kan bli effektivare i de enskilda företagen och hela försörjningskedjorna i aluminiumindustrin. Detta inkluderade att studera energieffektiviseringsåtgärder, potentialer för energieffektivisering och energibesparing samt vilka faktorer som hindrar eller driver arbetet med energieffektivisering. Syftet och frågeställningarna besvarades genom litteraturstudier, fokusgrupper, enkäter samt beräkningar av påverkan på primärenergianvändning, växthusgasutsläpp och energi- och koldioxidkostnader.

Denna avhandling identifierade flera energieffektiviseringsåtgärder som kan genomföras av de enskilda företagen inom aluminiumindustrin och aluminiumgjuterierna. De enskilda företagen har stora potentialer för effektivare energianvändning. Energieffektiviseringsåtgärder inom elektrolysen har stor påverkan på primärenergianvändning, växthusgasutsläpp samt energi- och koldioxidkostnader.

Denna avhandling visade att det gemensamma arbetet mellan företagen i aluminiumindustrins försörjningskedjor är viktigt för att uppnå ytterligare effektiviseringar av energianvändningen jämfört med om de individuella företagen skulle arbeta enbart på egen hand. Det gemensamma arbetet mellan företagen i försörjningskedjan är viktigt för att undvika suboptimering av den totala energianvändningen i hela försörjningskedjan. Bättre kommunikation och närmare samarbete mellan alla företagen i försörjningskedjan är två av de viktigaste aspekterna i det gemensamma arbetet för att uppnå effektivare energianvändning. En energikartläggning av hela försörjningskedjan kan genomföras som ett första steg i det gemensamma arbetet mellan företagen. En annan viktig aspekt är att öka användningen av sekundärt aluminium eller omsmält processkrot snarare än att använda primärt aluminium.

Företagen i den svenska aluminiumindustrin och aluminiumgjuterierna har kommit en bit på vägen i deras arbeten mot effektivare energianvändning inom deras egna anläggningar. Dock visade resultaten i denna avhandling att kostnadseffektiv teknik och förbättrad energiledning totalt kan spara 126–185 GWh/år i den svenska aluminiumindustrin och 8–15 GWh/år i de svenska aluminiumgjuterierna.

Denna avhandling identifierade flera krav rörande ekonomi, produktkvalitet och -prestanda samt miljö som ställs på företagen och produkterna i försörjningskedjorna och som påverkar energianvändningen och arbetet mot effektivare energianvändning. Dessa krav kan ibland motverka varandra och vissa krav är viktigare att möta än att effektivisera energianvändningen. Detta innebär att det ibland kan vara svårt att energieffektivisera försörjningskedjorna samt att designa energianvändande produkter så att de är energieffektiva i användningsfasen. Resultaten i denna avhandling visar att det skulle vara fördelaktigt om företagen granskar kraven för att se om något av kraven skulle kunna ändras.

Både de ekonomiska aspekterna och krav från kunder och myndigheter visade sig vara viktiga drivkrafter för energieffektivisering i försörjningskedjorna. Om krav ställs på energieffektiv produktion och effektivare energianvändning inom ett företag behöver de aktörer som ställer kraven ha djupare kunskaper jämfört med om de till exempel skulle kräva användandet av grön energi. Ett krav på implementeringen av ett energiledningssystem för att säkerställa ett aktivt arbete med energieffektivisering skulle vara lättare för kunden att ställa än att kräva en viss energieffektiviseringsnivå i leverantörens processer. Dessutom kan energikartläggningar och krav på genomförda energikartläggningar fungera som drivkrafter för energieffektivisering i försörjningskedjorna.

Denna avhandling visade att de viktigaste hindren mot energieffektivisering inom de enskilda företagen är olika typer av risker samt kostnader för produktionsstörningar, komplexa produktionsprocesser och att tekniken inte är applicerbar inom anläggningen. I likhet med försörjningskedjorna uppkom de ekonomiska aspekterna och krav från kunder och myndigheter som viktiga drivkrafter för energieffektivisering inom de enskilda företagen. Dock är de viktigaste faktorerna för att driva på arbetet med energieffektivisering inom de enskilda företagen tillgången till och utnyttjandet av kunskap inom företaget, företagskulturen, en långsiktig energistrategi, nätverkande inom branschen, information från teknikleverantörer och energikartläggningar.

To my parents, brother and friends

“Even the finest sword plunged into salt water will eventually rust” – Sun Tzu

*“He that breaks a thing to find out what it is, has left the path of wisdom”
– J.R.R. Tolkien*

“All we have to decide is what to do with the time that is given us” – J.R.R. Tolkien

“It’s the nature of time that the old ways must give in” – Sabaton

Appended papers

This thesis is based on the work described in the following papers. The papers are not listed chronologically but rather in an order reflecting the order of the research questions of the thesis. A more detailed description of the papers is given in section 1.4.

Paper I

Joakim Haraldsson, Maria T. Johansson

Review of measures for improved energy efficiency in production-related processes in the aluminium industry – From electrolysis to recycling

Renewable and Sustainable Energy Reviews 2018; 93: 525–548, Elsevier; DOI: [10.1016/j.rser.2018.05.043](https://doi.org/10.1016/j.rser.2018.05.043)

Paper II

Joakim Haraldsson, Maria T. Johansson

Effects on primary energy use, greenhouse gas emissions and related costs from improving energy end-use efficiency in the electrolysis in primary aluminium production

Submitted to Energy Efficiency

Paper III

Joakim Haraldsson, Maria T. Johansson

Energy efficiency in the supply chains of the aluminium industry: The cases of five products made in Sweden

Energies 2019; 12(2): 245, MDPI; DOI: [10.3390/en12020245](https://doi.org/10.3390/en12020245)

Paper IV

Maria T. Johansson, Joakim Haraldsson, Magnus Karlsson

Energy efficient supply chain of an aluminium product in Sweden – What can be done in-house and between the companies?

eccee Industrial Summer Study proceedings 2018; ISBN 978-91-983878-3-4 (online), 978-91-983878-2-7 (print); ISSN 2001-7987 (online), 2001-7979 (print); 2018: 369–377, eccee

Paper V

Joakim Haraldsson, Maria T. Johansson

Barriers to and drivers for improved energy efficiency in the Swedish aluminium industry and aluminium casting foundries

Sustainability 2019; 11(7): 2043, MDPI; DOI: [10.3390/su11072043](https://doi.org/10.3390/su11072043)

Other publications not included in the thesis

Joakim Haraldsson, Maria T. Johansson

Impact analysis of energy efficiency measures in the electrolysis process in primary aluminium production

WEENTECH Proceedings in Energy 2019; 4(2): 177–184, Weentech Ltd.; DOI: [10.32438/WPE.8818](https://doi.org/10.32438/WPE.8818)

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Abbreviations

ACD	Anode-cathode distance
BAT	Best available technique
EC	European Commission
EU	European Union
EU ETS	EU's Emission Trading System
GHG	Greenhouse gas
PEF	Primary energy factor
PFC	Perfluorocarbon

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1 Introduction

This chapter provides an introduction to the thesis including a motivation for the research, the aim and research questions, the scope and delimitations, a description of the appended papers, and the research journey.

Energy is an essential resource in the daily lives of humans. However, the extraction and use of energy has an impact on the environment. Political goals have been formulated at international [1,2] and European [3] levels as well as in Sweden [4,5] for improved energy efficiency, increased share of renewables, reduced environmental impact and increased sustainability. The EU has a directive on energy efficiency (Directive 2012/27/EU) that establishes a common framework for promoting energy efficiency improvements within the EU [6]. The aim of the directive is to ensure the achievement of the EU's 2020 target for improved energy efficiency and to lay the ground for further energy efficiency improvements beyond 2020 [6]. There is a law in Sweden requiring large companies to conduct energy audits at least every fourth year [7]. The Swedish Energy Agency is currently developing strategies for achieving the Swedish 2030 energy efficiency improvement goal [8]. One strategy each will be developed for five different sectors, of which the industrial sector is one [8]. Goals regarding improved energy efficiency have been formulated by aluminium associations at both international [9] and European [10,11] levels. The European Aluminium Association [12] has developed a roadmap for improving the sustainability of the European aluminium industry by 2025, which includes a goal of a 10% improvement in energy efficiency. The roadmap states that the European Aluminium Association and its members need to explore opportunities for improved energy efficiency in current technology and to support the development of innovative technologies for achieving the goal of improved energy efficiency [12]. Additionally, the roadmap states that the European Aluminium Association and its members will reduce direct greenhouse gas (GHG) emissions through advancing R&D in breakthrough low-carbon production technologies and pilot advanced smelting technologies [12]. The European Aluminium Association [13] has also formulated a roadmap for contributing to a low carbon economy in Europe by 2050.

In 2017, the industrial sector accounted for 37% of the final energy use and 24% of GHG emissions (direct emissions including both energy- and process-related emissions) globally [14]. Together, primary

and secondary aluminium production accounted for about 3.5% of global direct CO₂ emissions from the industrial sector in 2017 [14]. In 2017, the global primary production of aluminium (refining of alumina and electrolysis of alumina into pure aluminium) accounted for about 1 240 TWh [15] of the 43 333 TWh used in the global industrial sector [14]. In Sweden, the industrial sector accounted for about 38% of the final energy use [16] and about 33% of GHG emissions [17] in 2017. In 2011, the Swedish aluminium industry used about 2.1 TWh and the Swedish aluminium casting foundries used about 170 GWh [18].

The largest source of industrial GHG emissions is energy use [19]. Improved energy efficiency is one of the most important approaches for reducing industrial GHG emissions [19]. Thus, improving industrial energy efficiency is important for achieving the goals regarding reduced climate change and improved energy efficiency. Another factor working in favour of improving energy efficiency in industry is the competitive advantage for the companies stemming from the cost reductions that energy efficiency improvements yield.

1.1 Motivation for research

The production and processing of aluminium is energy- and GHG-intensive, and uses significant amounts of fossil fuels and electricity. At the same time, the demand for aluminium is predicted to double or even triple globally by the year 2050 [20-22]. Energy efficiency improvements (reduced energy use for supplying one unit of service, product or output [23]) in the production and processing of aluminium is needed in order to reduce primary energy use and GHG emissions, and to achieve the political goals mentioned in the previous section. Energy efficiency improvements also strengthens the competitiveness of the aluminium industry through reduced costs for companies.

The need to consider the entire supply chain (see section 3.2 for a definition of supply chains) when working with improved energy efficiency [24], reduced energy use [25], reduced environmental impact [26-28] and improved sustainability (environmental, economic and social) [24,29,30] has been highlighted in previous research. The importance of considering the entire supply chain and lifecycle of products has also been recognised by aluminium associations at Swedish [31], European [10] and international [32] levels. The importance of the supply chain perspective is acknowledged in the energy efficiency improvement strategy for the Swedish industrial sector that is being developed by the Swedish Energy Agency [33]. A system perspective on the supply chain provides the holistic approach needed to avoid deci-

sions that are optimal for an individual unit but suboptimal for the entire system, and thus to optimise the entire supply chain [24,29]. The supply chain perspective could provide opportunities for improved energy efficiency that are hidden for individual companies [24]. Additionally, more potential areas for improved energy efficiency are provided through the supply chain perspective compared to only viewing the individual companies separately, e.g. logistics and waste management [24]. Large savings for the entire supply chain could also be achieved through energy efficiency measures with low savings, and thus long payback periods, for the company implementing the measure [24]. Energy efficiency improvements in supply chains is a broader perspective studying the overall effects of energy efficiency improvements, rather than the sum of the improvements in individual companies [24].

Previous studies on industrial energy efficiency improvements indicate that cost-effective energy efficiency measures are not always implemented [34-38], which implies the existence of an energy efficiency gap [34,36-38]. The energy efficiency gap is the difference between the actual and optimal implementation of energy efficiency measures [35,38], and is commonly explained by barriers inhibiting the implementation of energy efficiency measures [34-38]. Drivers for improved energy efficiency are interesting to study along with these barriers, because they could provide the means for overcoming these barriers [35]. A basis for finding causes and solutions for closing or reducing the energy efficiency gap could be provided by studying barriers and drivers [39].

Information sources on energy efficiency measures are needed in order to provide companies with the information needed to identify and implement potentially relevant energy efficiency measures. Credibility and trust in the information sources are important for the information regarding energy efficiency investments to be accepted [36] and for effective information dissemination [40]. It is thus relevant to study the perceived usefulness of different information sources.

To the author's knowledge, this thesis is the first study focusing on energy efficiency improvements for both entire supply chains and individual companies within the supply chains in any industrial sector.

1.2 Aim and research questions

The aim of this thesis is to study improved energy efficiency in the individual companies and the entire supply chains of the aluminium industry.

The following research questions (RQs) will be covered in the thesis:

RQ1. How can energy efficiency be improved in the supply chains of the aluminium industry and to what extent?

RQ2. Why are energy efficiency measures implemented or not implemented in the supply chains of the aluminium industry?

Table 1 shows how the appended papers contribute to the research questions.

Table 1. The appended papers' contributions to the research questions.

	Paper				
	I	II	III	IV	V
Research question 1	X	X	X	X	
Research question 2			X		X

1.3 Scope and delimitations

This thesis will only study foundries casting aluminium alloys and not foundries casting other metals. Additionally, the thesis will focus on production and support processes that are used in the Swedish aluminium industry and Swedish foundries casting aluminium alloys. This means that mining of the aluminium ore (bauxite), refining of bauxite into aluminium oxide and production of anodes for electrolysis in primary aluminium production are not included in the thesis. As discussed in section 8.4, some of the results are also applicable to other countries since the processes used in Sweden are used in other countries as well and do not differ significantly from those used in other countries.

Improving energy efficiency means reducing the energy needed to supply the same service, product or output, or to supply a better service, product or output for the same amount of energy use [23]. Supply chains are systems consisting of companies, people, processes, resources and information needed for obtaining and converting resources, raw materials and components into intermediary and final products, and distributing the final products to consumers [24,41,42]. The terms “improved energy efficiency” and “supply chain” will be described in more detail in chapter 3.

An evaluation of the economic feasibility of the energy efficiency measures was excluded from the thesis. In those cases where environmental impact is presented or discussed, the focus is on GHG emissions.

Measures that save material and reduce material waste are considered energy efficiency measures. Measures that reduce material waste

save energy due to a reduced need to remelt the material waste. Additionally, some metal is lost during remelting due to metal oxidation, which needs to be replaced with primary aluminium [43]. These types of measures would thus improve the energy efficiency of the entire supply chain. However, waste product recovery is also considered to be an energy efficiency measure, since the recovery of waste products would replace energy-intensive primary production. Additionally, reducing reprocessing due to e.g. poor quality is considered to be a measure that improves energy efficiency.

RQ1 focuses on both the individual companies and the entire supply chains. This is to gain a broad understanding of how energy efficiency can be improved in the supply chains of the aluminium industry and by how much.

RQ2 also focuses on both the individual companies and the entire supply chains. A detailed study of barriers to and drivers for improved energy efficiency, and of information sources on energy efficiency measures, was conducted for the individual companies and includes the companies in the Swedish aluminium industry and Swedish foundries casting aluminium. For the entire supply chain, a study was conducted to identify which demands different actors (e.g. customers and authorities) placed on the companies and products, and how these demands affect energy use in the supply chains and the products as well as the work to improve energy efficiency.

1.4 Paper overview and co-author statement

This thesis is based on the work described in the following papers. The papers are not listed chronologically but rather in an order reflecting the order of the research questions of the thesis.

Paper I

Joakim Haraldsson, Maria T. Johansson

Review of measures for improved energy efficiency in production-related processes in the aluminium industry – From electrolysis to recycling

Renewable and Sustainable Energy Reviews 2018; 93: 525–548, Elsevier; DOI: [10.1016/j.rser.2018.05.043](https://doi.org/10.1016/j.rser.2018.05.043)

The paper reviewed literature to identify potential energy efficiency measures in the aluminium industry. The paper focused on the production-related processes for production and processing of aluminium. The processes included were electrolysis, recycling, alloying in both primary and secondary aluminium production, casting of ingots, slabs

and billets, shape casting, extrusion, rolling, heat treatment and anodising. Mining of bauxite, refining of alumina and production anodes for primary aluminium production were not included. The paper included both currently available energy efficiency measures and innovative measures that are under development.

Maria Johansson came up with the original idea and supervised the work. Joakim Haraldsson conducted the literature review, although Maria Johansson provided a list of articles to start looking at. Joakim Haraldsson wrote the paper. Maria Johansson read and commented on the drafts of the paper, but also discussed ideas for the paper. Magnus Karlsson and Mats Söderström read and commented on the final draft of the paper.

Paper II

Joakim Haraldsson, Maria T. Johansson

Effects on primary energy use, greenhouse gas emissions and related costs from improving energy end-use efficiency in the electrolysis in primary aluminium production

Submitted to Energy Efficiency

The paper studied the effects on primary energy use, GHG emissions and energy and CO₂ costs when energy efficiency measures are implemented in the electrolysis process. The paper studied both a single production plant and the entire global production through the electrolysis process.

Maria Johansson came up with the original idea and supervised the work. Joakim Haraldsson conducted the study and wrote the paper. Maria Johansson and Magnus Karlsson read and commented on the drafts of the paper, but also discussed ideas for the paper.

Paper III

Joakim Haraldsson, Maria T. Johansson

Energy efficiency in the supply chains of the aluminium industry: The cases of five products made in Sweden

Energies 2019; 12(2): 245, MDPI; DOI: [10.3390/en12020245](https://doi.org/10.3390/en12020245)

The paper studied how the companies in the supply chains of the aluminium industry can work together with improved energy efficiency, i.e. which energy efficiency measures the companies can conduct together. Additionally, the paper studied which demands from actors within and outside the supply chains are placed on the products and companies, and how these affect the energy use and work with improved energy efficiency. The paper studied the supply chains for a heat

exchanger for trucks, a balcony glazing system, a motor component for cars, a truck chassis part and a piece of furniture. The paper focused on the parts of the supply chains that supplied the aluminium component of the respective product. The products are produced in Sweden.

Maria Johansson came up with the original idea and supervised the work. Joakim Haraldsson and Maria Johansson designed and co-operatively conducted the focus groups. Joakim Haraldsson transcribed and coded the focus group discussions and analysed the data from the focus groups. The authors wrote the paper jointly, although Joakim Haraldsson provided a first draft summary of each focus group separately. Magnus Karlsson read and commented on the final draft of the paper.

Paper IV

Maria T. Johansson, Joakim Haraldsson, Magnus Karlsson

Energy efficient supply chain of an aluminium product in Sweden – What can be done in-house and between the companies?

eccee Industrial Summer Study proceedings 2018; ISBN 978-91-983878-3-4 (online), 978-91-983878-2-7 (print); ISSN 2001-7987 (online), 2001-7979 (print); 2018: 369–377, eccee

The paper studied the degree of implementation of energy efficiency measures in a supply chain for a motor component produced in Sweden. Additionally, the paper analysed the potentials for further improvements in energy efficiency. The paper studied both energy efficiency measures within the individual companies and measures that the companies can conduct together.

Maria Johansson came up with the original idea and supervised the work. Joakim Haraldsson and Maria Johansson designed and co-operatively conducted the focus group. Joakim Haraldsson transcribed and coded the focus group discussions and analysed the data from the focus group. Maria Johansson designed and conducted the questionnaire and analysed the data from the questionnaire, and Joakim Haraldsson commented on the questionnaire draft. The authors wrote the paper jointly, although Joakim Haraldsson provided a first draft summary of focus group.

Paper V

Joakim Haraldsson, Maria T. Johansson

Barriers to and drivers for improved energy efficiency in the Swedish aluminium industry and aluminium casting foundries

Sustainability 2019; 11(7): 2043, MDPI; DOI: [10.3390/su11072043](https://doi.org/10.3390/su11072043)

The paper studied the importance of different barriers to and drivers for the implementation of cost-effective energy efficiency measures in the individual companies comprising the Swedish aluminium industry and Swedish foundries casting aluminium alloys. Additionally, the paper studied the perceived usefulness of different information sources on energy efficiency measures. Furthermore, the perceived changes in the companies' prioritising of energy issues were studied.

Maria Johansson came up with the original idea and supervised the work. Joakim Haraldsson designed and conducted the questionnaire and Maria Johansson commented on the questionnaire draft. Joakim Haraldsson analysed the data and wrote the paper. Maria Johansson read and commented on the drafts of the paper, but also discussed ideas for the paper.

1.5 Other papers not included in the thesis

Joakim Haraldsson, Maria T. Johansson

Impact analysis of energy efficiency measures in the electrolysis process in primary aluminium production

WEENTECH Proceedings in Energy 2019; 4(2): 177–184, Weentech Ltd.; DOI: [10.32438/WPE.8818](https://doi.org/10.32438/WPE.8818)

This paper is an early version of Paper II.

1.6 Research journey

This thesis is the result of the completed research project “Increased energy efficiency in the supply chains of aluminium industry – a carbon neutral industry in 2050” funded by the Swedish Energy Agency. The aim of the project was to investigate potential energy efficiency improvements and the possibilities to realise these in the supply chain of the aluminium industry.

Figure 1 shows an approximate timeframe for the work with the different papers appended to the thesis.

Figure 1. The work with the papers. The length of the arrows does not correspond to the actual time spent on each paper.

2 Aluminium industry and aluminium casting foundries

This chapter describes the production processes used in the aluminium industry and aluminium casting foundries. The Swedish aluminium industry and Swedish aluminium casting foundries are also described.

Aluminium is the third most abundant element and the most abundant metal on Earth, as well as being the most widely used metal after steel due to its versatility [44]. Aluminium has a low density compared to other metals, a high strength to weight ratio, and excellent corrosion resistance [44].

This thesis defines the aluminium industry as companies working with the primary aluminium production (excluding mining of bauxite and production of carbon anodes), secondary aluminium production, rolling and profile extrusion. The Swedish Standard Industrial Classification (SSIC) (see [45]) provided a basis for this categorisation. Aluminium production, rolling and profile extrusion belong to code 24.420 in the SSIC, while shape casting of aluminium into semi-finished products (the main production process at aluminium casting foundries) belongs to code 24.530 in the SSIC [46]. Therefore, aluminium casting foundries will, to a large extent, be presented separately in the thesis. Mining of bauxite belong to code 07 in the SSIC (more specifically code 07.290) that deals with the extraction of metal ores [46], i.e. the mining industry. Production of carbon electrodes belong to code 27 in the SSIC (more specifically code 27.900) that deals the production of electrical equipment [46]. Therefore, mining of bauxite and production of carbon anodes are not included in the aluminium industry.

2.1 Production processes

This section will describe the main production processes involved in the production and processing of aluminium. Figure 2 shows a schematic drawing of the material flow for aluminium products with the main production processes included. As mentioned earlier, mining of bauxite, alumina refining and anode production will be excluded from this thesis.

Figure 2. Schematic drawing of the material flow for aluminium products. Bauxite is the aluminium ore. Alumina is another name for aluminium oxide (Al_2O_3). Revised from Paper I.

2.1.1 Electrolysis and alloying

The electrolytic process called the Hall-Héroult process is the major process for extracting pure aluminium from alumina [47]. The process takes place in electrolytic cells, which are connected in series to form electrical reduction lines [48]. A schematic picture of an electrolysis cell is shown in Figure 3. The electrolysis is a continuous process operating 24/7 all year around.

The electrolyte consists mainly of cryolite (Na_3AlF_6) with the addition of fluoride compounds and other compounds [43,47,48]. Cryolite is used as solvent for the dissolution of alumina [47]. The addition of fluoride and other compounds improves the operating conditions in

the cells, e.g. lowering the operating temperature [43,47,48], and improving conductivity, solubilities and electrolyte density [43]. About 960°C is the operating temperature for most commercial cells [43,47,48].

The anodes are continuously consumed as a part of the chemical reaction since carbon dioxide and carbon monoxide are formed by the carbon in the anodes combining with the oxygen in the alumina [48]. The carbon in the anodes supplies some of the energy needed for the cell operation [43]. However, the main energy carrier in electrolysis is electricity. Although the cathode is not consumed during the process, it needs to be replaced after four to eight years due to cracking, swelling and erosion from absorbing electrolyte [48].

The two main types of electrolytic cells are Søderberg and prebaked [48]. Søderberg cells only have one anode each [48]. The anode is regenerated by adding carbon material and is baked by the heat rising from the molten bath and the current passing through the anode [48]. Prebaked anode cells have multiple anodes manufactured in separate anode plants [48]. The anodes need to be changed when about 80% of the anode is consumed [48], which is about every four weeks in modern plants [43]. Prebaked anode cells of the point feeder type (illustrated in Figure 3) are the most commonly used type in Europe [48]. The prebaked anode technology accounts for about 95% of the global production of primary aluminium [49].

The so-called anode effect occurs when the concentration of alumina in the cells is too low [43,48]. Anode effects result in the emission of the PFC gases CF_4 and C_2F_6 [43,47,48], which are two strong GHGs [43]. Anode effects are also accompanied by a sudden increase in voltage and a corresponding decrease in amperage [47].

The GHG emissions from electrolysis can be divided into two parts: (1) energy-related emissions from use of electricity and (2) process-related emissions from consumption of anodes and anode effects (see above).

Figure 3. Schematic picture of an electrolysis cell for the production of primary aluminium. The illustrated cell is a prebaked anode cell of point feeder type. Based on [43,50]. Reprinted with permission from Paper I.

The molten aluminium from electrolysis is stored in induction or reverberatory holding furnaces, where alloying additions and additions to refine the metal grain are also carried out [48]. Process scrap, either internal or bought, is also melted at primary aluminium sites and should be free from oil, paint, plastics or any other substances [48]. The scrap is either added to a furnace containing molten metal or melted separately before adding the molten metal from electrolysis [48].

2.1.2 Recycling and alloying

Secondary aluminium is produced by melting scrap from end-of-life products, i.e. post-consumer scrap. There is a variety of raw material (scrap) that can be used, which leads to a variety of furnace types being employed [48].

Sorting of the raw material into wrought alloys and cast alloys is the first step [47,48], and easily identifiable scrap, e.g. extrusion scrap, is sometimes separated from the wrought scrap [47]. It is preferable to recycle the scrap back into the same alloy and product [47], which minimises the need for reprocessing [48]. However, this requires information about the alloy or type of alloy used in the scrap [47].

The required product quality and the type and composition of the scrap are the main factors when deciding on appropriate treatment

processes, furnace type and other process steps [48]. Before melting the scrap, processes to remove materials other than aluminium alloys, e.g. other metals and impurities (e.g. oil emulsion), are employed [47]. The majority of wrought alloys are melted in reverberatory furnaces, while cast alloys are mainly melted in rotary drum furnaces (sometimes tiltable) [48]. Other types of furnaces, e.g. induction furnaces, can also be used [47,48].

The addition of alloying elements may sometimes be needed to produce the desired alloy [51]. Alloying elements can be added either directly to a casting system or through a transfer system into a holding furnace [48]. Mixing scraps of different alloy element compositions can also be used to achieve the desired alloy [47]. Gases and unwanted metals are removed from the aluminium alloy through refining in either the holding furnace or an in-line reactor [48].

It is important to distinguish between recycling and remelting. Recycling is the recovery of aluminium from post-consumer scrap. Remelting is the recovery of process scrap occurring during the production of products, i.e. scrap occurring before the products have reached the consumer.

2.1.3 Generation of skimmings, dross and salt slag

Skimmings, dross and salt slag are generated as by-products in the aluminium industry [48]. There are both white dross and black dross [47,52,53]. Both primary and secondary aluminium production result in skimmings and dross in the holding and treatment processes [48]. Salt slag is generated through the use of a salt flux in rotary furnaces in secondary aluminium production to reduce oxidation, increase yield and thermal efficiency, and promote removal of impurities [48]. Salts, metallic aluminium and alumina are present to varying degrees in skimmings, dross and salt slag [52-54].

2.1.4 Casting

Both primary and secondary production use vertical direct chill casting machines with water-cooled metal moulds to cast ingots, slabs and billets [55]. Primary production can also use horizontal direct chill casting for billets and slabs with smaller cross-sections [55]. Additionally, primary production can use static or continuously moving metal moulds [55]. Secondary production can use moulds to cast a variety of smaller ingots [55].

Shape casting is basically the pouring or injection of molten aluminium alloys into moulds with one or more cavities of the desired shape [43]. Table 2 describes some common shape casting methods.

Table 2. Description of common shape casting methods. Based on [43].

Casting method	Description
Pressure die casting	The metal is injected into water-cooled steel moulds at pressure up to around 70 MPa.
Green sand casting	Sand, binders and moisture are blended to produce the moulds.
Dry sand casting	The sand particles in the moulds are coated with air or thermal setting chemicals.
Permanent mould casting	Gravity or counter-gravity means are used to inject molten metal into iron or steel moulds.
Investment casting	Low temperature melting pattern materials are repetitively immersed into ceramic slurries to produce the moulds and the ceramic is hardened through drying. Heating the mould is done to remove the pattern material. The mould is normally preheated before metal pouring. The metal may be poured under vacuum.

2.1.5 Profile extrusion

The extrusion forms a billet into an elongated shape with a consistent cross-section (a profile) by forcing the billet through a steel die using hydraulic pressure [43]. Horizontal extrusion is used in virtually all modern extrusion presses [43]. The billet is preheated before being charged into the extrusion press, typically to between 450°C and 550°C, and the temperature is determined by the product design, the desired mechanical characteristics and the alloy [43].

There are both direct and indirect extrusion processes, with the difference being that the billet is the moving part in direct extrusion, while the die is the moving part in indirect extrusion [43], as shown in Figure 4. Material wastage in direct extrusion occurs due to the retainment of the billet surface in the extrusion container and does not become a part of the profile [43]. Thus, the skin layer does not need to be removed by scalping prior to the extrusion [43]. For indirect extrusion, the billet surface becomes a part of the profile and scalping is therefore needed [43].

Figure 4. Schematic picture of direct and indirect extrusion. Based on [56]. Reprinted with permission from Paper I.

2.1.6 Rolling

The rolling process is used to produce plates, sheets and foils by passing a slab between counter-rotating steel rolls several times to reduce its thickness [43], as shown in Figure 5. The slab normally goes through both a hot rolling step and a cold rolling step [43]. The slab is preheated to between 400°C and 500°C, depending on the alloy, prior to hot rolling [43]. The cold rolling step is normally performed at room temperature after the hot rolling step [43].

The edges of the metal need to be cut off after both hot and cold rolling to remove parts of the metal with cracks and ragged edges [43]. The ends of the metal also need to be cut off to maintain the squareness of the metal [43]. The top layer of the slab surfaces need to be scalped off for reasons of quality and uniformity [43].

Figure 5. Schematic picture of the rolling process. Based on [56]. Reprinted with permission from Paper I.

2.1.7 Heat treatment

Heat treatments in furnaces are used to adjust the metal's physical and mechanical properties to make the metal more appropriate for certain applications or to facilitate manufacturing regarding e.g. formability or machining [57].

Common heat treatment processes are homogenisation, annealing and ageing. Homogenisation is used to achieve a uniform distribution of alloying elements in the metal, remove particles and segregation gradients, control grain size, and improve ductility [58]. The metal is typically heated to 450–600°C [59]. Annealing is used to promote softening of the metal [60]. Annealing is conducted at a temperature range of 300–410°C, depending on the alloy, and the heating time varies between 0.5 and 3 hours [60]. Ageing (or age hardening) is used to

harden the metal and can be achieved either at room temperature (natural ageing) or through heat treatment in a furnace (artificial ageing) [60]. Artificial ageing is conducted at a temperature range of 115–200°C, and the heating time varies between 5 and 48 hours [60]. The term “ageing” will hereafter be used interchangeably with “artificial ageing”.

2.1.8 Anodic oxidation (anodising)

Anodic oxidation (anodising) is an electrolytic process that aims to enhance the properties of the metal surface by producing an oxide layer on the surface by improving the metal’s natural ability to oxidise [61]. An electrolyte based on sulphuric acid is used in 90% of cases to anodise aluminium [61]. An electrolyte based on phosphoric acid, chromic acid, sulphuric/salicylic acids or sulphuric/oxalic acids, for example, can be used for special applications [61]. Pre-treatment processes, e.g. for cleaning purposes, may be needed [61].

The sulphuric acid anodising is typically followed by a sealing process (either a hot or cold process) to further improve the surface’s properties [61]. Hot sealing closes the pores in the oxide layer by hydrating the aluminium oxide to create boehmite [61]. The hot sealing process uses either hot or boiling (minimum 95–96°C) deionised water, or steam [61]. There are also sealing processes operating at both 15–25°C and about 60°C [61]. The processes operating at about 60°C use nickel salts to close the pores [61].

2.1.9 Energy use

Electrolysis uses 14.21 kWh/kg Al of electricity [62] and is the most energy intensive process within the aluminium industry [21]. Secondary aluminium production requires 0.56–2.5 kWh/kg Al, where higher energy use is typically associated with lower quality scrap [48]. The production of secondary aluminium requires around 5% of the energy used to produce the same amount of primary aluminium (from mine to finished metal) [47,48]. This value depends, of course, on the technology used to recycle the scrap [47].

Casting, rolling and extrusion use electricity. Furnaces used for different purposes, e.g. preheating, melting, holding and heat treatments, typically use electricity or fossil fuels. Anodising uses electricity, while the sealing process following anodising can use both electricity and fossil fuels. Information about energy use for specific processes in the production of semi-finished products is scarce. Table 3 shows the energy use and material yield for entire production flows within some facility types associated with the supply chains of the aluminium industry.

Table 3. Energy use and material yield for the entire production flow within some facility types associated with the supply chains of the aluminium industry. These values are taken from a study on the aluminium industry in the USA. Based on [43].

Facility	Energy use	Energy carriers	Material yield
Foundry	2.56 kWh/kg cast product	~100% fossil fuels ~0% electricity ~0% other fuels	45%
Profile extrusion plant	1.30 kWh/kg extruded product	87% fossil fuels 7% electricity 6% other fuels	69%
Rolling mill			
- Cold rolling	0.64 kWh/kg rolled product	42% fossil fuels 55% electricity 3% other fuels	84%
- Hot rolling	0.62 kWh/kg rolled product	57% fossil fuels 43% electricity 0% other fuels	82%

2.2 The Swedish aluminium industry and aluminium casting foundries

The Swedish aluminium industry has five companies. These companies deal with primary (from electrolysis onwards) and secondary production of aluminium, profile extrusion and rolling. There is no company in Sweden dealing with mining of bauxite, alumina production or production of anodes for electrolysis. The Swedish foundry industry covers a total of 100 foundries [63], of which 39 cast aluminium alloys. Around 80%, 10% and 10% of the produced tonnage of aluminium castings is produced using pressure die casting, permanent mould casting and sand casting (the reference does not specify whether this is green or dry sand casting), respectively [63].

In 2011, about 130 000 tonnes of alloyed primary aluminium, 50 000 tonnes of secondary aluminium, 75 000 tonnes of extruded profiles, 52 500 tonnes of rolled products and 32 500 tonnes of aluminium castings were produced in Sweden [18]. The difference between the produced amount of aluminium and the produced amount of semi-finished products could be due to, for example, exports and unrecovered material waste. The Swedish aluminium industry used a total of about 2.1 TWh/year in 2011, of which the majority was electricity [18]. In 2011, the Swedish aluminium casting foundries used about 170 GWh [18].

3

Concepts and definitions

This chapter defines and discusses terms and concepts used in the thesis.

3.1 Energy efficiency improvement and energy saving

The terms “energy efficiency improvement” and “energy saving” will be used extensively in this thesis. Pérez-Lombard, *et al.* [23] defined efficiency as “the ability to achieve a desired result wasting minimum resources”. Efficiency is commonly defined in engineering as the ratio of the desired output to the needed input [23]. One common type of indicator for energy efficiency is energy conversion efficiency, i.e. the useful energy output divided by the energy input [23]. Another commonly used type of indicator is energy intensity, i.e. the amount of energy used divided by the amount of service, product or output supplied [23]. Thus, improving energy efficiency means reducing the energy needed to supply the same service, product or output, or to supply a better service, product or output with the same amount of energy use [23]. This thesis will use energy intensity as an indicator of energy efficiency improvement. The term “saving” is the reduction in the absolute amount of a given resource used [23]. By contrast, efficiency is always a relative amount [23].

Energy efficiency improvements have been criticised for not reducing energy demand [64]. The term “rebound effect” covers several mechanisms reducing the potential energy savings from improved energy efficiency [64]. For example, manufacturers may increase output by using cost savings from improved energy efficiency [64].

There are other terms semantically similar to efficiency and saving, e.g. “efficacy”, “effectiveness” and “performance” [23]. These terms will not be defined since they are not used in the thesis.

3.2 Supply chains

The aim and research questions of the thesis include the supply chain perspective. Supply chains are systems consisting of companies, people, processes, resources and information needed for obtaining and converting resources, raw materials and components into intermediary and final products, and distributing the final products to consumers

[24,41,42]. Linkages between different processes and activities are constituted by many divergent and convergent flows of material, information and money, resulting in a supply chain being a complex network [41].

Some actions conducted by companies have no major consequences beyond the part of the supply chain where the action is carried out [65]. These actions can thus be seen as discrete and could be taken without reference to other parts [65]. On the other hand, some actions might give rise to effects elsewhere, which implies a need to put them into their wider context [65]. These actions should be conducted only when there is a good overview of the effects throughout the whole supply chain, so the wider implications of the action can be discerned [65]. This thinking is applicable when improving energy efficiency, both in supply chains and within individual companies.

Some of the components within the individual companies are the technical processes associated with production. These processes can be divided into production processes and support processes [66]. The production processes are used to produce products (e.g. melting and cutting) and the support processes support production (e.g. lighting and ventilation) [66].

3.3 Primary energy factor

The impact on primary energy use will be calculated in this thesis for the implementation of certain energy efficiency measures. The primary energy use is the energy needed to deliver one unit of energy to the end-user and should cover the energy needed for extraction, processing, storage, generation, transformation and distribution, for example [67]. In this way, an understanding of the energy demand throughout the entire life cycle from source to delivered final energy use is provided [68]. However, differences may occur between different energy sources, e.g. the chemical energy content of fossil fuels is included in the primary energy use, while the energy in wind and solar irradiation is not included [68]. The primary energy factor (PEF) is calculated as the amount of primary energy divided by the delivered energy [67]. However, the PEF can be calculated in different ways based on the numerous factors affecting the amount of primary energy needed to deliver one unit of final energy [69]. The method used for calculating and using a PEF is affected by the applied criteria regarding, for example, precision in reflecting reality, simplicity and transparency [69].

3.4 Assessment of GHG emissions

The impact on the amount of GHG emissions will be calculated in the thesis for the implementation of certain energy efficiency measures. Results regarding the impact on global GHG emissions from changes in energy systems, e.g. implementation of energy efficiency measures, can vary widely depending on the chosen method and system boundaries [70].

There are several approaches for assessing the impact on GHG emissions for electricity and which to use depends on the purpose of the study (bookkeeping or consequential) [71]. One approach is to utilise an average electricity generation mix for the geographic area studied and calculate an average emission factor for that mix [71]. Another approach is to use the operating marginal electricity generation, which is the generation unit with the highest operating cost and thus the first unit to stop generating if the electricity demand goes down [71]. A third way is to use the build margin approach, involving an assumption regarding which type of electricity generation facility would have been built if the electricity demand had not been reduced [72]. A fourth approach is to use the contracted type of electricity that is bought or the residual mix for consumers that do not have a contract for a specific type of electricity [71].

4

Previous research

This chapter presents previous research related to the topics of the thesis.

4.1 Improved energy efficiency in the aluminium industry

Aluminium production in general has attracted considerable interest in research. However, much of this research has focused on production-related factors and not on energy efficiency measures. Some scientific articles mention energy efficiency issues, but have a main focus on other subjects, e.g. development of a computational model or technology, and energy efficiency improvements fall into the background in these articles. The European Commission's reference documents for best available techniques (for example [55,61,73]) focus mainly on environmental aspects, and present only a few measures for improved energy efficiency. Kermeli, *et al.* [74] review 22 currently available energy efficiency measures in primary aluminium production (alumina refining, electrolysis, anode production and ingot casting). However, they do not include energy efficiency measures for recycling of aluminium or processing of aluminium into semi-finished products. Brown Construction Services Inc. [43] focuses mainly on electrolysis and process heating operations, and provides only a brief outline of the future prospects for energy efficiency improvements in other main production processes in the aluminium industry. This implies that there is a lack of scientific reviews studying energy efficiency measures within the individual companies of the entire aluminium industry including all types of production processes associated with the aluminium industry. Additionally, there is a lack of scientific reviews focusing both energy efficiency measures that are currently available and innovative measures that are being developed and not currently available. A scientific review covering the entire aluminium industry as well as both currently available energy efficiency measures and innovative measures under development will be conducted within the scope of this thesis.

4.2 Supply chains in relation to improved energy efficiency and reduced environmental impact

There are several previous studies on improved energy efficiency and reduced environmental impact of entire supply chains that focus on supply chains in general (e.g. [24,28,65,75-80]). Other studies have focused on supply chains in specific industries other than the aluminium industry, e.g. the automotive industry [27], the computer industry [81], the food industry [82-84], the clothing and furniture industries [83], the paper and steel industries [42], the plastics industry [85], the construction sector [86] and the aerospace industry [87].

Khoo, *et al.* [88] studied the transportation of goods between sites (only considering transportation mode and distance travelled) in a supply chain producing die-cast aluminium components. They also studied the delivery of metal in molten form to a casting plant. Ferretti, *et al.* [89] developed a mathematical model for evaluating the economic and environmental impact of molten aluminium delivery. Milford, *et al.* [21] studied the supply chains for three aluminium products and the effects on the embodied energy use and CO₂ emissions along the supply chains from improved metal yield. They also studied the energy saving and CO₂ emissions abatement potentials for the entire global aluminium sector from eliminating all yield losses. Tan and Khoo [90] conducted a life-cycle assessment for a supply chain for delivery of aluminium billets covering alumina refining, electrolysis and casting of the billet. They showed that improved energy efficiency in electrolysis could have significant effects on the overall environmental impact of the supply chain.

This thesis takes a more holistic approach to supply chains (by considering a wider range of aspects of the supply chains, e.g. product design and management) compared to Khoo, *et al.* [88], Ferretti, *et al.* [89], Milford, *et al.* [21] and Tan and Khoo [90]. Additionally, this thesis considers a wider range of case objects (both more objects and other objects) and uses other research methods compared to Khoo, *et al.* [88], Ferretti, *et al.* [89], Milford, *et al.* [21] and Tan and Khoo [90]. This thesis will also provide an understanding of how the companies in the supply chains of the aluminium industry can work together on improved energy efficiency, which is a relatively unexplored area within research on supply chain energy efficiency improvements.

4.3 The impact of energy efficiency measures on primary energy use, GHG emissions, and energy and CO₂ costs

Previous research regarding the impact of specific energy efficiency measures on primary energy use, GHG emissions and related costs for the aluminium industry is scarce. Schwarz, *et al.* [91] examined the global material flow of primary aluminium in 2010 compared to 1995 and the associated CO₂ emissions. However, the energy efficiency improvements in their study are not based on any specific energy efficiency measures but rather on a comparison between the average energy use for electrolysis in 1995 and energy use in modern or substantially upgraded electrolysis plants in 1995. Kermeli, *et al.* [74] and Liu, *et al.* [92] constructed conservation supply curves for a number of energy efficiency measures in alumina refining and aluminium electrolysis. Kermeli, *et al.* [74] estimated the total savings in final energy use, primary energy use and GHG emissions for the eleven countries with the largest aluminium production in the world. Liu, *et al.* [92] estimated the total GHG abatement potential from the implementation of energy efficiency measures in alumina refining and electrolysis within the aluminium industry in Henan Province, China. Myklebust and Runde [93] estimated the GHG emissions abatement potential for the direct carbothermic reduction compared to the electrolysis process. Obaidat, *et al.* [94] studied wettable cathodes, inert anodes and direct carbothermic reduction, and their impact on exergy and CO₂ and CO emissions compared to conventional electrolysis. Saygin, *et al.* [95] estimated the regional and global energy efficiency improvement potentials for alumina refining and electrolysis through an international benchmarking of energy use, i.e. not studying any specific energy efficiency measures.

This thesis contributes to the research gap regarding the effects on primary energy use, GHG emissions, and energy and CO₂ costs from the implementation of specific energy efficiency measures (both currently available measures and innovative measures being developed) in the aluminium industry. This thesis will also provide an understanding of the size of the potential savings for specific energy efficiency measures at site and global levels.

4.4 Barriers, drivers and information sources

There are several previous studies on barriers to and drivers for improved energy efficiency for different sectors within Swedish industry. The studied Swedish sectors are the pulp and paper industry [34], the

foundry industry [36], manufacturing SMEs [96], the non-energy-intensive manufacturing industry [37], the iron and steel industry [97,98] and industrial companies in Oskarshamn Municipality, as well as industrial companies participating in the Swedish “Uthållig kommun” (“Sustainable municipality”) policy programme [40]. Previous studies on barriers to [99] and drivers for [100] improved energy efficiency in European foundries (including Swedish foundries) have also been carried out. The studies mentioned thus far in this paragraph have been reviewed by Johansson and Thollander [39]. Nehler, *et al.* [35] studied barriers to and drivers for improved energy efficiency in compressed air systems. Barriers to and drivers for energy management in the Swedish pulp and paper industry have been studied by Lawrence, *et al.* [101].

Batterham [102] reviewed the drivers for technology innovation in alumina production that could drive companies to improve their processes, e.g. regarding energy efficiency. Bailey and Ditty [103] studied whether sufficient incentives for overcoming barriers to energy efficiency investments in energy-intensive sectors (aluminium, chemicals and cement) could be provided by economic policy instruments in the UK. Su, *et al.* [104] identified several barriers to improved energy efficiency when studying a Chinese foundry. Nagesha and Balachandra [105] studied barriers to improved energy efficiency in an Indian foundry cluster.

Previous research on how companies perceive the usefulness of information sources on energy efficiency measures is scarce. The perceived usefulness of information sources has been studied in Ghana’s largest industrial area [106], Swedish foundries [36] and industrial companies in Oskarshamn Municipality and among industrial companies participating in the Swedish “Uthållig kommun” (“Sustainable municipality”) policy programme [40].

The Swedish aluminium industry has not yet been studied regarding the importance of barriers to and drivers for improved energy efficiency, and the perceived usefulness of information sources on energy efficiency measures. Sector- and region-specific studies on barriers are needed because the importance of barriers differs depending on sector- and region-specific conditions [34,36]. This also applies to drivers and information sources. The Swedish aluminium industry is thus relevant to study. Rohdin, *et al.* [36], Trianni, *et al.* [99] and Thollander, *et al.* [100] studied foundries casting different types of metals (not only aluminium), while this thesis focuses on aluminium casting foundries. Although Trianni, *et al.* [99] present their results by country and by metal, it is not possible to identify which barriers are important for the Swedish aluminium casting foundries. Additionally, about 13 years

have passed since the paper by Rohdin, *et al.* [36] was published and things might have changed since then.

Centobelli, *et al.* [107] found that several scientific studies regarding which factors positively or negatively affect the implementation of measures for improving energy efficiency and reducing environmental impact in supply chains in general have already been conducted. However, they requested more empirical investigations regarding such factors due to the research gap they identified in their literature review. This thesis contributes to filling this research gap by studying the demands placed on the companies and products in the supply chains of the aluminium industry that can affect energy use and the companies' work with improving energy efficiency.

5

Description of system levels and cases

This chapter describes the system levels and cases studied in the appended papers and this thesis.

5.1 System levels

Figure 6 shows the system levels studied in the appended papers. It is worth noting that Paper IV includes several system levels, while the other papers only have one system level each. Paper IV studies the entire individual companies and supply chains on overall levels, and the production and the support processes within the companies. The other papers focus either on the process level (Papers I and II), or on the company (Paper V) or supply chain (Paper III) on an overall level.

The system levels for the research questions in this thesis are based on the system levels studied in the papers contributing to each research question. This means that RQ1 uses the system levels associated with Papers I–IV and RQ2 uses the system levels associated with Papers III and V.

Figure 6. The system levels studied in the appended papers. Some of the squares for production processes include a single production process while others include several production processes.

5.2 Cases studied

In Paper III, five products were studied: a heat exchanger for trucks, a balcony glazing system, a piece of furniture, a chassis part for trucks and a motor component for cars. The motor component for cars was also studied in Paper IV. Recommendations from the Swedish Aluminium Association¹ provided a basis for the selection of these products. The products, supply chains and companies were chosen to cover different application types and all the major production processes used within the Swedish aluminium industry. All large companies in the Swedish aluminium industry are covered by the five supply chains.

Figure 7 shows the supply chains studied in Papers III and IV together with the chosen system boundary. These supply chains will provide some understanding of how the companies in the supply chains of the aluminium industry can work together on improved energy efficiency, but will of course not provide the full picture of the production of the products. The aim was to study the production of aluminium products and the end-users of the products have therefore been excluded. No primary or secondary producer of aluminium was involved in the production of the truck chassis part. Instead, the chassis part producer has their own melting plant where they can produce billets from waste material from the chassis part production and from other components that the profile extruder produces.

Figure 7. The supply chains studied in Papers III and IV. From left: a heat exchanger for trucks, a balcony glazing system, a piece of furniture, a chassis part for trucks and a motor component for cars. Revised from Paper III.

¹ www.svensktaluminium.se

6

Methods and approaches

This chapter describes the methods and approaches that were used to answer the research questions in this thesis.

6.1 Research design

This section describes how the work with the thesis and the appended papers was structured. The aspects described in the section are mixed methods research approach, study types, inference types, interdisciplinarity and system thinking.

A mixed methods research approach was adopted in the thesis. The mixed methods research approach is the combination of different quantitative and qualitative methods within the same research project [108]. Bryman [108] stated that one reason for using a mixed methods research approach is that different research questions within a research project may need to be answered using different methods. The aim and research questions of the thesis can be broken down into several aspects, as indicated by sections 1.2, 1.3 and 1.4, and different methods are needed to study the different aspects. The methods used in the appended papers and thus in this thesis are shown in Table 4. When using a specific method, there are several factors that could affect the reliability of the results. This could, for example, be assumptions made in calculations or getting the correct person within the companies to be respondents for questionnaires or focus groups. Such factors are discussed in the appended papers.

Table 4. Methods used in the appended papers.

	Paper				
	I	II	III	IV	V
Literature review	X				
Assessment of effects on primary energy use, GHG emissions and energy and CO ₂ costs		X			
Focus group			X	X	
Questionnaire				X	X

Yin [109] divided research studies into three different types: descriptive, explanatory or exploratory. A descriptive study has the aim of describing a phenomenon in its real-world context [109]. Explaining how and why a condition came to be is the aim of an explanatory study

[109]. An exploratory study aims to identify research questions or procedures to be used in a future study [109]. Papers I–IV are all descriptive, while Paper V is explanatory.

There are three major types of inferences that can be used in research: deduction, induction and abduction [110]. The main difference between induction and deduction is the relationship between theory and research [108]. For deduction, theory is used to formulate hypotheses which are then tested and the results are used to reformulate the theory [108]. For induction, the theory is a result from a research effort, i.e. the generalisable conclusions from observations [108]. The abduction can be described as [111–113]: (1) the surprising (empirical) fact X is observed, (2) if hypothesis Y is (approximately) true, then X would be a matter of course, (3) hence, there is reason to, at least temporarily, believe that Y is plausible/true. Papers I–IV are all inductive, while Paper V is deductive. However, in line with Bryman [108], this distinction between inductive and deductive approach should be viewed as tendencies, rather than an unambiguous distinction that is always valid.

Wagner, *et al.* [114] stated that an interdisciplinary approach entails establishing a holistic view or common understanding of a complex issue, question or problem by integrating data, methods, tools, concepts and theories from different, separate disciplines. This thesis has adopted an interdisciplinary approach to gain a holistic view on how energy efficiency can be improved in the supply chains of the aluminium industry. For example, the thesis utilises different methods and tools to study the different aspects of the aim and the research questions. Additionally, the thesis also utilises concepts from different disciplines, e.g. engineering and organisational, economic, behavioural and environmental sciences.

System thinking, e.g. according to Churchman [115], was used implicitly in the work with the thesis and the appended papers, i.e. system thinking was used without the application of system theories. One reason for this is that the thesis and the appended papers mainly utilise a qualitative approach. System thinking is needed to achieve the highest possible energy efficiency improvement, as indicated by the discussions in the second paragraph of section 1.1 and the last paragraph of section 3.2. It is also necessary for understanding how companies work to improve energy efficiency and why the entire energy efficiency improvement potential is not always achieved in reality. For example, the company could have other objectives that are more important than working with improved energy efficiency.

6.2 Literature review

Energy efficiency measures for the production-related processes within the individual companies in the aluminium industry and aluminium casting foundries were identified through a literature review. A literature review was chosen as method since it would give the opportunity to identify potential energy efficiency measures that are specific to the aluminium industry and the aluminium casting foundries. It would also give the opportunity to identify a wide range of energy efficiency measures that are either currently available or under development.

The literature review can be divided into one unsystematic part and one systematic part. In the unsystematic part, a wide range of search strings was used, and the search process was characterised by probing. Further search strings were inspired by the references found in the previous search strings. In some cases, literature from the reference lists of the literature that already been found was also included. The EC's reference documents for BAT regarding non-ferrous metals industries [55], smitheries and foundries industries [73], and surface treatment of metals and plastics [61] provided a starting point for the work with the review. These documents provided some understanding of the field which was helpful for the continued work with the review, as well as a number of energy efficiency measures that were included in the results from the review.

To complement the unsystematic part, a more systematic search for literature was done in the second part of the review. Figure 8 illustrates the systematic search process. The search terms were searched for in titles, abstracts and keywords of articles indexed in the database Scopus. In a first step, the searches were limited to articles written in English or Swedish, and to the time period 2007–2016. The full-text availability through Linköping University Library was checked, and the titles and abstracts of the articles were read to limit the number of hits further. The final step consisted of a full-text analysis of the articles to identify the articles with relevant information about energy efficiency measures, which were included in the review.

The above search process identified some relevant energy efficiency measures for which the description of the measures was insufficient in the identified references. For these specific energy efficiency measures, additional searches for information were performed, mainly in Scopus but in some cases also in Google Scholar and Linköping University Library's UniSearch. The name or description of the energy efficiency measures was used to formulate the search strings in these cases.

Figure 8. The systematic search process. Reprinted with permission from Paper I.

The review includes 111 scientific references and six references from organisations and companies. The systematic part identified 90 scientific references, of which some were also found in the unsystematic part.

6.3 Calculation of the effects of energy efficiency measures on primary energy use, GHG emissions and related costs

This section describes the calculations carried out to estimate the effects on primary energy use, GHG emissions, and energy and CO₂ costs when energy efficiency measures are implemented in the electrolysis process in primary aluminium production. The calculations are limited to the electrolysis process due to a lack of data for the other production processes. The calculations have been carried out for both a single electrolysis plant that does not have the energy efficiency measures implemented yet and the entire global production through the electrolysis.

6.3.1 General assumptions

Only the prebaked anode technology will be considered in the calculations since around 95% of primary aluminium production worldwide uses the prebaked anode technology [49]. Table 5 shows the global averages for energy intensity and process-related GHG emissions for the electrolysis process.

Table 5. Global averages for energy intensity and process-related GHG emissions for electrolysis. Reprinted with permission from Paper II.

	Used value	Reference
Energy intensity	14.21 MWh/tonne Al	[62]
Process-related GHG emissions ^a	2.053 tonne CO ₂ eq/tonne Al	[49,116]

^a Emissions from both anode consumption and anode effects are included.

The single electrolysis plant studied is hypothetical and was assumed to be located in Europe. The annual production of the plant was assumed to be 200 ktonnes Al/year, which was based on common industry values in Europe. The energy intensity and process-related GHG emissions for the plant were assumed to be the same as the global averages in Table 5. The electrolysis process amounted to a total aluminium production of 64 336 Mtonnes Al/year globally in 2018 [117].

The calculations of the effects on costs used a price for CO₂ emissions of around EUR 30² per tonne CO₂eq, which is equal to the EU stated policies for 2030 given in the International Energy Agency [118]. This value was chosen since the studied energy efficiency measures largely provide future energy efficiency improvements (see section 6.3.3), and the single plant was assumed to be located in Europe. In

² The currency exchange rate on 3 February 2020 was used to convert the price from dollars to euros.

order to be consistent and make the results comparable, the same value was used for the entire global production through the electrolysis.

6.3.2 The energy efficiency measures studied

The energy efficiency measures studied were identified through the literature review described in section 6.2, and only measures with values for the energy end-use efficiency improvement potential were chosen. Table 6 shows the studied energy efficiency measures with their respective energy end-use efficiency improvement potentials and savings in process-related emissions. The energy efficiency measures are briefly described in the section of Table B1 in Appendix B that deals with the measures identified for electrolysis, and a more detailed description can be found in Paper I. Only a single value for the energy end-use efficiency improvement potential was available for many of the energy efficiency measures. For the energy efficiency measures where several values for the energy end-use efficiency potential were available, the mean, minimum and maximum values were used. The inert anodes have a negative energy end-use efficiency improvement potential when implemented on their own, meaning that the energy use in electrolysis is increased. The elimination of the process-related GHG emissions is the reason why the inert anodes were studied. Electricity can be used to supply the heat needed for the direct carbothermic reduction [119-121]. Electricity was therefore assumed to be the energy source utilised in the direct carbothermic reduction.

The process-related GHG emissions from electrolysis are eliminated entirely when implementing the energy efficiency measures in Table 6 that utilise inert anodes including the vertical electrode cells. Thus, the savings in process-related emissions for these energy efficiency measures are equal to the value in Table 5. The chemical reaction utilised in the direct carbothermic reduction is different to the reaction utilised in electrolysis, and uses fossil carbon as a reaction material. The carbothermic reduction has theoretical process-related GHG emissions of around 2.45 tonne CO₂eq/tonne Al [43,93,122]. The difference between the process-related emissions for electrolysis (presented in Table 5) and process-related emissions for the direct carbothermic reduction constitute the change in process-related emissions for the direct carbothermic reduction. The change in process-related emissions for the direct carbothermic reduction is negative, implying an increase in the process-related emissions from the implementation of the direct carbothermic reduction. No industrial implementation of the direct carbothermic reduction has been conducted yet, and hence there are no statistics on the process-related GHG emissions, which is the reason why the theoretical value was used.

Table 6. The energy efficiency measures studied with their respective energy end-use efficiency improvement potentials and savings in process-related emissions. The values for the energy efficiency improvement potentials are based on the literature review described in section 6.2, U.S. Aluminum Association [123], Peng, *et al.* [124] and Naixiang, *et al.* [125]. The information regarding the availability of the energy efficiency measures is taken from Paper I. The table is reprinted with permission from Paper II.

Energy efficiency measure	Energy end-use efficiency improvement potentials [MWh/tonne Al]		Savings in process-related emissions [tonnes CO ₂ eq/tonne Al]	Currently available?
	Mean	Min Max		
Generation 3 control system	0.355		0	Yes
Anode pre-heating	0.04		0	Yes
Slotted or perforated anodes	0.781		0	Yes
Novel structure cathodes	0.802	0.478 1.146	0	Yes
Optimised cathode collector bar structure	0.738		0	Yes
Distributed pot suction system	0.4		0	Yes
Wettable cathodes	1.98	0.4 3.1	0	No
Inert anodes	-1.427	-2.85 0	2.053	No
Inert anodes + wettable cathodes	3.553 ^a		2.053	No
Vertical electrode cells ^b	4		2.053	No
Direct carbothermic reduction ^c	4.954	2 7.08	-0.397	No

^a The energy end-use efficiency improvement potential for the combination of inert anodes and wettable cathodes is given as 25% in Paper I. This has been calculated in MWh/tonne Al by multiplying by the energy intensity in Table 5. Additionally, as stated in Paper I, the 25% is an estimate of the best possible energy end-use efficiency improvement.

^b Vertical electrode cells use inert anodes, wettable cathodes and low-temperature electrolytes, as stated in Paper I.

^c Direct carbothermic reduction is an alternative process to electrolysis.

6.3.3 Choice of electricity

A build margin perspective was chosen since this is relevant when studying future changes to the electricity system (e.g. future energy efficiency improvements). The studied energy efficiency measures (presented in Table 6) can be seen as long-term strategic investments, and some of the measures are not currently available but may be available in the future. This implies that the energy efficiency improvements from the energy efficiency measures will largely occur in the future. The build margin perspective involves an assumption about type of electricity generation facility that would have been built if the electricity demand had not been reduced [72]. Wind power and coal power are the two options that were used in the calculations.

Primary energy factors, emission factors and the cost of wind power and coal power are shown in Table 7. Extraction, refining and conversion of the fuel, the construction, operation and demolition of the conversion facility, waste from the conversion facility and the end-use of the energy are included in the primary energy factors and emission factors [68]. The chemical energy content of the coal is included in the primary energy factor, while the energy content in the wind is not included in the primary energy factor [68]. The cost of electricity generation was used in the calculations, since no values for the price of electricity generated from specific energy sources could be found. The cost of wind power includes only the generation cost of electricity, while the cost of coal power includes both the generation cost of electricity and the CO₂ price given in section 6.3.1. Investment, operation and maintenance costs of the conversion facility, and fuel costs are included in the generation cost of electricity [126]. If the electrolysis plant buys electricity from the electricity market, a higher price than the stated values in Table 7 will probably be paid. Thus, the economic savings from the implementation of the studied energy efficiency measures would probably be higher than what is presented in the results.

Table 7. Primary energy factors, emission factors and cost of wind power and coal power. Reprinted with permission from Paper II.

	Wind power	Coal power	Unit	Refer- ence
Primary energy factor	0.05	2.26	MWh _{primary} /MWh _{electricity}	[68]
Emission factor	0.013	0.759	tonne CO ₂ eq/MWh _{electricity}	[68]
Cost	50 ^a	63 ^{a,b}	EUR/MWh _{electricity}	[118,126]

^a The currency exchange rate on 3 February 2020 was used to convert the cost from dollars to euros.

^b Both the cost of electricity generation and the CO₂ price are included.

6.3.4 Calculation of effects on primary energy use, GHG emissions, and energy and CO₂ costs

Equation (1) below was used to calculate the effects on primary energy use per tonne of aluminium [MWh_{primary}/tonne of Al].

$$\text{Effects on primary energy use} = \text{energy end-use efficiency potential} \cdot \text{primary energy factor} \quad (1)$$

Equation (2) below was used to calculate the effects on GHG emissions per tonne [tonne CO₂eq/tonne of Al].

$$\text{Effects on GHG emissions} = \text{energy end-use efficiency potential} \cdot \text{emission factor} + \text{saving in process-related GHG emissions} \quad (2)$$

Equation (3) below was used to calculate the effects on energy and CO₂ costs per tonne [EUR/tonne of Al].

$$\text{Effects on energy and CO}_2 \text{ costs} = \text{energy end-use efficiency potential} \cdot \text{electricity cost} + \text{saving in process-related GHG emissions} \cdot \text{CO}_2 \text{ price} \quad (3)$$

The total effects for the entire plant and global production through electrolysis were obtained by multiplying the effects per tonne of aluminium by the annual production.

6.4 Focus groups

Focus groups were used to study how the companies in the supply chains can work together on improving energy efficiency and which demands that are placed on the companies and products in the supply chains. A focus group is where a group of people is gathered to discuss a certain topic for a limited time period [127]. Even though a moderator initiates and leads the discussion, the discussion between the participants should be free [127]. The topic and/or stimulus material is given prior to the focus group and is initiated by the moderator at the beginning of the focus group [127]. Focus groups were used as a method due to the opportunity of interaction between the respondents from the companies along the supply chains. The respondents could react and discuss the demands and energy efficiency measures highlighted by other respondents. Therefore, the complexity of energy and material flows through the supply chains is better studied with focus groups than with individual interviews.

The companies were free to choose their respondents and had the opportunity to send more than one respondent to ensure the attendance of respondents covering all the discussed topics. The companies were expected to send one respondent with knowledge about the company's production processes and energy use. The companies also had the opportunity to send a respondent working with supplier or customer contacts to cover the topics of customer demands and intercompany discussions when designing a product component. The respondents received the questions to be discussed prior to the focus groups. This was to give the respondents the opportunity to prepare and to decide whether they wanted to bring colleagues to the focus groups, or to discuss the questions with colleagues prior to the focus groups.

The main themes for the focus group discussions were (1) what the companies can do together to improve energy efficiency in the supply chain, (2) the potentials for improved energy efficiency, and (3) the demands from different actors and how these affect energy use and the work to improve energy efficiency. The questions sent to the respondents prior to the focus groups revolved around these three themes and were phrased in a general manner, i.e. not focusing on any pre-determined energy efficiency measures or demands. These questions provided a basis for the discussions during the focus groups, but did not strictly guide the discussions. Instead, the respondents were free in their discussions and had the opportunity to ask each other questions. The moderator gave an introduction at the beginning of each focus group and asked the initial question: "What can the companies do to make the energy use of the entire supply chain as energy efficient as possible?" After that, the moderator only guided the discussions to pick up loose threads in the discussions and to make sure that all three themes were covered to a sufficient extent. There was no direct competition between the companies in each focus group that would impede the discussions and openness characterised the discussions. The moderator had the possibility to ask additional questions by phone or e-mail after the focus groups to clarify parts of the focus group discussions.

One focus group was conducted for each supply chain illustrated in Figure 7. Respondents from all levels of the supply chain participated in each focus group. The exception is the focus group for the furniture supply chain, where the respondent from the primary aluminium producer could not attend in person. However, this respondent supplied their views on the questions by participating in two of the other focus groups, which was raised during the focus group discussion by the moderator. Furthermore, it was possible to ask the respondent from

the primary aluminium producer supplementary questions after the focus group discussion was finished. Although the end-users did not participate in the focus groups, their demands placed on the products and aspects of their energy use were raised by participants of the focus groups. The aluminium recyclers' demands were included through their participation in the focus group of the motor component supply chain and through the other companies' reflections.

The focus group discussions were audio recorded and transcribed in full, but were also coded to facilitate the analysis of the material. A code is a word or a short phrase that gives a summative description of a larger piece of text [128]. Before the coding began, it was decided to use "measure" (short for "energy efficiency measure"), "demand", and "potential" (short for "energy efficiency potential") as the "main" codes. More specific codes were developed based on the focus group material during the coding process itself. The specific codes for energy efficiency measures were created by adding a name or a short description of the measures. The type of demand and the actor making the demand provided a basis for the development of the specific codes for the demands. The energy efficiency potentials raised during the focus group discussions could concern either specific energy efficiency measures or the entire supply chain. The specific codes for the energy efficiency potentials could thus include either the name or a description of the specific energy efficiency measure, or the word "general" for potentials regarding the entire supply chain. Parts of the focus group material were considered potentially relevant to include in the articles despite not being directly related to the aim and research questions of the articles. Specific codes in addition to the "main" codes were developed for these parts of the focus group material.

The descriptive analysis approach described by Wibeck [127] was used when analysing the focus group material. The analysis started by grouping together all parts of the material from a focus group that dealt with the same aspect, e.g. energy efficiency measure or demand. The material for each aspect provided a basis for formulating a summarised description of the aspect. A separate text for each focus group was written that included the results from the specific focus group. These texts were sent to the respondents to verify the accuracy of the interpretations and to give the respondents the opportunity to supply additional information that they had thought of. Finally, the texts for the separate focus groups were combined.

6.5 Questionnaires

Two questionnaires were used in the research. The first was used to determine the status of the implementation of energy efficiency measures in the individual companies (questionnaire 1 below). The other was used to study the perceived importance of the barriers and drivers, and the usefulness of the information sources (questionnaire 2 below).

Questionnaires are advantageous when dealing with a large number of respondents and typically have mostly closed-ended questions [108]. Both questionnaires mostly used closed-ended questions. To answer the questions in the questionnaire described in section 6.5.1, the respondents needed to gather information that might be spread across several documents or among several employees. Both questionnaires were distributed to a relatively large number of respondents. These aspects make questionnaires suitable as a method in these cases.

The online software Survey&Report was used to distribute and answer both questionnaires. The first questionnaire was distributed during spring 2017, while the other was distributed during spring 2018. The companies' energy managers were prioritised as respondents and the questionnaire was sent to the CEO, production manager, or corresponding positions if there was no energy manager at the company. If an employee was considered better suited to answer the questionnaire, the respondents had the possibility to forward the questionnaire to that employee.

6.5.1 Questionnaire 1

The main part of the questionnaire consisted of a list of 82 energy efficiency measures. The energy efficiency measures that were included in the questionnaire are listed in Appendix A. All energy efficiency measures were grouped based on the type of measure or which process they are applicable to. The respondents were given the opportunity to add energy efficiency measures not found in the questionnaire. The respondents were asked to state whether each of the energy efficiency measures were (1) implemented, (2) planned to be implemented or implementation in progress, (3) possible to implement but not planned, (4) not technically applicable, or (5) unknown to the respondent. The respondents also had the opportunity to comment on their own answers.

Questions about the company's energy use and the potentials for improved energy efficiency for the entire company were also added to the questionnaire.

The literature review described in section 6.2 provided a basis for the inclusion of energy efficiency measures relating to production processes. The authors' knowledge about energy auditing in industry provided energy efficiency measures regarding support processes and additional measures for production processes.

A draft of the questionnaire was discussed at a workshop with representatives from the five large companies in the Swedish aluminium industry and the Swedish Aluminium Association.

Two reminders were sent by e-mail. A third reminder was conducted by sending the questionnaire in printed format to the respondents. For the third reminder, the respondents were given the opportunity to answer the printed version and send it back, or to answer the questionnaire online.

The questionnaire was initially sent out to a large number of companies. In Paper IV, the answers from the companies in the supply chain for the motor component (illustrated in Figure 7) were presented. However, all answers from companies in the Swedish aluminium industry and Swedish aluminium casting foundries are included in this thesis. The five companies in the Swedish aluminium industry and 39 aluminium casting foundries received the questionnaire. Four of the companies in the Swedish aluminium industry answered the questionnaire, resulting in a response rate of 80% for the aluminium industry. For the aluminium casting foundries, four complete and one partial answer were received, resulting in a response rate of 10% and 13%, respectively. The response rate for the entire population was 18% for complete answers and 20% when including the partial answers.

Answers on specific questions that were considered odd or apparently unreasonable were excluded from the presentation of the results in section 7.2.2.

6.5.2 Questionnaire 2

The questionnaire included 39 barriers, 48 drivers and 12 information sources. A Likert scale with the options "Never important", "Rarely important", "Fairly important", "Often important", and "Always important" was used, with the respondents being asked to rate the importance of each barrier and driver. Additionally, a Likert scale with the options "Do not use", "Not very good", "Fairly good", "Good", and "Excellent" was used, with the respondents being asked to rate the usefulness of each information source.

The questionnaire included a question regarding the changes in the companies' prioritisation of energy issues during the time intervals before 1996, 1996–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2018. The respondents were asked to rate the change within each

time interval on a Likert scale with the options “Do not know”, “Decreased priority”, “Unchanged priority”, and “Increased priority”. To verify the answers to this question, a question about how many years the respondents had worked at their respective companies was added to the questionnaire.

The following statement was presented to the respondents: “Energy efficiency measures exist that are not yet implemented at the company and that are cost-effective according to the company’s payback criteria.” A Likert scale with the options “Fully agree”, “Partially agree”, “Neutral”, “Partially disagree”, “Fully disagree”, and “Do not know” was used, with the respondents being asked to rate their agreement with the statement.

The questionnaire included questions about the following aspects of the companies:

- Number of employees
- Annual turnover
- Whether the companies had been profitable over the past three years
- What the payback criteria for energy efficiency investments were
- Whether the companies had a written long-term energy strategy
- How energy costs were allocated among divisions

Comparisons between the different respondents’ answers were facilitated by using closed-ended questions and Likert scales. Previous questionnaires and studies on Swedish industry (e.g. Nehler, *et al.* [35], Johansson and Thollander [39] and Lawrence, *et al.* [101]) provided a basis for formulating the questions, but some additional questions were added. This means that most questions have already been tested in action. The formulation of the questions was discussed at a workshop with representatives from four large aluminium companies in Sweden, the Swedish Aluminium Association and another research institute besides Linköping University. Additional comments were given by another person from the Swedish Aluminium Association through e-mail correspondence. A draft of the questionnaire was also reviewed by two PhD students working within the same research field.

Four reminders were issued in total, with the first two being sent by e-mail. The last two reminders were provided by telephone and the respondents were given the opportunity to answer the questionnaire either by telephone or online.

All five companies constituting the Swedish aluminium industry and 36 Swedish foundries casting aluminium alloys received the questionnaire. This questionnaire was sent to a lower number of aluminium

casting foundries than questionnaire 1 described in the previous section. One foundry was removed since they made it clear that they did not want to be part of the research project when they received the first questionnaire. Additionally, both questionnaires were sent to both the parent company and the three subsidiaries in one corporate group. The parent company answered this questionnaire and their answers were assumed to be applicable to the entire corporate group. In the first questionnaire (described in the previous section), the subsidiaries were included instead of the parent company, since there may be differences in how far the respective subsidiary has come in their work to improve energy efficiency.

All five companies in the Swedish aluminium industry answered the questionnaire, resulting in a response rate of 100% for the aluminium industry. Ten complete and two partial answers were received from the aluminium casting foundries, resulting in a response rate of 28% and 33% of the 36 aluminium casting foundries, respectively. The response rate for the entire population of 41 companies was 37% for complete answers and 41% when including the two partial answers. Technical difficulties with the software Survey&Report gave rise to the two partial answers. The respondents were asked to answer the remaining questions after the difficulties were identified and corrected but they did not do so.

7

Results and analysis

This chapter presents and analyses the results from the conducted research³. The structure of this chapter reflects the order of the research questions. The chapter starts with section 7.1, which identifies an energy efficiency gap and trends in the prioritisation of energy issues within the Swedish aluminium industry and Swedish aluminium casting foundries. The results for RQ1 are then presented and analysed in section 7.2 about improved energy efficiency within the individual companies and section 7.3 about improved energy efficiency for the entire supply chains. Finally, the results and analysis for RQ2 are presented in section 7.4 covering factors inhibiting or driving the work to improve energy efficiency in both the individual companies and the entire supply chains.

7.1 Existence of energy efficiency gap and changes in priority of energy issues

Respondents from all five companies in the Swedish aluminium industry agreed that energy efficiency measures existed that were cost-effective according to the companies' payback criteria and that had not yet been implemented. For the aluminium casting foundries in Sweden, respondents from nine companies agreed that such measures existed, while one respondent was neutral. This means that there was an energy efficiency gap in both the Swedish aluminium industry and the Swedish aluminium casting foundries.

Paper V showed that there was a trend of increased prioritising of energy issues during the period 2010 onwards in both the Swedish aluminium industry and aluminium casting foundries. The increase started even earlier in some companies.

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³ Some results are presented for specific respondents. The respondents have been numbered consistently in the thesis, i.e. respondent 1 is the same respondent throughout the thesis. This also means that not all respondents may be represented in all parts of the results and analysis.

7.2 Improved energy efficiency within the individual companies

This section will focus on improved energy efficiency within the individual companies in the aluminium industry and aluminium casting foundries.

7.2.1 Energy efficiency measures found in literature

Table 8 shows the energy efficiency measures identified through the literature review described in section 6.2. Many of the energy efficiency measures also have other benefits in addition to improved energy efficiency, e.g. time savings, higher productivity, lower dross generation, and lower environmental impact. Some of the energy efficiency improvements from oxy-fuel combustion will be offset by the energy needed to produce the oxygen.

Note that the energy efficiency improvement potential for the direct retrofit of inert anodes in Table 8 is negative, which means that the energy use for electrolysis increases. However, there is a potential energy efficiency improvement over the lifetime of the anodes when taking the energy use for anode production into account. The increase in energy demand in electrolysis (not considering anode production) from using inert anodes is the reason why inert anodes are considered together with technologies saving energy such as low-temperature electrolytes or wettable cathodes [129].

Paper I presents a detailed analysis of which energy efficiency measures can be combined. The analysis shows that many of the energy efficiency measures for each of the processes can be combined, i.e. there is no technical obstacle to combining the energy efficiency measures. The largest energy efficiency improvement could be achieved by combining the energy efficiency measures. However, energy efficiency measures may affect each other's energy efficiency improvement potentials when implemented together [130]. This results in the energy efficiency improvement potential for the combination possibly being lower than the sum of the energy efficiency improvement potentials for the individual energy efficiency measures. Even though energy efficiency measures can be combined, there may be occasions where it is sufficient to choose only one of the energy efficiency measures, since they achieve the same positive effect. In such cases, the measure with the highest energy efficiency improvement potential should be used. However, an investigation must be conducted in every case since not all energy efficiency measures may be applicable in every

case and the energy efficiency improvement potentials for the energy efficiency measures may vary from case to case.

All energy efficiency measures in Table 8 relating to electrolysis (except carbothermic reductions) can be combined, which would yield a larger energy efficiency improvement than implementing the individual energy efficiency measures separately. No energy efficiency improvement potential for this combination was found in the literature. Additionally, the energy efficiency improvement potential may be lower than the sum of the energy efficiency improvement potentials for the individual energy efficiency measures, as discussed in the previous paragraph. This makes it hard to determine how the combination of the energy efficiency measures for electrolysis compares to carbothermic reduction.

For recycling, the energy efficiency improvement potential achievable in each case varies depending on which recycling technique is employed. The recycling technique is, to a large extent, chosen based on the scrap type handled and may be less suitable for other scrap types. For example, recycling through hot extrusion and SPS is better suited to smaller scrap, e.g. chips and filings, and may not be suitable for larger scrap. Similarly, the energy efficiency improvement potential for casting may depend on the casting technique used.

Table 8. The energy efficiency measures found through the literature review described in section 6.2. A short description of each energy efficiency measure can be found in Appendix B and a more detailed description can be found in Paper I. – means that no energy end-use efficiency improvement potential was found. Revised from Paper I.

Process	Energy efficiency measure	Currently available?	Energy end-use efficiency improvement potential
General measures	Heat recovery and heat loss reduction, e.g. ^a :	Yes	Up to 40% [131,132]
	- Regenerative burners		23% [132]
	- Heat exchanger on flue gas, large furnace		2–5% [74]
	- Better insulation material		10–30% [74]
	- Pre-heat combustion air with heat from exhaust gases		15% [132]
	- Pre-heat hearth	Yes	10–20% [133]
	Stirring system or metal pumping, e.g.:		Up to 66.7% [134]
	- Metal pumping system, reverberatory furnace		50–60% [22,73]
	Immersed furnace heater		–
	Oxy-fuel combustion		5–15% [74]
	Non-stationary flame burners		5–10% [74]
	Furnace operation improvements, e.g. ^a :		5–10% [74]
	- The use of air-fuel control system	Yes	5–10% [74]
	- The use of furnace pressure system		5–10% [74]
	- Adjustment of burners for energy efficient operation		5–10% [74]
	- Improved control systems		15% [135]
	Gas purging system		18% or 0.3 kWh/kg Al [136]
	Increased aluminium surface emissivity		6% [21]
	Reduction of process scrap		–
	HTS induction furnace	No	–

^a More sub-measures are presented in Paper I, although no energy end-use efficiency potentials were found for those sub-measures.

Table 8. (continued)

Process	Energy efficiency measure	Currently available?	Energy end-use efficiency improvement potential
Electrolysis	Process performance improvements, e.g. ^a :	Yes	
	- Fuzzy controller with mathematical model for process temperature		0.6 kWh/kg Al [137]
	- Improved cell control point-feeding systems of existing point feeder prebaked cells		0.2 kWh/kg Al [74]
	- Generation 2 control system		0.4 kWh/kg Al [138]
	- Generation 3 control system		0.355 kWh/kg Al [138]
	Cell voltage noise reduction		-
	Ensure good anode quality		-
	Anode preheating		0.04 kWh/kg Al [139]
	Slotted or perforated anodes		0.781 kWh/kg Al [140]
	Optimised anode rod assembly design		-
	Graphitised cathode		-
	Novel structure cathodes		0.56–1 kWh/kg Al [124,125,141]
	Optimised cathode collector bar structure		0.738 kWh/kg Al [142]
	Reduced cell ventilation, e.g.:		-
	- Distributed pot suction system		0.4 kWh/kg Al [143]
	Addition of lithium fluoride		-
	Current switch bypass		-
	Improved electrical contact		-
	Lower temperature electrolytes		-
	Wettable cathodes		0.4–3.1 kWh/kg Al [144–147]

^a More sub-measures are presented in Paper I, although no energy end-use efficiency potentials were found for those sub-measures.

Table 8. (continued)

Process	Energy efficiency measure	Currently available?	Energy end-use efficiency improvement potential
Electrolysis	Inert anodes	No	-2.85–0 kWh/kg Al [148]
	- Electrolysis with direct retrofit		1 kWh/kg Al or 7% [148]
	- Electrolysis + anode production with direct retrofit		25% [123]
	- Electrolysis with inert anodes and wettable cathodes		2.4 kWh/kg Al during anode production + an energy efficiency improvement during electrolysis from using wettable cathodes [144]
	- Electrolysis with inert anodes and wettable cathodes		–
	Gas anodes	No	4 kWh/kg Al or 25–30% [129]
	Vertical electrode cells	No	–
	Corrosion-resistant sidewall refractory	No	–
	Carbothermic reduction ^b	No	2–7.08 kWh/kg Al or 15.4–51.3% [43,119,122,149]
	- Direct carbothermic reduction		–
	- Indirect carbothermic reduction		Up to 1 kWh/kg Al [47]
Recycling	Selecting appropriate melting furnaces and feed material	Yes	–
	Tilting rotary furnace	Yes	–
	Melting clean scrap	Yes	–
	Internal burner system	Yes	–
	Proper sealing of furnace door	Yes	–
	Targeted fume collection	Yes	–
	Reverberatory furnace with side well, charge well and metal pumping/stirring	Yes	–
	Recovery of components in skimmings, dross and salt slag	Yes	–
	Recycling through hot extrusion	Yes	90% [150]
	Spark plasma sintering	No	90–95% compared to hot pressing sintering [151]

^b These are alternative processes to electrolysis.

Table 8. (continued)

Process	Energy efficiency measure	Currently available?	Energy end-use efficiency improvement potential
Casting	Supply molten aluminium for direct moulding	Yes	1 kWh/kg Al [55]
	Arranging orders	Yes	–
	Electromagnetic casting	Yes	–
	Improved practices for molten metal transfer	Yes	–
Rolling	CRIMSON casting	No	64% when producing filter housing [152]
	Combined casting and rolling	Yes	1.3–7.19 kWh/kg Al [153,154]
	Al-Cu-Mn-Zr sheet alloys	No	25% [43]
	Isothermal extrusion	Yes	–
Heat treatment	Microwave heat treatment	Yes	–
	Heating ageing treatment or cooling ageing treatment	Yes	–
	Heat treatment based on casting method	Yes	–
	New sealing methods	Yes	–

7.2.2 Effects on primary energy use, GHG emissions, and related costs from improved energy efficiency in the electrolysis process

Figures 9, 10 and 11 show the savings in primary energy use, GHG emissions, and energy and CO₂ costs, respectively, from implementing energy efficiency measures at an electrolysis plant with an annual production of 200 ktonnes/year. Figures 12, 13 and 14 show the savings in primary energy use, GHG emissions, and energy and CO₂ costs, respectively, from implementing energy efficiency measures in the entire global production through the electrolysis process. It is worth noting that the savings potentials for the entire global production through electrolysis may be lower than what is stated in the figures, since some of the energy efficiency measures may already be implemented at some of the production sites worldwide.

Figure 9. The primary energy use savings from implementing energy efficiency measures at a single electrolysis plant with an annual production of 200 ktonnes/year. Both the savings per kilogram of aluminium and the total savings are shown by each bar. More than one value for energy end-use efficiency improvement was available for some energy efficiency measures, and a range in the primary energy use savings is shown for these measures. Reprinted with permission from Paper II.

Figure 10. The GHG emission savings from implementing energy efficiency measures at a single electrolysis plant with an annual production of 200 ktonnes/year. Both the savings per kilogram of aluminium and the total savings are shown by each bar. More than one value for energy end-use efficiency improvement was available for some energy efficiency measures, and a range in the GHG emission savings is shown for these measures. Reprinted with permission from Paper II.

Figure 11. The energy and CO₂ cost savings from implementing energy efficiency measures at a single electrolysis plant with an annual production of 200 ktonnes/year. Both the savings per kilogram of aluminium and the total savings are shown by each bar. More than one value for energy end-use efficiency improvement was available for some energy efficiency measures, and a range in the energy and CO₂ cost savings is shown for these measures. Reprinted with permission from Paper II.

Figure 12. The primary energy use savings from implementing energy efficiency measures in the entire global production through the electrolysis process. Both the savings per kilogram of aluminium and the total savings are shown by each bar. More than one value for energy end-use efficiency improvement was available for some energy efficiency measures, and a range in the primary energy use savings is shown for these measures. Reprinted with permission from Paper II.

Figure 13. The GHG emission savings from implementing energy efficiency measures in the entire global production through the electrolysis process. Both the savings per kilogram of aluminium and the total savings are shown by each bar. More than one value for energy end-use efficiency improvement was available for some energy efficiency measures, and a range in the GHG emission savings is shown for these measures. Reprinted with permission from Paper II.

Figure 14. The energy and CO₂ cost savings from implementing energy efficiency measures in the entire global production through the electrolysis process. Both the savings per kilogram of aluminium and the total savings are shown by each bar. More than one value for energy end-use efficiency improvement was available for some energy efficiency measures, and a range in the energy and CO₂ cost savings is shown for these measures. Reprinted with permission from Paper II.

The results in this section indicate that the type of electricity generation used has a significant impact on the potential savings in primary energy use, GHG emissions, and energy and CO₂ costs. The reason for this is that higher primary energy factors, emission factors and electricity costs generally result in higher savings from improving energy end-use efficiency. However, the energy efficiency measures with the highest savings in all three aspects (primary energy use, GHG emissions, and energy and CO₂ costs) include vertical electrode cells and the combination of inert anodes and wettable cathodes. These two measures would be among the measures with the highest savings, irrespective of whether the electricity generation in a specific region in the world depends on renewables or coal power, since the results indicate that these measures were among the measures with the highest savings when using either wind power or coal power.

The savings in primary energy use and energy and CO₂ costs from implementing direct carbothermic reduction are among the highest savings among the studied energy efficiency measures. Additionally, direct carbothermic reduction has one of the highest savings in GHG emissions when using coal power. However, there are increased GHG emissions from implementing the direct carbothermic reduction when using wind power. This is explained by the emission factor for wind power being too low to enable the GHG emission savings from the reduced energy use to compensate for the increased process-related GHG emissions. For wind power, the inert anodes are among the energy efficiency measures with the highest GHG emission savings. Thus, from a GHG emission perspective, direct carbothermic reduction is the more beneficial choice in regions with a large share of coal power, while inert anodes are the more beneficial choice in regions with a large share of renewables. The increased energy end-use in electrolysis from the implementation of the inert anodes implies that the inert anodes, in contrast to the other energy efficiency measures presented in Figures 9–14, benefit from the lower primary energy factor, emission factor and cost of wind power compared to coal power.

The negative saving in primary energy use when implementing the inert anodes by themselves implies increased primary energy use. This is explained by the increased energy end-use from implementing the inert anodes on their own. There are increased GHG emissions because of the increased energy use when implementing the inert anodes on their own. In most cases, an overall saving in GHG emissions is achieved, since the elimination of the process-related GHG emissions compensates for the increased GHG emissions from the increased energy use. There is an increase in energy and CO₂ costs when implementing the inert anodes by themselves, since the increased energy costs

due to the increased energy end-use are not compensated for by the reductions in CO₂ costs due to the elimination of the process-related emissions. However, a cost saving occurs for the inert anodes when the energy end-use remains unchanged, and the cost saving is only obtained from the elimination of the process-related GHG emissions. This suggests that a price may need to be imposed on GHG emissions in order to make inert anodes cost-effective by themselves. However, savings in all three aspects (primary energy use, GHG emissions, and energy and CO₂ costs) are achieved when inert anodes are combined with wettable cathodes or are part of vertical electrode cells.

7.2.3 Degree of implementation of energy efficiency measures

Table 9 shows the degree of implementation of the energy efficiency measures within the individual companies in the Swedish aluminium industry and Swedish aluminium casting foundries. The respondents had the opportunity to add energy efficiency measures not found in the questionnaire, which none of the respondents did. It can be seen that the companies have come some way in their work to improve their energy efficiency since there are energy efficiency measures that have already been implemented or are in the process of being implemented. However, there are still further improvements that can potentially be done since there are energy efficiency measures that are technically possible to implement but not yet planned to be implemented by the companies. The respondents did not give any values for how large the energy efficiency improvement potential for each energy efficiency measure was.

Some of the energy efficiency measures designated as not technically applicable by the respondents may not be applicable because of how the processes are designed within the companies. For example, there are several different types of furnaces that could be employed and some of the energy efficiency measures for furnaces might not be relevant for all furnace types.

Some of the energy efficiency measures that respondent 4 has assigned as unknown to the respondent could be possible to implement at their company, e.g. more efficient internal transportation and better insulation of building envelope. Hence, their company probably also has the potential for further energy efficiency improvements. This should be taken with some caution due to the limited knowledge about the company's pre-requisites for implementing the energy efficiency measures.

In Table 9, it can be seen that respondent 1 has not come as far in the work to improve energy efficiency as the other companies in the Swedish aluminium industry. Additionally, it can be seen that respondent 8 has a higher number of implemented energy efficiency measures than the other Swedish aluminium casting foundries. It can also be seen that respondent 18 has a higher number of energy efficiency measures where the implementation is in progress or planned than the other Swedish aluminium casting foundries. One explanation for these differences between companies could be the differences in the perceived importance of barriers and drivers. However, it is hard to draw any conclusions regarding the impact on how far the companies have come in their work to improve energy efficiency from differences in the perceived importance of barriers and drivers. One reason is that there is no significant difference between respondent 1 and the other companies in the Swedish aluminium industry, and between respondent 8 and the other Swedish aluminium casting foundries regarding the perceived importance of barriers and drivers (see Appendix C). Respondent 18 did not answer the questionnaire for the barriers and drivers. There could be other factors affecting how far the companies have come in their work to improve energy efficiency, and further investigations are needed to determine these factors.

Table 9. The degree of implementation for the energy efficiency measures within the individual companies in the Swedish aluminium industry and Swedish aluminium casting foundries. Only answers for processes that each company has within their organisation are included in the table. The respondents were able to choose several options for the same energy efficiency measure. Only respondents answering the questionnaire described in section 6.5.1 are included in the table.

Respondent	Number of energy efficiency measures				
	Imple- mented	Implemen- tation in progress or planned	Possible but not planned	Not techni- cally appli- cable	Unknown to the re- spondent
Aluminium industry					
1	7	4	50	5	0
2	15	22	22	8	6
3	25	16	21	12	0
4	30	23	0	0	31
Foundries					
7	9	3	19	4	27
8	27	4	15	16	0
17	11	7	7	10	28
18	11	21	11	6	13
19 ^a	8	12	7	14	3

^a This respondent did not answer the entire questionnaire.

Figures 15, 16 and 17 show the degree of implementation for the energy efficiency measures for production processes, support processes and others, respectively. It can be seen that the improvements in energy efficiency have mainly focused (energy efficiency measures where the implementation is finished, in progress or planned) on furnaces, support processes and others. The high degree of implementation for furnaces, support processes and others may be a result of the fact that those types of energy efficiency measures can be conducted by the majority of the companies. For example, all companies have furnaces and ventilation within their facilities. Another reason may be that furnaces, support processes and others, in many cases, have a higher number of energy efficiency measures included in the questionnaire than the other processes (see Appendix A).

Further improvements in energy efficiency can mainly be achieved in furnaces, recovery, space heating, energy management, ventilation and compressed air (energy efficiency measures which are possible to implement but not planned). There might be further energy efficiency improvements that could be achieved but are not accounted for here since energy efficiency measures might exist that are not included in the questionnaire. However, none of the respondents added any additional energy efficiency measures, which reduces the risk of any potential measures being missed.

Figure 15. The degree of implementation for the energy efficiency measures for production processes. Only answers from companies that have the specific process within their organisation are included under each process (primary aluminium production: one company; casting: nine companies; extrusion: one company; material choice, heat treatment, surface treatment: three companies; sorting of scrap: four companies; furnaces: nine companies). One respondent did not answer the entire questionnaire. Each process includes several potential energy efficiency measures (see Appendix A). The frequency is the number of times each alternative was chosen by the nine respondents for all included energy efficiency measures⁴.

⁴ For example, for the measure “magnetic stirrer in furnace” within the process “furnace”, the respondents answered as follows: three respondents chose “implemented”, two chose “implementation in progress or planned”, two chose “not technically applicable”, and one chose “unknown to the respondent”.

Figure 16. The degree of implementation for the energy efficiency measures for support processes. All companies answering the questionnaire utilise the processes included in the figure. Steam systems have been excluded from the diagram since none of the companies had steam systems within their facilities. One respondent did not answer the entire questionnaire. Each process includes several potential energy efficiency measures (see Appendix A). The frequency is the number of times each alternative was chosen by the nine respondents for all included energy efficiency measures⁴.

Figure 17. The degree of implementation for other energy efficiency measures. All companies answering the questionnaire utilise the processes included in the figure. One respondent did not answer the entire questionnaire. Each process includes several potential energy efficiency measures (see Appendix A). The frequency is the number of times each alternative was chosen by the nine respondents for all included energy efficiency measures⁴.

7.2.4 Energy saving potentials for the companies

Figure 18 shows the energy saving potentials as percentages of the total energy use in-house at individual companies in the Swedish aluminium industry and aluminium casting foundries as estimated by respondents from the companies. The cost-effectiveness of the technology is according to the companies' payback criteria. It can be seen that respondent 17 has the largest percentage saving. Respondent 2 has among the lowest percentage savings, but has the largest savings measured in MWh/year due to their large energy use. In total, 126–185 GWh/year can be saved in the Swedish aluminium industry through both improved technology and management, which corresponds to 5.1–7.4% of the total energy use. The Swedish aluminium casting foundries can save a total of 8–15 GWh/year through both improved technology and management, which corresponds to 11–21% of the total energy use. Respondent 19 is excluded from the total energy saving for the foundries since they only gave a percentage saving and no energy use. Additional energy savings can be achieved by the companies that did not answer the questionnaire described in section 6.5.1 (and are therefore not included in Figure 18).

It can also be seen that respondents 17 and 18 have stated that there is no potential for energy savings through managerial measures within their companies. Respondent 17 ranked “no opportunities for improved energy management” as a fairly important barrier to improved energy efficiency within the individual company. This means that although respondent 17 does not believe that there are any energy savings through improved energy management within their company, they do not perceive that the lack of opportunities for improving energy management is a major barrier to improved energy efficiency. The improved energy efficiency would instead be associated with the utilisation of more energy-efficient technology. This is supported by respondent 18, who stated that the remaining potential at their company only relates to improved technology since they have been successful in their work with energy management.

The payback criteria for energy efficiency measures are <3 years for respondents 1, 2 and 4, depend on the investment for respondent 3 and are lacking for respondents 7 and 8. Information regarding the payback criteria is not available for respondents 17, 18 and 19, since they did not answer the questionnaire described in section 6.5.2. It is not possible to draw any conclusions regarding the impact of the payback criteria on the stated values for the energy saving potentials.

Figure 18. Energy saving potentials as percentages of total energy use for individual companies in the Swedish aluminium industry and aluminium casting foundries as estimated by respondents from the companies. The blue bars are for cost-effective technology only, while the orange bars show the size of additional saving that could be achieved through energy management. Most companies gave intervals for the potentials, while some respondents gave single values, which is indicated in the figure. Only respondents answering the questionnaire described in section 6.5.1 are included in the figure.

7.3 Improved energy efficiency in the entire supply chains

7.3.1 Energy efficiency measures for supply chains

Table 10 shows a compilation of measures and areas for improved energy efficiency where the companies in the supply chains can work together. The joint work between the companies in the supply chains is needed for achieving further energy efficiency improvements compared to the companies only working on their own. For the material waste, the most beneficial measure from an energy perspective would be to reduce the amount of scrap generated, but the scrap should be utilised if it does occur.

Table 10. Brief compilation of measures and areas for improved energy efficiency where the companies in the supply chains can work together. The measures and areas were identified through the focus groups described in section 6.4. The table is based on Paper III. A more detailed description of the areas and measures is found in Paper III.

Measure/area	Description	Positive effects
Product design	Working with the product design both in the initial design phase and for existing products to improve the energy efficiency of the product and its production.	Easier and more efficient production, e.g. lower energy use, material use and material waste. More efficient products in use.
Communication and collaboration	Communication and collaboration between all the companies in the supply chain.	Avoiding sub-optimisation of the energy use in the supply chain, and unnecessary product disposal and material waste.
Transportation between sites Delivery of molten aluminium Material waste reduction	Optimisation of transportation, reducing the transportation distance and increasing payload of trucks. Delivering metal in molten form to a foundry using special trucks equipped with thermally insulated transport crucibles. Reducing material waste throughout the supply chain.	Reduced fuel demand per transported tonne of product. Eliminating the need to remelt the metal at the foundry. Reducing energy needed to remelt the material waste. Reducing the amount of primary aluminium needed to replace the oxidation losses occurring during remelting.
Closed-loop remelting	Material waste throughout the supply chain is remelted within the company or sent back to the supplier for remelting instead of being sold on the open market.	A minimal environmental impact per produced tonne of metal due to avoided need to dilute impurities and add alloying elements [155].
Metal source	Replacing primary aluminium with secondary aluminium or remelted material waste from the supply chain.	An energy efficiency improvement of about 95% in metal production.

Table 10. (continued)

Measure/area	Description	Positive effects
Assisting energy audits at suppliers	Larger companies in the supply chain can offer a service to conduct energy audits at other companies in the supply chain that lack their own resources for conducting energy audits. This service can ideally be offered to a supplier with a demand that the supplier's monetary savings from the energy efficiency measures should result in a lower product price.	Improved energy efficiency at companies without resources for conducting their own energy audits.
Energy audit for the entire supply chain	Auditing the energy use of the entire supply chain and visualising it to the companies.	Provides information for understanding the energy use and discussing where the main focus of the work to improve energy efficiency should be directed.
Environmental classification	An environmental classification system where both suppliers and products are scored based on different aspects.	The classification system could act as a driver for improved energy efficiency and reduced environmental impact since it becomes clear what is measured.
More research	More research regarding energy issues within the aluminium industry.	Identification of new ways for the companies to achieve energy efficiency improvements.

The joint work between the companies in the supply chain is needed in order to avoid sub-optimisations in the total energy use of the entire supply chain and to achieve energy efficiency improvements. One reason for this is that decisions made by one company could affect the other companies in the supply chain and their energy use. For example, the strength of the alloy used in the product has a direct impact on how easy the metal is to extrude and thus the energy use within the company working with profile extrusion. Another reason is that some energy efficiency measures involve two or more of the companies in the supply chain, e.g. collaboration on product design. Finally, some energy efficiency measures can result in an increased use of energy or other resources in one part of the supply chain but reduced use in another part, resulting in an overall saving when considering the entire supply chain. One example of this is the delivery of molten aluminium to a foundry.

An energy audit for the entire supply chain could be conducted as a first step in the joint work between the companies in the supply chains. The reason for this is that energy audits provide information needed for making decisions on where the joint work on improved energy efficiency should be directed.

Better communication and closer collaboration between all the companies in the supply chain is one of the most important aspects of the joint work to improve energy efficiency. It would be beneficial to discuss energy aspects explicitly rather than indirectly, and to have a continuous discussion about energy aspects with more collaborative work and regular meetings. A wider exchange between the companies than only having a couple of contact persons at the other companies would facilitate discussing a wider range of questions. Discussing and communicating decisions made by one company to the other companies is needed in order to avoid increased energy use. Knowledge about the other companies' production processes and the correlated energy use facilitates the joint work to improve energy efficiency in the supply chain. It would be beneficial to allow all companies in the supply chain to give feedback and suggestions on product design, both in terms of the initial design and when improving the design of existing products.

Another important aspect is the use of secondary aluminium or remelted material waste rather than primary aluminium. The companies in the supply chains should work together to increase the use of secondary aluminium in their products. This could be facilitated by reviewing the product specifications, the demands on material properties and how much these can deviate from the specified values. It is also important that the companies facilitate the recycling of the aluminium when the product reaches the end of its life, e.g. by making changes to the product design.

7.3.2 Energy efficiency improvement potentials for supply chains

The greatest energy efficiency improvement potential would probably be within each individual company through its own individual work and not in the joints between the companies in the supply chain. This was agreed on during the focus group discussion for the motor component. However, the supply chain perspective was highlighted as being important by the respondents in order to gain an understanding of the broader picture and to optimise the energy use of the entire supply chain, both within the companies and between the companies.

During the focus group discussion for the balcony glazing system, it was stated that the primary aluminium producer has a large internal energy efficiency improvement potential, which has no direct effect on their customers. The primary aluminium producer estimated that only 5% of the potential energy efficiency improvements would come from working with other companies, while the remaining 95% relates to improvements within their own company. On the other hand, the balcony glazing system producer believed that there are no major energy efficiency improvements that can be achieved in their production, since their processes are so basic. This difference arises due to (1) the production processes used by the primary aluminium producer being more energy-intensive than the production processes used by the balcony glazing system producer, and (2) the maturity levels of the companies. This can be interpreted as suggesting that the types of production process used at the company and their energy intensity determine, to some extent, whether the largest energy efficiency improvement potential is within the company or in the joint work with the other companies in the supply chain. This implies that the companies may be differently inclined to work together with the other companies in the supply chains, since some companies may have a greater energy efficiency improvement potential within their own facilities. However, even if a company's main energy efficiency improvement potential is within its own operations, there are benefits of working together with the other companies in the supply chain.

7.4 Factors hindering or driving improved energy efficiency

There are factors that have impacts on the work to improve energy efficiency both within the individual companies and in the entire supply chains. There are barriers that inhibit the implementation of energy ef-

efficiency measures within the individual companies in the Swedish aluminium industry and the Swedish aluminium casting foundries. Additionally, there are drivers that incentivise the implementation of energy efficiency measures within the individual companies. Similarly, energy use and the work to improve energy efficiency in the supply chains can be directly or indirectly affected by demands that different actors (either internal or external to the supply chain) place on the companies and the products. These demands can be categorised as dealing with either economics, product quality and performance, and environment.

Paper V showed that different types of risks, as well as the cost of production disruption, complex production processes and technology being inappropriate at the site, are among the most important barriers to improved energy efficiency within the individual companies.

Economic drivers were ranked as the most important category of drivers by respondents in the aluminium casting foundries when improving energy efficiency within the individual companies. Respondents in the aluminium industry ranked economic drivers as the third most important category of drivers. However, many of the economic drivers were viewed as often or always important by respondents in the aluminium industry (see Table C3 in Appendix C). Similarly, the economic aspect was found to be an important driver for improving energy efficiency in the supply chains. Examples are price demands from customers and monetary savings from improved energy efficiency that can help lower the product price.

Paper V showed that the companies' profitability does not appear to affect how they perceive the importance of access to or lack of money to invest in improving energy efficiency. There is an incentive for the studied companies to work to improve energy efficiency, regardless of their profitability, since both the aluminium industry and the aluminium casting foundries are energy-intensive and improving energy efficiency can reduce costs. Paper V also found that the companies' profitability does not appear to affect how they perceive the importance of the barrier "uncertainties regarding the company's future".

Access to knowledge within the companies about their processes and daily operations and the ability to make use of and spread this knowledge are important factors for improving energy efficiency within the individual companies. This was also perceived as important drivers for improved energy efficiency by the respondents. Access to knowledge is needed for overcoming some of the barriers perceived as being the most important by the respondents. One example is the barrier "complex production processes". More knowledge about the processes and their operation is needed when dealing with complex processes to avoid negative effects on the processes and production when

making changes. Other examples are “technical risks such as risk of production disruption”, “risk of poor performance of purchased equipment or after changed working routines”, “risk of changes affecting production capacity” and “risk of changes affecting product quality”. Such risks and the best ways to deal with them could be foreseen with knowledge about the processes. The identification of potential energy efficiency measures requires knowledge about the processes and their operation. Employees’ knowledge about the processes and their operation, and about energy efficiency measures and energy-efficient operation of the processes, should be improved through education provided by the companies.

A culture within the company that promotes the work to improve energy efficiency is an important factor for driving this work within the individual companies. Employees with real ambitions about energy efficiency improvements and supported from top management and company owners are important. An employee with real ambitions could, for example, propose energy efficiency measures or influence other employees through their work. The person with real ambitions should ideally be represented in the top management of the company [36]. Well-functioning relations within the company are important, e.g. when utilising the knowledge of employees. It is important to have two-way communication between the company’s management team and the production and operation teams when working with improved energy efficiency [101].

A long-term energy strategy is important for driving the work to improve energy efficiency and to achieve continuous improvements, since it provides a basis for the work to improve energy efficiency and is something that employees can relate to in their daily work. A long-term energy strategy is an important element of successful energy management [39,156], and the strategy acts as a driver for overcoming strict payback criteria [37,100] and other barriers [34].

Networking within the sector could provide companies with information on energy efficiency measures [157] and inspiration for working with improved energy efficiency [158], and is therefore an important factor for working with improved energy efficiency. This networking could be facilitated by the trade organisation providing an arena for networking. The trade organisation and colleagues within the sector are familiar with the conditions within the specific industry and the production processes it uses. Additionally, the best way to reach out to the companies is targeted information from close range through such channels as meetings and networks [40].

Paper V showed that there appears to be a potential for improving the product information on energy use/efficiency and performance of

equipment from technology suppliers. A policy demand for energy labelling of industrial equipment similar to the one for household appliances could facilitate the improvement of product information. Information on energy-efficient operation of the equipment should also be provided by the technology suppliers.

Respondents from both the aluminium industry and aluminium casting foundries ranked energy audits as among the most useful information sources for improved energy efficiency within the individual company. Additionally, demands to conduct energy audits were ranked as an “often important” driver for improved energy efficiency within the individual companies by the aluminium industry. Energy audits provide an overview of a company’s energy use and how the energy use is allocated between the processes used by a company [130]. They also provide a list of potential energy efficiency measures that can be implemented within the company [130]. Larger companies in supply chains can assist other companies in the supply chain that do not have their own resources for conducting energy audits, as stated in Table 10. This can be one way of providing an additional driver for the work to improve energy efficiency within the individual companies, since the benefits associated with energy audits are spread to a larger number of companies. Energy audits for entire supply chains were mentioned during the focus group discussions as a potential energy efficiency measure for the supply chains. This implies that energy audits and demands to conduct energy audits could also act as drivers for improved energy efficiency in the entire supply chains.

Demands from customers and authorities were found to be important drivers for improved energy efficiency in the supply chains. Demands and questions from customers were also perceived as an important driver for improved energy efficiency within the individual companies in the Swedish aluminium industry and the Swedish aluminium casting foundries (see Tables C3 and C4 in Appendix C). Additionally, most of the drivers categorised as governmental and policy drivers were perceived as being fairly or often important for improving energy efficiency within the individual companies in the Swedish aluminium industry and the Swedish aluminium casting foundries (see Tables C3 and C4 in Appendix C). This means that demands from customers and authorities are also important for improving energy efficiency within the individual companies. Although the companies can save money through improved energy efficiency, demands from customers and authorities would provide an additional incentive to engage in the matter. Economic policy instruments were highlighted by respondents in one of the focus groups as a way of increasing the companies’ interest in energy and environmental issues.

Demands from customers regarding energy commonly relate to the use of green energy rather than improved energy efficiency. Placing demands on energy-efficient production and a company's improved energy efficiency would require the actors (placing the demand) to have deeper knowledge compared to demanding green energy. However, the primary aluminium producer believed that requiring a company to implement an energy management system certified according to ISO 50001 to ensure active work to improve energy efficiency would be easier for the customer than demanding a certain level of energy efficiency in the company's processes. On the other hand, the furniture producer believed that the values and corporate cultures of their suppliers are of greater importance than the suppliers having ISO certifications. Similarly, the aluminium industry has ranked drivers that can be classified as relating to corporate culture ("full support from top management", "demands from owners" and "well-functioning relations within company") as more important than energy management systems (see Table C3 in Appendix C). Customers may start to demand extracts from their suppliers' energy audit reports to see how their energy use is allocated among the various processes. The environmental classification system stated in Table 10 is another way to formulate demands, regarding improved energy efficiency and reduced environmental impact, in a clear way.

The demands placed on the companies and products in the supply chains can sometimes counteract each other. For example, end-users have demands in terms of a car's horsepower, which makes it harder to meet another common demand from end-users, namely improved energy efficiency of the car. Some demands are more important to meet than improving energy efficiency, for example demands regarding economic feasibility and product quality. Thus, improving the energy efficiency of the supply chains and designing the products to be energy efficient in use phase can sometimes be hard. Reviewing the demands to see whether any of them could be changed would be beneficial. For example, some demands may be changed to allow for the use of secondary aluminium instead of primary aluminium, resulting in large energy efficiency improvements in the first parts of the supply chains. Another example is that unnecessary scrapping of metal that does not fulfil surface finish demands could be reduced by lowering unnecessarily high demands in terms of the surface finish for product parts that are not visible.

8

Discussion

This chapter discusses the results in the thesis. Additionally, the achievement of carbon neutrality in the production and processing of aluminium and the generalisability of the results are discussed. Finally, the chapter discusses relevant recipients of the results. The same numbering of respondents is used in this chapter as in the previous chapter.

This thesis identified several opportunities for improved energy efficiency both within the individual companies and in the entire supply chains. These would have significant potentials for improving energy efficiency in the aluminium industry and its supply chains, both in Sweden and internationally. This thesis also identified several factors affecting whether these potentials would be realised in the aluminium industry and its supply chains.

8.1 Energy efficiency measures

It is not possible to prioritise the energy efficiency measures presented in this thesis using the information available about the measures. The energy efficiency measures would be prioritised using information regarding, for example, the energy efficiency improvement potentials, investment cost, economic feasibility, the ease of implementing the measures and other potentially relevant aspects. Values for the energy efficiency improvement potentials are available for some of the measures, but not all of them. Information regarding investment cost, economic feasibility and ease of implementation for the energy efficiency measures identified through the data collection of the thesis is scarce.

Some processes have attracted more interest in the work to improve energy efficiency associated with the companies in the Swedish aluminium industry and aluminium casting foundries. There could be several reasons for this. One factor could be the complexity of the technology. Westling [159] states that procuring technology is easier for single components or simple systems than for complicated systems or entire facilities. The barrier “complex production processes” was perceived as often important by the Swedish aluminium industry and fairly important by the Swedish aluminium casting foundries. The size of the investment cost for the energy efficiency measure could have an

impact on how the decision process for investing in the measures is conducted [160]. Another factor could be that for some processes, e.g. lighting and compressed air, there are energy efficiency measures that could be viewed as standard solutions and can be implemented by most companies utilising the specific process. Finally, the perceived importance of barriers to the implementation of energy efficiency measures could vary depending on the characteristics of the energy efficiency measures [161]. Certain processes could attract more or less interest in the work to improve energy efficiency depending on which barriers and drivers are the most prominent for the specific processes. Further research is needed to determine which factors affect the degree of implementation of energy efficiency measures in specific processes and to determine why certain processes have attracted more interest in the work to improve energy efficiency than others.

8.2 Energy efficiency improvement and energy saving potentials

Energy saving potentials of 5.1–7.4% in the Swedish aluminium industry and 11–21% in the Swedish aluminium casting foundries including both cost-effective technology and improved management were identified in section 7.2.4. These values are comparable to the 9.7% identified in the Swedish iron and steel industry [98], the 12% identified in Swedish manufacturing industries [162], the 13% identified in the Swedish wood industry [163], and the 14% identified in the European pulp and paper industry [164]. The values from Brunke, *et al.* [98] and Backlund, *et al.* [162] include both cost-effective technology and improved management. The value from Johnsson, *et al.* [163] includes both technical and managerial measures, but how great a proportion of the values is cost-effective is not indicated in their paper. The value from Moya and Pavel [164] includes both available technical measures and breakthrough innovations.

The energy efficiency improvement and energy saving potentials stated in this thesis should be viewed with caution. Some potentials have been estimated by respondents in the Swedish aluminium industry and aluminium casting foundries. Some potentials are taken from literature and the potentials may vary from case to case, with a site-specific investigation being required for each case. The difference between the technical and economic potential must also be acknowledged. The economic potential is typically lower than the technical potential since energy efficiency measures that are not cost-effective have been excluded [165], although they may be technically possible to implement. An economic evaluation was not conducted in this thesis due

to a lack of data necessary for an economic evaluation. However, the energy saving potentials for the individual companies in Figure 18 are showing the economic potentials, which were estimated by respondents from the companies.

8.3 Factors affecting the work to improve energy efficiency

The results in the thesis show that both economic aspects and other aspects, e.g. demands from customers and authorities, and knowledge and the culture within the company, are important for driving the work to improve energy efficiency, both within the individual companies and in the entire supply chains. Similar results have been identified in previous research on both individual companies (e.g. [34,40,97]) and supply chains (e.g. [87,107,166]).

Some policy implications can be drawn from the results in this thesis. The economic aspects were shown to be important drivers and the economic feasibility of energy efficiency measures can be affected by different economic policy instruments. It would also be beneficial to formulate policy measures relating to other important drivers or barriers, e.g. long-term energy strategies and energy audits.

There are a couple of factors affecting the reliability of the results regarding barriers to and drivers for improved energy efficiency within the individual companies. The first is the variations in the answers for all barriers and most drivers for both the aluminium industry and the aluminium casting foundries. A more unanimous view on the importance of a specific barrier or driver is indicated by smaller variations in the answers. The other factor is the low response rate for the aluminium casting foundries (28–33%). This means that the results for the aluminium casting foundries are applicable to the companies answering the questionnaire rather than the entire aluminium casting foundry industry. However, Paper V showed that some results for the aluminium casting foundries may be viewed as more general since some barriers, drivers and information sources were given a similar rating in the paper as in previous research on foundries.

8.4 Achieving carbon neutrality in the production and processing of aluminium

There is a future potential of achieving carbon neutrality in the production and processing of aluminium. For electrolysis, one approach

would be to combine inert anodes with wettable cathodes, low-temperature electrolytes, vertical electrodes and the other energy efficiency measures presented in this thesis. Additionally, carbon-neutral electricity should be used in the process. This will eliminate both process-related and energy-related GHG emissions, as well as reducing energy use and most likely energy costs. The inert anodes will not be consumed in the process, which results in a lower dependence on coal. The dependence on coal may be eliminated altogether depending on which materials are used for inert anodes, wettable cathodes and corrosion-resistant sidewall refractory.

Another approach for electrolysis would be to use anodes made from carbon from biomass sources. Alternatively, electrolysis could be replaced with a (direct or indirect) carbothermic reduction utilising carbon from biomass sources as the reaction material. The advantage of using carbothermic reduction (either the direct process or any of the indirect ones) is the lower energy use compared to electrolysis without any major energy efficiency improvements. However, all energy efficiency measures for electrolysis presented in Table 8 (excluding carbothermic reduction) can be combined. No energy efficiency improvement potential was identified in the literature for such a combination, which makes it hard to make a comparison with direct carbothermic reduction. No values for the energy efficiency improvements were found for any of the indirect carbothermic reductions, which makes a comparison with electrolysis impossible. Direct carbothermic reduction has the disadvantage of higher demand for reaction material (carbon) compared to electrolysis (theoretically about 0.67 tonnes C/tonne Al [149] for direct carbothermic reduction compared to about 0.46 tonnes C/tonne Al in industrial applications [49] and a theoretical value of about 0.33 tonnes C/tonne Al for electrolysis [94]). Lorentsen [167] estimated that more than 100 million tonnes of bio-coke per year would be needed to replace the aluminium production in 2014 with direct carbothermic reduction. Biomass can be viewed as a limited resource, and both local and international competition for biomass is to be expected in the future [168]. There is a risk that the demand for biomass in aluminium production cannot be met by the biomass available globally, or that use of biomass will not be economically feasible since the price of the biomass will become too high.

Industrial companies may be more inclined to choose the direct carbothermic reduction over the inert anodes due to the significant savings in energy and CO₂ costs indicated by Figures 11 and 14. However, this would result in increased GHG emissions if the company use low-carbon electricity and fossil coal as reaction material. When a com-

pany uses low-carbon electricity, inert anodes would be a better solution from a GHG emission perspective. However, the change to inert anodes means that the energy use for electrolysis will increase or in the best case be unchanged. There is a trade-off between low energy use and low GHG emissions when only taking electrolysis into account and only implementing the inert anodes on their own, although there is an energy efficiency improvement in the anode production. The increased energy use will lead to higher costs for electrolysis. However, the longer lifetime of inert anodes could lead to lower costs compared to replacing carbon anodes that are consumed after about four weeks. Inert anodes are still under development [169], which makes an evaluation of the cost balance of inert anodes hard today. However, Padamata, *et al.* [169] believe that inert anodes are economically beneficial due to the expensive production of carbon anodes. Combining inert anodes with other energy efficiency technologies, e.g. wettable cathodes or as a part of vertical electrode cells, would be necessary to keep the energy use as low as possible in electrolysis. The vertical electrode cells and the combination of inert anodes and wettable cathodes have comparable savings in energy and CO₂ costs as the direct carbothermic reduction, as indicated by Figures 11 and 14. Another factor that can improve the cost-effectiveness of inert anodes compared to carbon anodes is a policy that puts a price on GHG emissions, e.g. a carbon tax or an emission trading system. However, an economic evaluation taking into account all costs associated with inert anodes, e.g. investment cost, the longer lifetime of inert anodes compared to carbon anodes and the increased energy costs, is needed in order to make a decisive recommendation on how high the price on GHG emission should be to make the inert anodes cost-effective.

To achieve carbon neutrality in the electrolysis process, further research and development is needed for the energy efficiency measures that are not currently available (see Table 8). For the other processes used to produce and process aluminium, carbon neutrality is achieved by utilising carbon-neutral energy in the processes. These processes would also benefit from improved energy efficiency and some energy efficiency measures are presented in this thesis.

There are several factors that can either inhibit or drive the work to achieve carbon neutrality in the production and processing of aluminium. The results and discussion in the thesis regarding barriers, drivers and demands are, to a large extent, also applicable to the work to achieve carbon neutrality, due to the importance of energy efficiency improvements for achieving carbon neutrality. Additionally, some results regarding barriers, drivers and demands are more widely applica-

ble than only for improved energy efficiency. For example, the economic aspect and demands from customers and authorities were found to be important drivers for improved energy efficiency both within the individual companies and in the supply chains. The economic aspects and demands from customers and authorities would also be important for achieving carbon neutrality. The demands from authorities can, for example, be formulated as actual reductions in GHG emissions or as economic policy instruments putting a price on GHG emissions. The demands from customers can, for example, be formulated as actual reductions in GHG emissions or as the use of carbon-neutral energy in the processes.

8.5 Generalisability of the results

There are variations in how generalisable the results in the thesis are. The energy efficiency measures and the corresponding energy efficiency improvement potentials identified in the literature (section 7.2.1) are based on the production processes used in the aluminium industry. For many of the processes, there are no major differences worldwide in how the processes work. This means that the energy efficiency measures and energy efficiency improvement potentials are applicable worldwide. Some of the results could even be applicable in industries other than the aluminium industry, where similar processes are used. However, the energy efficiency improvement potentials could vary from case to case, and the stated values provide an understanding of how large the potential energy efficiency improvements are. A site-specific investigation is needed to identify how large the energy efficiency improvement potential is for the specific case.

The results regarding the energy efficiency gap and changes in the priority of energy issues (section 7.1), the degree of implementation of energy efficiency measures (section 7.2.3) and the energy saving potentials for the companies (section 7.2.4) are specific to the studied companies. However, similar results and conclusions could be achieved by studying the aluminium industry and aluminium casting foundries in other countries.

The results regarding improved energy efficiency in supply chains (section 7.3) and the results regarding the demands placed on the companies and products in the supply chains (section 7.4) are based on studying five supply chains located in Sweden. However, most of the energy efficiency measures that the companies can conduct together touch upon general areas within supply chains and supply chain management. Additionally, Paper III identified clear links between the results in the paper and the results of previous research. This implies that

the energy efficiency measures would also be applicable to other supply chains and countries. Many energy efficiency measures are even applicable to other industries. Similar results regarding the energy efficiency improvement potentials for the supply chains (section 7.3.2) could be found for other supply chains and countries. The demands placed on the companies may be more specific to these particular supply chains. Some of the demands are specific to the particular geographic area studied, e.g. demands from authorities. Some demands are quite general and similar demands may also be imposed in other supply chains and countries.

The results regarding the impact on primary energy use, GHG emissions and energy and CO₂ costs from implementation of energy efficiency measures in the entire global production through the electrolysis process (section 7.2.2) are applicable worldwide. However, the results regarding the hypothetical electrolysis plant cannot be generalised to all electrolysis plants in the world. A site-specific investigation is needed to identify how large the potential savings are for the specific case. However, the results indicate the sizes of the potential savings for a single plant.

The results regarding barriers, drivers and information sources (section 7.4) are specific to the Swedish aluminium industry and aluminium casting foundries. However, many of the barriers, drivers and information sources are applicable to other countries as well. The perceived importance of the barriers and drivers, and the perceived usefulness of the information sources, may vary from country to country. Country-specific studies are needed due to differences depending on country-specific conditions [34,36].

8.6 Relevant recipients of the results

The results in this thesis and the appended papers are relevant for industrial companies, primarily in the aluminium industry and its supply chains but also in other industries. The reason for this is that the results provide information that is relevant for the companies' work to improve energy efficiency, e.g. on energy efficiency measures, potentials for improved energy efficiency, and factors affecting the work to improve energy efficiency. The results are also relevant for policymakers in terms of understanding the potentials for energy efficiency improvements, and due to the policy implications proposed in both the thesis and the appended papers. Furthermore, the results are relevant for the research community since the thesis and the appended papers address the research gaps identified in previous research and propose some areas for future scientific studies.

9

Conclusions

This chapter draws conclusions from the results in the thesis. The conclusions are divided up between the respective research questions.

The aim of this thesis was to study improved energy efficiency in the supply chains of the aluminium industry. The thesis has contributed to the existing research by addressing the research gaps identified in previous research. To the author's knowledge, this is the first study focusing on energy efficiency improvements for both entire supply chains and individual companies within the supply chains in any industrial sector.

9.1 Research question 1

RQ1: How can energy efficiency be improved in the supply chains of the aluminium industry, and to what extent?

This thesis identified several energy efficiency measures that can be implemented by the individual companies in the aluminium industry and the aluminium casting foundries. The individual companies have large potentials for improving their energy efficiency. Energy efficiency measures within the electrolysis process have significant effects on primary energy use, GHG emissions and energy and CO₂ costs.

The joint work between the companies in the supply chains of the aluminium industry is needed for achieving further energy efficiency improvements compared to the companies only working on their own. The joint work between the companies in the supply chain is needed to avoid sub-optimisation of the total energy use throughout the entire supply chain. Better communication and closer collaboration between all the companies in the supply chain are two of the most important aspects of the joint work to improve energy efficiency. An energy audit for the entire supply chain could be conducted as a first step in the joint work between the companies in the supply chains. Another important aspect is to increase the use of secondary aluminium or remelted material waste rather than primary aluminium.

The companies in the Swedish aluminium industry and aluminium casting foundries have come some way in their work to improve energy efficiency within their own facilities. However, there are still further

potentials that could be realised. Some production and support processes within the companies have attracted greater interest in the work to improve energy efficiency. It was also shown that the companies have made different amounts of progress in their work to improve energy efficiency.

Cost-effective technology and improved management can, in total, save 126–185 GWh/year in the Swedish aluminium industry and 8–15 GWh/year in the Swedish aluminium casting foundries. The energy savings might be higher for the foundries since not all Swedish aluminium casting foundries are included in the estimate. Further energy savings could be made by implementing the energy efficiency measures not covered by the respondents' estimations of their respective company's energy saving potential.

9.2 Research question 2

RQ2: Why are energy efficiency measures implemented or not implemented in the supply chains of the aluminium industry?

There are factors that either inhibit or drive the work to improve energy efficiency, both within the individual companies and in the supply chains. Both the economic aspects and demands from customers and authorities were shown to be important drivers for improved energy efficiency in both the individual companies and the entire supply chains.

Among the most important barriers to improved energy efficiency within the individual companies are different types of risks as well as the cost of production disruption, complex production processes and technology being inappropriate at the site. The following aspects are among the factors that are important for driving the work to improve energy efficiency within the individual companies:

- Access to knowledge about the processes and their operation, and the ability to make use of and spread this knowledge
- A culture within the company promoting the work to improve energy efficiency
- A long-term energy strategy
- Networking within the sector
- Improved product information on energy use/efficiency and the performance of equipment from technology suppliers
- Energy audits conducted at the companies

The demands placed on the companies and products in the supply chains can sometimes counteract each other, and some demands are

more important to meet than improving energy efficiency. This implies that improving the energy efficiency of the supply chains and designing products to be energy efficient in use phase can sometimes be hard. Reviewing the demands to see whether any of them could be changed would be beneficial. Energy audits and demands on conducted energy audits could act as drivers for improved energy efficiency throughout the supply chains.

10

Further work

This chapter gives some suggestions for further work.

Further research and development is needed for the energy efficiency measures in Table 8 designated as not currently available. Previous research has highlighted that lower operating temperatures in electrolysis [170] through the use of low-temperature electrolytes [171,172] is a way to significantly reduce the corrosion rate of inert anodes and thus facilitate the use of inert anodes. Further research and development of low-temperature electrolytes and their combination with inert anodes would be beneficial. Additionally, evaluations of which technologies are most beneficial from energy, environmental and economic viewpoints require further research, especially the comparison between electrolysis with inert anodes and major energy efficiency improvements, and carbothermic reduction.

It can be seen from Table 8 that the number of energy efficiency measures found for processes used to process aluminium into semi-finished products (casting, rolling, extrusion, heat treatment and anodising) are generally quite low. Future research and development could focus on developing energy efficiency measures for these processes.

Information about energy use is needed to identify the processes where it may be most useful to implement energy efficiency measures. Future studies can focus on which tools can be used to analyse energy use and GHG emissions.

Further research on improved energy efficiency in the supply chains of the aluminium industry can focus on specific aspects of supply chains and supply chain management, e.g. collaboration and procurement. Future studies can also focus on estimating the energy efficiency improvement potential for entire supply chains.

Further research can focus on the interaction between different supply chains. Most companies are parts of several supply chains, not just one supply chain. How would this affect the work to improve energy efficiency in the supply chains? In some areas, there would probably be some trade-offs, while in other areas such trade-offs will not be found. This could be done for supply chains in any industrial sector.

Economic evaluations have not been possible for the energy efficiency measures presented in this thesis. Economic evaluations could be carried out in future studies instead. This would provide a basis for prioritising the energy efficiency measures presented in the thesis.

This thesis studied the impact on primary energy use, GHG emissions and energy and CO₂ costs when energy efficiency measures are implemented in the electrolysis process. Future studies can study the impact on primary energy use, GHG emissions and energy and CO₂ costs when energy efficiency measures are implemented in the other processes associated with the production and processing of aluminium.

Further research is needed to determine which factors affect the degree of implementation of energy efficiency measures in specific processes and to determine why certain processes attract greater interest in the work to improve energy efficiency than others. Studying different types of industrial sectors in different countries would provide a broader perspective on this issue since factors may differ depending on region- and sector-specific conditions. Further research can also focus on which factors determine why companies in the same industry in the same country have made different amounts of progress in the work to improve energy efficiency.

The perceived importance of barriers [34,36] and drivers and the perceived usefulness of information sources differ between different countries and regions. Demands placed on the products and companies in supply chains can also vary depending on country and region as well as between different supply chains within the same country or region. Further studies on the barriers, drivers and information sources with a focus on countries other than Sweden are needed in order to understand which factors hinder or drive the work to improve energy efficiency within the individual companies in the aluminium industry globally. Further studies on the demands placed on the products and companies in supply chains with a focus on countries other than Sweden and on supply chains other than those studied in this thesis are needed in order to understand which demands are imposed and how these demands affect energy use and the work to improve energy efficiency. Additionally, the perceived importance of the demands as barriers or drivers can be studied. Further studies on barriers, drivers, information sources and demands can be conducted for industries other than the aluminium industry and aluminium casting foundries to gain a broader understanding of these factors in the industrial sector. The reasons why a certain information source is perceived as useful or not useful could also be studied in further studies.

Further studies can focus on the end-user's attitudes to improved energy efficiency in supply chains for both the aluminium industry and other industrial sectors.

References

1. UN. Paris Agreement. UNFCCC: Bonn, Germany, 2015. Available online: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf (accessed on 23 March 2018).
2. UNDP. Sustainable development goals. 2015. Available online: https://www.undp.org/content/dam/undp/library/corporate/brochure/SDGs_Booklet_Web_En.pdf.
3. European Commission. 2030 climate & energy framework. Available online: https://ec.europa.eu/clima/policies/strategies/2030_en#tab-0-0 (accessed on 2 April 2019).
4. Swedish Energy Agency. Sveriges energi och klimatmål [Sweden's energy and climate targets] (in Swedish). Available online: <http://www.energimyndigheten.se/klimat--miljo/sveriges-energi--och-klimatmal/> (accessed on 3 April 2019).
5. Government Offices of Sweden. Det klimatpolitiska ramverket [The climate policy framework] (in Swedish). Available online: <https://www.regeringen.se/artiklar/2017/06/det-klimatpolitiska-ramverket/> (accessed on 3 April 2019).
6. European Union. Directive 2012/27/EU of the European Parliament and of the Council. European Union, 2012. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32012L0027&from=sv#d1e727-1-1>.
7. Swedish Energy Agency. Lagen om energikartläggning i stora företag [The law on energy audits in large companies] (in Swedish). Available online: <https://www.energimyndigheten.se/energieffektivisering/jag-vill-energieffektivisera-min-organisation/energikartlaggning/energikartlaggning-i-stora-foretag/> (accessed on 12 December 2019).
8. Swedish Energy Agency. Om sektorsstrategierna [About the sector strategies] (in Swedish). Available online: <https://www.energimyndigheten.se/energieffektivisering/program-och-uppdrag/Sektorsstrategier-for-energieffektivisering2/om-sektorsstrategierna/> (accessed on 3 February 2020).
9. International Aluminium Institute. Greenhouse gases. Available online: <http://primary.world-aluminium.org/aluminium-facts/greenhouse-gases/> (accessed on 13 November 2019).

10. European Aluminium Association. I+ Manifesto. Available online: <https://www.european-aluminium.eu/manifesto/> (accessed on 15 June 2018).
11. European Aluminium Association. Energy and climate. Available online: <https://www.european-aluminium.eu/policy-areas/energy-climate/> (accessed on 13 November 2019).
12. European Aluminium Association. *The European aluminium industry's sustainability roadmap towards 2025*; European Aluminium Association: Brussels, Belgium, 2015.
13. European Aluminium Association. *An aluminium 2050 roadmap to a low-carbon Europe: Lightning the load*; European Aluminium Association: Brussels, Belgium, 2012.
14. International Energy Agency. Industry: Tracking clean energy progress. Available online: <https://www.iea.org/tcep/industry/> (accessed on 3 September 2019).
15. International Aluminium Institute. International Aluminium Institute's statistics. Available online: <http://www.world-aluminium.org/statistics/> (accessed on 19 December 2019).
16. Swedish Energy Agency. Energiläget i siffror [Energy in Sweden – Facts and figures]. 2019. Available online: <https://www.energimyndigheten.se/globalassets/statistik/energilaget/energilaget-i-siffror-2019.xlsx> (accessed on 15 November 2019).
17. Swedish Environmental Protection Agency. Territorella utsläpp och upptag av växthusgaser [Territorial emissions and uptake of greenhouse gases] (in Swedish). Available online: <http://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser-territoriella-utslapp-och-upptag/> (accessed on 15 November 2019).
18. Swedish Aluminium Association. *Material och energiflöden i svensk aluminiumindustri – Slutrapport GeniAl [Material and energy flows in the Swedish aluminium industry – Final report from the GeniAl project]* (in Swedish); Swedish Aluminium Association: Västerås, Sweden, 2013.
19. Worrell, E.; Bernstein, L.; Roy, J.; Price, L.; Harnisch, J. Industrial energy efficiency and climate change mitigation. *Energy Efficiency* **2009**, *2*, 109–123, doi: 10.1007/s12053-008-9032-8.
20. Cullen, J.M.; Allwood, J.M. Mapping the global flow of aluminum: From liquid aluminum to end-use goods. *Environmental Science and Technology* **2013**, *47*, 3057–3064, doi: 10.1021/es304256s.
21. Milford, R.L.; Allwood, J.M.; Cullen, J.M. Assessing the potential of yield improvements, through process scrap reduction, for energy and CO₂ abatement in the steel and aluminium sectors.

- Resources, Conservation and Recycling* **2011**, *55*, 1185–1195, doi: 10.1016/j.resconrec.2011.05.021.
22. Liu, G.; Bangs, C.E.; Müller, D.B. Unearthing potentials for decarbonizing the U.S. aluminum cycle. *Environmental Science & Technology* **2011**, *45*, 9515–9522, doi: 10.1021/es202211w.
  23. Pérez-Lombard, L.; Ortiz, J.; Velázquez, D. Revisiting energy efficiency fundamentals. *Energy Efficiency* **2013**, *6*, 239–254, doi: 10.1007/s12053-012-9180-8.
  24. Marchi, B.; Zanoni, S. Supply chain management for improved energy efficiency: Review and opportunities. *Energies* **2017**, *10*, doi: 10.3390/en10101618.
  25. Zanoni, S.; Bettoni, L.; Glock, C.H. Energy implications in the single-vendor single-buyer integrated production inventory model. In Proceedings of IFIP Advances in Information and Communication Technology, Rhodes, Greece; pp. 57–64.
  26. El Saadany, A.M.A.; Jaber, M.Y.; Bonney, M. Environmental performance measures for supply chains. *Management Research Review* **2011**, *34*, 1202–1221, doi: 10.1108/01409171111178756.
  27. Lee, K.H.; Cheong, I.M. Measuring a carbon footprint and environmental practice: The case of Hyundai Motors Co. (HMC). *Industrial Management and Data Systems* **2011**, *111*, 961–978, doi: 10.1108/02635571111144991.
  28. Ji, G.; Gunasekaran, A.; Yang, G. Constructing sustainable supply chain under double environmental medium regulations. *International Journal of Production Economics* **2014**, *147*, 211–219, doi: 10.1016/j.ijpe.2013.04.012.
  29. Zhang, Q.; Shah, N.; Wassick, J.; Helling, R.; van Egerschot, P. Sustainable supply chain optimisation: An industrial case study. *Computers & Industrial Engineering* **2014**, *74*, 68–83, doi: 10.1016/j.cie.2014.05.002.
  30. Xie, G. Cooperative strategies for sustainability in a decentralized supply chain with competing suppliers. *Journal of Cleaner Production* **2016**, *113*, 807–821, doi: 10.1016/j.jclepro.2015.11.013.
  31. Swedish Aluminium Association. Forskning och utveckling [Research and development] (in Swedish). Available online: <https://www.svensktaluminium.se/forskning-och-utveckling/> (accessed on 15 June 2018).
  32. International Aluminium Institute. The sustainability challenge. Available online: <http://recycling.world-aluminium.org/re/the-campaign/> (accessed on 15 June 2018).
  33. Swedish Energy Agency. Produktion i världsklass [World-class production] (in Swedish). Available online:

- <https://www.energimyndigheten.se/energieffektivisering/program-och-uppdrag/Sektorsstrategier-for-energieffektivisering2/sektorer/produktion-i-varldsklass/> (accessed on 13 November 2019).
34. Thollander, P.; Ottosson, M. An energy efficient Swedish pulp and paper industry: Exploring barriers to and driving forces for cost-effective energy efficiency investments. *Energy Efficiency* **2008**, *1*, 21–34, doi: 10.1007/s12053-007-9001-7.
  35. Nehler, T.; Parra, R.; Thollander, P. Implementation of energy efficiency measures in compressed air systems: Barriers, drivers and non-energy benefits. *Energy Efficiency* **2018**, 1–22, doi: 10.1007/s12053-018-9647-3.
  36. Rohdin, P.; Thollander, P.; Solding, P. Barriers to and drivers for energy efficiency in the Swedish foundry industry. *Energy Policy* **2007**, *35*, 672–677, doi: 10.1016/j.enpol.2006.01.010.
  37. Rohdin, P.; Thollander, P. Barriers to and driving forces for energy efficiency in the non-energy intensive manufacturing industry in Sweden. *Energy* **2006**, *31*, 1836–1844, doi: 10.1016/j.energy.2005.10.010.
  38. Backlund, S.; Thollander, P.; Palm, J.; Ottosson, M. Extending the energy efficiency gap. *Energy Policy* **2012**, *51*, 392–396, doi: 10.1016/j.enpol.2012.08.042.
  39. Johansson, M.T.; Thollander, P. A review of barriers to and driving forces for improved energy efficiency in Swedish industry: Recommendations for successful in-house energy management. *Renewable and Sustainable Energy Reviews* **2018**, *82*, 618–628, doi: 10.1016/j.rser.2017.09.052.
  40. Trygg, L.; Thollander, P.; Backlund, S.; Olsson, L. *Uthålliga energisystem i praktiken: Implementering av energieffektivitet inom industrier [Sustainable energy systems in practice: Implementation of energy efficiency in industries]* (in Swedish); Linköping University: Linköping, Sweden, 2010.
  41. Goetschalckx, M. *Supply chain engineering*; Springer Science & Business Media: New York, 2011.
  42. Kalenoja, H.; Kallionpää, E.; Rantala, J. Indicators of energy efficiency of supply chains. *International Journal of Logistics Research and Applications* **2011**, *14*, 77–95, doi: 10.1080/13675567.2010.551111.
  43. Brown Construction Services Inc. *U.S. energy requirements for aluminum production: Historical perspective, theoretical limits and current practices*; U.S. Department of Energy: Washington DC, 2007.
  44. AZO Materials. Aluminium – Specifications, properties,

- classifications and classes. Available online: <https://www.azom.com/article.aspx?ArticleID=2863> (accessed on 10 April 2019).
45. Statistics Sweden. Swedish Standard Industrial Classification (SNI). Available online: <https://www.scb.se/en/documentation/classifications-and-standards/swedish-standard-industrial-classification-sni/> (accessed on 13 February 2019).
46. Statistics Sweden. Sökning efter SNI-kod [Search by SNI-code] (in Swedish). Available online: <http://www.sni2007.scb.se/> (accessed on 26 March 2020).
47. Tabereaux, A.T.; Peterson, R.D. Aluminum production. In *Treatise on process metallurgy – Industrial processes, Volume 3*, Seetharaman, S., McLean, A., Guthrie, R., Sridhar, S., Eds.; Elsevier Ltd.: Kidlington, UK & Waltham, USA, 2014; Vol. 3, doi: 10.1016/B978-0-08-096988-6.00023-7; pp. 839–917.
48. Cusano, G.; Gonzalo, M.R.; Farrell, F.; Remus, R.; Roudier, S.; Sancho, L.D. *Best available techniques (BAT) reference document for the non-ferrous metals industries*; EUR 28648 EN; European Integrated Pollution Prevention and Control Bureau, European Commission's Joint Research Centre: Luxembourg, Luxembourg, 2017.
49. International Aluminium Institute. *2015 Life cycle inventory data and environmental metrics*; International Aluminium Institute: London, UK, 2017.
50. aluminum-production.com. Detailed description of a cell and its basic functioning. Available online: http://www.aluminum-production.com/Basic_functioning.html (accessed on 1 March 2017).
51. The Aluminium Association. Secondary production. Available online: <https://www.aluminum.org/industries/production/secondary-production> (accessed on 12 June 2019).
52. Schmitz, C. *Handbook of aluminium recycling: Fundamentals mechanical preparation metallurgical processing plant design*; Vulkan-Verlag GmbH: Essen, Germany, 2006.
53. Shinzato, M.C.; Hypolito, R. Solid waste from aluminum recycling process: Characterization and reuse of its economically valuable constituents. *Waste Management* **2005**, *25*, 37–46, doi: 10.1016/j.wasman.2004.08.005.
54. Tsakiridis, P.E. Aluminium salt slag characterization and utilization – A review. *Journal of Hazardous Materials* **2012**, *217–218*, 1–10, doi: 10.1016/j.jhazmat.2012.03.052.

55. European Integrated Pollution Prevention and Control Bureau. *Best available technique (BAT) reference document for the non-ferrous metals industries*; European Commission's Joint Research Centre: Seville, Spain, 2014.
56. dmitri_kopeliovich. Metals. Available online: <http://www.substech.com/dokuwiki/doku.php?id=metals> (accessed on 15 June 2017).
57. Rajkumar, K.; Rajan, P.; Charles, J.M.A. Microwave heat treatment on aluminium 6061 alloy-boron carbide composites. In *Proceedings of 1st International Conference on Structural Integrity*, 4–7 February 2014; pp. 34–41.
58. Dons, A.L. The Alstruc homogenization model for industrial aluminum alloys. *Journal of Light Metals* **2001**, *1*, 133–149, doi: 10.1016/S1471-5317(01)00007-4.
59. Rinderer, B. The metallurgy of homogenisation. *Materials Science Forum* **2011**, *693*, 264–275, doi: 10.4028/www.scientific.net/MSF.693.264.
60. AZO Materials. Aluminium and aluminium alloys – Heat treatment of aluminium and aluminium alloys. Available online: <https://www.azom.com/article.aspx?ArticleID=2540> (accessed on 14 November 2019).
61. European Integrated Pollution Prevention and Control Bureau. *Reference document on best available techniques for the surface treatment of metals and plastics*; European Commission's Joint Research Centre: Seville, Spain, 2006.
62. International Aluminium Institute. Primary aluminium smelting energy intensity. Available online: <http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/> (accessed on 22 August 2019).
63. Swedish Foundry Association. The Swedish Foundry Association's homepage (in Swedish). Available online: <http://www.gjuteriforeningen.se/> (accessed on 5 February 2019).
64. Sorrell, S. Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy* **2009**, *37*, 1456–1469, doi: 10.1016/j.enpol.2008.12.003.
65. Faruk, A.C.; Lamming, R.C.; Cousins, P.D.; Bowen, F.E. Analyzing, mapping, and managing environmental impacts along supply chains. *Journal of Industrial Ecology* **2001**, *5*, 13–36, doi: 10.1162/10881980152830114.
66. Söderström, M.; Carlsson, P.; Hall, O. *Enhetsprocesser – Ett sätt att strukturera industrins energianvändning [Unit processes – A way to structure industrial energy use]* (in Swedish); Linköping University: Linköping, Sweden, 1994.

67. Latõšov, E.; Volkova, A.; Siirde, A.; Kurnitski, J.; Thalfeldt, M. Primary energy factor for district heating networks in European Union member states. *Energy Procedia* **2017**, *116*, 69–77, doi: 10.1016/j.egypro.2017.05.056.
68. Gode, J.; Martinsson, F.; Hagberg, L.; Öman, A.; Höglund, J.; Palm, D. *Miljöfaktaboken 2011: Uppskattade emissionsfaktorer för bränslen, el, värme och transporter [Miljöfaktaboken 2011: Estimated emission factors for fuels, electricity, heat and transport in Sweden]* (in Swedish); Värmeforsk Service AB: Stockholm, Sweden, 2011.
69. Esser, A.; Sensfuss, F. *Evaluation of primary energy factor calculation options for electricity*; Fraunhofer-Institute für System- und Innovationsforschung (ISI), 2016.
70. Johansson, M.T. Improved energy efficiency and fuel substitution in the iron and steel industry. Ph.D. thesis, Linköping University, Linköping, Sweden, 2014.
71. Dotzauer, E. Greenhouse gas emissions from power generation and consumption in a nordic perspective. *Energy Policy* **2010**, *38*, 701–704, doi: 10.1016/j.enpol.2009.10.066.
72. Ådahl, A.; Harvey, S. Energy efficiency investments in kraft pulp mills given uncertain climate policy. *International Journal of Energy Research* **2007**, *31*, 486–505, doi: 10.1002/er.1261.
73. European Integrated Pollution Prevention and Control Bureau. *Reference document on best available techniques in the smitheries and foundries industry*; European Commission's Joint Research Centre: Seville, Spain, 2005.
74. Kermeli, K.; ter Weer, P.H.; Crijns-Graus, W.; Worrell, E. Energy efficiency improvement and GHG abatement in the global production of primary aluminium. *Energy Efficiency* **2015**, *8*, 629–666, doi: 10.1007/s12053-014-9301-7.
75. Faisal, M.N. Sustainable supply chains: A study of interaction among the enablers. *Business Process Management Journal* **2010**, *16*, 508–529, doi: 10.1108/14637151011049476.
76. Kadambala, D.K.; Subramanian, N.; Tiwari, M.K.; Abdulrahman, M.; Liu, C. Closed loop supply chain networks: Designs for energy and time value efficiency. *International Journal of Production Economics* **2017**, *183*, 382–393, doi: 10.1016/j.ijpe.2016.02.004.
77. Tsoulfas, G.T.; Pappis, C.P. A model for supply chains environmental performance analysis and decision making. *Journal of Cleaner Production* **2008**, *16*, 1647–1657, doi: 10.1016/j.jclepro.2008.04.018.
78. Srivastava, S.K. Green supply-chain management: A state-of-the-art literature review. *International Journal of Management*

- Reviews* **2007**, 9, 53–80, doi: 10.1111/j.1468-2370.2007.00202.x.
79. Jawahir, I.; Rouch, K.E.; Dillon, O.; Holloway, L.; Hall, A. Design for sustainability (DFS): New challenges in developing and implementing a curriculum for next generation design and manufacturing engineers. *International Journal of Engineering Education* **2007**, 23, 1053–1064.
  80. Duflou, J.R.; Sutherland, J.W.; Dornfeld, D.; Herrmann, C.; Jeswiet, J.; Kara, S.; Hauschild, M.; Kellens, K. Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Annals – Manufacturing Technology* **2012**, 61, 587–609, doi: 10.1016/j.cirp.2012.05.002.
  81. Rosen, C.M.; Beckman, S.; Bercovitz, J. Environmental supply-chain management in the computer industry: A transaction cost economics perspective. *Journal of Industrial Ecology* **2001**, 4, 83–103, doi: 10.1162/10881980052541963.
  82. Ala-Harja, H.; Helo, P. Green supply chain decisions – Case-based performance analysis from the food industry. *Transportation Research Part E: Logistics and Transportation Review* **2014**, 69, 97–107, doi: 10.1016/j.tre.2014.05.015.
  83. Rizet, C.; Browne, M.; Cornelis, E.; Leonardi, J. Assessing carbon footprint and energy efficiency in competing supply chains: Review – Case studies and benchmarking. *Transportation Research Part D: Transport and Environment* **2012**, 17, 293–300, doi: 10.1016/j.trd.2012.01.002.
  84. Berlin, J.; Sonesson, U.; Tillman, A.M. Product chain actors' potential for greening the product life cycle: The case of the Swedish postfarm milk chain. *Journal of Industrial Ecology* **2008**, 12, 95–110, doi: 10.1111/j.1530-9290.2008.00001.x.
  85. Mulder, K.F. Sustainable consumption and production of plastics? *Technological Forecasting and Social Change* **1998**, 58, 105–124.
  86. Leising, E.; Quist, J.; Bocken, N. Circular economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production* **2018**, 176, 976–989, doi: 10.1016/j.jclepro.2017.12.010.
  87. Roehrich, J.K.; Hoejmose, S.U.; Overland, V. Driving green supply chain management performance through supplier selection and value internalisation: A self-determination theory perspective. *International Journal of Operations & Production Management* **2017**, 37, 489–509, doi: 10.1108/IJOPM-09-2015-0566.
  88. Khoo, H.H.; Spedding, T.A.; Bainbridge, I.; Taplin, D.M.R. Creating a green supply chain. *Greener Management*

- International* **2001**, 35, 71–88.
89. Ferretti, I.; Zanoni, S.; Zavanella, L.; Diana, A. Greening the aluminium supply chain. *International Journal of Production Economics* **2007**, 108, 236–245, doi: 10.1016/j.ijpe.2006.12.037.
  90. Tan, R.B.H.; Khoo, H.H. An LCA study of a primary aluminum supply chain. *Journal of Cleaner Production* **2005**, 13, 607–618, doi: 10.1016/j.jclepro.2003.12.022.
  91. Schwarz, H.G.; Briem, S.; Zapp, P. Future carbon dioxide emissions in the global material flow of primary aluminium. *Energy* **2001**, 26, 775–795, doi: 10.1016/S0360-5442(01)00032-9.
  92. Liu, S.; Wang, S.; Wang, K.; Yue, H.; Liu, L.; Yang, S.; Zhang, P.; Zhang, R. Energy consumption and GHG emission for regional aluminum industry: A case study of Henan province, China. In Proceedings of The 8th International Conference on Applied Energy, Beijing, China, 8–11 October 2016; pp. 3391–3396.
  93. Myklebust, H.; Runde, P. Greenhouse gas emissions from aluminum carbothermic technology compared to Hall-Héroult technology. In Proceedings of TMS 2005 Annual Meeting & Exhibition, San Francisco, USA, 13–17 February 2005; pp. 519–522.
  94. Obaidat, M.; Al-Ghandoor, A.; Phelan, P.; Villalobos, R.; Alkhalidi, A. Energy and exergy analyses of different aluminum reduction technologies. *Sustainability* **2018**, 10, doi: 10.3390/su10041216.
  95. Saygin, D.; Worrell, E.; Patel, M.K.; Gielen, D.J. Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries. *Energy* **2011**, 36, 6661–6673, doi: 10.1016/j.energy.2011.08.025.
  96. Thollander, P.; Danestig, M.; Rohdin, P. Energy policies for increased industrial energy efficiency: Evaluation of a local energy programme for manufacturing SMEs. *Energy Policy* **2007**, 35, 5774–5783, doi: 10.1016/j.enpol.2007.06.013.
  97. Johansson, M.T. Improved energy efficiency within the Swedish steel industry: The importance of energy management and networking. *Energy Efficiency* **2015**, 8, 713–744, doi: 10.1007/s12053-014-9317-z.
  98. Brunke, J.C.; Johansson, M.T.; Thollander, P. Empirical investigation of barriers and drivers to the adoption of energy conservation measures, energy management practices and energy services in the Swedish iron and steel industry. *Journal of Cleaner Production* **2014**, 84, 509–525, doi: 10.1016/j.jclepro.2014.04.078.
  99. Trianni, A.; Cagno, E.; Thollander, P.; Backlund, S. Barriers to

- industrial energy efficiency in foundries: A European comparison. *Journal of Cleaner Production* **2013**, 40, 161–176, doi: 10.1016/j.jclepro.2012.08.040.
100. Thollander, P.; Backlund, S.; Trianni, A.; Cagno, E. Beyond barriers: A case study on driving forces for improved energy efficiency in the foundry industries in Finland, France, Germany, Italy, Poland, Spain, and Sweden. *Applied Energy* **2013**, 111, 636–643, doi: 10.1016/j.apenergy.2013.05.036.
101. Lawrence, A.; Nehler, T.; Andersson, E.; Karlsson, M.; Thollander, P. Drivers, barriers and success factors for energy management in the Swedish pulp and paper industry. *Journal of Cleaner Production* **2019**, 223, 67–82.
102. Batterham, R.J. Opportunities for improvements in alumina production: Balancing incremental and breakthrough innovation. In Proceedings of 26th International Mineral Processing Congress, IMPC 2012: Innovative Processing for Sustainable Growth, New Dehli, India, 24–28 September; pp. 396–411.
103. Bailey, I.; Ditty, C. Energy markets, capital inertia and economic instrument impacts. *Climate Policy* **2009**, 9, 22–39, doi: 10.3763/cpol.2008.0454.
104. Su, M.; Deng, J.; He, J. Energy efficiency and CO₂ abatement in China township and village foundries. *International Journal of Global Energy Issues* **2004**, 21, 69–78.
105. Nagesha, N.; Balachandra, P. Barriers to energy efficiency in small industry clusters: Multi-criteria-based prioritization using the analytic hierarchy process. *Energy* **2006**, 31, 1633–1647, doi: 10.1016/j.energy.2005.07.002.
106. Apeaning, R.W.; Thollander, P. Barriers to and driving forces for industrial energy efficiency improvements in African industries – A case study of Ghana's largest industrial area. *Journal of Cleaner Production* **2013**, 53, 204–213, doi: 10.1016/j.jclepro.2013.04.003.
107. Centobelli, P.; Cerchione, R.; Esposito, E. Environmental sustainability and energy-efficient supply chain management: A review of research trends and proposed guidelines. *Energies* **2018**, 11, doi: 10.3390/en11020275.
108. Bryman, A. *Samhällsvetenskapliga metoder [Social research methods]*, 3 ed.; Liber AB: Stockholm, Sweden, 2018.
109. Yin, R.K. *Case study research: Design and methods*, 5 ed.; SAGE publications, Inc.: London, UK, 2014.
110. Douven, I. Abduction. In *Stanford Encyclopedia of Philosophy*, Zalta, E.N., Ed.; Metaphysics Research Lab, Stanford University: Stanford, USA, 2017. Available online:

- <https://plato.stanford.edu/entries/abduction/> (accessed on 5 November 2019).
111. Haig, B.D. Scientific method, abduction, and clinical reasoning. *Journal of Clinical Psychology* **2008**, *64*, 1013–1018, doi: 10.1002/jclp.20505.
  112. Douven, I. Peirce on abduction. In *Stanford Encyclopedia of Philosophy*, Zalta, E.N., Ed.; Metaphysics Research Lab, Stanford University: Stanford, USA, 2017. Available online: <https://plato.stanford.edu/entries/abduction/peirce.html> (accessed on 16 November 2018).
  113. Kvale, S.; Brinkmann, S. *Den kvalitativa forskningsintervjun [The qualitative research interview]*, 3rd ed.; Studentlitteratur AB: Lund, Sweden, 2014.
  114. Wagner, C.S.; Roessner, J.D.; Bobb, K.; Klein, J.T.; Boyack, K.W.; Keyton, J.; Rafols, I.; Börner, K. Approaches to understanding and measuring interdisciplinary scientific research (IDR): A review of the literature. *Journal of Informetrics* **2011**, *5*, 14–26, doi: 10.1016/j.joi.2010.06.004.
  115. Churchman, C.W. *The systems approach*; Delta: New York, USA, 1968.
  116. International Aluminium Institute. Perfluorocarbon (PFC) emissions. Available online: <http://www.world-aluminium.org/statistics/perfluorocarbon-pfc-emissions/> (accessed on 22 August 2019).
  117. International Aluminium Institute. Primary aluminium production. Available online: <http://www.world-aluminium.org/statistics/primary-aluminium-production/#data> (accessed on 5 September 2019).
  118. International Energy Agency. *World Energy Outlook 2019*; OECD Publishing: Paris, France, 2019.
  119. Balomenos, E.; Panias, D.; Paspaliaris, I. Energy and exergy analysis of the primary aluminum production processes: A review on current and future sustainability. *Mineral Processing and Extractive Metallurgy Review* **2011**, *32*, 69–89, doi: 10.1080/08827508.2010.530721.
  120. Kemper, C.; Friedrich, B.; Balomenos, E.; Panias, D.; Paspaliaris, I. Thermodynamic analysis and experimental validation of carbothermically producing AlSi-alloy. In *Proceedings of 7th European Metallurgical Conference, EMC 2013*, Weimar, Germany, 23–26 June 2013; pp. 1027–1032.
  121. Li, J.; Zhang, G.; Liu, D.; Ostrovski, O. Low-temperature synthesis of aluminium carbide. *ISIJ International* **2011**, *51*, 870–877, doi: 10.2355/isijinternational.51.870.

122. Kvande, H.; Drabløs, P.A. The aluminum smelting process and innovative alternative technologies. *Journal of Occupational and Environmental Medicine* **2014**, *56*, S23–S32, doi: 10.1097/JOM.000000000000062.
123. U.S. Aluminum Association. Inert anode roadmap. U.S. Department of Energy: Washington DC, USA, 1998. Available online: <http://energy.gov/sites/prod/files/2013/11/f4/inertroad.pdf>.
124. Peng, J.; Feng, N.; Feng, S.; Liu, J.; Qi, X. Development and application of an energy saving technology for aluminum reduction cells. In Proceedings of TMS 2011 Annual Meeting & Exhibition, San Diego, USA, 27 February–3 March 2011; pp. 1023–1027.
125. Naixiang, F.; Jianping, P.; Yaowu, W.; Yuezhong, D.; Xian'An, L. Energy reduction technology for aluminum electrolysis: Choice of the cell voltage. In Proceedings of TMS 2013 Annual Meeting & Exhibition, San Antonio, USA, 3–7 March 2013; pp. 549–552.
126. Nohlgren, I.; Svärd, S.; Jansson, M.; Rodin, J. *Electricity from new and future plants 2014*; 14:45; Elforsk AB: Stockholm, Sweden, 2014.
127. Wibeck, V. *Fokusgrupper: Om fokuserade gruppintervjuer som undersökningsmetod [Focus groups: On focused group interviews as research method]*, 2nd ed.; Studentlitteratur AB: Lund, Sweden, 2010.
128. Saldaña, J. *The coding manual for qualitative researchers*, 2nd ed.; SAGE Publications: London, UK, & Thousand Oaks, USA, 2013.
129. Norgate, T.E.; Jahanshahi, S.; Rankin, W.J. Assessing the environmental impact of metal production processes. *Journal of Cleaner Production* **2007**, *15*, 838–848, doi: 10.1016/j.jclepro.2006.06.018.
130. Thollander, P.; Karlsson, M.; Rohdin, P.; Wollin, J.; Rosenqvist, J. *Introduction to industrial energy efficiency – Energy auditing, energy management and policy issues*; Academic Press: Amsterdam, The Netherlands, 2020.
131. Hassan, M.I.; Al Kindi, R. Feasibility study of regenerative burners in aluminum holding furnaces. *JOM* **2014**, *66*, 1603–1611, doi: 10.1007/s11837-014-1110-0.
132. White, T.D.W. Furnaces designed for fuel efficiency. In Proceedings of TMS 2011 Annual Meeting and Exhibition, San Diego, USA, 27 February–3 March 2011; pp. 1165–1172.
133. Bright, M.A.; Chandler, R.C.; Henderson, R.S.; Starczewski, R.J. Recent developments in molten metal pumps to enhance

- reverberatory furnace productivity. *Aluminium International Today* **2007**, *19*, 18–22.
134. Hassan, M.I.; Brimmo, A.T. CFD comparison of immersed heater and open fire burner designs for casting furnaces. In Proceedings of TMS 2015 Annual Meeting & Exhibition, Walt Disney World, Orlando, USA, 15–19 March 2015; pp. 915–920.
  135. Gamweger, K.; Bauer, P. Energy savings and productivity increases at an aluminum slug plant due to bottom gas purging. In Proceedings of TMS 2009 Annual Meeting & Exhibition, San Francisco, USA, 15–19 February 2009; pp. 169–171.
  136. Chandler, R.C.; Shull, P.D. Increasing the surface emissivity of aluminum shapes to improve radiant heat transfer. In Proceedings of TMS 2009 Annual Meeting & Exhibition, San Francisco, USA; pp. 713–716.
  137. Zeng, S.; Li, J.; Ren, X.; Zhao, Z. Fuzzy control with prediction of temperature in 300kA aluminum production pot lines. In Proceedings of 30th IASTED International Conference on Modelling, Identification and Control, Phuket, Thailand, 24–26 November 2010; pp. 93–98.
  138. Mulder, A.; Gao, Y.; Zhou, D.; Wong, D.S.; Ming, L.; Lavoie, P.; Taylor, M.P.; Yang, X. New generation control for daily aluminium smelter improvement generation 3 process control for potlines. In Proceedings of TMS 2014 Annual Meeting & Exhibition, San Diego, USA, 16–20 February 2014; pp. 835–840.
  139. Fortini, O.; Garimella, S.; Kuhn, E.; Ruan, Y.; Yacob, B.; Sorensen, J. Experimental studies of the impact of anode pre-heating. In Proceedings of TMS 2012 Annual Meeting & Exhibition, Orlando, USA, 11–15 March 2012; pp. 595–600.
  140. Tian, Y.; Li, H.; Wei, L.; Cao, X.; Yin, J. Industry test of perforation anode in aluminium electrolysis technology. In Proceedings of TMS 2013 Annual Meeting & Exhibition, San Antonio, USA, 3–7 March 2013; pp. 567–571.
  141. Feiya, Y.; Dupuis, M.; Jianfei, Z.; Shaoyong, R. In depth analysis of energy-saving and current efficiency improvement of aluminum reduction cells. In Proceedings of TMS 2013 Annual Meeting & Exhibition, San Antonio, USA, 3–7 March 2013; pp. 537–542.
  142. Dongfang, Z.; Xiaodong, Y.; Wei, L. Development and application of SAMP's low voltage energy-saving technology. In Proceedings of TMS 2012 Annual Meeting & Exhibition, Orlando, USA, 11–15 March 2012; pp. 607–612.
  143. Segatz, M.; Hop, J.; Reny, P.; Gikling, H. Hydro's cell technology path towards specific energy consumption below 12 kWh/kg. In

- Proceedings of TMS 2016 Annual Meeting & Exhibition, Nashville, USA, 14–18 February 2016; pp. 301–305.
144. Galasiu, I.; Galasiu, R. Aluminium electrolysis with inert anodes and wettable cathodes and with low energy consumption. In *Molten salts chemistry and technology*, Gaune-Escard, M., Haarberg, G.M., Eds.; Wiley and Sons: Chichester, UK, 2014; pp. 27–38.
  145. Keniry, J. The economics of inert anodes and wettable cathodes for aluminum reduction cells. *JOM* **2001**, *53*, 43–47, doi: 10.1007/s11837-001-0209-2.
  146. Norgate, T.; Jahanshahi, S. Reducing the greenhouse gas footprint of primary metal production: Where should the focus be? *Minerals Engineering* **2011**, *24*, 1563–1570, doi: 10.1016/j.mineng.2011.08.007.
  147. Pawlek, R.P. Wettable cathodes: An update. In Proceedings of TMS 2010 Annual Meeting & Exhibition, Seattle, USA, 14–18 February 2010; pp. 377–382.
  148. Kvande, H.; Haupin, W. Inert anodes for Al smelters: Energy balances and environmental impact. *JOM* **2001**, *53*, 29–33, doi: 10.1007/s11837-001-0205-6.
  149. Warner, N.A. Conceptual design for lower-energy primary aluminum. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science* **2008**, *39*, 246–267, doi: 10.1007/s11663-008-9134-x.
  150. Paraskevas, D.; Vanmeensel, K.; Vleugels, J.; Dewulf, W.; Deng, Y.; Duflou, J.R. Spark plasma sintering as a solid-state recycling technique: The case of aluminum alloy scrap consolidation. *Materials* **2014**, *7*, 5664–5687, doi: 10.3390/ma7085664.
  151. Musa, C.; Licheri, R.; Locci, A.M.; Orrù, R.; Cao, G.; Rodriguez, M.A.; Jaworska, L. Energy efficiency during conventional and novel sintering processes: The case of Ti-Al₂O₃-TiC composites. *Journal of Cleaner Production* **2009**, *17*, 877–882, doi: 10.1016/j.jclepro.2009.01.012.
  152. Zeng, B.; Jolly, M.; Dai, X. Designing novel CRIMSON running system through numerical simulation method for the purpose of reducing the energy content of aluminium investment casting. In Proceedings of TMS 2013 Annual Meeting & Exhibition, San Antonio, USA, 3–7 March 2013; pp. 39–46.
  153. Dai, X.; Jolly, M.; Zhang, B. Reduction of energy consumption and GHGs emission in investment casting process by application of a new casting method. In Proceedings of TMS 2012 Annual Meeting & Exhibition, Orlando, USA, 11–15 March 2012; pp. 15–22.
  154. Jolly, M.; Dai, X. Energy efficiency improvement by

- implementation of the novel CRIMSON aluminium casting process. In Proceedings of TMS 2011 Annual Meeting & Exhibition, San Diego, USA, 27 February–3 March 2011; pp. 55–64.
155. Paraskevas, D.; Kellens, K.; Dewulf, W.; Duflou, J.R. Environmental modelling of aluminium recycling: A life cycle assessment tool for sustainable metal management. *Journal of Cleaner Production* **2015**, *105*, 357–370, doi: 10.1016/j.jclepro.2014.09.102.
  156. Schulze, M.; Nehler, H.; Ottosson, M.; Thollander, P. Energy management in industry: A systematic review of previous findings and an integrative conceptual framework. *Journal of Cleaner Production* **2016**, *112*, 3692–3708, doi: 10.1016/j.jclepro.2015.06.060.
  157. Paramonova, S.; Ivner, J.; Thollander, P. Outsourcing industrial energy management: Industrial energy efficiency networks provided as an energy service. In *Outsourcing: Strategies, challenges and effects on organisations*, Deering, A., Ed.; Nova Science Publishers, Inc.: New York, USA, 2014; pp. 71–98.
  158. Paramonova, S. Re-viewing industrial energy-efficiency improvement using a widened system boundary. Ph.D. thesis, Linköping University, Linköping, Sweden, 2016.
  159. Westling, H. Final management report: Annex III co-operative procurement of innovative technologies for demand-side management. International Energy Agency: Paris, France, 2000. Available online: <http://www.ieadsm.org/Files/Tasks/Task%203%20-%20Co-operative%20Procurement%20of%20Innovative%20Technologies%20for%20Demand-Side%20Management/General%20Information/FRpt.pdf>
  160. Rasmussen, J. The investment process for capital investments: The case of industrial energy-efficiency investments and non-energy benefits. Licentiate thesis, Linköping University, Linköping, Sweden, 2016.
  161. Cagno, E.; Trianni, A. Evaluating the barriers to specific industrial energy efficiency measures: An exploratory study in small and medium-sized enterprises. *Journal of Cleaner Production* **2014**, *82*, 70–83, doi: 10.1016/j.jclepro.2014.06.057.
  162. Backlund, S.; Broberg, S.; Ottosson, M.; Thollander, P. Energy efficiency potentials and energy management practices in Swedish firms. In Proceedings of eceee 2012 Summer Study on Energy Efficiency in Industry, Arnhem, The Netherlands, 11–14 September 2012; pp. 669–678.

163. Johnsson, S.; Andersson, E.; Thollander, P.; Karlsson, M. Energy savings and greenhouse gas mitigation potential in the Swedish wood industry. *Energy* **2019**, *187*, doi: 10.1016/j.energy.2019.115919.
164. Moya, J.A.; Pavel, C.C. *Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry*; EC's Joint Research Centre: Luxembourg, Luxembourg, 2018.
165. Nadel, S.; Shipley, A.; Elliott, R.N. The technical, economic and achievable potential for energy-efficiency in the US – A meta-analysis of recent studies. In *Proceedings of 2004 ACEEE Summer Study on Energy Efficiency in Buildings*; pp. 8.215–8.226.
166. Walker, H.; Phillips, W. Sustainable procurement: Emerging issues. *International Journal of Procurement Management* **2009**, *2*, 41–61.
167. Lorentsen, O.A. 125 years of the Hall-Héroult process – What made it a success? In *Molten salts chemistry and technology*, Gaune-Escard, M., Haarberg, G.M., Eds.; John Wiley & Sons Ltd: Chichester, UK, 2014; doi: 10.1002/9781118448847.ch1k; pp. 103–112.
168. Johansson, M.T. Effects on global CO₂ emissions when substituting LPG with bio-SNG as fuel in steel industry reheating furnaces – The impact of different perspectives on CO₂ assessment. *Energy Efficiency* **2016**, *9*, 1437–1445, doi: 10.1007/s12053-016-9432-0.
169. Padamata, S.K.; Yasinskiy, A.S.; Polyakov, P.V. Progress of inert anodes in aluminium industry: Review. *Journal of Siberian Federal University, Chemistry 1* **2018**, *11*, 18–30, doi: 10.17516/1998-2836-0055.
170. Sadoway, D.R. Inert anodes for the Hall-Héroult cell: The ultimate materials challenge. *JOM* **2001**, *53*, 34–35.
171. Tian, Z.; Lai, Y.; Yang, S.; Li, J.; Hwang, J.Y.; Liu, Y. Anodic corrosion behavior of NiFe₂O₄-based cermet in Na₃AlF₆-K₃AlF₆-AlF₃ for aluminum electrolysis. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science* **2015**, *46*, 1257–1261, doi: 10.1007/s11663-015-0328-8.
172. Tkacheva, O.; Spangenberg, J.; Davis, B.; Hryn, J. Aluminum electrolysis in an inert anode cell. In *Molten salts chemistry and technology*, Gaune-Escard, M., Haarberg, G.M., Eds.; John Wiley & Sons, Inc.: Chichester, UK, 2014; doi: 10.1002/9781118448847.ch1f; pp. 53–69.

Appendix A: Energy efficiency measures included in the first questionnaire

Table A1. Energy efficiency measures included in the questionnaire described in section 6.5.1.

Main type	Process	Energy efficiency measure
Production processes	Furnace	Insulation of furnace for better control of heating and cooling
		Sealing of furnace and optimisation of oven pressure
		Optimisation of air-to-fuel-ratio in furnaces
		Oxygen enrichment of combustion air (e.g. oxy-fuel burners)
		Regenerative burners
		Recuperative burners
		Magnetic stirrer in furnace
		Furnace with better energy class
		Heating furnace with a fixed hood, loaded from below with a moving floor
		Tilted rotating furnace
		Preheating of scrap
		Replacement of furnace with continuous input of material to batch-input
		Replacement of furnace with batch-input of material to continuous input
		Replacement of heating technology (e.g. gas burner, induction, IR, plasma)
		Replacement of energy carrier in furnace
		Control of furnace for optimal operation (e.g. heating time, holding time, idle time)
		Buys molten metal in thermally insulated transport crucibles
	Sorting of scrap	Sorting of scrap metal with magnet or eddy current separator
		Sorting of scrap metal with x-ray fluorescence (XRF)
		Sorting of scrap metal with Laser Induced Break-down Spectroscopy (LIBS)
		Automatic sorting of scrap metal with on-line analysis equipment in combination with robotics
Material choice, heat treatment, surface treatment		Material choice resulting in improved energy efficiency (e.g. easier forming and extrusion, reduced need for heat treatment)
		Development of existing and new heat treatment processes including improved energy efficiency
		Development of existing and new surface treatment processes including improved energy efficiency
		Lid on surface treatment baths

Table A1. (continued)

Main type	Process	Energy efficiency measure
Production processes	Extrusion	Energy efficient hydraulic system Isothermal extrusion
	Casting	Continuous casting New mould resulting in less material waste New dimensions of ingot, slab or billet resulting in less material waste in processing
	Primary aluminium production	Converting to prebaked cell with point-feeding Larger dimensions of busbars between cells (leading to reduced voltage drop) Multi-material foam for improved contact between electric conductors Slotted anodes (reduced voltage drop) Cast iron in connections between carbon cathode and cathode collector bar Automatic anode effect suppression Cathode collector bars made of copper
Support processes	Pumps	Pumps with better energy class Pumps with time control Demand control of pumps (e.g. frequency converters, sectioning)
	Lighting	LED lights or other energy efficient lighting Active control of lights (e.g. motion detectors) Optimisation of number and location of lights
	Compressed air	Sealing leaks in compressed air system Lowering system pressure in compressed air system Control system for optimal operation of compressed air system Replacement of old air compressor with more energy efficient ones Sectioning of compressed air system Replacement of equipment run on compressed air with electrical machines
	Ventilation	Frequency converters for speed control of fans Point exhausts instead of forced ventilation in the entire production area Ventilation system built for optimal heat recovery Ventilation adapted to demand
	Internal transportation	Efficient internal transportations Converting to other energy carrier in vehicles
	Space heating	Insulation of building envelope Converting heating system to other alternative (e.g. district heating) Other target values for indoor temperature Automatic doors (opening on demand)
	Steam system	Lowered pressure in steam system Converting steam use to, e.g., hot water use Insulating steam system

Table A1. (continued)

Main type	Process	Energy efficiency measure
Others	Recovery	Heat recovery (in-house) to production processes
		Heat recovery (in-house) to space heating and hot tap-water
		Heat recovery (external use) to district heating
		Heat recovery (external use) to other facilities (district heating excluded)
		Electricity production from excess heat
		Power regeneration
		Recovery of dross, skimmings and salt slag
		Bore holes for excess heat storage
		District cooling
	Process optimisations and quality management	Optimisation of process flow
		Optimisation of individual process
		Quality work leading to less material waste and reprocessing
		Control system that optimises cooling system
	Energy management	Capacity of equipment and machines meeting the demand (not over-dimensioned)
		Energy management system
		Energy manager at the company
		Appointed energy hosts on department or group level
		Education in energy for employees
		Dissemination of energy information to employees
		Continuous on-line energy measurements and allocation of energy use

Appendix B: Energy efficiency measures identified in literature

Table B1. The energy efficiency measures identified through the literature review described in section 6.2 with a short description of each measure. A more extensive description of the measures can be found in Paper I.

Process	Energy efficiency measure	Description
General measures	Heat recovery and heat loss reduction	Recover heat and reduce heat losses in processes with excess heat. Heat recovery can be achieved by, e.g., heat exchangers, regenerative burners, preheating combustion air with recovered heat from exhaust gases, and preheat hearth. Heat loss reductions can be achieved by, e.g., better refractory/insulation material, and changing operating temperatures where applicable. See Paper I for more examples of sub-measures.
	Stirring system or metal pumping	Used to reduce temperature gradient between top and bottom of a furnace.
	Immersed furnace heater	The furnace heaters are immersed into the molten metal to improve heat transfer by utilising conduction.
	Oxy-fuel combustion	Pure oxygen is used instead of air in the combustion of the fuel.
	Non-stationary flame burners	Heat transfer to preferred parts of the furnace is achieved by directing the flame to those parts. Higher firing rates are used for areas with more metal than areas with less metal.
	Furnace operation improvements	Implementing operational improvements, e.g. reducing door opening time and holding time, implementing control systems for different parameters, stirring and furnace pressure system, improving control systems, and adjusting burners for efficient operation.
	Gas purging system	Inert or reaction gases are blown into the melt through porous plugs.
	Increased aluminium surface emissivity	The absorption of radiant heat in furnaces can be improved by applying a dark surface coating to the aluminium.
	Reduction of process scrap	Reducing the amount of scrap produced throughout the supply chain of a product. ^a

^a There might be an upper limit on the amount of process scrap that can be reduced, due to technical reasons, for example.

Table B1. (continued)

Process	Energy efficiency measure	Description
General measures	HTS induction furnace	An induction furnace with high-temperature superconducting (HTS) magnets that have a higher efficiency than conventional induction furnaces.
Electrolysis	Process performance improvements	Performance improvements including automatic feeding of alumina at several points, automatic anode effect suppression, and computer-aided monitoring and control systems.
	Cell voltage noise reduction	Implementing a control system that suppresses the voltage noise quickly. Some noise can be reduced by novel structure cathodes (see below).
	Ensure good anode quality	The anodes should, for example, be free from cracks and made from high-quality coke.
	Anode preheating	The anodes should be preheated to avoid a layer of frozen electrolyte bath from forming on the bottom surface of the anodes.
	Slotted or perforated anodes	Slotted or perforated anodes reduce the discharge distance for the anode gas and thus the thickness of the bubble layer on the bottom of the anodes.
	Optimised anode rod assembly design	Changed rod dimensions and improved welding technologies are examples of how anode rod assembly can be optimised.
	Graphitised cathode	Use fully graphitised carbon instead of anthracitic carbon in the cathodes.
	Novel structure cathodes	Novel structure cathodes have surfaces with shape arrangements instead of plane surfaces.
	Optimised cathode collector bar structure	Includes changing the collector bar's conductive structure, adjusting the cathode carbon height and the collector bar size, and adjusting the cathode assembly's resistance distribution through optimising the assembly form of the cathode carbon and the collector bar.
	Reduced cell ventilation	Reducing the ventilation rate while ensuring maintained heat balance. Another option is the technology distributed pot suction system which allows the ventilation rate to be varied within a wide range.
	Addition of lithium fluoride	Adding lithium fluoride to increase the conductivity of the electrolysis bath.
	Current switch bypass	Parallel bypass-short circuit busbars are used to allow a single cell to be overhauled without interrupting other cells.

Table B1. (continued)

Process	Energy efficiency measure	Description
Electrolysis	Improved electrical contact	Improving electrical contact in electrical connections by using a metallic foam.
	Lower temperature electrolytes	Basing the electrolytes on compounds that allow for lower operating temperatures, e.g. potassium cryolite or ionic liquids.
	Wettable cathodes	New cathode materials or coatings on existing materials that allow the cathode to be wetted by the molten metal.
	Inert anodes	Non-consumable anodes with a much longer lifetime than carbon anodes and eliminating the process-related GHG emissions.
	Gas anodes	Based on supplying methane through porous anodes, either carbon or inert anodes, to the electrolysis cell.
	Vertical electrode cells	New cell design with several vertical electrodes where every second electrode is a cathode and every alternate is an anode. The design is based on wettable cathodes, inert anodes and low-temperature electrolytes.
	Corrosion-resistant sidewall refractory	Corrosion-resistant sidewall refractory can be used to eliminate the need for a solid cryolite ledge.
Recycling	Carbothermic reduction	A chemical reduction of aluminium that could potentially replace the electrochemical reduction used today. There are one direct and three indirect carbothermic reductions.
	Selecting appropriate melting furnaces and feed material	Different scrap types have their own particular challenges in the melting process. Thus, it is important to adapt the melting process based on the scrap used.
	Tilting rotary furnace	A tilting rotary furnace can be used to remove impurities through mixing of the melt and adequate cover of the melt with less salt.
	Melting clean scrap	Melting scrap that is free from contaminants.
	Internal burner system	Using internal burner systems rather than afterburners to combust organic compounds in the flue gases.
	Proper sealing of furnace door	Proper sealing of the furnace door helps to maintain a positive pressure in the furnace. Embedding the door frame into the refractory material lowers the area for heat transfer to the outside.

Table B1. (continued)

Process	Energy efficiency measure	Description
Recycling	Targeted fume collection	Fume sources can change over the operation cycles and collection fan capacity can be directed to the changing fume sources.
	Reverberatory furnace with side well, charge well and metal pumping/stirring	Combining a reverberatory furnace with a side well, a charge well and metal pumping/stirring to improve performance and allow for a wider range of raw materials to be used compared to a simple reverberatory furnace.
	Recovery of constituents in skimmings, dross and salt slag	Recycling and utilisation of the different constituents in skimmings, dross and salt slag to replace primary raw materials and reduce waste disposal.
	Recycling through hot extrusion	Recycling of small scrap, e.g. chips and filings, through hot extrusion to reduce losses through oxidation.
	Spark plasma sintering	Scrap (turnings or chips) are pre-compacted at room temperature and then sintered below the solidus temperature under 200 MPa pressure to produce billets, or near-net or even final-shape products.
Casting	Supply molten aluminium for direct moulding	Supplying aluminium in molten form instead of as solid ingots to avoid remelting at the foundry.
	Arranging orders	Arranging orders so that orders with similar alloys are placed in conjunction to each other.
	Electromagnetic casting	Ingots with better quality and mechanical properties can be achieved by applying a magnetic field to the casting process.
	Improved practices for molten metal transfer CRIMSON casting	Implementing practice improvements to reduce metal temperature losses between furnace tapping and mould pouring. A shape-casting method employing an induction furnace and up-caster.
Rolling	Combined casting and rolling	Continuous production of aluminium sheets directly from molten aluminium by combining casting and rolling.
	Al-Cu-Mn-Zr sheet alloys	Alloys of the Al-Cu-Mn-Zr system can be used to produce cold rolled sheets directly from cast slabs without homogenisation.
Extrusion	Isothermal extrusion	Ensuring constant temperature throughout the entire extrudate to avoid the quality losses of parts of the extrudate.

Table B1. (continued)

Process	Energy efficiency measure	Description
Heat treatment	Microwave heat treatment	Applying an electromagnetic field to the metal rather than using conventional furnaces.
	Heating ageing treatment or cooling ageing treatment	Non-isothermal ageing treatment processes rather than isothermal processes.
	Heat treatment based on casting method	Better design of heat treatment for components cast by processes with high cooling rates.
Anodising	New sealing methods	Implementing sealing methods operating at lower temperatures.

Appendix C: Ratings of barriers and drivers

Tables C1 and C2 show the ratings of the barriers for the Swedish aluminium industry and Swedish aluminium casting foundries, respectively. One respondent did not want to answer the questionnaire, but stated that a lack of budget funding for energy efficiency improvements and uncertainties regarding the company's future (due to profitability) hindered their work to improve energy efficiency.

Table C1. The rating of the barriers for the Swedish aluminium industry. The table shows both the mean rating and each respondent's rating. A Likert scale from "Never important" (1) to "Always important" (5) was used to evaluate the barriers. The barriers within each category have been sorted in descending order based on the mean rating. The sorting is additionally based on the size of the variations in the respondents' ratings for barriers with the same mean rating (smaller variations indicate a more unanimous view on the importance of the barrier and are therefore ranked higher). Reprinted with permission from Paper V.

Category	Barrier	Respondent					Mean
		1	2	3	4	5	
Technol- ogy	Risk of changes affecting production capacity	5	4	5	5	5	4.8
	Complex production processes	4	4	5	4	5	4.4
	Technical risks such as risk of production disruption	5	3	4	5	5	4.4
	Risk of poor performance of purchased equipment or after changed working routines	4	4	4	4	5	4.2
	Technology is inappropriate at this site	3	5	4	3	5	4
	Lack of sub-metering on machine or division level	4	4	4	3	4	3.8
	Risk of changes affecting product quality	2	2	5	5	5	3.8
	Technical lifetime of equipment decides when energy efficiency measures are implemented	5	2	3	3	3	3.2
Econom- ics	Cost of production disruption	5	4	5	4	5	4.6
	Cost of identifying opportunities and analysing cost-effectiveness	3	5	4	4	4	4
	Lack of budget funding for energy management	4	5	4	3	4	4
	Other priorities for capital investments	4	4	4	3	4	3.8

Table C1. (continued)

Category	Barrier	Respondent					Mean
		1	2	3	4	5	
Economics	The benefits of energy efficiency improvements are not expected to outweigh the costs	3	4	4	3	5	3.8
	Uncertainties regarding future energy prices and economic policies	3	5	4	3	4	3.8
	Lack of access to capital	2	4	4	4	5	3.8
	Lack of budget funding for energy efficiency improvements	3	4	4	3	4	3.6
	Uncertainties regarding hidden or indirect costs	3	3	4	5	3	3.6
	Cost of staff replacement, retirement, and retraining	2	3	4	4	5	3.6
Organisation	Slim organisation	4	5	3	4	4	4
	Lack of time or other priorities	5	3	3	5	4	4
	Non-energy related work tasks have higher priority	4	4	3	4	4	3.8
	Top management not prioritising energy issues	3	3	4	5	4	3.8
	Energy manager lacks influence	4	2	4	5	4	3.8
	Long decision chain	2	5	2	5	4	3.6
	Improved energy efficiency not part of core activities	4	3	3	3	4	3.4
	Difficulties in collaborating between divisions	3	4	2	4	4	3.4
	Energy objectives not integrated into operating, maintenance, or purchasing procedures	3	2	4	4	4	3.4
	Department/workers not accountable for energy costs	2	3	4	4	4	3.4
	Conflicts of interest within the company	3	3	3	3	4	3.2
	No opportunities for improved energy management	2	3	3	3	4	3
	Uncertainty regarding the company's future	1	3	2	3	4	2.6

Table C1. (continued)

Category	Barrier	Respondent					Mean
		1	2	3	4	5	
Information & behaviour	Lack of technical skills regarding energy efficient technology	4	2	4	5	5	4
	Lack of internal expertise	4	4	3	4	4	3.8
	Lack of external expertise	4	4	3	4	4	3.8
	Lack of knowledge about daily operations	3	4	3	4	5	3.8
	Lack of staff awareness regarding energy issues	5	4	3	3	4	3.8
	Poor information quality regarding energy efficiency opportunities	3	2	3	4	4	3.2
	Staff reluctant to changes they have no experience of	4	2	3	3	4	3.2
	Difficult to obtain information on the energy use of purchased equipment	3	1	4	4	3	3

Table C2. The rating of the barriers for the Swedish aluminium casting foundries. The table shows both the mean rating and each respondent's rating. A Likert scale from "Never important" (1) to "Always important" (5) was used to evaluate the barriers. The barriers within each category have been sorted in descending order based on the mean rating. The sorting is additionally based on the size of the variations in the respondents' ratings for barriers with the same mean rating (smaller variations indicate a more unanimous view on the importance of the barrier and are therefore ranked higher). Reprinted with permission from Paper V.

Category	Barrier	Respondent																Mean
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
Technology	Risk of changes affecting product quality	5	2	5	5	5	4	5	5	5	5	5	5	5	5	5	5	4.67
	Risk of changes affecting production capacity	5	2	4	5	5	4	5	5	5	5	5	5	5	5	5	5	4.58
	Technical risks such as risk of production disruption	5	2	5	5	5	4	4	4	5	5	5	5	5	5	4	4	4.42
	Technology is inappropriate at this site	5	5	3	3	4	4	4	5	4	5	5	5	5	3	3	4	4.17
	Technical lifetime of equipment decides when energy efficiency measures are implemented	5	4	4	5	4	5	2	3	4	4	4	4	4	4	4	4	4
	Risk of poor performance of purchased equipment or after changed working routines	5	4	3	4	4	4	3	3	4	4	4	5	4	5	4	4	3.92
	Lack of sub-metering on machine or division level	5	2	3	5	4	4	2	3	4	3	3	3	3	3	3	3	3.42
	Complex production processes	5	4	3	1	4	4	3	4	1	5	4	3	3	4	3	3	3.42
Economics	Cost of production disruption	5	5	4	3	5	5	4	5	5	4	4	4	4	4	4	4	4.42
	Uncertainties regarding future energy prices and economic policies	5	5	3	4	4	4	3	5	5	3	3	3	5	3	5	5	4.08
	Other priorities for capital investments	5	5	3	3	3	4	5	4	4	3	5	3	5	3	5	3	3.92
	Cost of identifying opportunities and analysing cost-effectiveness	5	4	3	4	3	5	4	5	4	3	3	4	3	3	4	4	3.92

Table C2. (continued)

Category	Barrier	Respondent																
		6	7	8	9	10	11	12	13	14	15	16	17	Mean				
Economics	The benefits of energy efficiency improvements are not expected to outweigh the costs	5	4	3	3	4	4	3	5	3	4	5	3	3.83				
	Lack of access to capital	5	5	3	4	2	4	4	4	3	5	3	4	3.83				
	Cost of staff replacement, retirement, and retraining	5	5	3	3	3	5	2	5	3	3	3	4	3.67				
	Uncertainties regarding hidden or indirect costs	5	4	2	5	3	4	3	5	3	3	3	3	3.58				
	Lack of budget funding for energy efficiency improvements	5	4	2	3	3	4	5	3	4	3	4	2	3.5				
Organisation	Lack of budget funding for energy management	5	4	2	3	3	4	5	3	3	3	4	2	3.42				
	Non-energy-related work tasks have higher priority	5	5	3	3	3	3	5	5	4	3	4	3	3.83				
	Lack of time or other priorities	5	4	2	2	3	4	5	5	3	4	3	5	3.75				
	Slim organisation	5	5	2	2	2	5	3	5	4	3	3	4	3.58				
	Improved energy efficiency not part of core activities	5	3	3	4	3	3	4	5	3	2	3	4	3.5				
	No opportunities for improved energy management	5	3	2	4	2	4	3	5	1	3	3	3	3.17				
	Energy objectives not integrated into operating, maintenance, or purchasing procedures	5	4	3	2	3	4	2	5	1	3	3	3	3.17				
	Energy manager lacks influence	5	3	2	5	2	4	3	4	1	3	3	2	3.08				
	Uncertainty regarding the company's future	5	3	3	3	2	4	3	2	1	2	4	4	3				

Table C2. (continued)

Category	Barrier	Respondent																Mean
		6	7	8	9	10	11	12	13	14	15	16	17					
Organisation	Department/workers not accountable for energy costs	5	3	2	5	2	3	2	4	1	2	4	2	4	2	2.92		
	Top management not prioritising energy issues	5	3	2	2	2	4	4	4	1	3	1	3	3	2.83			
	Difficulties in collaborating between divisions	5	3	2	2	2	4	3	2	1	2	1	2	2	2.42			
	Long decision chain	5	3	2	2	2	3	3	2	1	2	2	1	2	2.33			
	Conflicts of interest within the company	5	3	2	3	2	3	3	2	1	1	1	1	1	2.25			
Information & behaviour	Lack of internal expertise	5	3	3	3	3	3	4	5	4	3	3	4	3	3.58			
	Lack of staff awareness regarding energy issues	5	3	3	5	3	2	4	5	4	2	3	4	3	3.58			
	Poor information quality regarding energy efficiency opportunities	5	3	2	4	3	4	4	5	3	3	3	3	3	3.5			
	Lack of technical skills regarding energy efficient technology	5	3	3	3	3	3	4	5	4	3	2	4	3	3.5			
	Difficult to obtain information on the energy use of purchased equipment	5	3	2	5	3	4	4	2	3	3	3	4	3	3.42			
	Lack of external expertise	5	3	2	4	3	3	4	5	2	2	4	4	4	3.42			
	Staff reluctant to changes they have no experience of	5	3	3	5	3	4	3	4	3	1	3	4	4	3.42			
	Lack of knowledge about daily operations	5	3	3	4	3	2	2	3	2	3	3	3	3	3			

Tables C3 and C4 show the ratings of the drivers for the Swedish aluminium industry and Swedish aluminium casting foundries, respectively.

Table C3. The rating of the drivers for the Swedish aluminium industry. The table shows both the mean rating and each respondent's rating. A Likert scale from "Never important" (1) to "Always important" (5) was used to evaluate the drivers. The drivers within each category have been sorted in descending order based on the mean rating. The sorting is additionally based on the size of the variations in the respondents' ratings for drivers with the same mean rating (smaller variations indicate a more unanimous view on the importance of the driver and are therefore ranked higher). Reprinted with permission from Paper V.

Category	Driver	Respondent					Mean
		1	2	3	4	5	
Economics	Cost reductions due to lower energy use	4	5	4	5	5	4.6
	Improved work environment	5	4	4	4	5	4.4
	Access to capital/budget funding for energy efficiency improvements	3	5	4	4	5	4.2
	Reduced power charge/avoid exceeding power peaks	3	5	4	4	5	4.2
	Reduced waste	3	4	4	4	5	4
	Reduced maintenance	4	4	4	3	5	4
	Threat of rising energy prices	4	4	4	2	5	3.8
	Investment subsidies for energy efficient technologies	2	3	3	4	4	3.2
	Incentive agreement/Third-party financing/Energy performance contracting	2	2	4	3	2	2.6
	Beneficial loans for energy efficiency investments	2	2	3	2	3	2.4
Organisation	Full support from top management	5	5	5	5	5	5
	Long-term energy strategy	5	5	5	4	5	4.8
	Demands from owners	5	5	4	5	5	4.8
	Well-functioning relations within organisation	5	5	5	4	5	4.8
	Environmental company profile	5	3	4	4	5	4.2
	Allocation of energy costs based on sub-metering	4	4	5	4	4	4.2
	Environmental management system	5	4	5	2	5	4.2
	Energy management system	3	5	5	2	5	4
	Quality or other management systems	5	3	5	2	5	4

Table C3. (continued)

Category	Driver	Respondent					Mean
		1	2	3	4	5	
Information & behaviour	People with real ambition	5	5	5	5	5	5
	Ability to make use of and spread individuals' knowledge about support and production processes	5	5	4	5	5	4.8
	Access to internal expertise with knowledge about the processes	4	5	5	5	5	4.8
	Knowledge about daily operations	5	5	5	4	5	4.8
	Detailed support from energy experts when implementing energy efficiency investments	4	5	4	4	4	4.2
	Internal education	4	4	4	4	5	4.2
	Network outside company or company group	4	4	4	4	4	4
	Network within the sector or trade organisation	4	4	4	4	4	4
	Network within the company or company group	3	4	4	5	4	4
	Access to external expertise with knowledge about the processes	2	4	4	5	5	4
	Information and support through trade organisation	3	4	4	4	4	3.8
	General energy advice through seminars	3	5	4	4	3	3.8
	General energy advice through journal/brochure	3	5	4	3	3	3.6
	Local authority energy consultancy	1	3	4	2	3	2.6
Market	International competition	3	5	3	3	5	3.8
	Demands and questions from customers	5	4	3	3	4	3.8
	Pressure from different environmental NGOs	3	3	3	3	3	3
	ESCOs responsible for operation and maintenance of buildings	2	2	3	3	3	2.6

Table C3. (continued)

Category	Driver	Respondent					Mean
		1	2	3	4	5	
Govern- ment & policy	Energy efficiency requirements due to current law (e.g., the Swedish Environmental Code)	5	4	4	4	5	4.4
	EU ETS	5	4	4	3	5	4.2
	Demands for a conducted energy audit with proposed energy efficiency measures	5	3	4	4	5	4.2
	The municipality's energy plan/energy strategy	3	4	3	4	4	3.6
	Electricity Certificate Systems	3	3	4	3	5	3.6
	Demands for improved efficiency from the Swedish county administrative boards	4	2	4	3	5	3.6
	Taxes (energy tax, carbon tax, etc.)	4	1	4	4	5	3.6
	Publicly financed energy audits by energy consultant or sector organisation	3	3	3	4	4	3.4
	Annual environmental report to the Swedish county administrative boards, including an energy plan and proposed energy efficiency measures	4	2	4	3	4	3.4
	Voluntary long-term agreements with tax exemption (PFE)	3	2	4	3	5	3.4
	Public sector as role model	1	2	3	3	3	2.4

Table C4. The rating of the drivers for the Swedish aluminium casting foundries. The table shows both the mean rating and each respondent's rating. A Likert scale from "Never important" (1) to "Always important" (5) was used to evaluate the drivers. The drivers within each category have been sorted in descending order based on the mean rating. The sorting is additionally based on the size of the variations in the respondents' ratings for drivers with the same mean rating (smaller variations indicate a more unanimous view on the importance of the driver and are therefore ranked higher). Reprinted with permission from Paper V.

Category	Driver	Respondent															
		6	7	8	9	10	11	12	13	14	15	16	17	Mean			
Economics	Cost reductions due to lower energy use	5	5	5	4	4	4	5	5	5	4	5	5	4	5	5	4.67
	Reduced power charge/avoid exceeding power peaks	5	5	5	5	4	4	4	4	5	5	2	4	5	4	5	4.42
	Improved work environment	5	4	4	5	4	4	3	4	4	4	5	5	5	5	5	4.33
	Reduced waste	5	4	5	5	4	4	2	5	5	3	5	5	3	5	5	4.33
	Reduced maintenance	5	5	4	5	4	4	2	5	4	3	5	5	3	5	5	4.25
	Threat of rising energy prices	5	5	4	4	4	4	3	5	4	3	4	5	3	4	5	4.17
	Access to capital/budget funding for energy efficiency improvements	5	4	3	3	4	4	5	5	3	3	4	5	3	4	5	4
	Investment subsidies for energy efficient technologies	5	5	2	2	4	4	4	5	4	2	3	4	2	3	4	3.67
	Incentive agreement/Third-party financing/Energy performance contracting	5	3	1	3	4	4	3	5	3	3	4	3	3	4	3	3.42
	Beneficial loans for energy efficiency investments	5	5	1	2	3	4	4	4	5	4	2	2	4	2	4	3.42
Organisation	Full support from top management	5	4	4	5	4	4	5	5	2	4	5	3	4	5	3	4.17
	Quality or other management systems	5	3	4	5	4	4	5	3	4	4	4	5	3	4	5	4.08
	Long-term energy strategy	5	4	4	5	4	4	2	4	5	3	5	3	5	3	5	4
	Environmental management system	5	4	4	5	4	4	3	3	4	3	4	3	5	3	5	3.92

Table C4. (continued)

Category	Driver	Respondent															
		6	7	8	9	10	11	12	13	14	15	16	17	Mean			
Organisa- tion	Environmental company profile	5	5	4	5	4	4	2	4	3	3	5	3	3	3.92		
	Well-functioning relations within organisation	5	5	4	5	4	3	4	5	3	2	4	3	3	3.92		
	Energy management system	5	3	4	5	4	4	2	4	4	3	5	3	3	3.83		
	Allocation of energy costs based on sub-metering	5	4	4	5	4	4	2	4	3	2	3	3	3	3.58		
	Demands from owners	5	2	4	5	4	4	2	4	2	3	4	3	3	3.5		
Information & behaviour	Access to internal expertise with knowledge about the processes	5	5	5	5	4	5	4	5	4	4	4	3	4	4.42		
	Knowledge about daily operations	5	5	4	5	4	4	4	5	4	4	4	3	4	4.25		
	Ability to make use of and spread individuals' knowledge about support and production processes	5	5	3	5	4	5	4	5	4	3	5	3	4	4.25		
	People with real ambition	5	5	4	5	4	5	3	5	3	4	5	3	4	4.25		
	Internal education	5	5	3	5	4	4	3	4	5	4	4	3	4	4.08		
	Access to external expertise with knowledge about the processes	1	5	2	5	4	4	2	5	5	4	5	3	3	3.75		
	Detailed support from energy experts when implementing energy efficiency investments	1	5	4	4	3	3	3	5	4	4	5	2	2	3.58		
	Information and support through trade organisation	1	3	4	4	4	3	3	5	4	2	5	2	2	3.33		
	Network outside company or company group	5	3	3	4	3	3	2	5	2	2	4	3	3	3.25		
	Network within the company or company group	5	4	3	3	3	3	2	3	2	2	4	1	1	2.92		
	Network within the sector or trade organisation	1	3	3	4	3	3	2	4	2	2	5	2	2	2.83		

Table C4. (continued)

Category	Driver	Respondent															
		6	7	8	9	10	11	12	13	14	15	16	17	Mean			
Information & behaviour	General energy advice through seminars	1	4	2	4	3	3	2	3	3	2	4	1	2.67			
	Local authority energy consultancy	1	4	2	4	3	3	2	1	3	2	4	2	2.58			
	General energy advice through journal/brochure	1	3	2	2	3	3	2	3	3	2	4	1	2.42			
Market	International competition	5	5	3	4	3	5	4	5	4	2	5	4	4.08			
	Demands and questions from customers	5	2	4	4	4	5	5	2	3	2	5	5	3.83			
	Pressure from different environmental NGOs	1	3	3	2	4	3	2	2	4	2	5	4	2.92			
	ESCOs responsible for operation and maintenance of buildings	1	3	3	2	4	2	2	2	4	1	1	2	2.25			
Government & policy	Taxes (energy tax, carbon tax, etc.)	5	5	5	4	4	4	5	5	5	2	4	5	4.42			
	Energy efficiency requirements due to current law (e.g. the Swedish Environmental Code)	5	5	5	5	4	3	2	3	3	3	4	5	3.92			
	Voluntary long-term agreements with tax exemption (PFE)	5	5	3	2	4	4	4	4	3	2	3	5	3.67			
	Publicly financed energy audits by energy consultant or sector organisation	2	5	4	2	4	3	4	4	4	3	3	3	3.42			
	Electricity Certificate Systems	5	1	3	2	4	4	2	3	4	2	4	5	3.25			
	Demands for a conducted energy audit with proposed energy efficiency measures	2	4	5	3	4	3	2	3	3	2	4	3	3.17			
	Annual environmental report to the Swedish county administrative boards, including an energy plan and proposed energy efficiency measures	2	3	3	3	4	3	2	3	3	3	5	3	3.08			

Table C4. (continued)

Category	Driver	Respondent														
		6	7	8	9	10	11	12	13	14	15	16	17	Mean		
Government & policy	Demands for improved energy efficiency from the Swedish county administrative boards	2	3	3	2	4	3	2	4	4	3	3	3	3		
	EU ETS	5	1	3	2	4	3	2	3	3	1	4	4	2.92		
	The municipality's energy plan/energy strategy	2	4	3	2	3	3	2	3	3	2	3	3	2.75		
	Public sector as role model	1	4	3	1	2	3	2	1	2	2	1	3	2.08		

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