Tools for Evaluating Energy Efficiency of Steel Production

Lessons from Sweden and Europe

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Till min farmor, Else-Britt,
för allt stöd under årens lopp.

Abstract

The European Union faces challenges related to climate change, security of energy supply, and competitiveness of European industries. Energy efficiency indicators are required for monitoring and controlling the effectiveness of policies such as the recently endorsed Energy Efficiency Directive. This thesis aims at assessing whether traditionally used energy efficiency indicators capture the development of energy efficiency in the iron and steel sector. The study is based on results from two statistical methods: a top-down, i.e. *Malmquist productivity index*, and a bottom-up, i.e. *partial least squares regression*.

The *specific energy consumption* (the indicator representing the sector within the *Odyssee energy efficiency index*) was scrutinised together with associated indicators based on economic production using the aforementioned statistical methods. The results demonstrated the *specific energy consumption* does not capture the characteristics of the value chain of steel products. Therefore, it is not sufficient for capturing the energy efficiency of iron and steel industries. Previous studies suggest using indicators based on economic production (e.g. *value added*) since they represent the value chain to larger degree. However, the value creation process of companies belonging to larger international groups cannot be estimated reliably. Furthermore, the trends of both types of indicators tend to be highly influenced by structural changes, veiling the actual efficiency development.

Energy use statistics published by international organisations were also compared for the Swedish case. The results demonstrated that international organisations use different methodologies for allocating energy use statistics between consumption and transformation sectors. The method has significant implications on the trends observed, if based on openly available statistics.

This thesis complements previous research by reviewing implications of traditional energy efficiency indicators based on company data, national statistics or openly available statistics and contributes with insights essential for future efforts towards improving energy efficiency indicators for the steel industry.

Keywords
energy efficiency, indicators, iron and steel sector, systems analysis

Sammanfattning

Den europeiska unionen står inför utmaningar relaterade till minskad klimatpåverkan, säkerställd energitillgång samt konkurrenskraften hos europeisk industri. Energieffektiviseringsindikatorer krävs för att övervaka och kontrollera effektiviteten hos energipolicy såsom det nyligen antagna energieffektiviseringsdirektivet. Den här avhandlingen syftar till att bedöma om traditionellt använda energieffektiviseringsindikatorer fångar järn- och stålsektorns utveckling inom energieffektivitet. Studien är baserad på resultat från två statistiska metoder: en *top-down*-metod, *Malmquists produktivitetsindex*, och en *bottom-up*-metod, *partiella minsta kvadratmetoden*.

Den *specifika energikonsumtionen* – indikatorn som representerar sektorn i *Odyssees energieffektiviseringsindex* – granskades tillsammans med andra energieffektivitetsindikatorer med hjälp av de ovan nämnda statistiska metoderna. Resultaten visade att *specifik energikonsumtion* inte fångar karaktären av stålprodukternas värdekedjor. Indikatorn är därför inte tillräcklig för att fånga energieffektivitet inom järn- och stålindustrier. Tidigare studier föreslår att använda indikatorer baserade på ekonomisk produktion (exempelvis förädlingsvärdet) då de representerar värdekedjan till högre grad. Förädlingsvärdet kan dock inte uppskattas tillförlitligt för företag som tillhör större internationella grupper. Trenderna hos båda typerna av indikatorer tenderar dessutom att påverkas av strukturella förändringar, vilka döljer den riktiga effektivitetsutvecklingen.

En jämförelse gjordes även av energianvändningsstatistik publicerad av olika internationella organisationer för det svenska fallet. Resultaten demonstrerade att internationella organisationer använder olika metoder för att allokera energianvändning mellan konsumtions- och omvandlingssektorer i statistiken. Metoden påverkar observerade trender signifikant om de baseras på öppet tillgänglig statistik.

Avhandlingen kompletterar tidigare forskning genom att belysa innebörden av traditionella energieffektiviseringsindikatorer baserade på företagsdata, nationell statistik eller öppet tillgänglig statistik samt bidrar med insikter som kommer att vara väsentliga för framtida satsningar i att förbättra energieffektiviseringsindikatorer för stålindustrin.

Nyckelord

energieffektivitet, indikatorer, järn- och stålsektorn, systemanalys

Preface

This thesis was completed at the Energy and Climate Studies (ECS) unit at KTH Royal Institute of Technology under the supervision of Professor Semida Silveira, head of the ECS unit. Research at ECS has an interdisciplinary character with a strong systems approach, linking issues related to energy technology and policy, climate change, and sustainable development. ECS currently focuses on four thematic areas: bioenergy systems, energy and development, energy systems efficiency, and urban sustainability.

This thesis addresses issues related to energy efficiency and climate change mitigation in the industrial setting. The outcomes of this research are useful for policy-makers in Europe and Sweden as well as for industry organisations and the iron and steel producers themselves.

The research was an integral component of the *Robust Energy and Climate Indicators for the Steel Industry* project, funded by the Swedish Energy Agency and carried out in collaboration with *Jernkontoret* (the Swedish steel association) as well as three Swedish steel producers – *Höganäs AB*, *Sandvik AB* and *SSAB EMEA AB*. This project is also an outcome of cooperation within the innovation project *Energy Systems Analysis Agency (ESA²)*, funded through the KIC InnoEnergy initiative by the European Institute of Innovation and Technology (EIT).

Stockholm, September 2014
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Acknowledgements

First of all, I would like to express my gratitude to my supervisor, Professor Semida Silveira, for giving me the opportunity to develop as a researcher in this topic. Semida has not only provided continuous support throughout the realisation of this research, but also given me the freedom to design and carry out the projects as an independent researcher. This has made me grow as a researcher as well as at a personal level. I also want to thank my co-supervisor, Wouter Nijs, for fruitful discussions and great collaboration over the years. I hope that we can continue collaborating also in the future. Wouter is affiliated with the Flemish Institute of Technological Research (VITO) in Belgium and currently working for the Joint Research Centre of the European Commission in Petten.

Furthermore, I would like to thank the participants in the project group for their commitment to our project and interesting discussions: Alena Nordqvist, *Jernkontoret*; Tomas Hirsh and Jan Pettersson, *SSAB EMEA AB*; Magnus Pettersson, *Höganäs AB*; and Susanne Lindqvist, *Sandvik AB*.

I would like to thank my family – Peter, Inga-Lill and Klara – for their continuous understanding and support throughout all the endeavours of my life and career. Special thanks to Simon, who convinced me that I could do this and supported me throughout the ups and downs of my time at KTH. Thanks also to Abel for taking the time to proofread my thesis. I would also like to thank all my great friends; some geographically far away, but equally close in thought. I would never have made it this far without you.

I would also like to thank my colleagues in the ECS unit and at the department of Energy Technology for interesting discussions in scientific as well as non-scientific settings. It is a luxury to work with great people and it has made it fun to work also during days of low inspiration.

Finally, I would like to acknowledge the generous funding provided by the Swedish Energy Agency and KIC InnoEnergy that made the studies covered in this thesis possible.

Publications

This thesis is based on the following scientific papers:

I. Morfeldt, J. and Silveira, S., 2014. *Methodological differences behind energy statistics for steel production – implications when monitoring energy efficiency*. Submitted to Energy.

II. Morfeldt, J. and Silveira, S., 2014. *Capturing energy efficiency in European iron and steel production – comparing specific energy consumption and Malmquist productivity index.* Energy Efficiency. Accepted. Available online. DOI: 10.1007/s12053-014-9264-8.

III. Morfeldt, J., Silveira, S., Hirsh, T., Lindqvist, S., Nordqvist, A., Pettersson, J. and Petterson, M., 2014. *Economic and operational factors in energy and climate indicators for the steel industry.* Submitted to Energy Efficiency.

An earlier version of Paper II was presented at the 11th International Conference on Data Envelopment Analysis in Samsun, Turkey, 27th – 30th June 2013. Research posters have also been presented at the 3rd KIC InnoEnergy Scientist Conference in Lisbon, Portugal, 28th – 30th May 2014; KTH Energy Dialogue in Stockholm, Sweden, 7th Nov 2013; and KTH Energy Dialogue in Stockholm, Sweden, 22nd Nov 2012.

For all papers, the first author contributed with the conceptual design of the research, performing the necessary literature review, analysing the data as well as interpreting the results and drawing the conclusions. The second author acted as a mentor and as reviewer of the papers. The additional authors of Paper III contributed in interpreting the results and as reviewers of the paper.

Additional publications

IV. Morfeldt, J., Nijs, W., Silveira, S., 2014. *The impact of climate targets on future steel production – an analysis based on a global energy system model.* Journal of Cleaner Production. Accepted. Available online. DOI: 10.1016/j.jclepro.2014.04.045.

V. Xylia, M., Morfeldt, J., Silveira, S., 2014. *Implications of an energy efficiency obligation scheme for the Swedish energy intensive industries – an evaluation of costs and benefits.* Submitted to Energy Policy.

VI. Morfeldt, J., Nijs, W., Silveira, S., 2013. *Shaping our energy system – combining European modelling expertise. Case study: how to decarbonize European steel production? A global perspective.* Energy Systems Analysis Associates (ESA^2): Karlsruhe, Germany. URL: www.esa2.eu.

VII. Silveira, S., Morfeldt, J., Nijs, W., Lodewijks, P., 2012. *Sectoral energy report on the iron and steel sector*. Energy Systems Analysis Associates (ESA^2): Karlsruhe, Germany. URL: www.esa2.eu.

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1 Introduction

The European Union (EU) faces challenges related to climate change as well as security of energy supply and competitiveness of European industries. Regional policies have been implemented to address these challenges. The Energy Efficiency Directive governs actions towards increased energy efficiency as a means of addressing these challenges (European Commission, 2012). In this context, energy intensive industries such as the iron and steel industry are of particular interest. The iron and steel industry is considered strategic in many countries due to its importance for infrastructure development (Moynihan and Allwood, 2012). Nevertheless, it is also one of the major contributors to anthropogenic CO_2 emissions (International Energy Agency, 2007).

Energy efficiency indicators are required for monitoring and controlling the effectiveness of regional as well as national initiatives towards increasing energy efficiency. Energy performance indicators are also a requirement within the new standard for energy management systems (i.e. ISO 50001) (International Organization for Standardization, 2011). The *Odyssee energy efficiency index* (also known as ODEX) has been developed and is recommended by the European Commission as a top-down method for monitoring changes in energy intensity (Enerdata, 2012; European Commission, 2012, 2006). The *specific energy consumption*, the unit consumption indicator proposed for steel production within the *Odyssee energy efficiency index*, has the limitation of comparing total energy consumption with the production of one specific product (Patterson, 1996; Pérez-Lombard et al., 2013; Schenk and Moll, 2007; Worrell et al., 1997). Since *specific energy consumption* for steel considers a crude product as benchmark (i.e. crude steel production), there is a risk of not capturing the full value of production, especially for steel producers focusing on high-value segments of the market (Swedish Energy Agency, 2011).

The dynamics of the market for iron and steel products are changing. European producers are modifying their product portfolios towards high-value market segments in response to increasing global competition (ECORYS SCS Group, 2008; Okereke and McDaniels, 2012). This leads to new challenges in assessing and understanding the trends of the sector, especially trends in response to energy and climate policy. This is particularly the case for Swedish iron and steel production, which is concentrated on niche markets for high-quality and high-strength steels, leading to high value creation. Swedish products often require more energy in the refining stages of production, and are well beyond the point of crude steel in the value chain (Sandberg et al., 2001). For that reason, the *specific energy consumption* indicator may not be adequate for monitoring energy efficiency improvements (Swedish Energy Agency, 2011). Nevertheless, the *specific energy consumption* for steel production is the indicator presently used as part of the *Odyssee energy efficiency index*. This indicator is also used for monitoring energy efficiency trends by other organisations (World Energy Council 2012, 2008). Furthermore, it has been used in a large number of scientific articles (e.g. Arens et al. 2012; Oda et al. 2012; Phylipsen et al. 1997; Schenk and Moll 2007; Siitonen et al. 2010; Worrell et al. 1997).

The Swedish Energy Agency (2011) has suggested an alternative indicator based on economic production, i.e. the *value added*. The *energy intensity based on value added* has the benefit of capturing the actual value of production. Hence, the system boundary of the production corresponds to the system boundary of the total energy consumption captured by the indicator. Indicators based on economic production have the benefit of being easily aggregated throughout the economy (International Atomic Energy Agency, 2005). However, the estimates of economic production may be affected by changing market dynamics and the development of the economy at large. In addition, economic indicators fail to capture technical improvements behind the shifts in energy use (Patterson, 1996; Schenk and Moll, 2007; Worrell et al., 1997).

This thesis provides insight into the aspects of energy efficiency that traditional indicators actually measure in the case of the iron and steel sector. The traditional indicators considered were *specific energy consumption*, *energy intensity based on value added* and *energy intensity based on production value.* The thesis builds upon case studies using aggregated data at the European level as well as real data from three Swedish iron and steel producers. The case studies extend previous research by analysing energy efficiency of European iron and steel production using a *top-down* method previously applied to analyse energy efficiency of the Chinese iron and steel sector by Wei et al. (2007), and by using a *bottom-up* approach applied by Siitonen et al. (2010) to assess what factors affect observed energy efficiency trends for different indicators. While Siitonen et al. (2010) only considered indicators based on physical production, this thesis also analyse energy efficiency indicators based on economic production. Furthermore, the latter study was based on real company data from three Swedish iron and steel producers using different production processes and focusing on different segments of the iron and steel market, in contrast to Siitonen et al. (2010), who used data from one integrated[1] steel mill.

The insights provided by this thesis are useful for improving the methodologies behind energy efficiency indicators as well as energy use statistics published in statistical databases. The case studies confirm the limitations of traditional energy efficiency evaluation tools and provide support for recommendations essential for future indicator development.

1.1 Objective and Research Questions

The overarching objective of this thesis is to assess whether traditionally used energy efficiency indicators capture the development of energy efficiency in the iron and steel sector. The objective was split into three more specific questions, addressed in the corresponding appended papers.

I. *What are the implications of the methodological differences of energy use statistics presented in international databases?*

II. *Does the specific energy consumption indicator capture actual energy efficiency improvements in European iron and steel production?*

III. *What factors affect the trends observed in traditional energy and climate indicators for steel production, and in what way do these indicators capture product differentiation?*

The hypothesis considered in this thesis is that traditional energy efficiency indicators, used for ex-post policy evaluation, do not fully

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1 In an integrated steel mill, steel is produced from iron ore using a blast furnace and a basic oxygen furnace. An integrated mill covers the whole chain of production, including coke production, steel making as well as rolling and finishing processes (Siitonen et al., 2010).

capture the development of the iron and steel sector. The Swedish Energy Agency (2011) criticises the use of *specific energy consumption* on a conceptual basis, supporting this hypothesis, while energy efficiency indicators based on economic production have been criticised in several other studies (Patterson, 1996; Schenk and Moll, 2007; Worrell et al., 1997). The implications of using any of these indicators to monitor the development of iron and steel production may significantly affect how industries contribute to meet targets set by regional and national policies.

The study uses established statistical methods to evaluate the characteristics of the analysed indicators. Finally, the thesis aims to provide recommendations for improvements of tools for evaluating and monitoring actions towards increased energy efficiency in the iron and steel sector.

1.2 Methodology

This research has a *hypothetico-deductive* character, starting from a hypothesis and using various quantitative tools to study patterns that can serve to support or refute the hypothesis as well as provide insight towards potential improvements (Lawson, 2005). The research combines top-down and bottom-up approaches. The difference between these approaches lies in the simulation of reality. Top-down tools analyse society at large, and often use economic relations (e.g. production functions – a relationship between economic development and production of commodities) to understand the development of various segments (e.g. the industrial sectors and their sub-sectors). In contrast, bottom-up tools focus on the activities of physical plants or households, showing trends that may be aggregated if necessary (Fortes et al., 2009; Sue Wing, 2008).

While top-down tools are useful for understanding trends in the economy as a whole, they do not capture technological changes at sectoral level. Bottom-up tools, on the other hand, can be used to show changes at the plant level and aggregation of large numbers of plants, but may not capture societal trends fully (Fortes et al., 2009; Sue Wing, 2008). Thus, the combined insights from top-down and bottom-up tools provide a more comprehensive understanding of variations in energy efficiency in the industry both at sectoral and economy levels.

This thesis is based on results from two different methodological approaches, one top-down and one bottom-up, that is, *Malmquist productivity index* based on national statistics for EU Member States and *partial least squares regression* analysis based on company-level data, respectively. A summary of each methodology used is provided below, while detailed descriptions of the tools can be found in the corresponding papers and chapters of the thesis.

In addition, differences in energy use statistics published in international databases were scrutinised for the case of Sweden in a third study. Various authors have pointed out the difficulties in providing reliable statistics on energy use for the iron and steel industry. Energy use statistics for the iron and steel sector published in international databases suffer from issues such as double counting of self-generated gases (i.e. blast furnace gas and basic oxygen furnace gas) and diverging system boundaries depending on database (Farla and Blok, 2001; Tanaka, 2008). However, these studies did not address the method for allocating energy use between consumption and transformation sectors and its implications on observed energy efficiency trends. A comparison of *final energy use, final energy consumption* and *specific energy consumption* from four international databases demonstrated the differences in methodologies and were discussed in detail (Paper I).

The top-down approach (i.e. *Malmquist productivity index,* based on *data envelopment analysis*) was used to understand the historical trends of energy efficiency in the steel sector of each EU Member State. The results were compared with the indicators *specific energy consumption* and *energy intensity based on value added.* A thorough discussion for the case of Sweden highlights the indicator's ability to capture energy efficiency improvements (Paper II). *Malmquist productivity index* was first introduced by Malmquist (1953) and was enhanced by authors such as Färe et al. (1994) over the years. The method was first developed for measuring economic productivity (e.g. Chou et al., 2012; Li et al., 2005; Liu and Wang, 2008; Mohammadi and Ranaei, 2011; Morita et al., 2005; Ng, 2011; Pires and Fernandes, 2012). Nevertheless, it has been used extensively for analysing trends in energy efficiency and greenhouse gas emissions during recent years (e.g. Azadeh et al., 2007; Blomberg et al., 2012; Honma and Hu, 2009; Pardo Martínez, 2012; Rao et al., 2012; Wei et al., 2007; Wu et al., 2012; Zou et al., 2013). Details on these studies are given in the literature survey presented in Paper II.

Partial least squares regression analysis was used in a bottom-up study to assess how economic and operational factors affect traditional indicators for energy efficiency and greenhouse gas emission reductions.

The analysis was based on real data gathered from three Swedish steel companies (Paper III). *Partial least squares regression* is a method that was originally developed for use in chemistry due to its ability to analyse the relation between a large number of factors despite the statistical sample being relatively small (Abdi, 2010; Wold et al., 2001). Siitonen et al. (2010) applied this method for analysing the factors influencing *specific energy consumption* and *specific CO_2 emissions* for the case of one integrated steel mill. However, the analysis was limited to the type of steel production employed in the analysed mill and, also to physical energy and CO_2 indicators. In contrast, Paper III considered three traditional energy efficiency indicators, as described in the next section, plus three equivalent indicators for monitoring CO_2 emission trends. The analyses were done for three steel companies using different processes and focusing on different segments of the iron and steel market.

The traditional indicators analysed are defined using the following formulae:

$$SEC = \frac{Energy\ Consumption}{Crude\ Steel\ Production}, \qquad (1)$$

$$EIPv = \frac{Energy\ Consumption}{Production\ Value}, \qquad (2)$$

$$EIVa = \frac{Energy\ Consumption}{Value\ Added}, \qquad (3)$$

where

SEC = specific energy consumption,

EIVa = energy intensity based on value added,

EIPv = energy intensity based on production value.

The economic term v*alue added* is considered to be the industries contribution to the Swedish gross domestic product in the case of its sectoral estimation. The *production value*, on the other hand, is the equivalent of the total price of production. The *production value is* sometimes referred to as *gross production* (International Atomic Energy Agency, 2005; Statistics Sweden, 2013). At company-level, economic production was defined to harmonise with available national statistics (Statistics Sweden, 2013) and estimations were based on the simplified formulae:

$$Production\,Value = Net\,Turnover + Other\,Income, \quad (4)$$

$$Value\,Added = EBIT + Depreciation + Staff\,Costs, \quad (5)$$

where

EBIT = earnings before interest and taxes (i.e. operating income).

1.3 Scope and Limitations

Final energy use is defined as the input of final energy to an industrial activity. Energy transformation (or conversion) is defined as the amount of energy that is used for performing the activity of generating a new energy carrier (e.g. producing petrol from crude oil in a refinery). The transformation efficiency may be below 100 %, resulting in the energy transformation input being higher than the energy transformation output. While energy consumption is allocated to the end-user (i.e. the iron and steel sector in this case), energy transformation – and transformation losses in the case of transformation efficiencies below 100% – is allocated to the energy sector in energy use statistics.

The analyses of energy efficiency indicators were based on statistical data. In these cases, the iron and steel sector was defined in line with international statistics: the economic sub-sectors 24.1-24.3 and 24.51-24.52 in NACE 2.0 statistical classifications (*Nomenclature statistique des activités économiques dans la Communauté européenne*). This means that all iron and steel production processes including crude steel production (blast furnaces/basic oxygen furnaces and electric arc furnaces), rolling mills etc. (warm and cold rolling as well as warm and cold drawing), refinement processes (annealing and coating) as well as iron and steel foundries were covered. However, coke ovens are not included since they are considered an energy transformation activity (i.e. 19.1 in NACE 2.0 statistical classifications). Coke ovens produce coke and coke oven gas from hard coal. Also, sintering and pelletizing processes are outside the iron and steel sector boundary as they are counted as part of the iron ore mining sector (i.e. 7.10 in NACE 2.0 statistical classifications) (European Commission, 2008).

Territorial accounting of energy use and CO_2 emissions was applied and energy use data was based on final energy use statistics for the specific sector or company. Hence, the energy and emissions embodied in raw materials and intermediary products were not considered in the analysis. Such contributions should ideally be included in energy efficiency analyses at the systems level. However, the hypothesis of this thesis is related to traditional indicators. The traditional indicators are today based on territorial accounting and final energy use rather than primary energy use. Hence, the analyses follow these assumptions. Future development of indicators is recommended to take embodied energy into account.

1.4 Organisation of the Thesis

The second chapter provides an introduction to steel production technologies, discusses the transformations in the global iron and steel market, and the state-of-art of energy efficiency indicators. Energy use statistics are vital for the calculation of energy efficiency indicators. In the third chapter, energy use statistics published by international organisations are compared and differences are discussed. The fourth chapter critically discusses the methodological differences between the *specific energy consumption* and the more comprehensive *Malmquist productivity index* as energy efficiency indicators for the iron and steel sector. The fifth chapter presents factors affecting energy efficiency indicators for the iron and steel sector based on results from *partial least squares regression* analyses. Finally, the sixth chapter presents the main conclusions of the study and provides recommendations for improving energy efficiency indicators for the iron and steel sector.

2 Energy Use in the Iron and Steel Sector

In this chapter, the characteristics of the iron and steel production technologies are explained as well as the reasons behind the global shift observed in recent years towards high-end niche markets. The state-of-art of energy efficiency indicators used for evaluating the performance of the iron and steel sector are also presented.

2.1 Iron and Steel Technologies and their Energy Requirements

Traditionally, iron and steel production has been divided into two production routes. The primary route uses virgin materials, i.e. iron ore, as ferrous resource. These technologies are characterised by high energy demand per tonne of steel produced. Reduction of iron ore to iron, which is traditionally done in a blast furnace, requires large amounts of coal as reduction agent. The reduction process, together with the high temperatures required, results in the high energy demand of the process. The iron is then refined into steel in a basic oxygen furnace or the more energy intensive open-hearth furnace, which is only used to small extent today. Some of the primary production technologies use a limited amount of scrap to supplement the iron ore. There are also some direct reduction technologies in use, also referred to as solid-state reduction, in which iron ore is reduced to steel or other iron products directly. Traditional primary production technologies result in high CO_2 emissions, but research and development in the sector aims at reducing emissions by optimising current processes and developing innovative approaches (Morfeldt et al., 2014).

The secondary production route uses steel scrap as ferrous resource and is less energy intensive than the primary route. Steel production from scrap has a lower energy requirement since the scrap has already gone through the reduction process during its previous life cycle. The scrap is smelted in an electric arc furnace. Current technology in the secondary route uses electricity as its main source of energy. Hence, the route could theoretically be close to CO_2 emission free depending on the energy source and technology used for electricity generation (Morfeldt et al., 2014).

Between the late 1990s and 2012, total steel scrap use increased approximately 60% from 350 million tonnes to more than 550 million tonnes. Crude steel production increased by 90% in the same period (Bureau of International Recycling, 2013, 2010; World Steel Association, 2014). Despite the relatively slow growth of scrap-based steel in the past decades, structural shift towards increased share of production of steel based on recycled materials offers a plausible pathway for reducing the CO_2 emissions from steel production in the long run. However, as shown in previous studies, scrap availability is limited by the historic production and the time lag of its use in society (Davis et al., 2007; Grosse, 2010; Müller et al., 2011, 2006; Pauliuk et al., 2013).

In addition to recycling, other solutions exist to reduce the CO_2 emissions from steel production, including new and innovative processes for primary production of steel. The European Ultra-Low CO_2 Steelmaking (also known as ULCOS) initiative aims at reducing CO_2 emissions from steel production technologies by 50% compared to current best practice. Three groups of options at different stages of development are considered within this initiative: (i) carbon capture and storage embedded in current steel production technologies, (ii) decarbonised steel production using hydrogen or electrolysis in the reduction process (e.g. the MIDREX process can use synthetic gas containing approximately 70% pure hydrogen as reduction agent), and (iii) use of biomass as reduction agent (potentially together with carbon capture and storage). These processes have high potential to reduce emissions, but their implementation will require significant investments, which are not foreseen in the short-term (Birat, 2009; Birat et al., 2008; Elliot et al., 2009; Gojić and Kožuh, 2006).

2.2 Increasing Global Competition

Global crude steel production has doubled since the early 1990s and continues growing. Capacity increases in Asian production accounts for most of the recent growth, especially in China (see Figure 1). This is contributing to changes in the global dynamics of iron and steel markets, together with the intensified actions towards climate change mitigation. In addition to the challenge of increased competition with Asian producers, international competition for resources has intensified worldwide (ECORYS SCS Group, 2008; Platts, 2013).

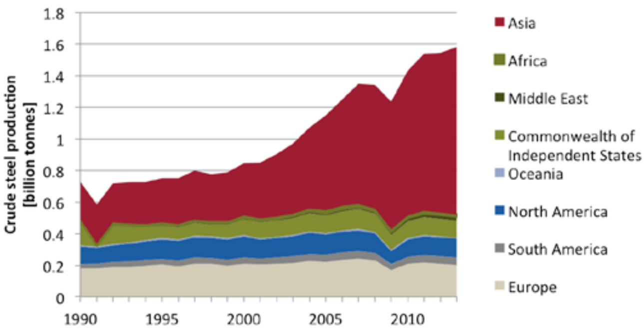

Figure 1: Global crude steel production from 1990 to 2013 (World Steel Association, 2014).

As a result of increased global competition, the global iron and steel sector has undergone privatisation as well as consolidations from the 1990s onwards. A range of different producers have emerged since then, which can be divided into four sub-categories: (i) global players, (ii) regional players in low-cost countries focused on a variety of steel products, (iii) regional players in low-cost countries focused on basic iron and steel products, and (iv) niche specialists. ArcelorMittal is the only true global player, although several other actors have been consolidated into larger groups (Deforche et al., 2007; González and Kamiński, 2011).

The managing director for Accenture Metals emphasised the opportunities for increased value creation for iron and steel industries by becoming more client-oriented (Accenture, 2012). The focus of steel industries has previously been on optimising the supply chain of raw materials upstream of crude steel production (see a simplified representation of the value chain of steel products in Figure 2). However, in response to competition, a downstream focus on the needs of the clients may grant steel producers higher margins on their products. According to ECORYS SCS Group (2008), increased productivity, client-oriented business models, and restructuring towards becoming niche specialists have granted European producers competitive positions in domestic as well as international markets.

Nevertheless, the steel industries as well as groups providing support documents for European policy-making have expressed concerns regarding the competitiveness of European steel producers. The largest of these concerns is related to the global over-capacity of production. The pressure of regional environmental policies comes in second place together with rising energy and raw material prices (ECORYS SCS Group, 2008; Okereke and McDaniels, 2012; Platts, 2013). In response, the European Commission (2013a) recently published an action plan for ensuring a competitive and sustainable steel industry.

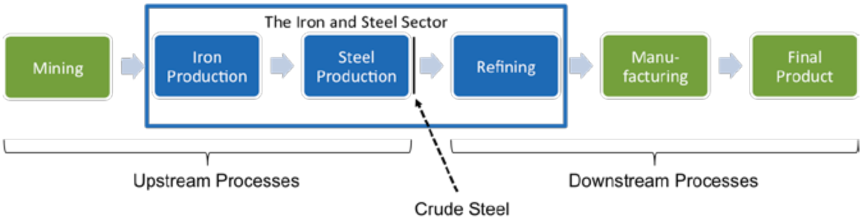

Figure 2: Simplified graphical representation of the value chain of a steel product.

The report by ECORYS SCS Group (2008), which has received significant contribution from steel industry representatives, suggests that the iron ore based production in particular will have difficulties passing CO_2 costs to their customers. The industry also claims that the iron ore based production route has reached its technological limit for drastic reductions in CO_2 emissions (Okereke and McDaniels, 2012). However, Okereke and McDaniels (2012) argue that the industry's claim that the technological limit has been reached may relate to the fact that it has not properly considered the pressure of the CO_2 cost since they have been exempted from paying the CO_2 price. Furthermore, European producers should be able to influence pricing of their products due to their focus and dominance on high-end niche markets. Hence, European producers might not risk competitiveness by passing the cost of CO_2 emissions or mitigation actions to their customers (e.g. the emission allowances required for industries within the EU Emission Trading Scheme).

The changing market conditions and the on-going debate show the complexity that needs to be taken into account when designing energy and climate policy focused on the steel industry. Regional energy and climate policy (i.e. the Energy Efficiency Directive and the Emission Trading Scheme of the EU) introduce targets that affect European industries. Energy and climate indicators are used as monitoring tools for ensuring that these targets are met.

However, there is concern that traditional energy efficiency indicators cannot fully capture the trends of the sector. The Swedish Energy Agency (2011) criticises the use of the indicator "final energy use per crude steel production", also known as *specific energy consumption*. This is the indicator proposed for monitoring the effects of the Energy Efficiency Directive. Assigning the energy requirement of refined products to a relatively crude benchmark product may negatively affect Swedish steel producers, who are concentrated on niche markets for high-quality and high-strength steels, all entailing high value. The Swedish products often require more energy in the refining stages of production, which are well beyond the point of crude steel production (Sandberg et al., 2001).

2.3 State-of-Art of Energy Efficiency Indicators

The body of scientific literature on the topic of energy efficiency – as well as on the indicators used for evaluation of energy efficiency policy – is vast. The topic of how to define indicators for evaluating energy efficiency of industrial activities has been discussed since the 1990's. On the other hand, the topic of tracking CO_2 emissions of industrial activities in the context of policy evaluation is more recent in the literature.

There are two main types of indicators: descriptive and explanatory. Descriptive indicators are used to depict trends over time and explanatory indicators are used to explain the characteristics of the trends shown by the descriptive indicators. These are often only estimated for specific years due to lack of data (Eichhammer and Mannsbart, 1997; Patterson, 1996; Phylipsen et al., 1997). Descriptive energy efficiency indicators can be purely thermodynamic (i.e. the ratio between the heat content of a fuel and its work potential in energy terms), thermo-physical (i.e. the ratio between energy use and physical production), thermo-economic (i.e. the ratio between energy use and economic production) or purely economic (i.e. the ratio between the cost of energy use and the value of produced good or service) (Patterson, 1996). Tanaka (2008) added two indicators to the ones defined by Patterson (1996), the absolute energy use and diffusion rate of energy efficient equipment. Tanaka (2008) also identified *reliability*, *feasibility* and *verifiability* as important aspects that are not always considered in energy analyses. Essentially, indicators need to be defined using consistent system boundaries and data with high reliability.

Patterson (1996) found thermodynamic indicators to be less useful as no product or service is related to the output. Thermo-physical indicators alleviate this problem by relating energy use to production of physical quantities. Phylipsen et al. (1997) further elaborate these basic concepts into recommendations for indicators for various industries in the context of international comparisons. In the case of iron and steel production, the *specific energy consumption* was proposed as a descriptive indicator, complemented by additional insight from explanatory indicators, such as the share of use of different processes, the share of fuels and the share of raw materials.

The International Atomic Energy Agency (2005) proposes a number of energy indicators for sustainable development. For industrial activities the agency suggests using energy intensity based on economic production (i.e. thermo-economic energy efficiency indicators). Economic production may be represented by *value added* as well as *production value* (i.e. *gross output*). The *value added* has the benefit of representing the company's contribution to the *gross domestic product*. The International Atomic Energy Agency (2005) argue that although the *production value* is more stable over time, there is a risk of double counting if that indicator is used to represent economic production. Since the *production value* is equivalent to the total price of production, it also includes cost of raw materials that have already been represented in the energy intensity of other sectors. The International Atomic Energy Agency (2005) also suggests the *specific energy consumption* as an alternative, but indicate that defining the physical output may be difficult.

The International Energy Agency (2007) investigated the use of intensity indicators for tracking industrial energy efficiency and CO_2 emissions. Although the agency proposes a number of indicators that could complement *specific energy consumption,* the differentiation is made on the basis of the production technology upstream from crude steel (see Figure 2). This example confirms the statement made by a managing director at Accenture (2012), that focus has been given to optimising upstream activities rather than downstream activities in the iron and steel sector. Downstream processes have neither been considered in energy nor CO_2 emission indicators. The challenge of tracking energy efficiency and CO_2 emissions downstream of crude steel essentially boils down to a problem of aggregation. The product mix becomes more diversified downstream, which imposes a challenge to how production should be represented in the indicator (Nanduri et al., 2002; Pérez-Lombard et al., 2013). One of the major issues with the *specific energy consumption,* as pointed out by the Swedish Energy Agency (2011), is that the indicator does not capture product differentiation. This is especially important for industries concentrated on niche markets for high-quality and high-strength steels (i.e. industries that focus on products downstream of crude steel production).

2.3.1 The Aggregation Problem

The aggregation problem has to do with how to aggregate statistics of sectors of the economy (e.g. energy intensity or production levels), and this has been discussed in scientific literature for quite some time. The focus has been on how to aggregate sectoral indicators to sector- or economy-wide indices for tracking energy efficiency or CO_2 emissions (see Figure 3).

An economy-wide index can be based on an aggregation of a chain of sectoral indices and indicators (e.g. the *Odyssee energy efficiency index* (Enerdata, 2012)). The economy is divided into its major sectors at the sectoral indices level, such as transportation, industry, agriculture. The sectoral indicators come into play at the next level. It is at this level that the *specific energy consumption* has been preferred for the case of iron and steel sector. However, national and international statistics rarely provide data at a more disaggregated level than what is needed for formulating sectoral indicators. Sub-sectoral and process-specific indicators are generally explanatory indicators.

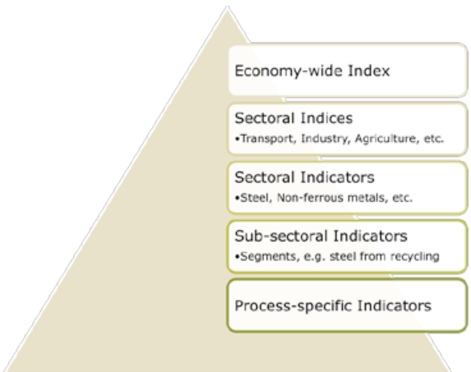

Figure 3: Graphical representation of the relationship between indicators and indices, inspired by Taylor et al. (2010).

Nanduri et al. (2002) provide an extensive review of methods for addressing the aggregation problem. The methods include the fixed basket approach, the Laspeyres physical index and actual SEC / reference SEC ratio. The fixed basket approach defines aggregated energy intensity as a weighted average using the sub-sector's share in energy use as statistical weight. Hence, the fixed basket approach requires the output of each sector to be of the same unit. The Laspeyres physical index approach resolves this issue by using the production level of a specific base year as statistical weight and indexing energy intensities to the same base year, enabling combinations of energy intensities in different units. Finally, the actual SEC / reference SEC ratio is a rather self-explanatory approach where the energy intensity is compared with a reference value of a specific time period to yield an index. In this case, production levels are also used as weighting factors for the various sectors. The actual SEC / reference SEC ratio has been applied in e.g. Salta et al. (2009) for analysing the energy efficiency of Greek manufacturing and Xu and Flapper (2011) for analysing energy efficiency and greenhouse gas emissions of the sub-sectors of dairy production.

Each of these approaches requires assumptions, which may impose uncertainty and reduce the interpretability of the index. For example, the Laspeyres physical index as well as the actual SEC / reference SEC depend to large degree on the time period chosen as reference. Moreover, no scientific consensus has been reached on what approach to use and, hence, no final solution is given for the aggregation problem, as concluded by Pérez-Lombard et al. (2013) in their more recent review of approaches for measuring energy efficiency.

Another example of indicators aggregated into an economy-wide index is the *Odyssee energy efficiency index*. This index is based on a weighted average of the energy efficiency indicators for each sub-sector of the system under study. The index may be used for a sector of the economy or the economy at large. The statistical weights are the relative energy use for each sector for the base year of the analysis. The sectoral indicators are all indexed to the same base year, enabling aggregation despite units being different for the sectors (Enerdata, 2012). The *Odyssee energy efficiency index* actually represents a Laspeyres physical index, as defined by Nanduri et al. (2002), although the statistical weight is the relative energy use rather than production level.

To solve the problem of representing product differentiation in sectoral indicators, the Swedish Energy Agency (2011) proposes to use the indicator *energy intensity based on value added* as an alternative for the iron and steel sector. One benefit of using this indicator is that production is represented by its contribution to value creation for the company rather than its physical mass. In theory, the value added would resolve the aggregation problem in the case of industries focused on markets requiring products refined beyond the point of crude steel – and associated with a higher market value per tonne. Since the value added of a company represents its contribution to the national gross domestic product, such an indicator would facilitate national aggregation. However, there is a risk that thermo-economic indicators (e.g. *energy intensity based on value added*) are affected by market dynamics and the development of the economy at large. For example, the value added depends on the industry's ability to sell their products. If there is an economic recession, the industry may have to lower the price of the product to remain competitive in the market. This may result in a lower profit margin and, also, a lower contribution to the value added. However, the energy intensity of production would still remain the same (given that production volumes remain constant). In addition, economic indicators fail to capture technical improvements behind the shifts in energy use (Patterson, 1996; Schenk and Moll, 2007; Worrell et al., 1997).

Apart from the aggregation problem, aggregated indicators suffer from not differentiating between structural changes, activity and technological improvements, also known as the *structural effects problem* (Eichhammer and Mannsbart, 1997; Pérez-Lombard et al., 2013). This may reduce the interpretability of the indicator and veil technological improvements or potentials. As the results of Paper II and III showed, this is also a problem for sector- as well as company-specific indicators.

Farla and Blok (2001) have developed a methodology for an energy efficiency indicator that addresses the aggregation problem in the case of the iron and steel sector. The method aims to compensate for the effect of structural shifts on physical energy efficiency indicators (i.e. *specific energy consumption*), but also proposes a way of representing product differentiation. The authors propose a physical production index for aggregating production of pig iron, electric arc furnace steel, basic oxygen furnace steel, ingots, semi-finished steel products as well as hot rolled and cold rolled products, based on the *specific energy consumption* of each process. The statistical weights used to form the index were based on the best practice of each process. The formed index describes the development of the iron and steel sector compared to best practice and was tried in a case study comparing energy efficiency of iron and steel production in selected countries based on national statistics. Taylor et al. (2010) use a similar approach to represent product differentiation and compensate for structural shifts for aggregating industry sectors. In this case, the reference is given by the base year of the analysis instead of the best practice as statistical weights for estimating hypothetical energy use. This is the energy use that would have occurred if the structure of the sectors remained the same as in the base year.

Decomposition analysis is a widely used technique for identifying the contribution of structural change, activity and technological improvements in aggregated indicators and several attempts have been made to decompose the national energy efficiency trends of the iron and steel sector in different countries (Arens et al., 2012; Eichhammer and Mannsbart, 1997; Ozawa, 2002; Sheinbaum et al., 2010; Worrell et al., 1997). Decomposition analysis makes use of the differences between a similar approach to Farla and Blok (2001) and the traditional *specific energy consumption*. The best practice in terms of *specific energy consumption* is often used as a benchmark for differentiating improvements between structural improvements and efficiency improvements. Other studies have also done similar analyses but using the *specific* CO_2 *emissions* instead of the *specific energy consumption* (Kim and Worrell, 2002; Ozawa, 2002; Sheinbaum et al., 2010).

Although decomposing energy efficiency trends is not the main purpose of this study, it is interesting to note that the *Malmquist productivity index* approach (applied in Paper II) also provides a decomposed energy efficiency index. In the case of the *Malmquist productivity index* approach, the decomposition is relative to the population of *decision-making units* analysed. The *innovation effect* gives an indication to technological improvements made in the *decision-making unit* relative to the other units, while the *catching-up effect* gives an indication to efficiency improvements (see detailed results in Paper II). The fact that the results are relative may be considered a drawback compared to the decomposition studies mentioned above. However, in those studies the *specific energy consumption* benchmark used as statistical weight for the decomposition introduces an uncertainty that may be at comparable significance.

3 Energy Statistics

The basis for any energy efficiency indicator is published statistics, especially when aggregated beyond the gate of a steel mill. However, the international databases containing statistics on energy use for iron and steel production show diverging results. In this chapter, the statistics of such databases are scrutinised for the case of Sweden, highlighting the assumptions behind the differences and their implications.

3.1 Methodological Approach

Statistics on *final energy use* and *final energy consumption* from four international statistical databases were compared. The statistics were gathered from: Eurostat (European Commission, 2014), Odyssee (Enerdata, 2014), International Energy Agency (2013a) and United Nations Statistics Division (2011). The differences between the databases were scrutinised using the indicators *final energy use, final energy consumption* and *specific energy consumption*. The analysis highlighted the relation to national statistics provided by Statistics Sweden (2013) and the reasons behind the differences were discussed with experts from Statistics Sweden, the Swedish Energy Agency and the International Energy Agency.

3.2 Allocation of Coal and Coke

Iron and steel production processes produce energy carriers that can be used in other sectors of the economy. Therefore, some of the processes in the iron and steel sector can be partly considered as energy transformation activities. The energy balance that is built up by statistics reported to the databases requires that the sources of all energy carriers used be accounted for. In the case of the iron and steel sector, the gases produced in the blast furnace and basic oxygen furnace processes may be used for electricity generation, heat production or directly in other processes. Thus, it makes sense to make an allocation between the energy consumption for steel production and the energy transformation that results in energy that can be used in other services or applications.

Statistics from the four international databases show diverging results in terms of energy consumption (see Figure 4). The differences between Eurostat (European Commission, 2014), Odyssee (Enerdata, 2014), International Energy Agency (2013a) and United Nations Statistics Division (2011) are primarily related to the assumptions behind the allocation between energy consumption and energy transformation. There are also some minor statistical errors in the data related to the statistical surveys on which the statistics are based. These errors have been identified and discussed (see details in Paper I).

The question is how to determine how much of the energy use should be considered as contributing to the energy transformation activity and how much should be considered as energy consumption for the purpose of manufacturing iron and steel products. The guiding documentation for Eurostat, International Energy Agency and United Nations suggests that the fuels used to generate other energy carriers should be reported as transformation, but it does not provide a sound methodology for estimating the allocations (European Commission, 2003). Tanaka (2008) also indicate that allocating the full energy use of the blast furnace process as energy consumption would be misleading if the self-generated gases are used in other processes.

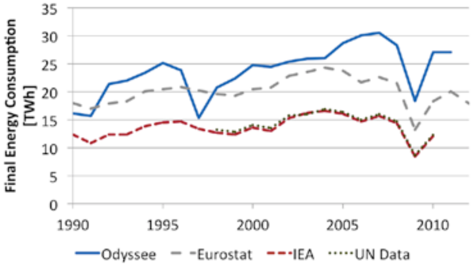

Figure 4: Final energy consumption in the Swedish iron and steel sector, as defined in Eurostat (European Commission, 2014), Odyssee (Enerdata, 2014), International Energy Agency (IEA) (2013a) and United Nations Statistics Division (UN Data) (2011).

The detailed analysis of each database showed that, while the Odyssee database fully allocates coal and coke used in the blast furnaces as energy consumption, other statistical databases use varying assumptions for how much to allocate as energy transformation activities (see Figure 4). In the case of Eurostat, the statistics show that the coal and coke used in the blast furnaces is allocated as energy transformation according to the heating value of the self-generated gases from the processes (including the amount that is flared). This means that Eurostat assumes a transformation efficiency of 100 % for producing the blast furnace and basic oxygen furnace gases.

Since the allocated energy for transformation also includes flared gases, the reported input to electricity and heat generation is larger than what is actually used. All other energy use in the blast furnace is allocated as consumption in the iron and steel sector. The self-generated gases that are used in the processes are reallocated as consumption within the iron and steel sector, while gases used for electricity and heat production are kept as energy transformation. If the produced electricity and/or heat are used in the iron and steel sector, it is reported as auto-production and included in energy consumption statistics as electricity or heat. In this case, the industry has an incentive to reduce consumption in the processes as well as increase the amount of self-generated gases. However, the transformation losses from self-generated gases to other energy carriers should also be accounted for to provide proper incentive to actually use the self-generated gases in the processes or for electricity and/or heat generation rather than simply flaring.

The statistics provided by International Energy Agency and United Nations show similar values for final energy consumption. The United Nations does not provide any documentation for the reasoning behind the allocation. However, it is likely that the reasoning is similar since the reported amounts are similar. In the case of International Energy Agency statistics, “a transformation efficiency such that the carbon input into the blast furnaces should equal the carbon output” is assumed. For simplicity, the International Energy Agency has adopted a transformation efficiency of approximately 40 %, such that if the reported transformation efficiency is lower than 40 %, some of the blast furnace inputs are proportionally reallocated as consumption within the iron and steel sector to reach the indicated transformation efficiency (International Energy Agency, 2013b). This means that a significant share of the coal and coke used in the blast furnace is considered to contribute to the generation of blast furnace and basic oxygen furnace gases.

This is problematic since the main activity and purpose of the blast furnace is to use coal and coke for iron and steel making. The iron and steel products are what generates value added for the industry, not the production of gases. Moreover, the blast furnace is not optimised for gasification of fuels. Using this methodology for allocation of coal and coke input may complicate identification of energy efficiency improvements in coal and coke use in the processes since the allocation does not correspond to the purpose of the activity. Furthermore, indicators based on International Energy Agency statistics do not provide any real insight into the industry's development since the allocation is a theoretical construct related to the assumed transformation efficiency of 40 %.

It should be pointed out that all the approaches to coal and coke allocation discussed above stand in contrast with the perspective of the industry itself. The industry considers coal and coke to be raw materials due to the core purpose of their use for steel production. However, simply excluding the use of coal and coke from the energy analysis not only distorts the energy balance, but also masks the differences in energy demand for various products and services consumed by society which result from the same material flows. This would make it more difficult to identify the potential for increasing energy efficiency at the system level, and to monitor variations. In other words, potential measures for increasing energy efficiency of processes, and for utilising self-generated gases would be overlooked by an energy efficiency analysis considering coal and coke solely as material input for iron and steel production.

3.3 Defining the Sectoral Boundary

From a resource efficiency perspective, the use of virgin material for steel production not only contributes to depleting the finite resources of iron ore but also to depleting the coal resources, while resulting in increased CO_2 emissions. The production route based on virgin materials is significantly more energy intensive than the production route based on recycled materials, since the material in the latter case has already gone through the chemical reduction process from iron ore to iron in its previous life cycle (Morfeldt et al., 2014).

The analysed databases do not currently provide enough information for separating energy consumption statistics for the two routes, which has been previously identified as vital for analysing the energy efficiency of steel production (International Energy Agency, 2007; Tanaka, 2008).

Thus energy efficiency analyses based on such data are likely to be affected by structural shifts between the two routes, veiling energy efficiency improvements at the process level. This risk was confirmed in the analysis of company-specific data presented in Paper III.

Furthermore, energy efficiency improvements related to coke production are not promoted due to the fact that coke ovens are seen as part of the energy sector, even if they are owned and operated by the steel companies in most cases. The allocation of the coking activity to the energy sector (i.e. fully allocated as energy transformation) is correct seen from the point of view of how the databases define the energy balances. However, the coke ovens are seldom considered when discussing the energy efficiency of steel production despite being an important part of the energy supply chain, and also being under the responsibility of the steel companies.

The same reasoning also applies for electricity and heat production from the self-generated gases that are allocated to the energy transformation sector. Considering the example of Eurostat, the heating value of the self-generated gases is allocated as energy transformation in the statistics, including the gas that is flared. The transformation losses for generating electricity and heat as well as losses for transporting the gases are allocated to the energy transformation sector. If only energy-consumption-based indicators (such as *specific energy consumption*) are used when analysing energy efficiency in the iron and steel sector, no incentives are given for reducing these losses.

Hence, a combination of energy-consumption-based indicators and indicators describing the efficiency of energy transformation activities within the steel mill would be the most appropriate to promote resource efficiency in the iron and steel sector and a greener economy at large.

4 A Physical Approach to Energy Efficiency

The indicator "specific energy consumption" has been criticised for not capturing energy efficiency trends in the iron and steel sector. In this chapter, the ability of the specific energy consumption to capture energy efficiency trends is compared with the more comprehensive top-down approach, Malmquist productivity index, for the case of the European iron and steel sector. A deeper analysis is provided for the case of Sweden.

4.1 Methodological Approach

Data envelopment analysis is a calculation technique for estimating the relative efficiency of a *decision-making unit* compared to the other units in a given sample set. The benefit of using *data envelopment analysis* lies in the possibility to evaluate efficiency without explicitly introducing a mathematical relationship between the inputs and outputs of the *decision-making units*. Multiple inputs and multiple outputs are evaluated relative to the frontier line constructed by the *decision-making units* with highest productivity, that is, either (i) utilising a minimum amount of inputs for producing a fixed amount of outputs, or (ii) utilising a fixed amount of inputs and maximising the amount of outputs (Chou et al., 2012; Cooper et al., 2007).

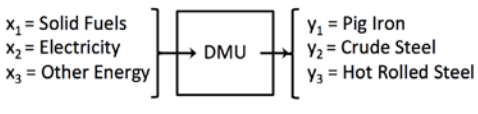

Figure 5: Inputs (x1, x2, x3) and outputs (y1, y2, y3) for each decision-making unit (DMU).

The approach applied in Paper II, as well as in a previous study by Wei et al. (2007), was based solely on physical statistics. The use of physical quantities alleviates the risk of the analysis being affected by changing market dynamics. The inputs and outputs chosen to represent the activities of iron and steel industries were defined as to represent the structural division between production from virgin materials and recycled materials (see Figure 5), which stands in contrast to Wei et al.'s (2007) application of the method. The inputs are the physical requirement of different energy carriers: solid fuels (coal and coke), electricity and other energy carriers. Steel production based on virgin materials uses mainly solid fuels (coal and coke), while steel production based on recycled materials uses electricity.

The products chosen for the analysis were pig iron, crude steel and hot rolled steel. The products represent three major steps in steel making, and also in terms of energy requirements. The products are intermediary products, but also sold independently by the steel manufacturers of the EU Member States. Pig iron production is the most energy intensive step. Crude steel production can be done through production based on virgin or recycled materials and pig iron represents the production based on virgin materials. Hot rolled steels were considered in the analysis to capture one additional degree of value creation. Hot rolled steel products can be sold as is, but may be refined further (e.g. through cold rolling, annealing etc.) into products designed for niche markets, thus, incurring higher prices, and creating higher value for the producers.

The *Malmquist productivity index* methodology produces an index, *total factor productivity*, describing the productivity change over time. One benefit of the method is that this index is composed of two sub-indices, *technical efficiency* and *technical efficiency change*. The sub-indices indicate two trend effects, the *catching-up effect* and the *innovation effect* respectively, which were first defined by Färe et al. (1994). To illustrate this, consider the following example.

The productivity of one *decision-making unit* using one input and producing one output is compared to a sample of *decision-making units* for two time periods. Two productivity frontiers have been constructed based on the productivity of the whole sample. The *catching-up effect* is then defined as the efficiency of the *decision-making unit* in the second time period compared with the frontier of the second time period divided by the efficiency of the *decision-making unit* in the first time period compared with the frontier of the first time period. If this is shown graphically, one could say that the distance from the *decision-making unit* to the frontier is compared between the first and second time period, hence a *decision-making unit* that increased its productivity will be catching up with the best-practice frontier (Figure 6). The *innovation* *effect* is demonstrated as an efficiency shift from the lower efficiency frontier of t_1 (dashed grey line in Figure 6) to the higher efficiency frontier of t_2 (blue line in Figure 6). The *catching-up effect* is illustrated in the figure as the decreasing distance when *decision-making unit* $DMU_1(t_1)$ compared with the frontier of t_1 moves to *decision-making unit* $DMU_1(t_2)$ compared with the frontier of t_2. The shift of the frontier is defined as the *innovation effect* since it describes the progress of the best-practice frontier in the vicinity of the investigated *decision-making unit* (Färe et al., 1994). Some studies also refer to this effect as the *frontier shift effect* (e.g. (Wei et al., 2007)).

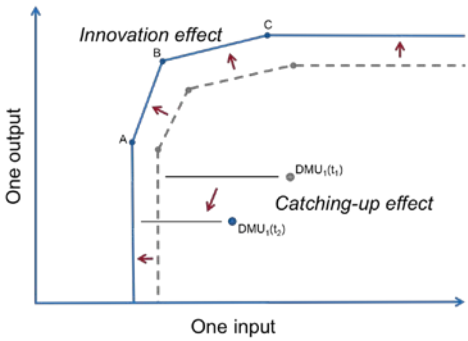

Figure 6: Innovation effect and catching-up effect of the Malmquist Productivity Index, inspired by illustrations in Cooper et al. (2007).

Data envelopment analysis as well as *Malmquist productivity index* has been widely used for evaluating trends in energy efficiency and greenhouse gas emissions. Azadeh et al. (2007) used *data envelopment analysis* to analyse energy efficiency of the petroleum refinement sector in a number of countries. In this case, principal component analysis and numerical taxonomy were integrated with *data envelopment analysis* to provide additional verification of the analysis. Pardo Martínez and Silveira (2012b) evaluated energy efficiency improvements and greenhouse gas emission reductions in the Swedish service sector under static conditions (using only *data envelopment analysis*), evaluating each segment of the sector as a *decision-making unit*. Blomberg et al. (2012) analysed electricity and oil use of Swedish pulp and paper industries in relation to labour requirements and physical output using *data envelopment analysis* at the company level. The study highlights the effects of a Swedish energy efficiency programme on electrical efficiency of the companies. Honma and Hu (2009) constructed a total-factor energy productivity index, an extension of the *Malmquist productivity index*, and showed how the development of consumption of different energy carriers contributed to the gross domestic product development in Japanese provinces. Rao et al. (2012) showed the energy efficiency of Chinese provinces and identified provinces with potential for improvements. *Data envelopment analysis* was used taking economic and energy inputs into account as well as economic outputs and undesired outputs (i.e. chemical oxygen demand and sulphur dioxide emissions). Zou et al. (2012) used *Malmquist productivity index* to show the energy efficiency disparity of Chinese provinces, suggesting policy changes to reduce the technology level imbalance in the provinces. Wu et al. (2012) showed that energy efficiency increased in Chinese industries mainly due to technological improvements, and that there is further potential for improvements. This study considered the Chinese provinces as *decision-making units*. The authors' conclusions were based on results from both static and dynamic models. Ramanathan (2006) analysed the linkage between CO_2 emissions, energy consumption and gross domestic product development using a version of *data envelopment analysis*.

To verify the ability of the *specific energy consumption* to capture energy efficiency development, the trends of the *specific energy consumption* were compared with the results of the approach presented above. Comparisons were also made with the final energy use per value added for the case of Sweden. To be able to compare the indicators, the *specific energy consumption* and the *energy intensity based on value added* were converted into indices; EEI_{SEC} and EEI_{EIVa} (see Paper II for mathematical description and details on the methodological approach). The results of the *Malmquist productivity index* based on *data envelopment analysis* are shown as an energy efficiency index, *EEI*, and decomposed into technical change index, *TI*, and technical efficiency change index, *EI*.

4.2 Energy Efficiency of the European Steel Sector

The EEI_{SEC} showed 16% average increase in energy efficiency in Europe during the period 2000-2010. In contrast, the *EEI* showed that energy efficiency actually regressed by 8 % during the same time period (see Figure 7). A closer look reveals that EEI_{SEC} followed the *EEI* closely until 2005. The two indices then diverge, showing the lower influence of the 2009 economic recession on the EEI_{SEC} than on the *EEI*.

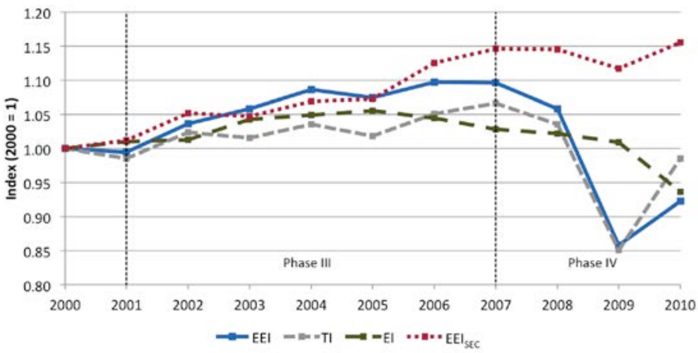

Figure 7: Comparison of the *Malmquist productivity index* (the cumulative energy efficiency index (EEI)), technical change index (TI) and technical efficiency change index (EI)) and *specific energy consumption* in index form (EEI_{SEC}) for European iron and steel production.

The reason behind this may be the difference in construction of the *EEI* compared to the *specific energy consumption*. The *EEI* was based on the trend in production quantities of three different products (i.e. pig iron, crude steel and hot rolled steel) that were all significantly affected by the economic recession. Since *specific energy consumption* is only based on the production quantity of one of these products, the effect on the indicator would logically be considerably lower. The same reasoning can be applied for the energy used in the production.

Furthermore, the structural change from coal-based steel production to electricity-based steel production affects the *EEI* to less extent than it affects the *specific energy consumption*. The reasoning behind this is that the structural split of the industry into coal-based and electricity-based production is reflected in the inputs as well as the outputs of the *EEI's* methodology. Pig iron is directly related to the amount of coal-based steel production and the use of solid fuels, and electricity is directly related to the structural split on the input side. A structural shift from coal-based to electricity-based production was observed during the economic recession and may account for the higher energy efficiency level seen in the EEI_{SEC}.

Although the impact of the economic crisis on EEI_{SEC} may have been reduced due to structural shifts, it is still visible in both approaches. However, the impact of the economic crisis seems to have been captured to higher degree by the *technical change index* rather than the *technical efficiency change index*. This means that the economic crisis had a larger impact on shifting the efficiency frontier than on how individual EU Member States are catching up with the frontier. This is logical since the economic crisis is likely to have affected all EU Member States similarly.

Nevertheless, it could be argued that these approaches emphasise the impact of production levels on energy efficiency rather than actual energy efficiency improvements, this being a result of the top-down methodologies. Steel production processes have a high base load energy demand, which is not affected by lower production levels and reduced capacity utilisation, as shown by e.g. Siitonen et al. (2010). Since these approaches do not take capacity utilisation into consideration, benefits from technological improvements may be hidden in the energy efficiency deterioration exhibited in aggregated statistics at times of low production levels. This can be seen as a weakness of the indicators if the energy efficiency analyses are aimed at providing support for promoting technological improvements.

4.3 Limitations of *Specific Energy Consumption*

The reasons behind the differences between the *specific energy consumption* and the *EEI* were scrutinised in the case of the Swedish iron and steel sector and compared with an economic indicator for energy efficiency, the *energy intensity based on value added* in index form. Analogous with EEI_{SEC} for the European aggregated steel production, the differences between the EEI_{SEC} and the *EEI* became more pronounced after 2004-2005 also in the Swedish iron and steel production.

Structural changes did not occur in Sweden during the analysed period, in terms of increased production based on recycled materials or increased use of the continuous casting process (i.e. a more energy efficient alternative to ingot casting), and cannot have affected energy efficiency trends (World Steel Association, 2014). The EEI_{SEC} seems to capture the energy efficiency minima as well as the *EEI*, while the EEI_{EIva} is less affected by energy efficiency deterioration (see Figure 8). However, during periods of higher energy efficiency, the differences between the approaches become more significant. For the year 2007, the *EEI* shows energy efficiency progress of 18 %, while the EEI_{SEC} shows progress of only 2 % compared to the level of 2004. The EEI_{EIVa}, on the other hand, shows progress of as much as 37 % compared to the level of 2004. The results for *EEI* in 2010 indicated a recovery to levels of energy efficiency seen before the start of the economic recession. The recovery is more pronounced in the *EEI* than both EEI_{EIVa} and EEI_{SEC}.

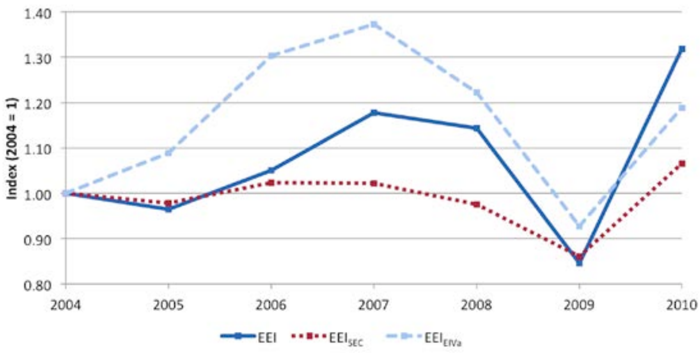

Figure 8: Comparison of the *Malmquist productivity index* (the cumulative energy efficiency index (EEI)), *specific energy consumption* in index form (EEI_{SEC}) and *energy intensity based on value added* in index form (EEI_{EIVa}) for Swedish iron and steel production.

The attention given to energy efficiency in Swedish manufacturing industries from mid-2000's and onwards is expected to have had an impact on the energy efficiency of the sector and may explain the development of the *EEI*. However, this reasoning cannot support the choice of one indicator over the other, although it may be considered explaining the development shown by the *EEI*.

While the *specific energy consumption* and *energy intensity based on value added* provide the ratio of two quantities (i.e. energy use and production in physical or economic terms), the *Malmquist productivity index* finds the optimal combination of a set of inputs for producing a set of outputs. It is evident from the observation of the Swedish case that the three approaches highlight different aspects of energy efficiency in the iron and steel sector (see detailed discussion in Paper II). *Specific energy consumption* compares energy use of the whole sector with one intermediary product. From the trends seen in crude steel production and *value added* (see Figure 9), it is clear that crude steel is not the main contributor to value creation since value creation actually increased in parallel with a decrease in crude steel production. Hence, the *specific energy consumption* does not capture value creation in the Swedish case, which actually results from refinements done to the product after the point of crude steel production. Thus there are significant implications of using different system boundaries for the numerator and the denominator of the *specific energy consumption*, a concern previously expressed by the (Swedish Energy Agency, 2011).

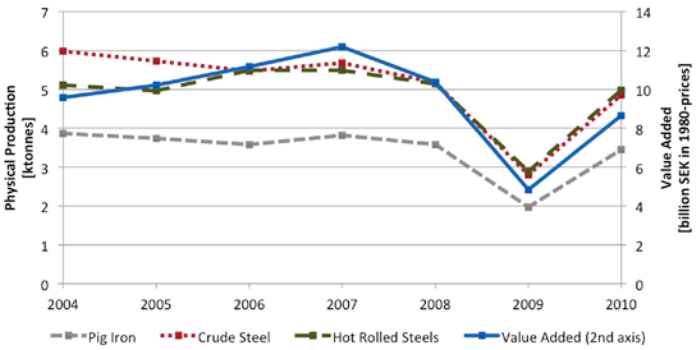

Figure 9: Comparison of physical production values (pig iron, crude steel and hot rolled steels) and economic value creation (value added – 2nd axis) for Swedish steel production.

While the *specific energy consumption* highlights the energy use compared to crude steel production, the *energy intensity based on value added* compares energy use with value creation. The comparison of the results showed that the *specific energy consumption* is not equipped to capture value creation in the Swedish case. However, there is a risk of capturing market dynamics rather than actual energy efficiency improvements, despite the *energy intensity based on value added* being adjusted for inflation. The *EEI* can be seen as a compromise. It is based on physical quantities, thus alleviating the drawbacks of the value added. It covers a wider range of products as opposed to only one product (crude steel) as benchmark for the *specific energy consumption*. On the other hand, the *Malmquist productivity index* methodology, as used in this study, provides a relative energy efficiency index. When analysing a single EU Member State, the results should therefore be seen as relative to the whole population of *decision-making units*.

In conclusion, the *specific energy consumption* is considered to be insufficient for estimating energy efficiency in European iron and steel production. This is especially the case in countries and regions that focus on a more diversified set of products than only crude steel. Combining a more in-depth analysis of the factors influencing energy efficiency in iron and steel production may help formulate more robust energy efficiency indicators. These shall be essential in a context of higher energy efficiency targets and greenhouse gas emissions reductions in the EU.

5 Factors Affecting Energy Efficiency Indicators

Further insight to what traditional energy efficiency indicators actually measure is needed as a basis for improvements in energy efficiency indicators. In this chapter, a bottom-up method, partial least squares regression analysis, was applied to assess economic and operational factors affecting traditional energy efficiency indicators, based on real data from three Swedish iron and steel producers.

5.1 Methodological Approach

Ideally, a mathematical relationship between the indicators and the economic and operational factors analysed should be identified. However, the interactions between an industrial system and its environment are highly complex and such interactions cannot be distinguished from each other or from the noise of other systems. Nevertheless, the statistical correlation between the indicators and the analysed factors can provide an indication of the relationships, and the potential influence of the analysed factors on the indicators. If correlation exists, it means that the trends seen in the specific factor analysed are reflected in the indicator. This can be interpreted in two ways. In the case of the analysed factor being an output of the system described by the indicator, correlation can be interpreted as the indicator capturing the trend of the factor (e.g. production of crude steel or another product group). In the case of the analysed factor being an input to the system or belonging to the environment (i.e. economic factors), the correlation can be interpreted as the indicator being influenced by the specific trend.

Linear regression analysis is an established methodology for assessing correlation of variables. Regression analysis quantifies the correlation with the aim of predicting the trend of a dependent variable y, based on the trend of an independent variable x. Multiple linear regression extends the concept and takes a set of x variables into account, under the assumption that all $x_1 \dots x_n$ are truly independent. Kandel et al. (2008) use a generalised least squares model to analyse the influence of factors related to weather, demographics and fuel use on energy consumption per capita for the USA. The generalised least squares method is an extension of the linear regression analysis for considering correlated observations. He et al. (2012) use multivariate linear regression to analyse factors, such as economic growth, grid investments, electricity price, etc., influencing the Chinese energy consumption per unit of GDP. Lin et al. (2011) use multivariate linear regression to analyse the influence of R&D intensity, energy saving investments, labour productivity and industry concentration on the energy savings potential of the Chinese steel sector. Combined with scenarios for different industrial policies, Lin et al. (2011) then use the model to estimates the energy savings potential for future years.

The influencing factors chosen for the *partial least squares regression* analyses conducted in this study were based on the suggested factors for adjusting indicators for energy efficiency in the Energy Services Directive (European Commission, 2006). The product mix, use of raw materials, amount of energy sold, outside temperature, price levels of raw materials and energy, investments and number of employees as well as the gross domestic product development and the net price index for Sweden were considered as influencing factors in the analyses. Only factors applicable for the company in question were considered in each analysis. Details on the factors and the reasoning behind including each of them can be found in Paper III.

Since these factors are expected to correlate with the indicators, the risk of them also being correlated to each other is high. Hence, the risk of multicollinearity[2] is high and the independence assumption of multiple linear regression cannot be fulfilled (Wold et al., 2001). *Partial least squares regression* is a multivariate regression analysis methodology used to large extent in the field of chemistry. It has the possibility to model how a number of measurable variables, called *predictors*, interact for producing a *response variable*. In chemistry, the *response variable* is difficult to measure directly, which is why the method is used as a prediction based on simpler measurements. *Partial least squares regression* is especially preferable if multicollinearity is present among

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2 In contrast to correlation, which is a linear relationship between two variables, multicollinearity indicates that a linear relationship exists between the variable and another variable or with a linear combination of a set of other variables (Alin, 2010).

the *predictors* and, also among the *response variables,* if multiple *response variables* exist (Abdi, 2010; Wold et al., 2001).

Since the method has the ability to reduce the complexity of the system, it is often used for analyses where the number of observations of the system is lower than the number of *predictors* being analysed, referred to as the “small *n*, large *p* problem” (Abdi, 2010; Mehmood et al., 2012). Assuming that a set of independent *latent variables* can explain the behaviour of the *response variables,* based on different combinations of the *predictors,* the issue of multicollinearity and relatively low number of observations can be alleviated. In *partial least squares regression*, a number of *latent variables* are identified based on the *predictors.* These vectors are orthogonal and linear combinations of the *predictors,* calculated to capture as much of the covariance between the *predictors* and the *response variables* as possible (Abdi, 2010; Martens and Martens, 2000; Wold et al., 2001). The method can handle multicollinear *predictors* as well as noisy data. Noisy data exist if the data are not correlated to the analysed system. Data not serving to explain the linear relationship between the *latent variables* and the *response variables* are collected in a *residual* term of the model, which is disregarded (Wold et al., 2001).

In Paper III, *partial least squares regression* was chosen for assessing the correlation between economic and operational factors and energy and climate indicators. Specifically, the *regression coefficients* give an indication of the magnitude of the correlation and whether it is positive or negative. Furthermore, the *variable importance in projection*-method may be used to identify factors that are more important for describing the trends of the *response variables.* Details on the methodological considerations that had to be made while applying the *partial least squares regression* methodology can be found in Paper III.

The regression analysis was based on real data from three Swedish steel producers: *Höganäs AB* (*Höganäs*); *Sandvik Materials Technology*, part of *Sandvik AB* (*Sandvik*); and *SSAB EMEA AB* (*SSAB*).

Höganäs uses two main processes for iron powder production: solid-state reduction of iron ore based on natural gas and coke breeze, and smelting of scrap and hot briquette iron in an electric arc furnace. The company’s products are specialised and require several annealing and coating steps after the initial iron reduction. The products are not related to crude steel since their applications and production processes differ significantly from those of crude steel.

Sandvik uses an electric arc furnace for producing stainless and carbon steels, mainly based on scrap as feedstock. Their product portfolio includes pipes, wires and strip steel products. The company's products require several refinement steps such as rolling, coating and annealing. *Sandvik* operates electrical and oil-fuelled boilers for steam and hot water provision. Although this activity is included within the boundary of the company, only some of the heat is used in the processes while its main purpose is space heating. Energy used in the boilers accounts for approximately 11 % of total energy use on average and large seasonal variations can be seen due to changing weather conditions.

SSAB operates three blast furnaces for reducing iron ore using coke. Their product portfolio includes high-strength plate steel and steels for construction. *SSAB* also operates coke ovens and several rolling facilities. The company's products are in the high-strength segment and therefore also require annealing. *SSAB* has three production sites included in the analysis: one integrated mill, one mill for crude steel production (includes blast furnace and coke oven) and one rolling mill. The three mills are situated in different regions of Sweden.

5.2 Capturing the Complexity of Value Creation

The results of the *partial least squares regression* analysis (provided in detail in Paper III) showed that the *specific energy consumption* captures the trends of crude products rather than the trends related to value creation. Some correlations were also seen between indicators using crude steel as benchmark and high value products. In these cases, the correlations were positive, meaning that increasing their production is correlated with increasing *specific energy consumption*. Hence, the disadvantage of not capturing the product differentiation when evaluating energy efficiency using the *specific energy consumption* is confirmed by the results. This strengthens the criticism of the Swedish Energy Agency (2011) when it comes to using it as basis for the *Odyssee energy efficiency index*.

The definition of crude steel is known in this study since the analyses are company-specific. The amount of crude steel produced was defined as the total tonnage after solid-state reduction and smelting in the electric arc furnace for *Höganäs*; after continuous casting for *Sandvik*; and after steel production in the basic oxygen furnace for *SSAB*. As these definitions show, there are large differences between companies, which impose uncertainty if aggregated at the sectoral level. Products with different characteristics may be summed to produce the sectoral production level. This emphasises the risks with using physical indicators based on one single sectoral benchmark. Nevertheless, such indicators may be useful for specific processes and in cases where the product can be uniformly defined.

The Swedish Energy Agency (2011) proposes to use the *energy intensity based on value added* as an alternative. Although some correlations were found between products contributing to high value creation and economic indicators, based on *value added* as well as *production value*, the results are only indicative. Also, the variance explained was in most cases lower for indicators based on *value added*. This may be due to the complex value creation process of international companies.

All three companies participating in this study are parent companies or part of larger international groups of subsidiaries spread all around the world. For some products, the full refinement may be done within Swedish borders but, since the market may be in another continent, the product may be sold at a lower price to the subsidiary within the group. The subsidiary will then charge the full value of the product, which means that the economic value created within Swedish borders is not the same as the actual physical contribution by Swedish industrial production. Hence, the *energy intensity based on value added*, as defined and calculated today, may not fully capture the value creation of these companies.

Furthermore, there is a risk of not capturing the embodied energy and emissions carried by imported intermediary products when using the *value added* as the basis for energy and climate indicators. Intermediary products may be bought from subsidiaries within the respective groups or from external suppliers. If these suppliers are in countries outside the EU, such imports may contribute to carbon leakage[3].

Also, the *value added* is sensitive to the revenue stream of the companies. During years of low revenue or even negative results,

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3 Carbon leakage is the phenomenon of CO_2 emissions increasing elsewhere as a result of implementing regional regulations to reduce emissions (i.e. the Kyoto Protocols mitigation policy's pressure on Annex B countries that could result in emissions increasing in non-Annex B countries) (Peters and Hertwich, 2008).

indicators based on *value added* may increase dramatically or even become negative. This was seen in the case of SSAB for some of the time periods analysed. Negative results are not as likely on an annual basis. Nevertheless, the trend of the indicator is more affected by the changes in value creation than the changes in energy use or CO_2 emissions, which has to be taken into account when considering the purpose of the analysis and which indicator to use.

5.3 Implications of System Boundary Choices

The current accounting of greenhouse gases is territorial, or production-based, meaning that only the emissions occurring within the borders of the specific region are taken into account (Peters and Hertwich, 2007). This translates into including only the facilities within the Swedish borders when estimating energy efficiency indicators and thus for the purpose of this study as well. The mill site boundary extends beyond the production processes up to the gates of the analysed mill. The mill site boundary is commonly used for national accounting of energy use as well as greenhouse gas emissions and has been shown to be favourable for following trends of the specific mill, since it captures not only the process related improvements but also improvements linked to production of various utilities, electricity and heat sold externally (Eichhammer and Mannsbart, 1997; Siitonen et al., 2010). On the other hand, the mill site boundary is problematic for aggregating statistics and enabling comparisons between mills or even nations due to the diverse activities that may be included in different mills (Giacone and Mancò, 2012; Siitonen et al., 2010; Tanaka, 2008).

The results showed that different system boundaries emphasise different characteristics of the energy system analysed. For *Höganäs*, setting the mill site system boundary meant that shifts between *Höganäs*'s two main facilities became a dominant factor of the system, while the production of heat for space heating became a dominant factor in the results of *Sandvik*. In the case of *SSAB*, the amount of energy sold for production of heat or electricity externally also became a dominant factor. Hence, energy efficiency indicators should be adjusted to better capture the real improvements, as suggested by European Commission (2006). The data also showed that deducting the energy sold from the indicator introduces a seasonal variation due to the shifting demand for heat. Not only does this seasonal variation increase the variance of the indicator, but it also points to an untapped potential for using excess heat from the processes in periods of low heat demand.

A narrower system boundary may be more favourable for capturing the real improvements in the steel production processes. However, such a boundary would require assumptions that may lead to increasing uncertainty and unreliability of the analysis due to lack of energy use statistics. A broader system boundary is generally more favourable when aiming at increasing energy efficiency and reducing CO_2 emissions at the system level. In that way, the improvements at the systems level can contribute to meeting the economy-wide energy and climate targets (Siitonen et al., 2010; Tanaka, 2008). However, to be effective, such a boundary should go beyond the gates of the mill, which would then fundamentally alter the traditional definition of industry sectors. At the national level, this is often referred to as consumption-based accounting of environmental impacts. This means that the emissions embodied in products are assigned to the consumer rather than the producer. Such accounting would alleviate carbon leakage and industrial relocation concerns in response to European climate policy (Peters and Hertwich, 2008; Peters, 2008).

Nevertheless, physical indicators, such as *specific energy consumption*, may still be useful for production planning at the company level. Several studies, including Paper II, have provided indications to the relationship between capacity utilisation and energy efficiency, and the results of Paper III also confirm this relationship indirectly (Lapillonne and Pollier, 2012; Natural Resources Canada, 2011; Siitonen et al., 2010). Depending on the aim of the energy efficiency analysis, the issue of capacity utilisation may have different implications. If the analysis is aimed at evaluating general energy efficiency, utilising capacity most efficiently (which is not always to reach the maximum capacity) may be one measure for reaching higher levels of energy efficiency. However, depending on the considered policy instrument, policy-makers may need to track the benchmark of specific processes (e.g. in the case of the emission trading scheme benchmarks for free emission allowance allocation in the EU) and in that case a decomposition of energy efficiency trends could differentiate between the contributions of optimised capacity utilisation and technical improvements.

Due to the production-based accounting of CO_2 emissions, no emissions related to electricity generation were included in the analysis.

These emissions amounted to 2 % for *Höganäs*, 12 % for *Sandvik* and 0.6 % for *SSAB* (estimated based on the Swedish electricity generation mix) compared to total emissions as defined in this study. Structural shifts related to electricity use may thus be underestimated in the current analysis, such as the shift between electrical and oil-based boilers for *Sandvik*. The underestimation of structural shifts is likely to be more significant if a similar approach was used for analysing companies in regions with a more CO_2 emission intensive electricity generation mix.

6 Concluding Discussion and Recommendations

The preceding chapters have presented evidence confirming that traditional energy efficiency indicators do not fully capture the development of the iron and steel sector. This chapter summarises the findings and provides overarching conclusions together with recommendations for future work in improving energy efficiency indicators for the iron and steel sector.

The comparison of methodologies governing energy use statistics in international databases showed that the allocation of coal and coke to energy transformation or energy consumption activities within the iron and steel sector has large implications for indicators that are based on these statistics. While the International Energy Agency and the United Nations consider the blast furnace process to have a transformation efficiency of 40% for producing blast furnace gas, Eurostat considers the efficiency to be 100%. The latter is more in line with the activity of the industry since the main activity is producing steel, while derived gases are only by-products. In contrast, the Odyssee database considers all coal and coke as energy consumption, which removes the incentive to increase energy efficiency at the systems level utilising energy by-products.

The results from the *Malmquist productivity index* analysis support the conclusion that the currently preferred indicator, the *specific energy consumption*, is not sufficient for monitoring energy efficiency in the European iron and steel sectors. The *specific energy consumption* overestimated the energy efficiency improvements at the European level compared to the *Malmquist productivity index*. These effects were strongest during the economic crisis of 2008 and 2009 as well as adjacent years. The fact that *specific energy consumption* only compares two quantities, while the *Malmquist productivity index* analyses six quantities seem to explain this effect since the economic crisis affected all six of the analysed quantities. On the other hand, *specific energy consumption* underestimated the improvements in the Swedish case compared to the *Malmquist productivity index*. A comparison with the *energy intensity based on value added* revealed that the *specific energy consumption* is not equipped to capture added value. The *Malmquist productivity index* may be seen as a compromise between *specific energy consumption* and *energy intensity based on value added* since it captures product differentiation to larger degree by including additional product categories.

The company-level analysis, using *partial least squares regression* analysis, showed that energy efficiency indicators tend to capture other aspects than the actual energy efficiency improvements. Activities such as structural shifts between processes and production of heat for space heating as well as electricity generation become drivers of the trends. Ultimately, structural shifts between these activities are captured due to varying system boundaries of the steel mills, together with the fact that production from virgin and recycled materials is considered equal in the eyes of the indicators. Hence, there is a risk that energy efficiency improvements are veiled by the captured structural shifts. The results also showed that using *energy intensity based on value added* might provide further insight to product differentiation. Meanwhile, the *value added* is difficult to estimate for the industries analysed. The reason is that the complex process of value creation cannot be represented reliably for companies belonging to larger international groups. Indicators based on *value added* may therefore not fully capture the value created by products, which is in many cases the reason behind the products' increased energy requirements.

All in all, the analyses presented in this thesis support the hypothesis that traditional energy efficiency indicators do not fully capture the development of the iron and steel sector, particularly in the Swedish case. Hence, the results corroborate with the criticism of the Swedish Energy Agency (2011), while they also provide support for refuting the proposed alternative: to use the *energy intensity based on value added* for tracking energy efficiency in the Swedish iron and steel sector.

The thesis complements previous research on energy efficiency indicators by highlighting the implications of using traditional energy efficiency indicators based on analyses using real company data. The iron and steel producers participating in the study represent different product portfolios and production processes, increasing the credibility of the results. The thesis also contributes with additional insight to how energy use statistics are handled by international organisations. It is vital to understand what lies behind the numbers used in the calculation of energy efficiency indicators. Indicators may be misleading if the methodologies and underlying assumptions used by international organisations when creating the data are not understood. Although data provided by Swedish industry as well as statistical offices may be correct, the methodologies used to process the data diverge among the databases. The results showed some errors in the energy use statistics, which may indicate a need to revisit the process of collecting and reporting energy use statistics from Sweden.

Thus, if traditional energy efficiency indicators are used without considerations of what is actually measured, they may lead to uninformed decisions at the company level as well as at policy level. The pressure that regional policies impose may affect competitiveness of European industries. In lack of a global agreement on CO_2 emission pricing, future energy efficiency policy evaluation tools need to consider the impact on industrial competitiveness to provide industries with the necessary incentives for action. *Integrated assessment*[4] may provide additional insight to future structural changes needed in the iron and steel sector to meet set targets as well as highlight the implications of climate targets on industrial competitiveness.

6.1 Recommendations for Future Research

One of the major obstacles in energy efficiency analyses is to capture product differentiation, particularly in the cases of the Swedish and European iron and steel industries that focus on downstream refinements. Although some previous studies have investigated the aggregation problem, new efforts are needed to better represent the production of iron and steel companies and the *value added* it contributes to. Furthermore, the structural shifts between production from virgin and recycled materials has to be compensated for in energy efficiency indicators. Several studies have decomposed energy efficiency trends of the iron and steel sector based on assumed benchmarks for the different processes (i.e. international best-practice). Ideally, a method should be defined to both compensate for structural shifts and represent

4 The term *integrated assessment* is commonly used for tools that assess the impact of climate change mitigation on the economy. Such tools often use cost-optimisation to identify cost-optimal technology pathways for meeting a set climate change mitigation target (Schwanitz, 2013).

product differentiation, instead of relying on single benchmark values. Future efforts towards improving energy efficiency indicators will aim at devising such a method. Furthermore, policy evaluation tools should be developed in relation to the new standard for energy management systems (i.e. ISO 50001). Implementation of such systems may facilitate the collection of data needed for the improved energy efficiency indicators.

The results of this thesis emphasise the significance of system boundary definitions when monitoring trends, in terms of energy use, CO_2 emissions as well as economic or physical production. While economic production has a strong link with the *gross domestic product*, physical production is more closely related to technological development. A compromise between the two may be the answer to steering the industry towards cleaner production. The purpose of the activity of the industry should also be reflected in how boundaries are set. For example, utilised energy by-products should be seen as contributing to increased resource efficiency. Therefore an allocation between energy consumption and energy transformation is needed. The losses of the transformation sector in relation to the self-generated gases have to be accounted for to promote increased use of self-generated gases in other sectors. Otherwise, there is a risk that flaring is equated with energy efficiency improvement, which it is not (although being used as a security measure). Combining indicators based on energy consumption statistics with indicators depicting utilisation trends of by-products from steel production could help alleviate this problem.

Integrated assessment may clarify the linkages between the iron and steel sector and the energy sector as well as other sectors for utilising energy by-products. It can provide policy-makers with additional insight to how sectors can work together towards achieving set targets. While previous research has mapped the linkages within the energy sector well, the iron and steel sector is not always fully represented in such analyses. Future research in the direction of *integrated assessment* will therefore focus on covering the complexity of the iron and steel sector in analyses of the energy system towards meeting energy and climate policy targets.

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