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Digitalization for Energy Efficiency in Energy Intensive Industries

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Abstract

A fourth industrial revolution (Industry 4.0) is on the horizon. It is enabled by advancements in information and communication technologies (i.e. digitalization) and concepts such as the Internet of Things and cyber-physical systems. Industry 4.0 is expected to have great impact on the manufacturing and process industries, changing how products are developed, produced and sold. However, Industry 4.0 is a novel concept and its impacts are still uncertain. An increasingly strict climate and energy agenda in Sweden is putting pressure on the industrial sector and it is, therefore, important that the sector exploits the full potential Industry 4.0 can provide for increased sustainability. This thesis examines the status of digitalization in the Swedish energy intensive industries (i.e. pulp and paper, steel, and chemical industries) and how it could impact energy efficiency in the sector. Qualitative research methods were used to carry out the study. A literature review and in-depth interviews with employees within the industries were conducted. The results show that, while digitalization is considered important for the future competitiveness of the Swedish energy intensive industries, the digital maturity of the sector is not considered high. Digital technologies can increase energy efficiency in a number of different ways (e.g. through better optimization tools, increased availability of processes and more efficient maintenance management). However, there is not a clear link between digital strategies and energy efficiency measures in the energy intensive industries in Sweden. Moreover, energy efficiency is not considered the main driver for implementing digital technologies, it is rather considered a positive side effect. To accelerate the implementation of digital technologies it is important to support further research in this area and encourage a closer cooperation between stakeholders as well as mitigating challenges such as uncertainty regarding return on investment and issues related to data security and ownership.

Sammanfattning

Industrin är på väg in i en fjärde industriell revolution (Industri 4.0). Revolutionen möjliggörs av framsteg inom informations- och kommunikationsteknologier (digitalisering) och koncept som internet av saker och cyberfysiska system. Industri 4.0 förväntas ha en stor påverkan på tillverknings- och processindustrin, vilket kommer att förändra hur produkter utvecklas, produceras och säljs. Industri 4.0 är dock ett nytt koncept och dess effekter är fortfarande osäkra. I samband med att en allt strängare klimat- och energiagenda i Sverige sätter press på industrisektorn, är det viktigt att sektorn utnyttjar den fulla potentialen som Industri 4.0 kan bidrag med för en ökad hållbarhet. Det här examensarbetet analyserar det nuvarande läget för digitalisering inom de svenska energiintensiva industrierna (dvs. massa och pappers-, stål- och kemisk industrin) och hur det kan påverka energieffektiviteten i sektorn. Studien genomfördes med hjälp av kvalitativa forksningsmetoder. En litteraturstudie och fördjupade intervjuer med anställda inom branscherna genomfördes. Resultaten visar att trots att digitalisering anses vara viktig för de svenska energiintensiva industriernas framtida konkurrenskraft, anses sektorns digitala mognad inte vara hög. Digital teknik kan öka energieffektiviteten på ett antal olika sätt (t.ex. genom bättre optimeringsverktyg, ökad tillgänglighet av processer och effektivare underhållshantering). Det finns dock ingen tydlig koppling mellan digitala strategier och energieffektivitetsåtgärder i de energiintensiva industrierna i Sverige. Dessutom anses energieffektivitet inte vara den främsta drivkraften för att implementera digitala teknologier, utan anses snarare vara en positiv bieffekt. För att påskynda implementeringen av digital teknik är det viktigt att fortsätta stötta forskningen inom området och uppmuntra till ett närmare samarbete mellan olika aktörer samt bemöta utmaningar som osäkerheten kring framtida avkastningar på investeringar och frågor relaterade till datasäkerhet och ägande.

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Specifically, I would like to thank my supervisors for their guidance when working on this thesis. Prof. Semida Silveira, with her vast experience, gave valuable advice and feedback throughout the process. I would like to thank Jazaer Dawody at the Swedish Energy Agency for giving me the opportunity to work on this project and for the support when carrying out the study. In addition, I would like to thank Thomas Björkman, Anders Pousette, Glenn Widerström and Thomas Nessen at the Swedish Energy Agency for their help and input in this project.

Finally, I would like to express my appreciation to all the people who agreed on being interviewed for this thesis, for taking the time to do so. This thesis would not have been possible without your input. It is vital that the industry is engaged in research and has a voice when policies for the sector are designed. The interviewees have, with their participation, acknowledged that importance.

Ívar Kristinn Jasonarson

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AI	Artificial Intelligence
DESI	Digital Economy and Society Index
EMS	Energy Management Systems
GDP	Gross Domestic Product
GHG	Greenhouse Gases
ICT	Information and Communication Technologies
IEA	International Energy Agency
IoT	Internet of Things
IT	Information Technology
KPIs	Key Performance Indicators
NRI	Network Readiness Index
OT	Operation Technology
PFE	Program for Improving Energy Efficiency
RDEE	Readiness for Digital Energy Efficiency

1 Introduction

Throughout the years, technological advancements have driven industrial productivity improvements, beginning with the first industrial revolution with the introduction of the steam engine and increased use of hydropower in the late eighteenth century. The second industrial revolution, enabled by electricity, lead to increased mass production in the late nineteenth century, followed by the third industrial revolution that resulted in a higher level of automation enabled by advancements in electronics and information technologies in the 1970s. Now, a fourth industrial revolution, often referred to as Industry 4.0, is on the horizon (Zhou et al., 2015). Driven by technological advancements and increased application of information and communication technologies (ICTs) (i.e. digitalization) and concepts such as the Internet of Things and cyber-physical systems, Industry 4.0 can have immense impact on how products are developed, produced and sold. Industry 4.0 offers opportunities to boost productivity, revenue growth and competitiveness as well as enabling development of new innovative business models. Furthermore, Industry 4.0 can lead to more sustainable manufacturing, improve quality of products and safety of workers. However, Industry 4.0 entails several challenges, for instance related to the security of data, capital intensity of investments and the lack of competency among industrial workers (Bonilla et al., 2018; Müller et al., 2018).

Sweden has a long and successful history as a strong industrial nation. The industry sector and its related services sector are drivers for growth in the Swedish economy, accounting for around a fifth of the country's gross domestic product (GDP) and three quarters of the total value of exports. The Swedish industry is competitive globally, not least because of its innovative vision and willingness of using modern technologies to transform environmentally unsustainable production processes, and many companies are world leaders or even pioneers in their field (Ministry of Enterprise and Innovation, 2016). However, in order for the Swedish industrial sector to remain competitive globally, it is vital that the sector harnesses the opportunities that Industry 4.0 offers (Teknikföretagen, 2018).

Sweden has an ambition to become the world's first fossil-free welfare state by achieving carbon neutrality in 2045 at the latest. The Swedish government has numerous objectives and has taken several measures to reach this goal. One of the objectives is to decrease the energy intensity of the GDP by 50% in 2030 compared to 2005 levels (Ministry of Infrastructure, 2020). The increasingly strict energy and climate agenda of the Swedish government is putting pressure on the Swedish industrial sector. Swedish industries account for almost two fifths of the total final energy consumption in the country, with the pulp and paper, steel and metal, and chemical industries being the most energy intensive (Energimyndigheten, 2019a). Furthermore, the industrial sector is responsible for around a third of the total greenhouse gas (GHG) emissions (Naturvårdsverket, 2019). The industrial sector, therefore, plays a pivotal role on the road to a fossil-free Sweden.

In addition to the increasingly strict energy and climate agenda in Sweden, the industrial sector faces several other challenges, such as more volatile energy prices and energy availability, and more customized and individualized demand. Digitalization offers opportunities for greater flexibility in production which enables companies to meet better the increasingly customized demand and adjust their production to availability and prices of energy with a smart demand response (Isaksson et al., 2018).

In recent years, industrialized countries have acknowledged the importance of Industry 4.0 to their competitiveness globally and digitalization is now at the core of industrial strategies in many countries. Since the German government introduced their strategy, Industrie 4.0, in 2012, many countries have followed with similar initiatives, such as the US' Advanced Manufacturing Partnership and Smart Manufacturing, China's Made in China 2025, South Korea's Manufacturing Innovation Strategy 3.0, UK's Catapults and the EU's Digitizing European Industry (Horst and Santiago, 2018; Wiktorsson et al., 2018). In 2016, the Swedish government launched a strategy for new industrialization, called Smart Industry. The strategy aims at strengthening companies' capacity for change and competitiveness in four focus areas: Industry 4.0, Sustainable production, Industrial skills, and Test bed Sweden. The strategy aims at making the Swedish industrial sector a leader of the digital transformation and the exploitation of digital technologies (Ministry of Enterprise and Innovation, 2016).

Despite a growing body of research on the topic of Industry 4.0, there is still uncertainty regarding the impact digitalization will have on industry, to what extent and when. The impact as well as the drivers and main challenges of Industry 4.0 can vary between sectors and countries (Bonilla et al., 2018; Müller et al., 2018). Studies on the status and impact of digitalization in the Swedish industrial sector are scarce. This thesis aims at contributing to research in that area.

1.1 Objective and Scope

This thesis is a part of the Swedish Energy Agency's (Energimyndigheten) project Production in World Class (Produktion i världsklass) within the program Sectoral Strategies for Energy Efficiency (Sektorsstragier för energieffektivisering). The aim of the program is to contribute to achieving the goal the government has set for energy efficiency improvement by establishing a structured and inclusive method for development and implementation of sectoral strategies for a resource-efficient and cost-effective use of energy in society.

The objective of this thesis is to give an overview of the current state of digitalization within Swedish industry and how it could impact energy efficiency in the sector. The main focus will be on the energy intensive industries in Sweden (i.e. pulp and paper, steel, and chemical industries) and the production plants in these industries. Due to the heterogeneity of the industries considered, specific processes and production technologies will not be analyzed in detail.

The study aims at gaining insights from companies within these industries in terms of their strategy related to digitalization, the status of digitalization and how it could impact energy efficiency in their industries. In addition, the main drivers for digitalization are to be identified along with the challenges these companies face when implementing digital technologies. Ultimately, this project can provide key insights for the Swedish Energy Agency that can be used to design support policies in this area.

Based on the objective of the thesis, a research question was formed:

> *What is the status of digitalization within the energy intensive industries in Sweden and how could digitalization impact energy efficiency in the sector?*

In order to be able to answer the main research question, several sub-questions have been identified:

> *Do companies within the energy intensive industries have a specific strategy related to digitalization and is it linked to energy efficiency measures?*
>
> *To what extent are production plants in the energy intensive industries digitalized?*

In what way can digitalization impact energy efficiency in the energy intensive industries?

What are the main drivers for digitalization in the energy intensive industries?

What are the main challenges of digitalization in the energy intensive industries?

What actions can be taken to accelerate the implementation of digital technologies that can improve energy efficiency in the energy intensive industries?

The rest of the report is organized as follows. Section 2 describes the methodology used for the study. Section 3 provides a background on the energy intensive industries in Sweden and previous energy efficiency measures as well as the overall situation in Sweden with regards to digitalization. Section 4 and 5 present the literature review findings and the empirical findings, respectively. The results are discussed in section 6 and, finally, the conclusion of the thesis is presented in section 7.

2 Methodology

The study is based on qualitative research methods. First, a literature review was conducted of both academic and grey literature to identify studies, trends, programs and technologies when it comes to digitalization in industry and its impact on energy efficiency. Second, in-depth semi-structured interviews were conducted with employees of companies within the Swedish energy intensive industries to gain their perspective on digitalization in the sector and its impact on energy efficiency. The next two sections describe the methodology in more detail.

2.1 Literature Review

A systematic literature review of digitalization, the concept of Industry 4.0, the impact on energy efficiency, and related political framework and initiatives was conducted. For this purpose, several different keywords were used in the search process, such as "industry 4.0", "industry 4.0 and energy efficiency", "digitalization and energy efficiency", and "IoT-based energy management". The focus of the literature review was on manufacturing and processing industries, specially the pulp and paper, steel, and chemical industries, both at European level and at national level in Sweden. Related peer reviewed papers were found using the search engines Google Scholar and Primo. Furthermore, Google was used to search for grey literature (e.g. reports from government agencies, intergovernmental agencies and consultancy firms) published on the topic. Additional literature was found by "snowballing", i.e. by identifying papers and reports listed as references in the literature found in the initial search.

2.2 In-depth Interviews

In-depth interviews were conducted with employees of companies in the sectors analyzed in this study to gain a deeper understanding of the status of digitalization and how it impacts energy efficiency within those sectors. The interviews were semi-structured, meaning that the interview format provided a level of structure to cover the main topics, but had flexibility allowing follow-up questions for further clarification. The interview structure included six main themes that were closely related to the research questions: (1) strategies of the companies related to digitalization and their linkage to energy efficiency; (2) the status of digitalization in the production plants, what digital technologies are in use and their applications; (3) the impact of digitalization on energy efficiency; (4) the drivers for digitalization; (5) the challenges of digitalization; and (6) actions that can be taken to accelerate the implementation of digital technologies in the industries. The full interview structure can be seen in Appendix A.

Potential interviewees were contacted by email and asked to participate in the study. They were made aware of the objective of the study and the main themes of the interview. If requested, they were sent the full interview structure for preparation before the interview. Approximately 30 companies were contacted, and in the end, nine employees agreed to participate in the study. The interviewees were representatives from nine different companies within the energy intensive industries in Sweden: three from the pulp and paper industry, three from the steel industry and three from the chemical industry. Seven out of the nine companies are large enterprises with more than 500 employees in Sweden while the other two are medium sized companies with more than 100 employees in Sweden. All the interviewees worked with energy related issues at their respective companies in one way or another, with titles such as energy coordinator, energy manager, energy efficiency manager, production manager and technical director. The interviewees are anonymized in this report and will hereafter be referenced according to Table 1.

Table 1: List of interviewees used for reference.

Interviewee no.	Industry sector
1	Pulp and paper
2	Pulp and paper
3	Pulp and paper
4	Steel
5	Steel
6	Steel
7	Chemical
8	Chemical
9	Chemical

The interviews were conducted via video conference software (either Zoom or Microsoft Teams). The interviews were conducted in English and lasted approximately 45-60 minutes. All the interviews were audio-recorded and transcribed in full with the interviewees' consent.

Following the interview, participants were asked to fill out a document with ten statements, evaluating their level of agreement with each statement. This was done to get further clarification on their perspectives on the topics covered in the interviews. Moreover, this was done to be able to better identify and visualize trends, for instance when comparing the three different sectors. The document with the statements was sent via email after the interview was conducted and the participants sent the document back via email once filled out. The statements can be seen in Appendix B.

2.3 Interview Analysis

For the analysis of the interviews, six categories related to the research questions were identified. They are listed in Table 2 along with a brief description.

Table 2: The categories identified for the interview analysis.

Category	Description
1. Digital strategies	Company strategies related to digitalization and their linkage to energy efficiency measures.
2. Status of digitalization	The status of digitalization in the companies' production plants.
3. Impact on energy efficiency	The impact of digital technologies on energy efficiency within the companies.
4. Drivers	The drivers for digitalization within the companies.
5. Challenges	The challenges the companies face when implementing digital technologies.
6. Action	Action that can be taken, both by the companies themselves and by the government or governmental agencies, to accelerate the implementation of digital technologies.

The transcript of each interview was read over and their content categorized according to the identified categories. For each of the categories, the data gathered from the interviews was analyzed using a thematic analysis method as described by Braun and Clarke (Braun and Clarke, 2006). The procedure of the thematic analysis is described in Table 3.

Table 3: Description of each step of the thematic analysis (Braun and Clarke, 2006).

Step	Description
1. Familiarizing with the data	Transcribing data, reading and re-reading the data, noting down initial ideas.
2. Generating initial codes	Coding interesting features of the data in a systematic fashion across the entire data set, collating data relevant to each code.
3. Searching for themes	Collating codes into potential themes, gathering all data relevant to each potential theme.
4. Reviewing themes	Checking if the themes work in relation to the coded extracts (Level 1) and the entire data set (Level 2), generating a thematic 'map' of the analysis
5. Defining and naming themes	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and names for each theme.
6. Producing the report	Selection of vivid, compelling extract examples, final analysis of selected extracts, relating the analysis to the research questions and literature, producing a report of the analysis.

Lastly, the data gathered from the statements each interviewee answered was analyzed by drawing a column chart and used to identify trends as well as to validate and clarify the interpretation of the interviews and the extracted themes.

3 The Swedish Context

This section provides background information on the energy intensive industries and previous energy efficiency measures for the industrial sector in Sweden as well as the overall situation in Sweden with regards to digitalization.

3.1 Energy Intensive Industries

The Swedish industrial sector is for the most part energy intensive but energy efficiency in the sector has improved significantly in the las decades (Energimyndigheten, 2015). Since 1970, the total yearly energy consumption of the sector has remained fairly constant at 140-150 TWh while the production has increased significantly. The sectors' energy consumption per unit value added has decreased by more than 60% since 1980, with most of the reduction occurring between 1980-2000. The consumption of petroleum products has decreased the most (Energimyndigheten, 2019b).

As mentioned in the Introduction, the most energy intensive industries in Sweden are the pulp and paper, steel and metal, and chemical industries. Together they account for around three quarters of the total final energy consumption of the industrial sector (Energimyndigheten, 2019a). The energy intensive industries mainly compose of large enterprises who have substantial exports and operate in highly competitive markets. Previous and ongoing work within the sector to improve competitiveness includes more efficient and integrated manufacturing processes, reducing the consumption of coal and coke in furnaces and replace fossil fuels with biobased materials, developing new and better models and tools for decision support and identifying ways to recycle and reuse raw materials and energy (Energimyndigheten, 2015).

The Swedish pulp and paper industry is one of the largest in the world with around 50 pulp and paper mills operating in the country. The sector accounts for approximately half of the total final energy consumption of the industrial sector and uses mainly biomass (69%) and electricity (28%) (Energimyndigheten, 2019b, 2019a). Moreover, the Swedish forestry sector is the largest purchaser of transport services in the country (Swedish Forest Industries, 2020). In recent decades the sector has transitioned towards renewable energy and increased energy efficiency. During the 1970s and 1980s, the sector substituted oil for biofuels in the form of by-products from the pulp manufacturing processes and internal electricity generation increased significantly. Furthermore, in 1973-1990, production of pulp and paper increased by 70% and 127% respectively, while the total energy consumption of the sector remained relatively constant. This resulted in a reduction of carbon emissions by around 80%. Today, the energy efficiency of the Swedish pulp and paper industry is higher than in other major pulp and paper producing countries, such as Brazil, the US and Canada (Bergquist and Söderholm, 2016). However, Thollander and Ottosson showed that there exists an energy efficiency gap in the sector, meaning that there exists untapped potential for cost-effective energy efficiency measures. The most significant barriers for energy efficiency improvements included the risk of production disruptions, the technology being inappropriate at the mill, lack of time and other priorities, lack of access to capital, and slim organization. The largest drivers were lower costs resulting from reduced energy consumption, long-term energy strategy within management, rising energy prices and incentives such as the electricity certificate system (Thollander and Ottosson, 2008).

The steel and metals industry is Sweden's second largest industrial energy user, accounting for 15% of the industry sector's total energy consumption (Energimyndigheten, 2019a). Moreover, the sector accounts for almost 40% of the industrial sector's total GHG emissions. The primary energy sources used in the sector are mainly coal, coke and electricity. In Sweden, steel is both produced from iron ore based processes (integrated steelmaking) and scrap-based processes (secondary steelmaking) (Johansson and Söderström, 2011). Iron and steel is produced at thirteen plants in Sweden, ten scrap-based steel production plants, two integrated iron and steel production plants and one ore-based direct reduction plant. In addition, there are approximately fifteen plants for the processing of steel (e.g. rolling mills, forging plants, wire-drawing plants and pipe and tube mills) located in Sweden (Jernkontoret, 2020). The Swedish iron and steel industry is considered unique. It focuses mainly on the production of advanced steel grades of which the majority is exported, and the companies are often the world leaders in their market niches. The high level of specialization results in a higher specific energy consumption and greater exports compared to other EU Member States (Brunke et al., 2014). Best available technologies for the iron and steel industry operate close to thermodynamic limits. However, an energy efficiency gap has been identified in the industry with the largest potential for energy efficiency improvements lying in support processes, energy recovery measures and optimization of operational practices (Johansson, 2015). According to companies within the Swedish iron and steel industry, the main barriers hindering the adoption of energy efficiency improvements in the Swedish iron and steel industry are mainly economic, including technical risks (e.g. production failures) and limited access to capital as financial investment in other areas is often prioritized. On the other hand, commitment from top management and a long-term energy strategy are considered the main drivers for increased energy efficiency measures in the sector as well as internal economic-related factors, such as the reduction of costs due to lower energy consumption. This means that, according to the companies, the effective point of leverage to improve energy efficiency is from within the company rather than from external drivers such as energy audit subsidies, investments subsidies for energy efficient technologies or third party financing (Brunke et al., 2014).

The chemical industry accounts for 9% of the Swedish industrial sector's total energy consumption. The sector consists of several different branches with varying manufacturing and production processes, including complex continuous processes for the production of base chemicals and small-scale processes for the production of specialty chemicals and pharmaceuticals as well as refineries (IVA, 2019). The production of base chemicals and oil-refineries are amongst the most energy intensive (SKGS, 2020). There is continuous work within the sector to increase energy efficiency and great progress has been made. A large part of the work is finding ways to increase the yield as well as minimizing and reusing energy waste (IVA, 2019). Furthermore, the sector is investigating different ways of switching to bio-based feedstock, gradually transforming the chemical plants into so-called biorefineries. Cooperation between different parties is also an important part of the work. For instance, several enterprises in the Stenungsund industrial cluster on the West Coast of Sweden have joined forces to increase efficiency and sustainability where increased heat and fuel integration between individual plants has been investigated (Jönsson et al., 2012).

In recent decades the Swedish government has had a strict energy and climate agenda and has directed the industrial sector on a path of improved sustainability. This has played a part in establishing the strong global position of the pulp and paper, steel and chemical industries. The government has supported energy efficiency measures in the industries in a number of different ways, some of which will be described in the following section.

3.2 Energy Efficiency Measures in Industry

Energy efficiency is a generic term with no clear way of measuring, but rather a set of indicators used to quantify it. In general, energy efficiency improvements refer to when less energy is used to produce the same amount of services or useful output and is often defined as the ratio between the useful output and the energy input of a process (Patterson, 1996). Energy efficiency is often called the "hidden fuel" and the International Energy Agency (IEA) views it as the first fuel of all energy transitions. It is considered one of the most cost-effective ways to improve the security of energy supply, to increase competitiveness and welfare and to decrease the environmental impact of the energy system (e.g. reducing GHG emissions) (IEA, 2019).

As mentioned in the Introduction, the Swedish government has set the goal of increasing energy efficiency by 50% by 2030 compared to 2005 levels. The target is measured in energy intensity of the GDP, i.e. supplied energy per unit GDP (fixed prices with 2005 as a base year). In recent years, Sweden has taken several measures to improve energy efficiency in the industrial sector. For instance, in 2005, the Program for Improving Energy Efficiency in Energy Intensive Industries (PFE) was launched which gave energy intensive companies in the manufacturing industry exemption from industrial process-related electricity tax if they took action to improve their energy efficiency and implemented a certified energy management system. The program was quite successful as participating companies reported improved electricity efficiency of 1.45 TWh in the first five years of the program (Energimyndigheten, 2011). Revised guidelines for the program were introduced in 2013 after it was ruled that the tax exemption contradicted EU State Aid rules and the program was gradually phased out in 2017, allowing participating companies to fulfill their commitments (European Commission, 2017a). In 2014, the government enforced a law called Lagen om energikartläggning i stora företag (EKL), which obligates large companies to map their energy demand and supply, and propose measures to reduce energy consumption and increase energy efficiency, every four years (Energimyndigheten, 2018a). In 2017, the Swedish government commissioned the Swedish Energy Agency to develop sectoral strategies for a resource-efficient and cost-effective use of energy in society. The Swedish Energy Agency, in cooperation with relevant stakeholders, has identified strategic areas for energy efficiency measures within five sectors: fossil-free transport, world-class production, a flexible and robust energy system, future trade and consumption and resource-efficient buildings (Ministry of Infrastructure, 2020). The world-class production strategy includes the manufacturing sector in Sweden, their products and the related service sectors. This is a key sector when it comes to achieving the targets of the climate and energy agenda of the Swedish government (Energimyndigheten, 2020). The most recent program supporting energy efficiency improvements in industry was launched in 2018 and is called Energisteget. The program provides financial support for projects and investments related to energy efficiency improvements to those who have participated in the EKL (Energimyndigheten, 2018b).

Sweden is on track to reach the target the government has set for energy efficiency improvements by 2030. The GDP has been growing steadily in recent years while energy supply has decreased slightly, showing a decoupling of GDP growth and energy supply. The energy intensity of the GDP decreased by 27% between 2005-2017 while total energy supply decreased by approximately 6% during the same period (Energimyndigheten, 2019c, 2019d).

In order for the Swedish industry to continue to grow and be competitive internationally, it is vital that it adapts and develops strategies for further efficiency improvements. Innovation, in areas such as digitalization, serves as the basis for increased implementation of energy efficient products, systems and services (Energimyndigheten, 2020). However, developing more energy efficient processes, methods and products is capital intensive. As the need for increased efficiency and more sustainable systems rises, and with it the need for high capital investments, a closer cooperation between different actors in industry, academia, government, consultancies and equipment suppliers is required (Energimyndigheten, 2015). Sweden is considered one of the world's leaders when it comes to digitalization and there is a tradition of close cooperation between different stakeholders which provides a good environment for innovation in that area (Bossen and Ingemansson, 2016; European Commission, 2019).

3.3 Digitalization

There is no clear and widely accepted definition of digitalization in the literature. The IEA describes digitalization as the process of growing application of ICTs across all sectors of the economy, including the industry sector. This results in more interaction and convergence of the digital and physical worlds. Digitalization has three fundamental stages as illustrated in Figure 1: data gathering, data analysis and physical action. Digitalization is driven by advancements in all three stages. Declining costs of sensors and data storage results in exponentially growing volumes of gathered data while faster and cheaper data transmission is enabling greater connectivity. Moreover, rapid progress is being made in computing capabilities and advanced data analytics (e.g. using artificial intelligence (AI) or machine learning) (IEA, 2019).

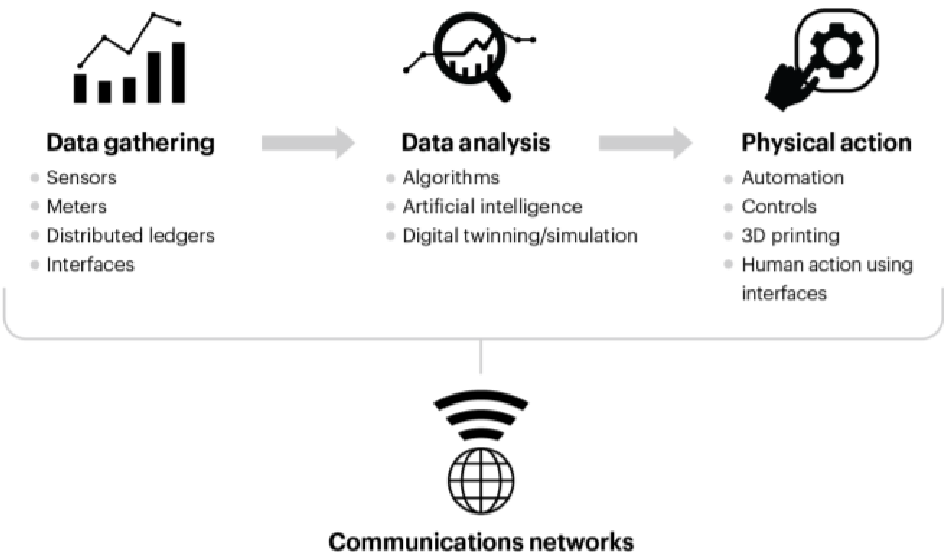

Figure 1: The three fundamental stages of digitalization (IEA, 2019).

The term digitalization encompasses various technologies and concepts, including smart sensors, digital twins, the Internet of Things (IoT) and cyber-physical systems. These technologies and concepts can have an immense impact on the industrial sector, specifically the manufacturing and process industries (IEA, 2017). Traditional sensors have been used for decades to gather data for a wide range of applications, but the use of smart sensors who have a broader range of applications is increasing. Smart sensors convert the data they gather into digital format, process the information and make decisions based on it as well as being able to send and receive communications (World Economic Forum, 2017a). Advanced data analytics can, for instance, enable the creation of digital twins that are used for better simulation and optimization of industrial design resulting in a more sophisticated and intelligent control of industrial processes and equipment. In addition, digitalization can lead to further automation of manufacturing through advanced robotics and additive manufacturing (3D-printing). Furthermore, digitalization is transforming the energy system as a whole. It is changing the way energy is consumed, breaking down boundaries between energy sectors, increasing flexibility of the energy system and integration between systems. Digitalization is removing the boundaries between supply and demand and can enable a smart demand response which allows a greater integration of intermittent renewable energy sources and helps dealing with volatile energy prices (IEA, 2017).

Sweden is considered to be amongst the world leaders when it comes to digitalization. Sweden ranks number one in the world in World Economic Forum's Network Readiness Index (NRI) which ranks countries on their application and utilization of ICTs based on four pillars: technology, people, governance, and impact. Sweden performs well in all four pillars, placing in the top ten in all of them. According to the NRI, Swedish companies have a high level of digital technology maturity compared to other countries, ranking fifth in the world when it comes to availability of latest ICT technologies and number three when it comes to companies' investments in emerging technologies (e.g. IoT, advanced analytics, AI, advanced robotics, 3D-printing) (Portulans Institute, 2019).

In 2019, Sweden was ranked second out of the 28 EU member states in the European Commission's Digital Economy and Society Index (DESI), after only Finland. The DESI is a tool that the European Commission uses to estimate the Member States' digital competitiveness in five categories: connectivity, human capital, use of internet services, integration of digital technology, and digital public services. Sweden ranks highest in the human capital category (2nd) with half of the population having above basic digital skills and 6.6% of the workforce being ICT specialists. However, there is a lack of professionals with advanced digital skills. Sweden ranks lowest in the category of integration of digital technology (6th), with Swedish companies lagging other countries when it comes to using big data. According to the DESI, data openness is the only parameter where Sweden is below the EU average, where it ranks 22nd (European Commission, 2019).

Sweden has for long had a successful ICT sector. In 2015, the added value of the sector and its subsectors accounted for around 7% of the total added value, the second highest in the world (OECD, 2017). Moreover, there is a tradition of cooperation between different sectors and a strong collaboration between academy, industry and the public sector in Sweden (Bossen and Ingemansson, 2016). A good example of that is Ericsson's 5G for Sweden program where the company teamed up with major industrial players, universities and research institutes aiming to take the lead in the digital evolution and strengthen the competitiveness of the Swedish industry through research, innovation and industrial pilot projects (Ericsson, 2015).

Even though the conditions for a digital transformation of the Swedish industry are relatively good compared to other countries, there is evidence that other countries are starting to catch up. For instance, the readiness of Swedish companies to exploit the potential of digitalization is slowing down when compared to the neighboring countries Norway and Denmark. A significantly higher share of Danish and Norwegian companies state that they have a strategy to leverage the potential of digitalization and can see a digital transformation of industry in the near future, compared to Swedish companies (Ministry of Enterprise and Innovation, 2016). It is vital that Sweden turns this development around and keeps its position as a global leader if the Swedish industry is to remain competitive.

4 Literature Review

This section presents the findings of the literature review. It begins by describing Industry 4.0 and the impact it can have on industries. Then a review of the status of Industry 4.0 in Sweden is presented, followed by an overview of how Industry 4.0 can impact energy efficiency. Then the challenges related to Industry 4.0 are discussed and, lastly, an overview of political framework and research initiatives within the area is given.

4.1 Industry 4.0

As mentioned in the Introduction, the industrial sector is now facing a digitally enabled fourth industrial revolution which is often referred to as Industry 4.0. The term Industry 4.0 was initially introduced by German researchers in 2011 as a paradigm shift for maintaining the future competitiveness of the German economy and quickly became the basis of the German industrial strategy (European Commission, 2017b; Stock et al., 2018). According to Smit et al.,

> *"Industry 4.0 describes the organization of production processes based on technology and devices autonomously communicating with each other along the value chain: a model of the 'smart' factory of the future where computer-driven systems monitor physical processes, create a virtual copy of the physical world and make decentralized decisions based on self-organization mechanisms. The concept takes account of the increased computerization of the manufacturing industries where physical objects are seamlessly integrated into the information network. As a result, manufacturing systems are vertically networked with business processes within factories and enterprises and horizontally connected to spatially dispersed value networks that can be managed in real time – from the moment an order is placed right through to outbound logistics. These developments make the distinction between industry and services less relevant as digital technologies are connected with industrial products and services into hybrid products which are neither goods nor services exclusively. Indeed, both the terms 'Internet of Things' and 'Internet of Services' are considered elements of Industry 4.0."* (Smit et al., 2016, p. 20)

The main principle of Industry 4.0 is the use of digital technologies to connect diverse manufacturing machines, facilities, units, and enterprises as well as other related and supporting enterprises, such as raw material suppliers, logistics enterprises, energy suppliers and customers. This integration across all levels creates a smart manufacturing network along the entire manufacturing value chain (Mohamed et al., 2019). That means that manufacturers can respond in real time to changes of both internal factors (e.g. process conditions) and external factors (e.g. technology options, demand) thus becoming more adaptive and diversified. This is creating enormous opportunities for the industry, transforming the way products are designed, fabricated, used, operated, and serviced post-sale as well as transforming the operations, processes and energy consumption of factories and the management of manufacturing supply chains (Ezell, 2016; Wiktorsson et al., 2018).

Modern plants and factories already have a high degree of automation on device and unit level, however, the networking between units, plants and enterprises is still limited. In order to increase the flexibility of industrial production the scope of automation and digital technologies needs to be increased from devices and units to networks within the enterprises and among enterprises (Isaksson et al., 2018). The automated manufacturing systems in most industries have some of the features associated with Industry 4.0, such as communication, flexibility, customization and real-time responsiveness. However, they lack advanced features such as decision-making, early detection of status changes, self-configuration and self-optimization that are enabled by advanced intelligent computerized algorithms that deal with both historical and real-time data (Mohamed et al., 2019).

Studies on the impact of Industry 4.0 often have a broad and general focus across industries while studies on the impact on specific industrial branches are scarce (Kramer et al., 2019). However, they are starting to emerge. The extent and pace of which digitalization impacts a particular industrial branch, enterprise or a specific production process is dependent on numerous different factors, including the characteristics of the given production process and the structure of the market as well the firms' financial capacity and flexibility of supply chains. Furthermore, the culture within firms can influence the way they are impacted by digitalization, e.g. whether they are willing to take risk by implementing a new technology or alter their established operating practices (Bossen and Ingemansson, 2016).

For instance, digitalization in the automotive industry will have an enormous impact on the way products are developed, manufactured and distributed as well as the vehicles themselves, enabling new innovative business models and new players entering the market. The machine industry is another sector that will be impacted significantly, both in terms of production processes and the products themselves. However, the transformation will likely happen at a slower rate compared to the automotive industry due to higher levels of fragmentation and longer investment cycles of production equipment resulting in slower implementation rates of new technologies. The process industries will be relatively less impacted by digitalization than other industries. They already have a high level of automatization and the potential to increase the digital content in the products are limited. However, digitalization can lead to higher quality of products, more efficient processes, increased flexibility, and shorter development cycles. Compared to other sectors, digitalization in the process industries will happen more gradually and be less disruptive (Bossen and Ingemansson, 2016).

The European pulp and paper industry is still in the early stages of Industry 4.0 with companies building up strategic awareness and starting single, unconnected projects. The main opportunities of digitalization in the pulp and paper industry are based on optimization of processes and the efficient use of available resources. This starts with the raw materials, as real-time information could be gathered about the amount, condition, and maturity of the tree stock. Trees could transmit their optimal harvesting time or signal information about their condition. This information could then be communicated throughout the whole value chain and processes adjusted where needed. Processes operate often at extreme conditions (e.g. high temperatures or pressure) and in corrosive environments, while the stability of the processes and accurate measurements and control are key to optimal performance. Digital technologies enable more accurate measurements and asset monitoring which, together with predictive analytics, can lead to better optimization and availability of processes. The logistics volumes in the pulp and paper industry are often large and that is another area where digitalization can have impact. Real-time and historical data about conditions at pick-up and recipient sites and the integration of that data between different actors, enable self-organized and flexible logistics as well as higher loading rates and capacities. The largest challenge when it comes to digital transformation in the pulp and paper industry is a general lack of awareness about the potential benefits it offers. Other challenges include the lack of internationally accepted common technical standards, cybersecurity issues, high investment costs, conservative management and company culture, and the lack of skilled workers (CEPI et al., 2015).

A study performed by the Fraunhofer Institute for Systems and Innovation Research ISI showed that all major actors of the European iron and steel industry are engaged in digitalization. The projects dealing with digitalization within the industry are mainly focused on prototype applications and demonstration while there are few strongly commercially oriented applications. Therefore, there is limited experience of the impact of digitalization in practice. Additionally, information of practical experience is rarely shared publicly. The largest improvements are expected to be related to process efficiency, where downstream production areas such as rolling, coating and finishing will be most affected (Neef et al., 2018). 3D-printing is a digital technology that has potential applications in the steel industry. For instance, steel companies could leverage the emerging 3D-printing market to sell new products (e.g. steel powder) or design new structures such as hollow honeycomb structures with better strength-to-weight ratios. However, the technology is still too expensive and lacks the speed and scale required for mass production, but that is starting to change (World Economic Forum, 2017a). Digitalization is also expected to affect the organizational domain of the steel sector as well enabling new business models and changing the way customers are interacted with. Internal management usually drives the implementation of projects related to Industry 4.0 while technology and production are also important but not considered as crucial. Furthermore, the main challenges when it comes to Industry 4.0 are more of organizational nature than technical. Legacy equipment, uncertainty of the impact on jobs and the lack of qualified personnel were identified as challenges along with short payback requirements and data protection and safety (Neef et al., 2018).

The European chemical industry has already made visible progress in the digital transformation, both in the technological and organization domains, with good connectivity and digitalizing analogue data. However, the use of advanced digital technologies, such as IoT, AI and big data analytics, is still relatively low though it is expected to increase in the near future. The digital maturity level is similar across different branches within the sector, however, the basic chemicals industry is slightly ahead of others, such as the specialty chemicals, pharmaceutical, and rubber and plastics industries (Kramer et al., 2019). Digitalization is expected to have great impact on how the chemical industry operates as well as its offerings and approach to collaboration. The advancement of digital technologies allows further improvements of efficiency, productivity and safety throughout the industry’s value chain. Today, chemical plants are generally considered highly automated environments, however, new technologies can take them beyond traditional control systems. While availability and utilization rates are often major priorities in the chemical industry, ageing assets are leading to higher levels of unplanned failures. Digital technologies allow better monitoring of asset condition, process quality and throughput and, in combination with real-time and predictive analytics, enable immediate intervention to prevent failures and reduce costly downtime of production. Another area where digitalization can have a great impact in the chemical industry is in research and development. Research activities will, to a greater extent, move from test tubes into, for instance, micro-reactors, micro-fermentation and computer simulations, allowing experiments with smaller quantities and higher efficiency over broad parameters (World Economic Forum, 2017b). According to representatives from the European chemical industry, the main challenges when it comes to digital transformation of the industry are the lack of advanced digital skills within the workforce and the lack of understanding of the benefits digitalization entails for the industry. Furthermore, uncertainty about the return on investment in digital infrastructure is considered a great challenge (Kramer et al., 2019).

It is clear that digitalization can have an immense and positive impact on the pulp and paper, steel, and chemical industries. The European industries are generally quite engaged in Industry 4.0 but are still in the early stages. However, this differs between countries in the region with some being more advanced than others.

4.2 Industry 4.0 in Sweden

Research on the situation of Industry 4.0 in Sweden generally has a broad focus across industries and studies on the impact on specific branches, such as the energy intensive industries, are rare. Sundberg et al. assessed the digital maturity of the manufacturing industry in an unspecified region in Sweden. The assessment was based on a survey sent out to organizations in the region. The organizations were, for instance, in the metal, machine repairs, wood and food industries. The assessment was based on numerous different variables, including strategic initiatives related to digitalization, organizational enablers (e.g. digital business models, competence of employees, standards and regulations), basic enablers (e.g. digital products, use of modern ICTs and customer maturity) and general enablers (e.g. digital business systems and use of customer management systems). The results show that a large part of the industries in the region has not implemented any projects related to Industry 4.0 while, overall, the organizational enablers were ranked higher than the basic enablers. This suggests that measures taken towards digitalization on executive level do not translate into actual technology implementations and projects. Organization size, customers' location, and level of technological output of the organization proved to impact the digital maturity. Large organizations with a majority of their customers outside the region and with a high level of technological output perceive their digital maturity higher than others. In addition, the organizations surveyed were asked to estimate the potential of digitalization in different areas. The biggest potential was considered to be in improving marketing, followed by reaching new markets and increasing productivity. Equality and ecological sustainability were the areas considered with the lowest potential for digitalization (Sundberg et al., 2019).

Antonsson assessed the maturity level of the Swedish manufacturing industry when it comes to Industry 4.0. Several companies operating in the automotive, aerospace, food, material handling, and furniture manufacturing industries were analyzed in terms of technology implementation of several different use-cases as well as management attention, priority given to topic and existence of strategy. The results showed that the maturity level when it comes to Industry 4.0 in the Swedish manufacturing industry is generally quite low. Furthermore, the study showed that the companies believe that Industry 4.0 will have a significant and positive impact on their industries while they are generally not prioritizing the topic, showing a discrepancy between the perception of the impact of Industry 4.0 and measures taken in the area (Antonsson, 2017).

A survey of around 400 employees working in the Swedish industry (mainly in the pulp and paper, steel and metal, mining, and vehicle industries) made by SKF in 2018 showed similar results. Around 80% of the participants agreed that it is important for Swedish industry to invest in digitalization while only a third agreed that the Swedish industry is at the forefront when it comes to Industry 4.0. Furthermore, around 57% of the respondents said their companies had a specific vision or a strategy related to digitalization. However, this varies significantly between branches. For instance, little over three quarters of the companies in the mining industries have a strategy for digitalization while around half of the companies in the pulp and paper industry and only around 40% in the iron and steel industry have specific digital strategies. Moreover, the results showed that the mining industry works with Industry 4.0 to a greater extent compared to the pulp and paper and iron and steel industries (SKF, 2018; Skold, 2020). This indicates that having a specific digital strategy can result in companies working with projects related to Industry 4.0 to a greater extent.

The three studies mentioned above all suggest that, while digitalization and Industry 4.0 is considered extremely important for the future competitiveness of the Swedish industrial sector, that does not seem to transfer well into companies' actions in that area and the digital maturity of the Swedish industry sector appears to be relatively low.

4.3 Industry 4.0 and Energy Efficiency

The lack of information and understanding on energy consumption in production processes is the main hindrance for energy efficiency improvement and evaluation in production plants. The recent advancements in ICTs and the concept of IoT are lowering that hindrance. Smart meters and sensors enable more accurate and larger amounts of data on energy consumption to be gathered and together with advanced data analytics, this data can be integrated better into production management and process optimization practices thus offering opportunities for energy efficiency improvements (Shrouf et al., 2014). It is difficult to estimate the total potential for energy savings that digitalization can yield in the industrial sector. The potential depends heavily on the industry in question and the type of activity, management systems, and the degree of integration (IEA, 2017). The IEA estimates that the cumulative impact from combining a range of digital technologies and advanced software applications in industry can result in energy savings of up to 30% globally (IEA, 2019).

The adoption of digital technologies for monitoring energy consumption is still at an early stage in the manufacturing and process industries and their full potential for improved energy management have not been realized yet. However, Shrouf and Miragliotta have identified six sets of benefits from IoT enhanced or enabled practices based on evidence from companies that have already adopted digital technologies for the monitoring of energy consumption. Those benefits include finding and reducing energy waste sources, improving energy-aware production scheduling, reducing energy costs, enhancing efficient maintenance management, improving environmental reputation, and supporting decentralization in decision-making at production level to increase energy efficiency. Furthermore, five more advanced practices that will allow the exploitation of newly acquired capabilities and attain a higher level of energy efficiency were identified. They include monitoring power quality, cost management, energy-aware processes design, reducing energy purchasing costs by connecting to the grid (i.e. smart demand response), and improving economics of self-generated power (in the case where a factory generates power) (Shrouf and Miragliotta, 2015).

A survey made by the American Society for Quality (ASQ) in 2014 showed that 82% of organizations that had implemented digital technologies for smart manufacturing claimed to have experienced increased efficiency, 49% had experienced fewer product defects, and 45% experienced greater customer satisfaction (Shrouf et al., 2014). Behrendt et al. estimate that Industry 4.0 will unleash the potential of productivity gains of 15-20%. This is achieved through numerous digitally enabled solutions, such as predictive maintenance which has the potential to reduce machine downtime by 30-50% thus increasing asset utilization greatly, and digital performance management together with advanced robotics and automated vehicles which has the potential to increase labor productivity by 40-50%. Furthermore, advanced analytics on machine processes in real time will allow to identify and address the underlying causes of process inefficiencies and problems with quality quicker and more effectively (Behrendt et al., 2017).

When a fault in machinery causes sub-optimal performance of a system, it is important to quickly discover and repair the fault so the system can transition back to its optimal operation. Timely and accurate fault detection and diagnosis can significantly improve the performance and reduce associated costs of manufacturing systems. Generally, manufacturing fault detection and diagnosis practices can be improved with digital applications as its allows better monitoring of different manufacturing machines and processes and a better integration between systems which can, for instance, be used to learn more about the systems' behavior, detect new fault types, and predict failures more accurately and timely based on historical and real-time data thus improving the maintenance schedule. An effective maintenance schedule is considered to have an enormous impact on energy consumption as it helps maintaining the optimal configurations of machines and can reduce the number of breakdowns and therefore avoid energy intensive restarts and warm ups (Mohamed et al., 2019).

More accurate and increased amounts of data, e.g. on energy prices, current orders, logistics capabilities, and ability to produce in-house energy can be utilized to schedule manufacturing processes for improved energy efficiency as well as to minimize energy costs. For instance, when a factory is connected to a smart grid that provides power with different prices at different times, it can increase its demand response capacity (Guo et al., 2017). A so-called smart demand response in industry is enabled by industrial demand site management where operational decisions are adapted to, for instance, changing energy prices and energy availability or other incentives. That is made possible with a real-time bi-directional information flow between grid operator and industrial facilities (Isaksson et al., 2018). Smart demand response can contribute to efficiency improvements of electricity systems through peak shaving or shifting, allowing increased integration of intermittent renewables, and better grid stability as well as reducing energy cost or consumption of end-users (Guo et al., 2017). Consequently, increased demand response capacity could reduce greatly the need for new investments in electricity infrastructure (IEA, 2019).

Temperature management is another area where digital solutions can impact energy efficiency. When working with extreme temperatures in production, e.g. in metal casting, energy is consumed at very high levels and even small variations in temperature can increase energy consumption significantly or affect the quality of products. Continuously collected data on temperature within and around the production areas along with data on the processes, quality of products and energy use can be fed into smart algorithms making it possible to quickly identify areas where temperature management can be improved. This enables a more optimal control of operations, temperatures and flow resulting in improved energy efficiency (Mohamed et al., 2019). In extreme conditions or hard to reach environments where physical sensors are not suitable, the use of so-called soft sensors can be extremely beneficial. Soft sensors combine robust signals from physical sensors with computerized models to derive and estimate additional process information that are otherwise difficult to obtain (Fortuna et al., 2007). With the advancement of ICTs, soft sensors can become more and more useful when it comes to energy efficiency improvements.

Furthermore, digitalization offers efficiency improvements in other areas than the production itself, for instance, in research and development. When research moves from physical to virtual environments, it becomes cheaper and requires less time. Moreover, virtual testing and modelling in digital twins of specific processes or entire plants, require fewer physical inputs, such as energy and raw materials, reducing environmental impact and costs. Furthermore, digitalizing research procedures that require low skills can release skilled personnel to work on higher value adding activities (World Economic Forum, 2017b).

Another area is in logistics management. Digital solutions, such as intelligent algorithms, can be used to optimize logistics processes, e.g. material and items handling, packaging, inventory, transportation, and warehousing, with regards to costs or energy consumption. For instance, the logistics schedule can be optimized with more accurate predictions for future orders allowing more consolidated transportation and resulting in less energy consumption (Mohamed et al., 2019).

Buildings can account for a significant share of the overall energy consumption of industrial facilities. Therefore, efficient building management can have a great impact on the overall energy efficiency of any industrial facility. Furthermore, the reliability of buildings is an important factor. Unstable environment (e.g. incompliant temperature and lighting conditions) can have a negative impact on the lifetime and reliability of manufacturing equipment as well as of raw material used for the production. Therefore, it is crucial to integrate building management and the energy efficiency measures of a manufacturing system. There, digital technologies can be helpful to collect more accurate and increased amount of data on the whole environment and connect different systems (Mohamed et al., 2019).

However, while digital technologies offer great opportunities for energy efficiency improvements, such as the ones listed above, they also demand energy and the net impact of digitalization on energy demand and energy efficiency are still uncertain. As devices become more and more connected and the amount of data gathered increases exponentially, the demand for network services and data storage in data centers increases and thus energy demand. However, while depending on the sector in question, digital technologies are expected to deliver great energy savings (IEA, 2017). Table 4 provides a summary of the main areas where digital technologies can be leveraged for improved energy efficiency in industry.

However, even though Industry 4.0 has great potential for improved energy efficiency, there are several issues that need to be resolved before the full potential can be realized. For instance, suitable and usable knowledgebase systems for different energy efficiency purposes in smart factories need to be developed along with optimization algorithms for different energy efficiency needs. Furthermore, modeling and simulation algorithms and tools to assist evaluating and comparing different possible alternatives for decisions, actions and processes related to energy efficiency need to be developed as well as algorithms with AI to enhance those processes (Mohamed et al., 2019).

Table 4: A summary of the main areas where digital technologies can be leveraged for improved energy efficiency in industry.

Area	**Brief Explanation**
Energy monitoring	Digital technologies (e.g. smart sensors and meters) enable the gathering of more accurate and larger amounts of data on energy consumption which can be used to identify potential for efficiency improvements.
Production management	Advanced data analytics of better and more accurate data can be integrated into production management and process control leading to optimization of processes and better production scheduling with regards to energy consumption.
Demand response capacity	Enabled by real-time data on e.g. energy consumption and energy prices, and a two-way information flow between grid operators and industrial facilities, operators can adjust energy demand based on energy prices or energy availability. This leads to, for instance, a more stable grid, lower energy costs for the industry, enables peak shaving and shifting, and a higher integration of intermittent renewable energy sources.
Maintenance management	Digital technologies enable better monitoring of assets and advanced data analytics allow a more timely and accurate predictions of failures in production. Better maintenance management leads to higher energy efficiency as it helps maintaining optimal configurations of systems, increases availability of processes, minimizes faults, and reduces the need for energy intensive restarts.
Temperature management	Advanced data gathering tools and soft sensors can lead to better monitoring of complex processes and extreme conditions, e.g. high temperatures. This can lead to a more efficient temperature management thus increasing energy efficiency.
Research and development	Research and development conducted using digital twins of certain processes or entire plants as opposed to physical systems is more resource efficient as it requires fewer physical inputs and less time.
Logistics	Accurate real-time and historical data on customer orders or transportation needs enable a more consolidated logistics schedule leading to decreased energy demand for transport.

Additionally, it is important to not only consider the diffusion of technologies for energy efficiency improvements, but also acknowledge that technology is a part of the organization as an integrated system. The combination of technology and energy management is important for improved energy efficiency. Furthermore, energy management systems (EMS) are an important tool to establish a sustainable mindset for energy efficiency improvements. This was recognized in the PFE (see section 3.2), where participating companies were required to install a certified EMS (Brunke et al., 2014).

Energy efficiency improvements can only be realized after an energy monitoring system has been installed and the data has been integrated in the information systems and decision-making processes. Shrouf and Miragliotta developed a three-level framework for integrating IoT-based energy data in production management decisions. The framework is presented in Figure 2. The first level illustrates the energy data monitoring and analysis. The data can be collected with smart meters and sensors in real-time and be stored and analyzed either at the factory or in the cloud. The data analysis is an important step to understand the energy consumption pattern, identifying waste sources and ultimately turn the data into information. The required level of energy awareness and improvements are key factors when choosing the appropriate technology (e.g. meters, sensors, communication), the appropriate level of implementation (e.g. components, machine, production line) and the appropriate data visualization techniques. The communication between data gathering tools and the existing IT systems can be complex. However, data from IoT based sensors and meters is available in various formats, over various protocols, and more structured formats for data exchange are emerging allowing sources to exchange and understand each other's data more easily. The second level represents the integration of the analyzed data into available production management systems and tools that support energy efficiency improvements (e.g. simulation tools, optimization algorithms, decision support systems, visualization tools, key performance indicators (KPIs)). The adoption of such tools depends on the objectives and existing practices of a given enterprise. Because of the more detailed data on energy consumption, which was not available before, it is important to create a set of new energy efficiency KPIs to enhance performance evaluation. Furthermore, the integration of energy data into production management requires the decision support systems to be energy aware. Optimization models are vital when it comes to operational energy efficiency, and more accurate and real-time energy data will improve such models. The third level portrays the production management decision for improved energy efficiency that needs to be adapted at the top level, e.g. in production planning and scheduling, demand response, machine configuration, process configuration, maintenance management and logistics (Shrouf and Miragliotta, 2015).

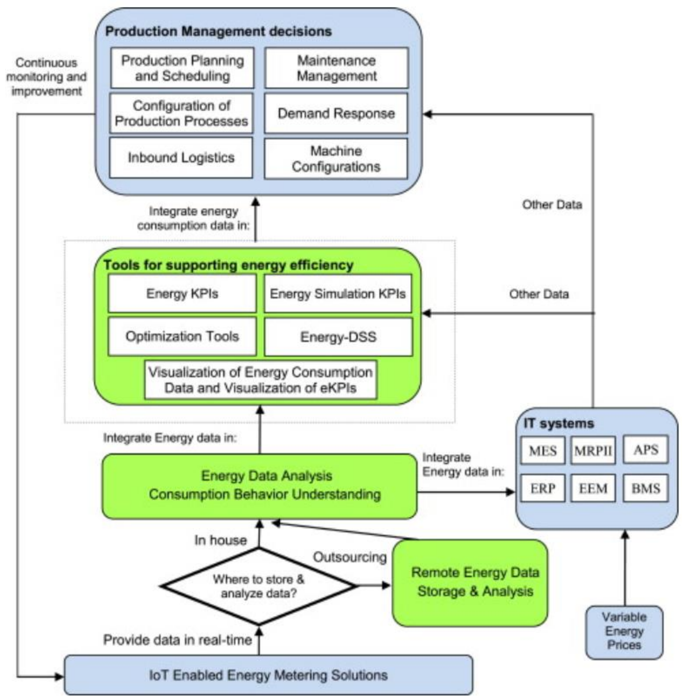

Figure 2: Framework for IoT-based energy data integration in Production Management decisions (Shrouf and Miragliotta, 2015).

4.4 Challenges of Industry 4.0

There are numerous challenges that can slow down the implementation of digital technologies and hinder the full potential of Industry 4.0 to be realized. One of the major challenges is the safety of data as cyber-attacks are becoming increasingly more common risking the continuity of operations and theft of valuable information as well as the availability of energy (IEA, 2017). Thames and Schafer identify cybersecurity and data privacy as the number one challenge faced by IoT which is at the heart of Industry 4.0 (Thames and Schaefer, 2017). Furthermore, a study made by SCM World in 2016 showed that the largest risk to the future supply chain management, which will mainly be shaped by digitalization, is data security and IT incidents (O'Marah, 2016). The McKinsey Global Experts survey on cybersecurity in IoT showed that even though cybersecurity is perceived as a priority by majority of experts, their companies were not well prepared to face cybersecurity challenges (Bauer et al., 2017). This is mainly due to the lack of accurate standards which companies can refer to and the lack of managerial and technical expertise needed to implement them (Lezzi et al., 2018).

Industry 4.0 environments are made up of various technologies across numerous different disciplines that are used by experts working within different areas. For instance, control engineers are working with operation technology (OT) on the manufacturing side while system administrators on the information technology (IT) side are working with traditional IT assets such as servers and software. The integration and cooperation between these two domains can be a significant challenge when it comes to cybersecurity because there are few standards and processes designed to assist each entity to speak a common language that appropriately aligns necessary objectives related to cybersecurity (Thames and Schaefer, 2017).

In addition to data privacy and security issues, the quality of data and information can be an issue. Reasons for incomplete information can be insufficient model accuracy, uncertainties caused by measurement errors, structural discrepancies, and limited precision of predictions. Furthermore, the data is not shared unconditionally between different enterprises resulting in an asymmetry between internal and external information (Isaksson et al., 2018).

Kiel et al. investigated the main challenges in the German manufacturing industry when it comes to Industry 4.0. Technical integration was identified as the largest challenge. Implementing modern IT infrastructure requires a technical transformation and modernization of production facilities and the harmonization of mechanical, electrical, digital, and connected components. The implementation of immature technologies can result in unstable systems risking product and process quality. Furthermore, there is a lack of industry-spanning standardized communication protocols for data interfaces to ensure efficient interaction between companies. Organizational transformation was considered another great challenge, i.e. increasing the involvement of top management and creating adaptable and flexible corporate culture to reduce the resistance for Industry 4.0 as some employees might doubt novel technologies and fear the loss of jobs. Other challenges mentioned were data security, increased competition and shifting market equilibrium, openness and level of trust when it comes to cooperation, high investments combined with uncertain profitability, and competency of employees (Kiel et al., 2017).

The SKF survey mentioned in section 4.2 showed that the biggest hindrance for the Swedish industry when it comes to new digital projects is the competence of personnel. The lack of time and budget were also considered significant challenges (SKF, 2018). Björkdahl et al. argue that the main challenges of the Swedish industry lie on the business side and the full potential of new business models based on digital technologies is not being exploited. Furthermore, the problem when it comes to data is not the availability, rather that the data is scattered, and structuring and identifying the opportunities the data offer can prove challenging (Björkdahl et al., 2018). If the full potential of Industry 4.0 is to be exploited, the abovementioned challenges need to be addressed and mitigated. That requires a cooperation between all stakeholders, including the industry, academia and policy makers.

4.5 Political Framework and Research Initiatives

Digitalization of the manufacturing industry will change the global landscape of manufacturing competition and the countries, industries and enterprises that will lead this digital transformation will gain first-mover advantage over other competitors. Policy measures impact the diffusion of digital technologies, i.e. how quickly enterprises can research, develop and adopt these technologies and how they are leveraged and, therefore, will highly influence the future global competitive landscape of manufacturing (Ezell, 2016).

It is difficult to realize the full potential of Industry 4.0 and the scope and scale of the impact is still highly uncertain. The impact is, to some extent, dependent on policy responses and it is of importance that efforts in this area are coordinated (Wiktorsson et al., 2018). It extremely difficult to precisely estimate digitalization's impact in the long term and, therefore, it is hard for policy makers to design long-term policies in this area. However, the IEA has identified ten no-regret policy actions that governments can take to prepare for an increasingly digitalized energy sector (IEA, 2017). Those actions are:

- Build digital expertise within staff.
- Ensure appropriate access to timely, robust, and verifiable data.
- Build flexibility into policies to accommodate new technologies and developments.
- Experiment, including through "learning by doing" pilot projects.
- Participate in broader inter-agency discussions on digitalization.
- Focus on the broader, overall system benefits.
- Monitor the energy impacts of digitalization on overall energy demand.
- Incorporate digital resilience by design into research, development and product manufacturing.
- Provide a level playing field to allow a variety of companies to compete and serve consumers better.
- Learn from others, including both positive case studies as well as more cautionary tales.

Industry 4.0 is gaining more attention from policy makers in the industrialized countries and emerging economies. There are several initiatives supporting Industry 4.0 development, both at the EU level and national level in Sweden. Introduced by the EU in 2016, Digitising European Industry is an umbrella initiative which aims at coordinating activities of the Member States, facilitating the establishment of common standards and building up specific skills related to Industry 4.0 in Europe. There are a number of different instruments under the initiative, ranging from coordination activities, regulatory measures and R&D projects (European Commission, 2018).

As mentioned in the Introduction, the Swedish government has adopted a strategy for new industrialization called Smart Industri, which has the objective of increasing the competitiveness and participation of the Swedish industrial sector, primarily in the high-quality segments of global value chains (Ministry of Enterprise and Innovation, 2016). The strategy was introduced in 2016, 4 years after Germany introduced its strategy, Industrie 4.0, which was the first of its kind in the world (Rojko, 2017). So far, two action plans have been presented for the strategy (Regeringskansliet, 2017; Regeringskansliet Näringsdepartementet, 2016). Industry 4.0 is one of the focus areas of the strategy where the objective is for "companies in the Swedish industrial sector to be leaders of the digital transformation and in exploiting the potential of digitalization" (Ministry of Enterprise and Innovation, 2016, p. 30). The implementation of the strategy is directed at the following areas (Ministry of Enterprise and Innovation, 2016):

- Stimulating the development, spread and use of the digital technologies that have the greatest potential to lead the industrial sector's transformation.
- Exploiting the potential of digitalization broadly, irrespective of industry, company size and geographical location.
- Encouraging new business models and organizational models in order to tap the potential of the new technology.
- Meeting new knowledge requirements that are brought about by digital development.
- Adapting framework conditions and infrastructure to the digital era.

Policies explicitly aimed at digital technologies for energy efficiency are not common but are starting to emerge. The IEA has developed a framework called the Readiness for Digital Energy Efficiency (RDEE) framework (see Figure 3). The RDEE framework was developed by identifying challenges faced by all related stakeholders (e.g. consumers, product manufacturers, service providers and utilities) and consists of eight different areas that governments need to consider when seeking to harness digital technologies for energy efficiency (IEA, 2019). While the framework is aimed at increasing energy efficiency across all sectors and not aimed specifically at the industrial sector, it can be applied to a large extent to the industrial sector.

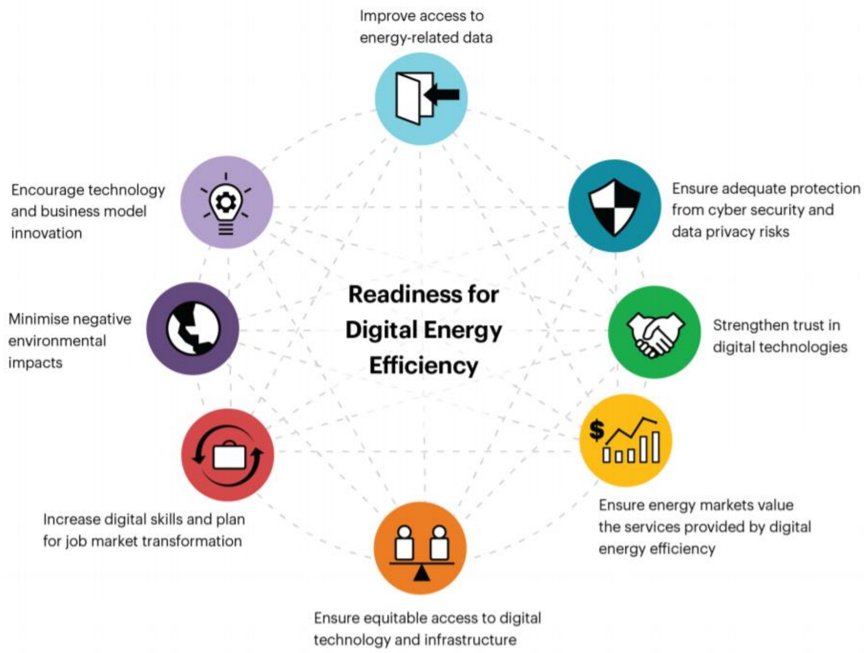

Figure 3: Policy principles comprising the Readiness for Digital Energy Efficiency framework (IEA, 2019).

Leveraging digital technologies for improving energy efficiency requires timely and standardized access to data on energy consumption as well as on other parameters such climate and demographics. Making data accessible to energy consumers and third parties is vital for energy efficiency improvements while issues related to data ownership and privacy need to be addressed. Governments need to support the development of secure platforms for managing and sharing data. When it comes to the smart demand response of industrial facilities, it is important that structures and rules recognizing the value it brings to the broader energy market are in place. Furthermore, it is important to consider the overall impact of digitalization on energy consumption with a system-wide perspective. The energy use of digital technologies and energy management devices is likely to be small compared to overall energy consumption of the industrial sector, especially in the energy intensive industries. However, the devices themselves are often resource intensive in production and contain embodied energy. While the net impact of digital technologies on energy consumption might be positive, the negative impact should still be minimized. Lastly, it is important that governments facilitate and help the private sector to develop education and training courses to build up advanced expertise of the industrial workforce, and support research and innovation within this area to accelerate the implementation of digital technologies (IEA, 2019).

Research in the area of digitalization is quite extensive in Sweden and has increased significantly in the last few years. The research is highly technology oriented and focuses mainly on the manufacturing industries, such as the vehicle industry, while there is little attention on other sectors. Furthermore, there are few research projects directly aimed at improving energy efficiency in industry. For instance, the majority of research projects related to digitalization in the steel industry focus on additive manufacturing. Moreover, there is little attention on addressing the challenges related to management, organization and the development of new business models. Björkdahl et al. argue that the research needs to focus more on the users of the technologies and how they can apply the solutions in practice rather than theoretical technical demonstration projects that often focus on challenges that companies do not see as actual problems, and suggest that researchers work closer with the industry. Furthermore, there is a need for the development of regulations and standards related to, for instance, data ownership, data sharing and integrity (Björkdahl et al., 2018).

The Swedish Governmental Agency for Innovation Systems (Vinnova), provides by far the largest financial support for research on digitalization. Vinnova supports a wide range of research activities and innovation projects. Process Industrial IT and Automation (PiiA) is an example of a strategic innovation program which is supported by Vinnova together with the Swedish Energy Agency and Formas which has the goal of ensuring that the process industry has the advanced IT and automation solutions it needs to harness digitalization more effectively compared to global competitors. For instance, PiiA supported a recent project where SCA, a company in the pulp and paper industry, together Calejo Industrial Intelligence tested an AI-model to optimize energy consumption in one of SCA's mills. With an accurate predictive analysis of the need for steam in the production processes, the need for producing steam with oil in bark boilers can be significantly reduced. This is one of the first successful projects of its kind in the process industries (PiiA, 2020).

After Vinnova, the Swedish Energy Agency is the main actor driving research on digitalization (Björkdahl et al., 2018). The Swedish Energy Agency has, for instance, an ongoing research program called Digitalisering möjliggör energi- och klimateomställningen, which supports research on how digitalization can accelerate the transition to a more sustainable energy system. One of the focus areas of the program is the use of connected equipment (e.g. sensors, meters, controls) for a more efficient energy consumption, but not specifically aimed at the industrial sector (Energimyndigheten, 2019e).

5 Empirical Findings

This section will present the empirical findings from the thematic analysis of the interviews conducted for this study as well as the analysis of the statements each interviewee answered. The main themes will be presented for each of the six categories identified for the interview analysis (see section 2.3) followed by the findings from the statements analysis.

5.1 Digital Strategies

The category of Digital Strategies focuses on the digital strategies of the companies, what areas they focus on and their link to energy efficiency measures within the company. Table 5 includes a brief summary of the main themes identified for this category. Below, each theme is explained in more detail with insights from the interviews.

Table 5: A summary of the main themes identified in the Digital Strategies category.

Theme	Brief Description
1. Digitalization is important for competitiveness	Digitalization is considered important for the future competitiveness of the energy intensive industries in Sweden. Moreover, it is vital that Sweden does not lag other countries when it comes to Industry 4.0.
2. Digital strategies focus on the whole value chain	Digital strategies are not limited to the production and processes, rather they aim to harness the benefits from digitalization in all areas of the value chain, both in technical and organizational domains.
3. Not a clear link between digital strategies and energy efficiency measures	Digital strategies are not explicitly linked to energy efficiency measures within the companies. Digitalization offers great opportunities for improved energy efficiency and companies could benefit from a closer coordination between those two areas.

Theme 1: Digitalization is Important for Competitiveness

The results from the interview analysis show that digitalization is considered extremely important for the competitiveness of the Swedish energy intensive industry. Furthermore, it is important for Sweden, as a small country, to be at the forefront of the digital transformation. Sweden needs to emphasize actions in this area and invest in digital infrastructure so that it will not lag other countries and risk its future competitiveness, as one interviewee working in the steel industry stated:

> *"If Sweden does not adopt to a new digital transformation of industry we will be left behind, and we don't have time to be left behind. On the contrary we should be ahead. Countries like China and the United States always have the chance to catch up because of the giant resources they have at hand. Sweden is a small country, we could never catch up, we need to be at the front from the start."* (Interviewee no. 4)

Theme 2: Digital Strategies Focus on the Whole Value Chain

According to the results from the interviews, companies in the energy intensive industries generally have a specific digital strategy. However, the focus of that strategy can vary greatly between different branches and companies depending on their characteristics and goals. In general terms, increasing the implementation of digital technologies is viewed as something that could increase value creation throughout the whole value chain (e.g. in production, administration, customer interaction, logistics etc.). Increased amounts of data generate more information and knowledge about different processes, both in technological and organizational domains, that can be used to optimize the processes and increase value creation.

> *"We have a strategy where we are trying to identify workstreams where digitalization can bring value for the company … One of the streams is, for example, efficient production, one is in administrative work and one is related to market analysis … I would say the initiative is to have a cluster between all the units where we discuss and prioritize different strategies within digitalization."* (Interviewee no. 3)

> *"We have an outspoken strategy to look for opportunities on how digitalization can help us to improve in, more or less, all aspects of our company. We have a digitalization plan that allocates different projects for testing and learning what could be improved and how we could gain from more intelligent and big data analysis. We do not only focus on the technical processes. We focus on administrative processes, safety aspects, even wellbeing and customer interaction as well. In digitalization we look for opportunities all over the place."* (Interviewee no. 2)

The focus when it comes to the production processes is to use digital technologies to generate more knowledge on the processes and use that data for better process control and increase operational efficiency. However, several of the interviewees stated that the digitalization of the production plants and the industrial processes can be challenging compared to other areas (see section 5.5). While it can be difficult to digitalize the production itself, the interviewees identified potential for digitalization in other parts of their companies where it might be easier to implement digital technologies. Therefore, the digital strategies often focus on other areas than the production itself. For instance, it is considered relatively easy to digitalize administrative systems.

> *"There are many commercial software programs available … Administration is the system that has come the longest way because it is quite easy to replace a low skilled worker with repetitive work with AI."* (Interviewee no. 1)

Many companies in the Swedish industrial sector are global enterprises with operations and customers all over the world. Digital technologies can enable better and more efficient communication between different enterprise segments as well as interaction with customers.

> *"There is some work within digitalization specifically targeted at customer interaction."* (Interviewee no. 4)

In the pulp and paper industry, the forestry part of the value creation chain has great potential for increased digitalization. The most important parameters for the profitability of a forestry farm is the time for pre-commercial thinning, the regular thinning, and the clean cutting. There, some kind of remote control enabled by satellite images and drone images could be extremely beneficial.

> *"Waiting too long to clean cut will be very devastating for the profitability. The forest will not tell you when it is ready for thinning or clean cutting. It is a signal from something telling you that when this area is larger than this area, then it is probably time for cutting. And there is by far the greatest potential for digitalization."* (Interviewee no. 1)

Theme 3: Not a Clear Link Between Digital Strategies and Energy Efficiency Measures

Despite the great opportunities for efficiency improvements that Industry 4.0 offers, there is no clear link between digital strategies in the companies and measures to increase energy efficiency. This is perhaps best illustrated in the fact that, while the majority of the interviewees are working with energy related issues, they were more often than not unfamiliar with their company's digital strategies or projects in that area. With that being said, energy efficiency measures are closely linked with digital strategies in some companies. The goal of implementing new digital technologies is often to improve operational efficiency, including energy efficiency. That requires a close cooperation between those working with energy related issues and those working with digitalization.

> *"Within the digitalization work put up tasks and collaborations with others who are focusing on more energy efficient work … We are a big company, but still, there is more or less the same people working with these kinds of questions."* (Interviewee no. 3)

Furthermore, several interviewees stated that even though their company's digital strategy is not linked to energy efficiency measures, they should do so and that might change in the future.

> *"I think we should develop some kind of an interface to convey data between all these systems as a first starting point and then of course we could start adding a lot of fancy things also that would help with energy conservation … I think we will get there, the question is when."* (Interviewee no. 4)

5.2 Status of Digitalization

Table 6 presents a summary of the main themes identified in the Status of Digitalization category which analyzes the status of digitalization in the companies' production plants. Below the themes are described in more detail with examples from the interviews.

Table 6: A summary of the main themes identified in the Status of Digitalization category.

Theme	**Brief Description**
1. Highly automated, not digitalized	The production plants are generally viewed as highly automated with advanced control systems but still in the early stages when it comes to digitalization. However, the digital maturity varies somewhat between specific enterprises.
2. Gradual development	Digitalization is generally viewed as a gradual development in the energy intensive industries, not a disruptive transformation.

Theme 1: Highly automated, not digitalized

When the interviewees were asked to elaborate on how far their company's production plants are digitalized, the answers varied somewhat. However, the majority views their production plants as highly automated with advanced process control systems, but still in the early stages when it comes to digitalization.

> *"I would say that we are automated to 95% but I would not say that we are digitalized in industrial processes."* (Interviewee no. 1)

"From an automation perspective, I think we've done very well. We are fairly modern, we have good systems, we have a good interface for our operators to see what is actually happening in the plants. But I would like to say that there is a difference between typical standard automation projects and digitalization which is sort of a level higher. We're still in what I would call a turn of the century mode with fairly efficient control system … but there is no independent action from the system more than control." (Interviewee no. 4)

"I would say that we have early digitalization. At the moment we are not in the front when it comes to digitalization in our processes. We have a control system as a baseline for all processes. And on top of that we have a modelling tool that actually decides, it's an adaptive system, but I would say that we are more in the first step of these algorithms. I think that the new digital technologies and algorithms are more advanced than the ones we use." (Interviewee no. 5)

Other interviewees considered their companies' production plants to be far along when it comes to digitalization.

"In general terms, I would say that we are quite far ahead. We have had the initiative for quite a few years now and really have a strong focus and the resources for it. We have already scalable solutions for predicting our problems, predicting quality, predicting failures, maintenance plans, safety aspects and safety supporting tools." (Interviewee no. 2)

"I would say we already use digitalization to reduce production costs and we are close to having these digital twins, for example. We use, you could say, a part of a digital twin to optimize the plant, but we use it also for operator training." (Interviewee no. 7)

This suggests that digital maturity is heterogenous across different enterprises. However, generally, production plants in the energy intensive industries are not considered to be far along in the digital transformation. Furthermore, when conducting the interviews, it became clear that not all interviewees perceive digitalization in the same way. That is not surprising as there is no clear and widely accepted definition of digitalization available. Therefore, the interviewees might have estimated their digital maturity level based on different assumptions.

Theme 2: Gradual Development

Many of the interviewees view digitalization as a continuous gradual development from automated systems to systems with more intelligence, rather than a transformative revolution, and sometimes it is hard to identify a clear difference between the two.

"Sometimes it's really hard to see the difference between the computerized and the digitalized processes, what's the difference? I don't know if it's a specific difference between those words. I fully understand that one part of the digitalization is that you collect a lot of data and you use fast computers to calculate and see patterns. We kind of do that in our modelling tools because they are designed a little bit like that but they are designed in the middle of the 90s, so of course they might not be fully up to date. But I would say that it's a kind of digitalization because they collect a lot of data, they model the data, see patterns and they are always adaptive." (Interviewee no. 5)

To move from a high level of automation to digitalization, the systems need to become more interconnected and obtain a certain level of intelligence where they are able to draw conclusions on their own as well being able to predict certain incidents based on historical and real-time data.

"What I would like to see in production to call it digitalization is another level of, for example, interaction between different types of indicators, process indicators, perhaps some kind of artificial intelligence for

optimization, perhaps providing some kind of decision support for operators and managers within operation." (Interviewee no. 4)

5.3 Impact on Energy Efficiency

The category of Impact on Energy Efficiency focuses on the impact digitalization is expected to have on energy efficiency. According to the interviewees, digital technologies are generally expected to have a positive impact and can improve energy efficiency in several different ways. The exact impact varies greatly between enterprises, industrial branches, and processes. The impact on specific processes is out of the scope of this study and will not be analyzed in detail. More general themes of the impact on energy efficiency will be presented. A summary of each theme is given in Table 7 after which each theme is described in more detail with insights from the interviews.

Table 7: A summary of the themes identified for the Impact on Energy Efficiency category.

Theme	**Brief Description**
1. Optimization of processes	More accurate information about processes that is fed into advanced data models to support optimization of processes and production scheduling can lead to improved energy efficiency.
2. More stable production	Better monitoring of equipment together with advanced analytics to predict failures lead to a more stable production and higher availability of processes thus improved energy efficiency.
3. Smart demand response	Real-time and historical data (e.g. energy consumption and energy prices) together with bi-directional information flow between energy suppliers and consumers can increase smart demand response capacity of industrial facilities. This leads to more effective overall energy system with more stable power grids, better ability to shift of shave demand peaks, lower energy costs, and better integration of intermittent renewable energy sources.
4. Logistics	Advanced data analytics (e.g. with predictive models) on data about customer demand and transportation needs together with increased data sharing between parties can lead to more consolidated logistics thus decreasing energy consumption.
5. Energy consumption of digital technologies considered insignificant	Energy consumption of digital technologies (e.g. for data storage) are generally considered negligible compared to the overall energy consumption of the facilities in the energy intensive industries and are not taken into account when implementing new digital technologies. Moreover, the energy efficiency improvement achieved by digital technologies is considered to outweigh the energy consumption of the technologies themselves.

Theme 1: Optimization of Processes

Optimal processes are the key to efficient production, and production managers and operators strive to run processes with minimum resources (e.g. energy and raw materials) per value created. The key to optimization is having information and data about the processes and having the tools to analyze that data to enable operators to make adjustments where and when needed. More advanced data gathering and data analysis tools generate more knowledge which can lead to better optimized and more resource efficient processes. Moreover, greater interconnectivity between different parts of the processes and different systems can lead to an improved overall efficiency.

> *"It's that kind of interconnectivity that I think would be the starting point, and with giving operators, production managers that information they could probably optimize the process, which I think would be step one. Then step two would be to use some kind of adaptive learning to that and to provide more complex information and support system to the decision-making system for operators and production managers. In that sense I think we could save a lot of energy overtime that we don't even know about today. I think we have optimized processes and yes, they are optimized based on the information available. The problem is that we do have more information, we just don't put it into the process … If it would have some kind of automated learning within the system, artificial intelligence or whatever you would like to call it, and you give that system access to everything and also to some sort of control, then you can reach another level of energy efficiency."* (Interviewee no. 4)

Theme 2: More Stable Production

Another extremely important part of efficient production, especially in the process industries, is the stability and availability of the processes. This can be vital for energy efficiency improvements in industries such as the chemical industry:

> *"The nature of the industry is that you want to have the plant running so a lot of efforts are put into keeping up the operating rate and, of course, you can use tools for that that you could say are partly digital… It will make the plant run longer, better and smoother to avoid upsets which would decrease production but also increase energy consumption."* (Interviewee no. 7)

Keeping processes running without operational upsets reduces waste and avoids start-ups that can be energy intensive.

> *"Avoiding operational upsets is a quite important thing to make our plant more energy efficient because we know that when we have an upset we run the plant in a very suboptimal way and we may even need to flare or burn our products because it does not fulfill the specifications."* (Interviewee no. 7)

> *"Digitalization can support stable operations and stable quality with more predictable analysis for giving advice for operators to really run the process optimally. That has immediately an impact on energy efficiency because all failures are lost energy, a lot of it."* (Interviewee no. 2)

Advanced data analytics using AI can be beneficial when it comes to keeping processes running. Being able to predict failures or upsets in production allows operators to make necessary adjustments earlier, avoiding production stops and reducing downtime.

> *"If we learn to predict production disturbance in the process, then you could stop putting energy in the process because you know in five minutes there will be a shut down. That will be a huge improvement where digitalization might have an impact."* (Interviewee no. 5)

Theme 3: Smart Demand Response

As described in section 4.3, digital tools can increase demand response capacity. Having a smart demand response where energy consumption, most often of electricity, is adjusted to energy prices or availability can be extremely beneficial, especially in sectors with high energy costs. Moreover, higher demand response capacity can help grid operators to make the grid more stable.

Historically, Sweden has had a relatively high share of hydropower which can be used to regulate the power grid. Therefore, in the past, there has not been a great need for a high demand response capacity. However, that is starting to change with the increased implementation of intermittent renewable sources, such as wind and solar.

> *"When we will have more variable power in the system, the price becomes more volatile and the industry will need to adopt. And here digitalization will help. If you could plug all the big consumers, everyone has its own dynamic, but you could still find algorithms and do things so you could automatically adjust and have an aggregator. If you steer and set that up in a good way, the system will benefit, consumers will benefit, and producers will not have to build additional infrastructure. A few years out this will be very important, and digitalization will be the key driver."* (Interviewee no. 8)

Similarly, one interviewee working in the pulp and paper industry said:

> *"We are looking into opportunities to adopt better to the variations on the power market. There are now mechanisms available on the power market, with very volatile electricity prices from the grid. The whole energy system, especially the electricity system, is very affected by this more unpredictable energy sources, like wind and solar for instance. And they are creating quite challenging situations for the grid owners, so the prices are very volatile, you even get paid for using electricity at certain times. We are looking into opportunities to take advantage of that with flexibility in our mills, a higher demand response. It's really the vision that we can build up a tool that can help us and give us the right advice to act on or even control our processes in an optimal view. Digital technologies can help with that."* (Interviewee no. 2)

A smart demand response is not only restricted to electricity demand as another interviewee from the pulp and paper industry stated:

> *"We are connected to a district heating facility from our industries. If we can combine our production costs or possibilities within the mill connected to the district heating stations and combine that data in some kind of models to foresee the needs and the production costs of them, that would optimize energy usage and costs."* (Interviewee no. 3)

Some industrial processes have a higher potential for demand response capacity than others depending on their characteristics. Moreover, increasing demand response capacity is not a priority in sectors who are not very affected by electricity prices. One interviewee from the chemical industry stated:

> *"We have investigated, together with our grid provider, to have some kind of an online application to use our plant to adjust hurts on the grid. But we have not really seen how that would make sense for us so far … Normally, we are not so sensitive to the electricity price."* (Interviewee no. 7)

Furthermore, some industries generate electricity internally which could be used to stabilize the grid and for peak shaving or shifting.

> *"We have a unit that generates electricity which we use internally. You can change the load on that and we use that to put a bid on the market, we could increase that load and buy less. We do that together with our*

provider. You could use that for wintertime when you have a higher probability to get peaks on the electricity market which we would then help to reduce with our unit." (Interviewee no. 7)

Theme 4: Logistics

Logistics is another area where digitalization can improve energy efficiency. Improved data on products and orders can be used to optimize transportation from warehouse to customers and logistics inside warehouses, which can lead to reduced consumption of transportation fuels. Perhaps the biggest potential for energy efficiency improvements in logistics is within the pulp and paper industry (or the forest industry) where the transportation volumes of wood from forestry farms to industrial sites is extensive. This segment could benefit from more data sharing and transparency between parties which can be enabled by digital solutions. One interviewee stated:

"There is a well-documented and well-known inefficiency in our segment of the transportation sector. For instance, if you are a truck driver and you drive from our industry to another place with no cargo. Then you drive past logs that are on the side of the road that you could have taken, because logs are logs, if it's the same quality and the same dimension then it doesn't matter who picks it up as long as it reaches its destination. You could have picked those logs up because you were driving past that road anyway. But you cannot, because you cannot access the information, so you don't know that these logs are on the side of the road. That is simply information sharing, but the catch is that this wood has probably been sold to someone other than us. Since you are employed by us, we will not give you that information because we don't have it." (Interviewee no. 1)

Theme 5: Energy Consumption of Digital Technologies Considered Insignificant

As stated in section 4.3, the net impact of digital technologies on energy demand is still uncertain. However, according to the interviewees, the energy consumption of the digital technologies themselves (e.g. for data storage) is not considered to be a part of the energy consumption of their respective industrial facility and is usually not taken into consideration when implementing new digital technologies.

"I would say it impacts our energy consumption indirectly. Of course, data handling and data storage increases energy consumption, but not at our facilities. We don't really take that into consideration" (Interviewee no. 2)

"If you look at a system overview, that's true that we add energy usage in that case. But to be honest, I don't think that we have taken into account how much a server somewhere increases its energy usage. I think you have to draw the borderline somewhere." (Interviewee no. 3)

Moreover, there was a harmony amongst the persons interviewed that the improvement in energy performance enabled by digital technologies would outweigh the energy consumption of the technologies themselves. Furthermore, the energy consumption of digital technologies is negligible compared to the overall consumption of the industrial facilities.

"Energy for data storage has not been taken into account so far. But I would guess that that energy is quite small compared to the efficiency improvements in the plant. That's usually how it works. Even if these data centers use a lot of electricity for cooling etc., it's still quite low compared to what the plant is consuming in terms on energy. I doubt that that would really have any impact on the decisions as such." (Interviewee no. 7)

However, in the digital future, companies might have to consider the system-wide impact to a larger extent as the amounts of data that needs to be stored and analyzed increases.

> *"If we would extrapolate this into some kind of a digital future with everything being stored in clouds, we would eventually spend more energy on cloud computing than we would spend on actual production. I think we would have to learn probably quite early what the optimum level is and how we can optimize the storage of information and data. Perhaps not everything should be stored on servers. If we are going to store every single input value, every sensor, and we are going to store it for decades with a high resolution and all the interconnectivity between different processes and sensors, then it will become ridiculous."* (Interviewee no. 4)

> *"The question is the labor cost for the analyzing. That could be the killing factor. Because to build a smart system, we have to gather enormous amount of data and set boundary conditions for I don't know how many parameters. And since we have such a variation of products, I see that as being difficult."* (Interviewee no. 6)

5.4 Drivers

The main drivers for digitalization in the energy intensive industries are analyzed in this category. Even though the interviews show that increased implementation of digital technologies improves energy efficiency, that is not considered the main driver for digitalization. Energy efficiency improvements are more considered as a positive side effect when implementing new digital technologies.

The main themes that were identified in the category of Drivers are listed in Table 8 with a brief description. Below, they are elaborated on in more detail with examples from the interviews.

Table 8: A summary of the main themes identified for the Drivers category.

Theme	Brief Description
1. Increased value creation	The main driver behind digitalization is to increase value creation through optimization of processes, higher productivity, availability of processes and improved quality of products. This often leads to increased energy efficiency but is not necessarily the main goal.
2. Better maintenance management	Maintenance costs are often a significant share of the overall operating costs in the energy intensive industries. Decreasing that cost is a driver for implementing digital technologies as they enable a better maintenance management (e.g. by predicting failures more accurately and decreasing downtime).
3. Customers	Customers' demand for more information about the production or processes can drive digitalization in the energy intensive industries. Moreover, better interaction with customers around the world can drive digitalization.

Theme 1: Increased Value Creation

Naturally, all industrial enterprises strive to maximize value creation through efficiency and productivity improvements and cost reductions which serves as the main driver for most decisions. That is also the case regarding decisions related to digitalization.

> *"If we get to rock bottom, it's of course value. What can we do more efficient? How can we earn more money? If there are smart ways of doing it within digitalization, then we are of course very interested."* (Interviewee no. 3)

The main driver behind implementing digital technologies in the production plants is increased value creation through better optimization tools enabled by more information about processes and advanced data analytics. This leads to optimal use of resources, including energy, and drives down costs. For companies with relatively high energy costs, improving energy efficiency is naturally a priority.

> *"We clearly see that we can make things more efficient with digitalization, advanced computing and data analytics, and we can lower our costs with that. The energy cost is huge, and anything wasted is a waste of money. So, energy is definitely a part of that."* (Interviewee no. 5)

Furthermore, value creation can be increased through higher quality of products as one interviewee from the steel industry stated:

> *"One of our strategies within digitalization is to use advanced computing and data analytics to improve all our products, make the products lighter and stronger … If the equipment can be lighter and last longer, then we will save material and energy … And that improves our business."* (Interviewee no. 5)

Theme 2: Better Maintenance Management

As described in section 4.3, digital solutions can enable better maintenance management. This was mentioned by several interviewees as one of the biggest drivers for increased implementation of digital technologies. The cost of maintenance is often a significant share of the overall costs in the energy intensive industries and being able to better monitor the condition of equipment and predict failures in production can increase the availability of processes and reduce maintenance costs.

> *"I would say increased availability and reduced maintenance was the main driver for the industrial part of our operations. Not only reduced downtime, but also the cost of maintenance."* (Interviewee no. 1)

> *"The maintenance question is a big part of this. Can we foresee anything that will happen to the mill and make planned activities according to that? Then we will improve our time efficiency and there's money in that."* (Interviewee no. 3)

Theme 3: Customers

The demand for sustainable products is growing as well as the demand for more detailed information about the products and specific production batches. This could drive digitalization in the energy intensive industries in Sweden, who often produce intermediate products that are used by other industries and manufacturers. One interviewee working in the steel industry stated:

> *"If you were a big regional equipment manufacturer you would like to see that your production chain would be digital to tap down all the value that could be brought by digitalization. Sooner or later you would reach a point where you would say to all of your suppliers: 'If you are not digital you cannot really cooperate with*

my operation, I need the input from your part of the value chain'. And then they would start putting demand on suppliers to be digital to some extent. And we've seen some aspects of that already in terms of customers requesting digital access to various parts of our information flow. So far, they don't want to have information about our production processes, but they would like to have all the quality parameters of the last batch that they were sent coming in digital format rather than sent as a piece of paper or with an email once a year. And sooner or later, I assume that this will require us to do some digital infrastructure inside our processes to be able to provide all the information that the customers are requiring." (Interviewee no. 4)

However, when digitalization is driven by customer demand, there is a risk that the digital infrastructure will be designed specifically to meet the demands of customers rather than the demands of the supplier.

"In that case, the infrastructure will not be that well targeted to our needs, for example, with respect to energy conservation. I'm fearing a situation where customer demands will drive digitalization … Having energy conservation and climate issues driving digitalization, I think that will be extremely hard considering the high investments needed to sort of start the transformation. On the other hand, there are a lot of other issues that could benefit from digital infrastructure, everything from safety, cost, quality, preventive maintenance, and perhaps manning. And if we could create a good structure to tap that value before the customers force us into some kind of a specific infrastructure, I think that would be a great advantage." (Interviewee no. 4)

Many of the enterprises in the Swedish energy intensive industry have operations and customers in many parts of the world. Digital tools can be extremely beneficial for coordinating organization across regions and improving customer interaction and relations.

"We deliver goods all over the globe and it is really important to be able to connect to customers, and support and cooperate with the them in the challenges that they have on a remote basis with more advanced tools." (Interviewee no. 2)

5.5 Challenges

The Challenges category focuses on the main challenges faced by the energy intensive industries when implementing digital technologies. Numerous different challenges were mentioned by the interviewees. The main themes that were identified are listed in Table 9 along with a brief description. Below, the themes are described in more detail with insights from the interviews.

Table 9: A summary of the main themes identified for the Challenges category.

Theme	Brief description
1. Lack of fundamental understanding of processes	Fundamental understanding of processes is a prerequisite of using advanced data analytics for process control. The processes in the energy intensive industries are often very complex and are not always fully understood which makes it impossible to design models around them. Moreover, the operating conditions are often extreme which makes it challenging to measure and gather data on certain parameters.
2. High investment costs and lack of long-term strategies	Digital projects require long-term vision as they are often capital intensive and have long payback periods. However, their

	benefits are often uncertain, and it can be difficult to motivate and get them prioritized within management.
3. Lack of competency	In some cases, the energy intensive industries lack the knowledge needed for the implementation of new digital solutions.
4. Old systems	The energy intensive industries are asset intensive and production plants and equipment is replaced rarely. Therefore, the systems in use are often relatively old and are not compatible with new and advanced digital technologies.
5. Cybersecurity	Issues related to the security of data and data ownership might hinder the implementation of digital technologies. The risk of vulnerable data getting into the wrong hands and cyberattacks threating production are a concern for many.
6. Conservative culture	Certain actors in the energy intensive industries can have conservative views that might decelerate the implementation of digital technologies.

Theme 1: Lack of Fundamental Understanding of Processes

Several of the interviewees stated that the digitalization of the production plants and the industrial processes can be challenging compared to other areas. Industrial processes are often very complex and sometimes the fundamental understanding of, for instance, the physics or thermodynamics is not good enough to be able to design computerized models describing the processes. Furthermore, the operating conditions are often extreme, e.g. with very high temperatures, where it is difficult to carry out accurate measurements to gather data. Therefore, the technical challenges are more related to the processes and measurement technologies, rather than the digital technologies themselves.

> *"On our side of the industry, it is not the technological development of the AI that is the weak spot, it's the technological development of a robust control signal or the fundamental understanding of the physics … In an industrial system, we always have a lack of information. There are so many of the thermochemical processes that are either not measured or not described, or perhaps not even known or possible to formulate in an equation in a way that a computer can use. If you want to predict something, then you must have access to, first, the measurements and then you need to put those measurements in some kind of an equation to be able to build a model. This model typically consists of a system of differential equations, but if you don't have any differential equation then the model is no longer a model and then what should you do?"* (Interviewee no. 1)

Furthermore, process industries are very heterogenous with the plants and processes differing greatly between enterprises. Therefore, digital solutions must be designed individually for each plant and cannot be generalized across enterprises. Whereas, in other industries with more homogenous operations (e.g. the vehicle industry), similar digital solutions can be applied at different plants.

> *"One important thing to understand is that every process that we have is unique, there is only one process in the world that is designed like the process we run. Every mill is unique, it cannot be compared to others. So, we need to develop everything ourselves. It cannot be applied to other processes. The thought can be applied, but it will be a completely different system so it's impossible to share with others … That makes it very difficult to be in the front end of digitalization."* (Interviewee no. 5)

Theme 2: High Investment Costs and Lack of Long-term Strategies

The value that digital technologies create can be uncertain and hard to estimate, and the companies often do not have the knowledge to identify the exact benefits. Therefore, it can be hard to motivate investments in digital infrastructure and get them prioritized within the management.

> *"As a company, if we were to increase digitalization, I think the main thing would be to have long-term strategy in this area to be able to realize the benefits … I think the difficult thing is to find the correct arguments and motivation for the management on why this is important."* (Interviewee no. 9)

Investing in digital infrastructure can be capital intensive and the return on investment is not immediate and often uncertain. Several interviewees mentioned investment costs as a major hindrance when it comes to digitalization. It is often hard to get digital projects prioritized within the company and resources are often put in other projects with shorter payback periods. With a more long-term perspective, perhaps companies would be more willing to invest in digital infrastructure.

> *"Digital transformation means huge upfront investments in various types of infrastructure and then it will take considerable time before you start getting payback from that. And whenever you start talking about huge investments, you will start competing with very high focus projects. Gaining new markets, having new production capacities and so on is always a lot sexier than building infrastructure for something that will pay off five years from now."* (Interviewee no. 4)

Theme 3: Lack of Competency

The lack of competency of employees in the energy intensive industries is a challenge when it comes to digitalization. One interviewee said that the heavy industry often has trouble recruiting skilled engineers to work with industrial automation systems and digital projects in industry. Workers with advanced IT skills find it more attractive to work in other sectors.

> *"The problem is that if everybody is developing new products to sell to the industry, and if the industry does not have the skills to estimate these new products, who is going to buy them?"* (Interviewee no. 4)

Furthermore, it can be a challenge to transfer knowledge between people working with the data analysis models and people who work with process control.

> *"If you want good results, you need to engage the right people that understand the process you need to digitalize. And that could be a bottleneck. It could also be difficult to transfer their knowledge to someone working with the algorithms etc., so they understand each other."* (Interviewee no. 5)

Theme 4: Old systems

The energy intensive industries in Sweden have a long history and often have old production plants that are replaced rarely. Many of those plants are using computerized control systems that were developed late last century and are not compatible with the digital technologies of today and the future. This can be a great challenge for the digital transformation of the energy intensive industry when compared to other industries that renew machinery more rapidly. An interviewee from the steel industry identifies this problem as a huge challenge that many might underestimate.

> *"We have a lot of plants of very different ages and different technologies involved. The interfaces that would be nice to have, the main reason we don't have them is the fact that a computerized control system from the*

1980s just doesn't communicate with a computerized control system from 2015. There is no interface available. And I think that this is and will be a main challenge. You have a lot of different generations of technology still in operation. The range of technologies that would have to adapt to a digital interface, I think that is a huge challenge. Digitalization could probably be done very well in plants producing, for example, computers, mobile phones, and cars, where you replace your entire production chain perhaps every five years. But we replace our production chain perhaps once every 70 years." (Interviewee no. 4)

Theme 5: Cybersecurity

As bigger amounts of data are gathered about processes and products, and devices become increasingly connected, enterprises become more vulnerable to cyberattacks risking the leakage of sensitive information or the stability of processes.

"We are working with data security, but it's a difficult area. I think we have become more skilled in it and we have more knowledge in that area. But to be honest, if someone wants to hack you or do something, their skills are developing quickly as well." (Interviewee no. 3)

Data ownership and data security is also an issue when enterprises cooperate with other parties, for instance when sharing data with a grid operator. But in that case, the risk is higher for the grid operators or power producers than the industrial facilities themselves.

"There is always the issue of security. For example, you can't expose yourself to someone who could hack the system and take control ... The issue of cybersecurity is something we talk about with our suppliers. But I think the challenge of security is higher on their side." (Interviewee no. 8)

As described in section 4.4, cybersecurity is considered by many the main challenge when it comes to digitalization. According to the interviewees, while identified as a significant challenge, cybersecurity is not considered as the main challenge when it comes to digitalization in the energy intensive industries.

"Data handling is still an issue. Who is owning the data? How can we handle it safely without letting it open up our systems to external threats? It will perhaps always be a question. We think that we will become better in that area, but now we need to find more sophisticated ways of handling data." (Interviewee no. 3)

Theme 6: Conservative Culture

The energy intensive industries in Sweden have a long tradition that goes back centuries and many enterprises have been in operation for a long time. A conservative culture within those industries, at least of some employees who doubt the benefits of digitalization, might slow down the digital transformation.

"We are an industry that has been in operation and gained knowledge over a long time and that leads to us being perhaps a little bit suspicious in some areas, or some people are. Can data models or machines really do this better than we can out in the mill? So, it is somewhat a culture thing and very dependent on persons." (Interviewee no. 3)

One interviewee in the steel industry wondered if digitalization would lead to more standardization and that could mean a loss of skills and knowledge that has been acquired over a long period of time.

"If you look at us from a historical view, a part of the pride people have is that they have skills and knowledge about producing steel with different properties that they have gathered over a long time, and we are trying to transfer that experience from one individual to the next. And if we go to digitalization, one thing that I could see as a potential danger, at least in my imagination, is that you are limiting yourself. The window of operation will be more standardized and you might have to reduce your product offering portfolio because you are standardizing. And then you might take away a little bit of that pride." (Interviewee no. 6)

Additionally, some enterprises are more conservative in nature because of the characteristics of their operations. This is the case for some companies in the chemical industry, where two of the interviewees stated:

"Our industry is quite conservative since the important thing for us is to have our plants running. We don't want to try things that might cause production losses because then you lose money quickly." (Interview no. 7)

"Our industry is quite conservative, it is struggling with low margins and some markets just have to survive. So, there is not much room for these kinds of improvements." (Interviewee no. 9)

5.6 Action

The Actions category focuses on the action that the Swedish government and governmental agencies or the industry itself can take to accelerate the implementation of digital technologies for improved energy efficiency. The main themes are listed and described shortly in Table 10. Below, each theme is described in more detail with examples from the interviews.

Table 10: A summary of the main themes identified for the Action category.

Theme	Brief Description
1. Financial support	Financial support systems will mitigate the challenge of high investment costs and are considered to encourage and accelerate investments in digital technologies.
2. Research	It is important to support and encourage further research in the field of digitalization for energy efficiency improvements. There is a special need for developing efficient measurement technologies for extreme conditions and to increase the understanding of the fundamentals of processes in order to be able to exploit the full potential of digital technologies in the energy intensive industries. Furthermore, it is important to demonstrate how digital solutions can work in practice.
3. Networking	Encouraging further networking between industry, academia and the public sector as well as cooperation between different industrial parties who can help each other and learn from one another will further support the digital transformation of the energy intensive industries.

Theme 1: Financial Support

As mentioned in the previous section, a great challenge for digitalization in the energy intensive industries is the capital intensity of digital infrastructure combined with long payback periods and often uncertain return on investment. Meeting this challenge with financial support or risk sharing could accelerate the implementation of digital technologies, according to several of the interviewees.

> *"Programs that you can apply for and get support to install something if you have a good idea. I think that kind of program could make some projects come on the table."* (Interviewee no. 5)

> *"Financing or sharing risk could be beneficial. If we try something and it doesn't work, the government could take risk in the projects. Then it will be easier to take the decisions."* (Interviewee no. 3)

However, not everyone considered financial support to be the right way forward.

> *"I don't like financial support systems. It's some kind of a respirator for things that aren't profitable enough themselves. I would like to see the technology being so attractive that you couldn't turn it down. And I'm not sure we are there quite yet ... I don't have a good solution, if it should be support systems for research or if the support system should be in the terms of assistance with designing the infrastructure necessary for a company. You could do this in a whole range of different ways. But just handing out a bag of money, I don't think that's an attractive solution."* (Interviewee no. 4)

Theme 2: Research

Measurement technologies that generate accurate information about processes is a prerequisite for using advanced analytics for process control. As discussed in the previous section, it can be challenging to gather data in extreme operating conditions (e.g. high temperatures). Furthermore, the lack of knowledge about the fundamentals of the processes is a great challenge when it comes to digitalization in the energy intensive industries. It is important to support research in this area.

> *"I think that developing new measurement technologies is an important way to go. We will never initiate that. We can buy it when it is available. But since we will not ask for it, probably the suppliers will not develop it either. We know from experience that when we have access to new measurement technologies that can produce a new robust control signal, then we learn much more about our process and then we will be able to reduce waste and hit an optimum point of operation. But the crucial part is to improve the measurement technologies of different parts of the production process. For instance, how to measure a certain concentration of a certain chemical in some of our process streams. That would be a perfect scope for Energimyndigheten to focus on."* (Interviewee no. 1)

Furthermore, industries where the continuity of processes is of high importance often avoid implementing new technologies that might jeopardize the stability of processes. Demonstration projects where new technologies can be tested in practice could be important to accelerate digitalization in the energy intensive industries.

> *"The important thing for us is to have our plants running. We don't want to try things that can risk the stability of our processes … Usually when we implement new technologies, we ask for other operators who have done similar things."* (Interviewee no. 7)

Theme 3: Networking

Cooperation between industry, academia and the public sector is crucial for a successful digital transformation of industry. That is especially important for small enterprises who do not have the resources to develop digital solutions on their own and will therefore not be at the forefront of digitalization.

"We are a small company and we do not see all the development that is ongoing. I don't see us being in the lead, but I'm sure we can benefit from digitalization in certain areas. We are more trying to follow what happens." (Interviewee no. 6)

Several interviewees mentioned that it would be beneficial to support further cooperation across sectors where different enterprises can collaborate and learn from each other. Though different industry sectors and even different enterprises within the same sector are diverse, there are a lot of similarities that can be built on.

"I think working across sectors and seeing what is common in these companies would be good because then there is suddenly a lot of more experience, skilled personnel, ideas and force." (Interviewee no. 5)

"We have these digitalization networks and activities related to universities. I think that is a good approach. In general, I think for these kinds of things it's important to see what others have done and that can help us to see what we can do in our situation." (Interviewee no. 7)

One interviewee mentioned that initiatives supporting different stakeholders to find each other are beneficial and encourage greater cooperation and networking between different stakeholders.

"I know that some governmental authorities are helping different parties to find each other. We have had some of those initiatives where we have explained our needs and they have put us together with different companies in different areas of the world. These are good initiatives and have helped us to see where we can find partners." (Interviewee no. 3)

5.7 Findings from the Statements Analysis

As mentioned in section 2.2, in order to get further clarification on the perspectives of the interviewees and to be able to better visualize trends, the interviewees were asked to estimate their level of agreement with ten statements. The full list of the statements is provided in Appendix B and the results are presented in Figure 4.

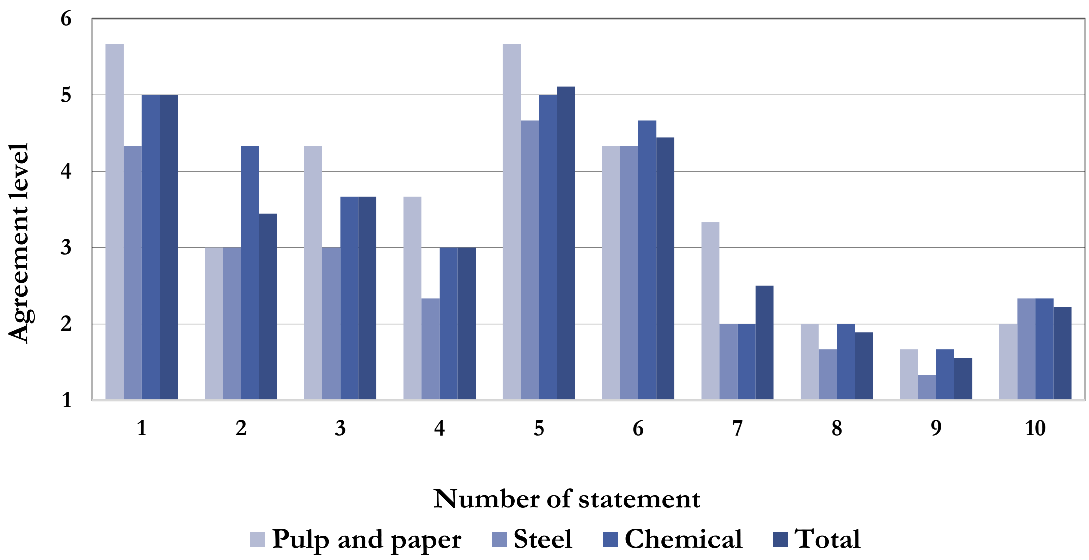

Figure 4: The results from the statements analysis.
Note 1: The bars show the average level of agreement, both disaggregated between branches and as a total of all branches.
Note 2: An agreement level of 1 means that the interviewee completely disagreed with that respective statement, while an agreement level of 6 means that the interviewee completely agrees with that statement.

As seen in Figure 4, there are no great differences between the three branches. There seems to be a strong consensus on the importance of digitalization to the competitiveness of the companies, as the average agreement level for statement number one is 5. For statement number two, which asked if the interviewees agreed that their production plants are digitalized, the answers varied greatly. Seven out of the nine interviewees had an agreement level of 2-4 while only two interviewees agreed strongly (agreement level of 5-6), both from the chemical industry. This indicates that the digital maturity of the energy intensive industries is not considered to be high. Moreover, this indicates that some companies in the chemical industry are further along in the digital transformation. However, the third interviewee from the chemical industry disagreed strongly with statement number two (agreement level 2), suggesting that the digital maturity level of the chemical industry varies significantly between enterprises.

Furthermore, the results show that digitalization of the production plants in the energy intensive industries is not explicitly linked to either energy efficiency measures or greenhouse gas mitigation, as the agreement level of statements number three and four was not high. However, the results show an indication that there might be a stronger link within the pulp and paper industry compared to the other branches while the link seems to be the weakest in the steel industry. Additionally, the total average agreement level of statement number four is slightly lower than of statement number three, indicating that digitalization is less likely to be linked to climate mitigation measures than energy efficiency measures.

As the answers to statements number five and six show, there is a consensus among the interviewees that increased implementation of digital technologies will both increase energy efficiency and decrease greenhouse gas emissions. Additionally, based on the results from statement number seven, increased implementation of digital technologies is not considered to increase electricity consumption in the production plants.

Even though digital technologies are considered to both improve energy efficiency and decrease greenhouse gas emissions, neither of the two are considered to be the main driver for digitalization of the production plants, as agreement level of statements number eight and nine was very low. Lastly, there was a low level of agreement across all branches with statement number ten, indicating that cybersecurity issues are not considered the main challenge when it comes to digitalizing production plants in the energy intensive industries.

6 Discussions

For the most part, the results from the statements analysis accord with the results from the thematic analysis of the interviews, validating the interpretation of the interviews and the extracted themes. However, the interviewees were relatively few, so one should be careful to draw strong conclusions on a quantitative basis from the results of the statements analysis, especially about the differences between the branches as there were only three interviewees from each branch. They should be considered more as indications of possible trends and differences between the branches. Furthermore, the results from the interview analysis give insights from nine employees within three large industrial branches and do not necessarily reflect the branches as a whole. However, the results give valuable insights on the state of digitalization within the Swedish energy intensive industries and how it could impact energy efficiency, and can be used to identify areas to be explored further and in more detail.

In general, the empirical findings of this study are in concurrence with the findings from the literature review. Digitalization is considered a key for the future competitiveness of the Swedish energy intensive industries and it is important that the sector does not get left behind in the digital transformation. The empirical findings of the study show that enterprises often have a specific strategy related to digitalization. Those strategies focus on all areas of the companies' value creation chain, from production to logistics and organizational systems. However, that is not reflected well in the digital maturity level of the sector and according to the statements analysis, the production plants in the energy intensive industries are generally not considered very digitalized. The results indicate that the production plants of some enterprises in the chemical industry might be the most digitalized. However, the extent of digitalization varies greatly between enterprises in the chemical industry which is not surprising as the sector is extremely heterogenous when it comes to production. Furthermore, the results from the interview analysis show that the production plants within the energy intensive industries are usually highly automated and have advanced process control systems. However, they generally do not have digital systems characterized by intelligence, such as being able to draw conclusions and predict certain incidents accurately based on historical and real-time data.

The empirical findings rhyme with the findings of Antonsson, Sundberg et al., and SKF mentioned in section 4.2 who suggest that even though digitalization is perceived as being vital for the future competitiveness, the level of digitalization in the Swedish industry is relatively low. This might be because digitalization in industry is still a novel topic and the companies might only now be starting to realize the potential benefits of Industry 4.0 and are still trying to figure out how those can be harnessed, or are on the verge of implementing new digital technologies. Comparing the status of digitalization in the Swedish energy intensive industries to that of other countries is not a part of the objectives of this thesis, however, doing that would give a valuable context to this topic and should be done in future research in this area.

The employees interviewed for the study do all work with energy related issues in one way or another, however, many were not particularly familiar with the digital strategies and projects related to digitalization within their respective company. Interviewing employees working more closely with digitalization would likely have given a more detailed insight of the ongoing work related to digitalization in the companies. This, however, indicates that there is not a strong connection between energy efficiency measures and digitalization in the energy intensive industries. Moreover, the empirical findings show that digital strategies of the companies are not linked closely with energy efficiency measures. To exploit the full potential digitalization offers for improved energy efficiency, it is important to connect the two areas more closely. Interestingly, the statement analysis indicates that the link between digitalization and energy efficiency measures might be the strongest in the pulp and paper industry out of the three sectors analyzed in this study while being the weakest in the steel industry. However, as mentioned earlier, no strong conclusions can be drawn from the statement analysis, and this needs to be explored further.

There is a strong consensus that digitalization will improve overall energy efficiency in the energy intensive industries. The results from the interviews concur with the literature in that digitalization can improve energy efficiency in a number of different ways, with the main ones being through better optimization of processes, more stable production and improved maintenance management. Therefore, linking digital strategies more closely to energy efficiency measures could further improve energy efficiency in the sector and contribute to achieving the target the Swedish government has set for energy efficiency improvement.

The energy consumption of the digital technologies themselves (e.g. for data storage) are not taken into consideration by actors in the energy intensive industries when implementing new digital technologies. It is considered small compared to the overall consumption of the industrial facilities and is perceived to be outweighed by the positive impact on energy efficiency. However, this might become an issue in the future when the industry is further along in the digital transformation. It is important that the impact of digital technologies is always evaluated on an overall systems level and that the negative impacts are minimized.

Despite the great opportunities that digitalization offers for improved energy efficiency, that is not considered the main driver for increasing the implementation of digital technologies in the energy intensive industries. Improved energy efficiency is rather considered a positive side effect of digitalization. Therefore, the actual impact of digital technologies on energy efficiency might not be measured or valued fully. The main driver for digitalization is improved value creation through, for instance, better optimization tools which can lead to higher energy efficiency. Additionally, higher availability of processes and better maintenance management were considered drivers for digitalization in the energy intensive industries, both of which can lead to higher energy efficiency, but also have other benefits such as improved quality and lower maintenance costs.

There are numerous different challenges industries face when it comes to digitalization, both of organizational and technical nature. The interviews gave insights into some of the challenges faced by the energy intensive industry in Sweden. Investments in digital technologies are capital intensive and often have long payback periods. Therefore, it requires long-term strategies within management. While employees working within the sector acknowledge the fact that digitalization and Industry 4.0 entail great opportunities for increased value creation throughout the whole value chain, it has proven challenging for some companies to identify where and how exactly those benefits can be realized. This makes it hard to motivate and prioritize investments in digital infrastructure. Moreover, conservative culture within the companies can hinder the implementation of new digital technologies.

The main technological challenges are not related to the digital technologies themselves. The prerequisite for controlling and optimizing processes is having accurate data and information about the processes. It is often challenging to gather data on the complex processes and in the often extreme operating environments in the energy intensive industries. Therefore, developing robust measurement technologies is vital to be able to better apply digital technologies in process control. Furthermore, understanding of the fundamentals of the complex processes is often limited which makes it impossible to design advanced analytical models around the processes.

The energy intensive industries in Sweden are considered asset intensive and the production plants and equipment is renewed or replaced seldom. Consequently, the industries often have relatively old systems that are not compatible with new digital technologies and that can be an enormous challenge. Another challenge is the lack of competency within the industry as the heavy industry in Sweden often has a hard time recruiting employees with advanced ICT skills. Data security, data sharing and data ownership is by many in the literature considered the greatest challenge when it comes to digitalization in industry. However, while identified as a challenge, it is not considered the main challenge when it comes to digitalization in the energy intensive industries.

The employees interviewed for this study suggested action in mainly three areas that would help to accelerate the implementation of digital technologies for improved energy efficiency. First, in order to overcome the challenge of high investment costs and long payback periods, financial support systems might accelerate the implementation of new digital technologies. Second, there is a need to support further research in this area, especially when it comes to developing measurement technologies and increasing the understanding of processes. As Björkdahl et al. state, the research on digitalization in Sweden does not focus enough on showing how digital solutions can work in the real world. Demonstration projects where companies can learn how to harness the benefits of digital technologies in practice could help accelerate their implementation. Moreover, research needs to focus more on the organization and business side of digitalization. Third, encouraging networking between different stakeholders could help accelerate digitalization. It is important to strengthen the cooperation between academia, industry and the public sector as well as collaboration between industrial parties who can learn from each other and assist one another.

7 Conclusion

This thesis examined the status of digitalization within the Swedish energy intensive industries and how it could impact energy efficiency within the sector. This was done by using qualitative research methods, i.e. by conducting a literature review and in-depth interviews with employees working with energy related issues in three energy intensive sectors (pulp and paper, steel and chemical industries).

The results show that while digitalization is considered important for the future competitiveness of the Swedish energy intensive industry sector, it is still in the early stages. Companies in the sector acknowledge the great opportunities that digitalization offers for increased value creation throughout the whole value chain and many have specific strategies to harness those benefits in different areas of their company. However, that is not reflected in the digital maturity of the sector as the production plants in the sector are generally not considered highly digitalized.

Furthermore, the results of the study show that digitalization can improve energy efficiency in a number of different ways, such as through better tools for optimization, increased availability of processes and more effective maintenance management. However, there is not a clear link between the digital strategies and energy efficiency measures within the energy intensive industries in Sweden. Furthermore, energy efficiency is not considered the main driver for digitalization, rather a positive side effect. Therefore, the actual impact of digital technologies on energy efficiency might not be measured or valued fully. To exploit the full potential of digital technologies for improved energy efficiency the two areas need to be linked together to a higher degree.

Additionally, there are numerous challenges that need to be mitigated if the implementation of digital technologies in the Swedish energy intensive industries is to be accelerated. Financial support systems could help lower the hindrance of high capital intensity and the uncertainty around return on investment of digital infrastructure. Further research on the fundamentals of the processes and development of robust measurement technologies for extreme operating conditions could support further application of digital solutions in the sector. Additionally, research should focus more on the organizational and business side (e.g. the development of new business models), as well as showing how digital solutions can be applied in practice. Encouraging networking between different stakeholders, such as industrial enterprises, academia and the public sector, can further accelerate the digital transformation as it enables a closer collaboration between different parties and gives them an opportunity to learn from each other.

If the Swedish energy intensive industry is to remain competitive globally, it is vital that the sector lies at the forefront of Industry 4.0. Furthermore, leveraging the full potential digital technologies offer for improved energy efficiency could contribute greatly to reaching the target the Swedish government has set for energy efficiency improvement and be an important step on the road to fossil-free Sweden.

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Appendix A

The interview structure that was used as a guidance for the interviews conducted for the study is presented in Table 11.

Table 11: The interview structure.

Questions and follow-up questions
1. Can you start by telling me shortly about your company and what you do? What are you mostly working on within the company?
2. Does your company have a specific strategy related to digitalization? - Can you describe it shortly? - What about specific strategies related to energy efficiency or climate mitigation? - Is there any link between digitalization and energy efficiency measures or climate mitigation measures inside the company?
3. What is driving digitalization in your company? - What about energy efficiency, do you consider that a driver for digitalization? - What about climate mitigation?
4. To what extent would you say that your production plants are digitalized today? - Which parts of your plants are digitalized and how? - What digital technologies do you use in your production plants? - What are these technologies used for?
5. How does the implementation of the digital technologies in your production plants impact energy efficiency? - What fuel is impacted the most (electricity, biofuels, coal, heat etc)? - Do you take into consideration increased energy use from digital technologies? - What about other resources, how will it impact the use of other resources/materials?
6. In which area of your company's operations does digitalization have the most impact? - Are there areas outside of your production that are impacted? - What will change and how?
7. What challenges do you face when implementing digital technologies? - Are there any energy related challenges?
8. In your opinion, what can be done to accelerate the implementation of digital technologies with the goal of increasing energy efficiency? - What can you do by yourself? - What kind of support is needed? - What could the government or the Swedish Energy Agency do?
9. Is there something of importance to this topic that we did not cover, and you would like to mention?

Appendix B

The interviewees were asked to estimate their level of agreement with ten statements from 1-6 (1 meaning that they completely disagree with the statement and 6 meaning that they completely agree with the statement). The statements are listed in Table 12.

Table 12: The statements.

Statements
1. Digitalization is important to my company's competitive advantage.
2. My company's production plants are digitalized.
3. Digitalization of my company's production plants is linked to energy efficiency measures.
4. Digitalization of my company's production plants is linked to climate mitigation measures (i.e. measures to reduce greenhouse gas emissions).
5. Increased implementation of digital technologies in my company's production plants will improve energy efficiency.
6. Increased implementation of digital technologies in my company's production plants will decrease greenhouse gas emissions.
7. Increased implementation of digital technologies in my company's production plants will increase electricity consumption?
8. The main driver for digitalization in my company's production plants is energy efficiency improvements.
9. The main driver for digitalization in my company's production plants is greenhouse gas emission reductions.
10. The main challenge when it comes to digitalization in my company's production plants is cybersecurity.