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

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Abstract

According to the Energy Efficiency Directive executed by the European Union, each member state is obliged to set a national target on energy efficiency. This requirement constitutes the basis for governments to formulate policy measures directed towards industrial companies. Such policy measures, along with the demand for cost-effective production to remain competitive on the market, motivates industrial companies to improve their energy efficiency. The aluminium industry is energy intensive and consumes substantial amounts of electricity and fossil fuels, resulting in both direct and indirect greenhouse gas emissions. This paper presents a study of the production of an aluminium product in Sweden in terms of implemented energy efficiency measures in the supply chain and potential areas for further improvement. Most previous studies have focused on energy efficiency measures in individual companies (value chains). However, this paper presents and analyses energy efficiency measures not only in each individual company but also in the entire supply chain of the product. The supply chain studied starts with secondary aluminium production followed by the production of a part of an automobile motor and ends with installing the motor detail in a car. Empirical data were gathered through a questionnaire and a focus group. The study shows the great potential for further energy efficiency improvements in the value chains of each individual company and in the whole supply chain. The work shown here is a part of a larger research project performed in close cooperation with the Swedish aluminium industry.

Introduction

The definition of energy efficiency is most commonly described as the relation between energy used and the produced amount of goods or the service completed. According to the IEA (2014), energy efficiency is central to addressing energy security and environmental and economic challenges. In 2016, the total energy used globally would have been 12 % higher than in 2000 unless efficiency improvements had prevented such an increase (IEA, 2017). The IEA (2017) also states that energy use in industry, in relation to economic output, was reduced by 20 % during the same period. Moreover, the aluminium electrolysis industry has reduced the energy intensity (MWh/tonne) by 6.9 % globally, mainly due to increased production capacity, primarily in emerging countries where old inefficient production units were replaced by new more energy efficient units (IEA, 2017). Energy efficiency has several other benefits, besides reducing energy use, and the IEA (2014) presents fifteen multiple benefits when implementing energy efficiency measures including enhanced energy system security, economic development, social development, environmental sustainability and increasing prosperity.

The aluminium industry involves many different processes. Production of primary aluminium demands energy amounting to 14.3 kWh per kilogram on average (only electrolysis) globally (International Aluminium Institute, 2017b), while secondary aluminium production (recycling of aluminium) substantially reduces the need for energy by approximately 95 % (Tabereaux and Peterson, 2014). Primary aluminium production demands large amounts of electricity in the electrolysis of alumina into metal aluminium. In addition, fossil fuels are used in e.g. heating furnaces. Secondary aluminium production uses energy in the form of electricity and fossil fuels. There are several pos-

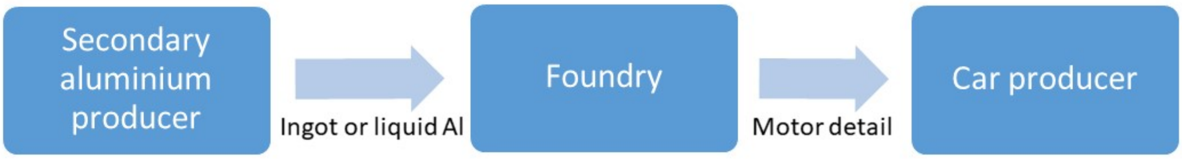

Figure 1. Schematic drawing of the studied supply chain.

sibilities to process the aluminium into different products, e.g. casting, extrusion and rolling.

In 2016, almost 91 million tonnes of aluminium were produced globally, where about two thirds came from primary sources, about 19 % from recycling of post-consumer scrap and about 14 % from remelting of process scrap (excluding internal remelting) (International Aluminium Institute, 2017a). Statistics on the amount of aluminium going to casting, extrusion and rolling, respectively, are scarce. A reason for this is that shipments of semi-finished products are considered confidential to the industry in many regions (Bertram et al., 2017). However, in 2009, the 71.5 million tonnes of aluminium produced was distributed as about 32.6 % to rolling, about 32.3 % to extrusion, about 31.7 % to casting and the rest to powder, paste and others (Liu et al., 2013).

Haraldsson and Johansson (2018) identified 52 possible energy efficiency measures in the aluminium industry. Most of these measures were found in the electrolysis in primary aluminium production, in the recycling of aluminium and in general measures which concern a range of processes. Fewer measures were found in other specific processes in the aluminium industry, such as extrusion, rolling and casting. Haraldsson and Johansson (2018) argued that the reason for the lower amount of measures for processing was partially that these processes are not as energy intensive as, for example, electrolysis and partially not as widely applicable as, for example, the measures regarding furnaces. Two examples of energy efficiency measures for casting, found by Haraldsson and Johansson (2018), are (1) receiving the metal in liquid form from the supplier and (2) improved practices for transferring molten metal within the company. Haraldsson and Johansson (2018) also analysed whether it was possible to combine the identified measures or whether they could only be implemented separately.

The term value chain focuses on the individual company (Porter, 2004). According to Porter (2004), the company is divided into strategically relevant activities, such as designing, producing and marketing a product. Goetschalckx (2011) defines a supply chain as a complex integrated network including the procurement of raw materials, and thereafter the processing of materials and the delivery of the final products to customers. The supply chain includes many entities besides manufacturing, e.g. providers of logistics, vendors and wholesalers (Goetschalckx, 2011). Several authors have studied different aspects for reducing an entire supply chain's environmental impact focusing on supply chains in general (see e.g. Tsoulfas and Pappis (2008); Faruk et al. (2001); Srivastava (2007); Faisal (2010), Ji et al. (2014); Jawahir et al. (2007); Duflou et al. (2012); Kadambala et al. (2017)) or on supply chains in industries other than the aluminium industry (e.g. the plastics industry (Mulder, 1998), the computer industry (Rosen et al., 2001), the food industry (Ala-Harja and Helo, 2014) and companies in South East Asia (Rao and Holt, 2005)). Khoo et al. (2001) present a case study of a supply chain delivering a die cast aluminium component with a focus on the transportation of goods between sites. In the same study, Khoo et al. (2001) also examine the possibility of delivering molten metal to a casting plant. To the authors' knowledge, no study examines how the companies in a supply chain of the aluminium industry can work together to improve energy efficiency and how each individual company can work to increase energy efficiency in-house.

The aim of this paper is to identify the actual status in terms of implemented energy efficiency measures in a supply chain of an aluminium product produced in Sweden and to analyse potentials for improvements. The study will analyse measures and potentials within each company and add the dimension of what the companies can do together to improve energy efficiency in the entire supply chain. Compared to Khoo et al. (2001), this paper addresses aspects of the whole supply chain.

The supply chain studied

This paper studies a supply chain for the production of a motor component for cars, which comprises three companies. The component was chosen based on the recommendation of representatives from the Swedish Aluminium Association[1]. Figure 1 presents a schematic picture of the supply chain, which shows that the studied supply chain starts with a company producing the desired aluminium alloy from mainly post-consumer scrap (secondary aluminium producer). The aluminium alloy is delivered to the next company, which produces the motor component through pressure die casting (foundry). The motor component is then delivered to the car producer ready for mounting in the car (car producer). Aspects of the final consumers' energy use (the car owners) and their demands on the product are not included, but enter the discussions indirectly.

Methods

To obtain an overview of the individual companies' status in terms of energy efficiency, a questionnaire was sent to the person responsible for energy issues at each of the three companies in the supply chain. These persons were also respondents in the focus group. The questionnaire comprised questions regarding the company's energy use and the potentials for improved energy efficiency. Furthermore, the main part of the questionnaire was a list of 75 measures for improved energy efficiency where the respondents were asked to mark whether the measures were (1) implemented, (2) planned to be implemented or implementation in progress, (3) possible to implement but not

1. www.svensktaluminium.se

planned, (4) not applicable or (5) unknown to the respondent. In addition, the respondents had the opportunity to comment on their answers and mention measures not found in the questionnaire. Measures that reduce material waste, reduce reprocessing due to e.g. poor quality, and recovery of waste products are considered measures that improve energy efficiency. The energy efficiency measures related to production processes had been chosen based on a literature review previously conducted by Haraldsson and Johansson (2018). Additional production related measures and measures regarding support processes were added based on the authors' knowledge about energy auditing in industry. The formulation of the questionnaire was discussed and the measures were confirmed during a workshop with representatives from five large aluminium companies in Sweden and one person from the Swedish aluminium industry's association. The questionnaire was distributed in the spring of 2017 and answered online using the software Survey & Report.

Potential energy efficiency measures when considering the entire supply chain were identified through a focus group. A focus group is based on a group discussion where persons discuss a given subject during a limited time (Wibeck, 2010). The discussion is initiated and led by a moderator, but the discussion should be free (Wibeck, 2010). The topic and/or a stimulus material is given before the focus group and initiated by the moderator (Wibeck, 2010). Focus group was chosen as method because it gives the respondents the possibility to react to each other's' comments in real time. Moreover, the complexity of the energy and material flows in the supply chain is better studied in a focus group, where respondents from the companies in the supply chain can interact, than through individual interviews.

Respondents from each of the three companies were gathered in the focus group. The respondents were expected to have knowledge about the production processes and energy use of their respective companies. However, the companies were free to choose their respondents and could send more than one respondent. In total, seven respondents from the companies participated in the focus group. The positions of the respondents were technical manager, production manager, process manager, environmental manager, purchasing manager, project manager and maintenance director. The focus group discussions revolved around how the companies can work together to improve the energy efficiency in the supply chain and on potentials for improved energy efficiency. Questions about these aspects were phrased and sent to the respondents before the focus group. The focus group discussions were based on, but not strictly guided by, the beforehand given questions. The discussions during the focus group were characterised by an openness between the respondents and there was no direct competition between the companies impeding the discussions. The moderator guided the discussions, but the discussions were quite free and the respondents could ask each other questions. To clarify ambiguous parts of the focus group discussion, the moderator posted additional questions by phone or e-mail after the focus group.

The discussions in the focus group were audio recorded, transcribed in full and coded. A code is a word or phrase that describes a larger piece of text in a summative way. "Measure" (short for "energy efficiency measure") and "potential" were used as "main" codes and more specific codes were developed with the focus group material as a basis. Other codes, in addition to the "main" codes, were developed for parts of the material that were not directly related to the aim of this paper, but might be worth including in the analysis.

The material was grouped into each measure and each potential. A summarising description of each measure and potential was written, and the text was sent to the respondents to verify that the interpretation of the material was correct and to provide an opportunity for the respondents to add additional information.

Results and analysis

INDIVIDUAL COMPANIES

In 2016, the three companies in the supply chain of the motor detail used 203 GWh energy in total, including electricity, district heating, liquefied petroleum gas (LPG) and diesel. The secondary aluminium producer used 60 GWh/y, whereof 77 % LPG, 19 % electricity and 4 % diesel, and the specific energy use was 0.8 MWh/tonne produced aluminium. The foundry used 67 GWh/y, whereof 67 % electricity, 29 % LPG and 4 % district heating, and the specific energy use was 3.6 MWh/tonne produced aluminium product. The car producer used 76 GWh/y, whereof 83 % electricity and 17 % district heating. Processes performed at the secondary aluminium producer were scrap handling, secondary aluminium production and remelting of aluminium. Processes found at the foundry were remelting of aluminium, casting and machining, while the car producer performed machining.

The results from the questionnaire showed that several potential areas existed for improving energy efficiency at each company. If considering only cost-effective technical measures at the individual companies, there is a potential to improve energy efficiency by 7–13 %. However, when including managerial measures, this potential improvement increases to 8–16 %. As can be seen in Figure 2, the energy efficiency potential varies between the individual companies, with the largest potential found at the foundry. This is also true when considering the potential amount of kWh saved. However, according to the respondent at the foundry, they have been successful with their energy management work and the remaining efficiency potentials relate to improved technology.

The results from the questionnaire revealed a large number of measures for improved energy efficiency that could potentially be implemented in-house at the individual companies in the supply chain studied. In addition, several measures had already been implemented or were planned to be implemented. Table 1 shows a compilation of the measures and the implementation status at each individual company, where the number in each cell represents how many of the three companies that have ticked the corresponding alternative in the questionnaire. Of the 75 energy efficiency measures in the questionnaire, nine were not technically applicable at any of the companies; thus, these measures are not shown in Table 1. The measures concerning steam generation and a steam distribution system were marked by all companies as not applicable at the company or unknown to the respondent and, as none of the companies performed extrusion, the measure isothermal extrusion was not relevant.

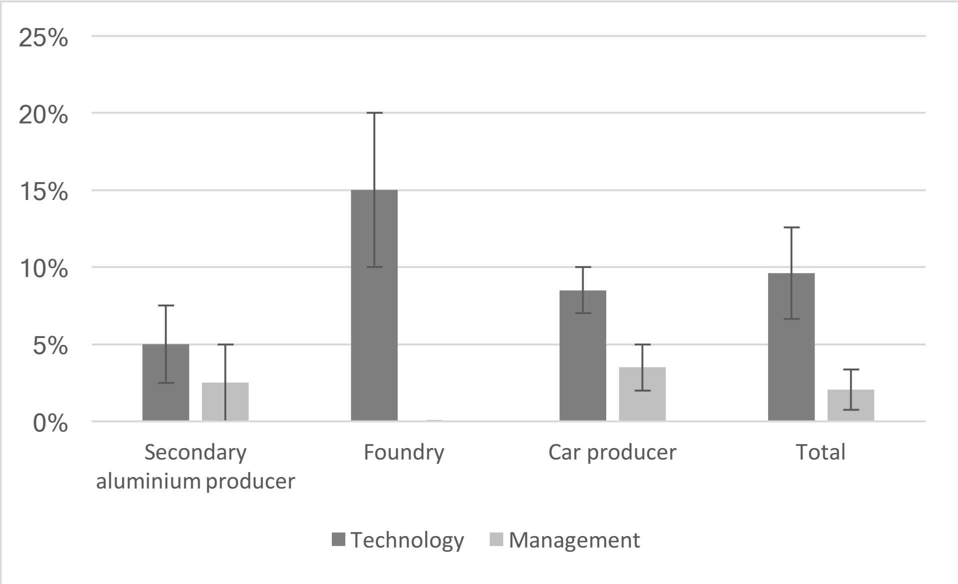

Figure 2. Estimated potentials for improved energy efficiency at each company and total in-house energy efficiency potential for all three companies. The dark-grey bars show the potentials considering only cost-effective technology and the light-grey bars show the additional potential when considering energy management.

Measures regarding scrap sorting were only applicable to the secondary aluminium producer, and measures regarding furnaces were not technically applicable to the car producer since no heating operations were performed at the company.

When taking into account technical applicability, the following energy efficiency measures had the highest rate of implementation (in place, in progress or planned): recovery of excess heat for internal use as space heating and hot tap-water; recovery of dross, skimmings and salt slag; use of LED lights or other energy efficient lighting; optimisation of air-to-fuel-ratio in furnaces; magnetic stirrers in furnaces; tilted rotating furnace; and replacement of furnace with continuous input of material to batch-input. The foundry buys liquid aluminium in thermally insulated transport crucibles, also known as thermoses, from the secondary aluminium producer, which results in reduced energy use at the foundry compared to purchasing solid aluminium and remelting it before casting.

The following energy efficiency measures were neither implemented nor planned to be implemented at any of the companies, even though it was possible to implement them: sectioning of a compressed air system; a ventilation system built for optimal heat recovery; ingot with dimensions that reduces material waste during processing; capacity of equipment and machines meeting the demand (not over-dimensioned); continuous casting; regenerative burners; recuperative burners; heating furnace with a fixed hood, loaded from below with a moving floor; replacement of furnace with batch-input of material to continuous input; replacement of energy carrier in furnace; control of furnace for optimal operation (e.g. heating time, holding time, idle time); energy efficient hydraulic system; new die resulting in less material waste; district cooling; and all measures for sorting scrap.

As can be seen in Table 1, two of the companies had an energy manager in place, and one of the companies with an energy manager had appointed energy hosts on a department or group level, provided education for employees in energy issues and communicated energy-related information to its employees. These measures are important for conducting successful energy management (Johansson and Thollander, 2018).

SUPPLY CHAIN

Product design

The energy use throughout the supply chain can be affected by the product design and the choice of material or alloy. The design stage is the starting point for the work with increased efficiency throughout the supply chain and lowered product price. It is important to reduce not only the product weight with the aim of reducing the amount of aluminium bought and thus the energy demand in the supply chain, but also the weight of the car and thus its fuel demand during operation.

The car producer believed that it would be easier to make the car more energy efficient if the end-user did not demand as much horsepower. Additionally, the work to improve the energy efficiency of the motor has led to larger stresses on the cylinder head, thus placing higher demands on the material properties and necessitating a change from secondary to primary aluminium alloys. Although the car has become more energy efficient, the use of primary aluminium makes the production of some product parts more energy demanding. The increased energy demand in production is mainly occurring in the production of the metal, where about 20 times more energy is used compared to producing the metal from secondary sources.

Communication and collaboration

The secondary aluminium producer stated that they had too little dialogue with the car producer, which implies that it could be beneficial to increase communication between all the companies in the supply chain and not only between the customer and the supplier. It was raised during the focus group that it could be beneficial to give all the companies in the supply chain the opportunity to give feedback and suggestions on the design. As an

Table 1. Measures for improved energy efficiency that are implemented, planned to be implemented or possible to implement but not planned at the three individual companies in the supply chain. The table shows the implementation status of the measure by presenting the number of companies that has chosen each alternative in the questionnaire.

	Implemented	Implementation in progress or planned	Possible but not planned	Not applicable	Unknown to the respondent
Recovery					
Heat recovery (in-house) to production processes	1	1	1		
Heat recovery (in-house) to space heating and hot tap-water	2	1			
Heat recovery (external use) to DH	1		2		
Heat recovery (external use) to other facilities (DH excluded)				2	1
Electricity production from excess heat				2	1
Bore holes for excess heat storage				2	1
Power regeneration				2	1
Recovery of dross, skimmings and salt slag	2			1	
Pumps					
Pumps with better energy class		1	2		
Pumps with time control	1	1	1		
Demand control of pumps (e.g. frequency converters, sectioning)		2	1		
Lighting					
LED lights or other energy efficient lighting		3			
Active control of lights (e.g. motion detectors)	1	1	1		
Optimisation of number and location of lights	1	1	1		
Compressed air					
Sealing leaks in compressed air system	2		1		
Lowering system pressure in compressed air system	2		1		
Control system for optimal operation of compressed air system	2		1		
Replacement of old air compressor with more energy efficient	1	1	1		
Sectioning of compressed air system			2	1	
Replacement of equipment run on compressed air with electrical machines		1	2		
Ventilation					
Frequency converters for speed control of fans	1	1	1		
Point exhausts instead of forced ventilation in the hole production area	1		1	1	
Ventilation system built for optimal heat recovery			2	1	
Ventilation adapted to demand	1		1		1
Process optimisation					
Optimisation of process flow (e.g. LEAN)	1	1	1		
Optimisation of individual process		2	1		
Quality work leading to less material waste and reprocessing	1	1	1		
Ingot with dimensions that reduces material waste during processing			1	1	1
Control system that optimises cooling system		1	2		
Capacity of equipment and machines meeting the demand (not over-dimensioned)			3		
Continuous casting			1	1	1

The table continues on the next page … →

Table 1. Measures for improved energy efficiency that are implemented … (continuation).

	Implemented	Implementation in progress or planned	Possible but not planned	Not applicable	Unknown to the respondent
Furnaces					
Insulation of furnace for better control of heating and cooling		2		1	
Sealing of furnace and optimisation of oven pressure		2		1	
Optimisation of air-to-fuel-ratio in furnaces	1	1		1	
Oxygen enrichment of combustion air (e.g. oxy-fuel burners)	1			2	
Regenerative burners			1	1	1
Recuperative burners			1	1	1
Magnetic stirrer in furnace	1	1		1	
Furnace with better energy class		1	1	1	
Heating furnace with a fixed hood, loaded from below with a moving floor			1	1	1
Tilted rotating furnace	1			1	1
Preheating of scrap	1		1	1	
Replacement of furnace with continuous input of material to batch-input	1			2	
Replacement of furnace with batch-input of material to continuous input			1	1	1
Replacement of energy carrier in furnace			1	2	
Control of furnace for optimal operation (e.g. heating time, holding time, idle time)			1	2	
Scrap sorting					
Sorting of scrap metal with magnet or eddy current separator			1	2	
Sorting of scrap metal with x-ray fluorescence (XRF)			1	2	
Sorting of scrap metal with Laser Induced Breakdown Spectroscopy (LIBS)			1	2	
Automatic sorting of scrap metal with on-line analysis equipment in combination with robotics			1	2	
Energy management					
Energy management system	1		2		
Energy manager at the company	2		1		
Appointed energy hosts on department or group level	1		2		
Education in energy for employees	1	1	1		
Dissemination of energy information to employees	1	1	1		
Continuous on-line energy measurements and allocation of energy use		1	2		
Internal transports					
Efficient internal transports	1	1	1		
Converting to other energy carrier in vehicles		2	1		
Other					
Energy efficient hydraulic system			1	1	1
New die resulting in less material waste			1	1	1
Buys liquid metal in thermally insulated transport crucibles	1		1	1	
Insulation of building envelope	1		2		
Converting heating system to other alternative (e.g. DH)	2		1		
District cooling			2	1	
Other target values for indoor temperature	1		2		
Automatic doors (opening on demand)	1		1	1	
Total number of energy efficiency measures	40	32	66	46	14

example, an optimised design could reduce the need for processing, and already existing production machines can be used instead of installing new ones. Moreover, facilitating the processing of the product could result in reduced energy use. To date, the energy aspect is not directly addressed to any large extent in the contact between the companies, but is rather addressed indirectly through other parameters such as monetary values or processing time. However, the respondents agreed that it could be beneficial to address the energy aspect more specifically.

The companies collaborate on where the processing of the product is best located, since there might be installed production machines with available capacity at any of the companies. It may be beneficial to optimise the use of the already installed production machines instead of buying a new production machine. Optimising the use of already installed machines could also have an indirect effect on the energy use and the environmental impact, e.g. minimising the idling of machines. Additionally, transporting the product between the production locations affect the energy use depending on the distance between the locations. Another parameter is the number of facilities along the supply chain between which the product is transported. Each facility adds a need for loading and unloading of material, which requires some energy and generates emissions.

Secondary aluminium instead of primary aluminium

The studied motor detail is produced mainly from secondary aluminium. This leads to about 95 % reduction in energy demand for the production of the metal compared to producing the metal from primary sources. To make the entire supply chain more environmentally friendly, secondary aluminium should be used. The respondents of the focus group addressed the challenge that the demand for secondary aluminium is much higher than the amount that can be produced from post-consumer scrap due to the long lifetime of aluminium products and the high demand for aluminium. This affects how much secondary aluminium that can actually be used from both availability and economic perspective

Some aluminium products demand extremely specific criteria of the aluminium, and the alloy is not allowed to diverge from the specification. Secondary aluminium is not always able to meet all of the demands in the product specification due to impurities and unwanted alloying elements in the material. However, it is worth examining the product specification to identify how much the product can differ from the specification with the aim of using secondary instead of primary aluminium. It is also worth exploring the possibility of changing the alloy to one that does not wear as much on the production tools, is easier to machine, and produces metal chips from processing that are easier to handle. The work involved in modifying the demands on material properties to allow for increased use of secondary aluminium could be conducted through collaboration between all companies in the supply chain.

Closed-loop remelting of process scrap

Closed-loop remelting means that the process scrap is not sold on the open scrap market, but is instead remelted internally at the company or sent back to the supplier for remelting. These scrap flows are commonly clean metal of specified alloys.

Scrap consisting purely of one aluminium alloy can be remelt by the foundry, while the secondary aluminium producer can recycle scrap containing several different alloys. From an energy perspective, it is better if the foundry remelt the scrap in-house rather than send it to the secondary aluminium producer. The remelting process accounts for the major part of the energy saving, while transportation of scrap between companies accounts for a minor part of the saving. However, many work hours would be required to sort the scrap and to keep the different materials apart. At the same time, the scrap volume needs to be large enough to make it economically feasible for the foundry. In addition, according to the respondent from the car producer, the company might have an existing contract with a recycling company, which might imply that the recycling company handles the collection of the scrap. Sending the car producer's scrap to the foundry could thus be prevented.

Delivery of liquid aluminium

The aluminium alloy produced by the secondary aluminium producer can be delivered to the foundry in liquid form using special trucks equipped with thermally insulated transport crucibles ('thermoses'). The foundry needs the metal to be a certain temperature for production. The secondary aluminium producer heats the metal enough to ensure that it is the right temperature on arrival at the foundry taking into account any heat loss during transportation. The crucibles need to be preheated. The delivered metal can be either used directly in the production without using an interim storage or stored in a holding furnace. The benefit of using the metal directly in the production is a production flow with fewer processes. For ensuring just-in-time delivery of the metal to the foundry to avoid heating of the metal at the foundry's site and to reduce the time spent in the preheating station at the secondary aluminium producer's site, good planning is needed.

About one third of the metal delivered to the foundry is delivered in liquid form. Delivering aluminium in liquid form could provide energy savings when viewing the entire supply chain. The respondents in the focus group were unable to give any estimate on how large the energy saving was. Another benefit is a reduced environmental impact; for example, the elimination of remelting at the foundry results in reductions in CO_2 emissions. The cost of transporting liquid aluminium is higher compared to transporting ingots.

Transportation

Optimised transportation

The foundry remelts some of their scrap themselves, which saves some transportation costs, and thus energy use, compared to sending it to the secondary aluminium producer. Scrap in the form of metal chips occurs at the foundry's site, which contain too many impurities, e.g. from lubricating oil, for the foundry to remelt in-house. Instead, the chips are pressed into briquettes and transported directly to the secondary aluminium producer, without passing a scrap dealing company; this is possible because of the well-defined alloy specification and the purity of the briquettes. This method shortens the transportation distance compared to if an intermediate company were to collect the briquettes and deliver them to the secondary aluminium producer. Additionally, as the trailers returning to the secondary aluminium producer with empty 'thermoses' have space available for most of the briquettes, this method provides fewer and cheaper transportations, since the trucks are returning to the secondary aluminium producer anyway.

Additionally, every truckload should be filled with as much material as possible. For reducing the energy use and environmental impact of the entire supply chain, optimised transportation is important. The respondents also state that this could be used as a sales argument.

Increased load factor

The fuel demand per transported tonne could be reduced by increasing the maximum allowed truckload weight. The linings of the crucibles for the liquid aluminium deliveries need to be changed when worn-out. Owing to technical development, it is possible to use a thinner lining, which makes the construction lighter. Thus, the payload is increased when the lining is changed.

Local sourcing of raw material

The transportation distance and thus the fuel demand and cost for transportation could be reduced by sourcing raw materials as locally as possible. Additionally, Sweden has a higher allowed truckload weight compared to, for example, Germany, which provides additional savings in the same way as stated in the previous section. Putting demands for local sourcing on all companies in the supply chain could achieve positive effects.

Mapping the energy use through the supply chain

The respondents highlighted that mapping and visualising the energy use of the entire supply chain would help to ease their understanding of the energy use at different stages of the supply chain and could provide a basis for deciding where to target the largest efforts for improved energy efficiency. The car producer buys car components from within Sweden and abroad, which makes it interesting for them to see how large part transportation contributes to the total energy use of the supply chain.

Energy efficiency potential

The respondents agreed that the largest potential for energy efficiency would likely be within each company and less likely to be between the companies in the supply chain. The work involving energy efficiency is usually conducted within each company. During the focus group, the respondents discussed energy efficiency measures within the individual companies on many occasions and considered their respective goals on energy use per produced unit. The respondents were asked to estimate how the measures brought up during the focus group would affect energy efficiency in the supply chain of the motor detail. However, they agreed that such estimations would be hard to make, concluding that it would be worth examining the entire supply chain to gain an understanding of the broader picture.

Concluding discussion

The results from the study show that the three individual companies in the supply chain have implemented several measures for improved energy efficiency. However, there are still potentials to improve energy efficiency in-house at each individual company in the supply chain by 8–16 % when including cost-effective technical and managerial measures. If this potential for improved energy efficiency could be realised, there could be a reduction in energy use in the supply chain by on average 24 GWh/y compared to today's energy use. According to the respondents at the three companies, the largest potential for improvement can be achieved through technical measures. The largest energy efficiency potential including both technical and managerial measures was found at the foundry. The foundry even stated that their energy efficiency potential was related to technical measures only since the company had a very effective energy management system.

Previous research has studied the potential for improved energy efficiency in other industry sectors, see e.g. Brunke et al. (2014), who showed an energy efficiency potential of 9.7 % in the Swedish iron and steel industry when including both cost-effective technology and energy management practices. However, their study included the whole iron and steel sector in Sweden, while our study only includes three companies. Backlund et al. (2012) studied the potential for improved energy efficiency in Swedish manufacturing industries and concluded that when considering both cost-effective technology and effective energy management, there was an estimated potential to improve energy efficiency by 12 %.

In addition, the three companies can take several joint measures to improve energy efficiency, particularly regarding transportation and communication. Communication between all three actors in the supply chain is important in all phases of the production planning, from designing and developing a new product to producing and delivering the product. Energy issues should be considered in all stages of the production planning, and knowledge and experience about each companies' opportunities and constraints regarding production processes, demand on quality, etc., should be analysed and discussed to avoid inefficiencies.

To the authors' knowledge, this study is the first to analyse potential areas for improved energy efficiency in-house in individual companies' value chains with the added dimension of what the actors in the entire supply chain of an aluminium product can do together to improve energy efficiency. We recommend studying more supply chains in the aluminium industry to gain a deeper understanding of opportunities and difficulties involved in improving energy efficiency in the aluminium industry.

Potentially relevant energy efficiency measures for the entire supply chain could have been missed because the respondents in the focus group were free in their discussions and the focus group was limited to two hours. In the questionnaire for the energy efficiency measures in the individual companies, a pre-defined list of measures was supplied to the respondents, which might not have been exhaustive. However, the respondents were asked to add measures not found in the list.

In summary, the largest potential for improving energy efficiency in the supply chain studied can be found in-house in each value chain (company). However, communication between companies in the supply chain and optimised transportations are important measures for achieving improved energy efficiency in the whole supply chain.

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