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Exploring practices, knowledge dynamics and policy evaluation

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Abstract

Mitigating climate change represents one of the most pressing challenges of our time. The EU has set the goal of reaching climate neutrality by 2050. The transition of manufacturing organizations is essential in reaching the EU's goal, since industry accounts for circa 25% of the total final energy use and about one-fifth of EU's GHG emissions. Energy efficiency stands as one of the essential pillars of industrial decarbonization, with energy management playing a pivotal role in reaching its full potential. To remain competitive in the long term and align with the EU's carbon neutrality goal for 2050, the manufacturing industry must enhance energy efficiency in a cost-effective way. Manufacturing companies are exploring new ways of working with energy management in order to meet the requirements for both radical and incremental innovations needed to achieve the climate neutrality goal. However, due to the high complexity of industrial energy systems and its high diversity among sectors, improving energy efficiency is a difficult task. Knowledge, especially extensive knowledge, is a key factor for adopting innovations in energy efficiency and industrial processes.

The aim of this thesis is to explore the role of industrial energy management in the transition toward sustainable energy systems using an extended system approach. Employing top-down and bottom-up approaches, this thesis specifically focuses on three key aspects: industrial energy management practices, knowledge dynamics in industrial energy management, and policy evaluation. Key aspects of this thesis have been studied by means of mixed methods, such as literature reviews, interviews, case study with action research approach, survey, and evaluations. This thesis advocates that energy management practices (EnMPs) include activities beyond energy efficiency improvements. Specifically, they incorporate activities related to the decarbonization of industrial processes, including energy supply (own and purchased) and fuel conversion, at the very least.

The results show that internal EnMPs revolve around a focus on technologies, processes, and leadership, for which knowledge creation is an ongoing and evolving process. EnMPs encompass a comprehensive set of strategies and actions undertaken by manufacturing organizations to enhance energy efficiency, reduce greenhouse gas emissions, and navigate the transition towards sustainable energy systems. Such practices consist of the following components: energy conservation, energy efficiency, process innovation, energy supply and compensation measures. Furthermore, this

thesis has shown that external EnMPs are connected to the participation in energy policy programs and voluntary initiatives and is a common practice in energy management work.

Organizations often employ a combination of these strategies to achieve climate neutrality and align with environmental sustainability goals. Successful implementation of EnMPs is contingent upon deep process knowledge, especially in the case of radical process innovations, which necessitate a thorough understanding of interdependencies and interconnected processes. Collaboration with external sources of knowledge, including universities and stakeholders, is essential to drive innovation and adapt to evolving energy systems. Leadership plays a vital role in navigating these complexities and ensuring a strategic approach to EnMPs implementation.

This thesis contributes to the field of research on energy management in different ways: i. re-viewing the role of energy management in the current context of transition toward sustainable energy systems, ii. advancing theoretical and practical understanding of energy management in manufacturing organizations, iii. enhancing the knowledge-creation perspective within energy management practices for enhancing the adoption of both energy efficiency and process innovation, and iv. advancing theoretical understanding of the knowledge-creation process for energy management through the development of a knowledge-based framework.

Keywords: energy management, practices, transition to sustainable energy systems, knowledge-creation, process innovation, incremental and radical innovations, voluntary initiatives, digital technologies for energy efficiency.

Sammanfattning

Att mildra klimatförändringarna är en av de största utmaningarna i modern tid. EU har satt upp målet att uppnå klimatneutralitet till 2050. Omställningen av tillverkningsindustrin är avgörande för att nå EU:s målet, eftersom industrin står för cirka 25% av den totala slutliga energianvändningen och ungefär en femtedel av EU:s växthusgasutsläppen. Energieffektivitet är en av de viktigaste pelarna för industriell dekarbonisering, där energiledning spelar en avgörande roll för att uppnå sin fulla potential. För att bibehålla långsiktig konkurrenskraft samtidigt som man bidrar till EU:s mål om klimatneutralitet till 2050 behöver tillverkningsindustrin förbättra energieffektiviteten på ett kostnadseffektivt sätt. Tillverkningsföretag utforskar nya sätt att arbeta med energiledningsåtgärder för att möta behovet att radikala och inkrementella innovationer som krävs för att uppnå omställningsmålen. Men på grund av den höga komplexiteten hos industriella energisystem och att det skiljer sig mycket åt mellan branscher är det svårt att förbättra energieffektiviteten. Kunskap är en nyckelfaktor för att hitta radikala och inkrementella innovationer för energieffektivitet och industriella processer.

Syftet med denna avhandling är att utforska rollen av industriella energiledning i övergången till ett hållbart energisystem med hjälp av ett utvidgat systemperspektiv. Genom att använda top-down och bottom-up-ansatser, fokuserar denna avhandling specifikt på tre nyckelaspekter: industriella energiledningsåtgärder, kunskapsdynamik inom industriell energiledning och policyutvärdering. Nyckelaspekter i denna avhandling har studerats med hjälp av blandade metoder, såsom litteraturstudie, intervjuer, fallstudier med deltagande observationer och aktionsforskningsmetod, och enkäter. Denna avhandling förespråkar att energiledningsaktiviteter (ELsA) inkluderar aktiviteter utöver energieffektiviseringar. Specifikt inkluderar de aktiviteter relaterade till dekarbonisering av industriella processer, inklusive energiförsörjning (egen och köpt) och bränslekonvertering, åtminstone.

Resultaten visar att intern energiledning kretsar kring fokus på tekniker, processer och ledarskap, för vilket kunskapsskapandet är en pågående och utvecklande process. ELsA omfattar en omfattande uppsättning strategier och åtgärder som vidtagits av tillverkande organisationer för att förbättra energieffektiviteten, minska utsläppen av växthusgaser och navigera övergången till hållbar energianvändning. Sådana åtgärder består av följande komponenter: energibesparing, energieffektivitet, processinnovation, energitillförsel och kompensationsåtgärder. Vidare har denna avhandling visat

att externa åtgärder kopplad till deltagande i energipolitiska program och frivilliga initiativ också är en vanlig praxis i energiledningsarbete.

Organisationer använder ofta en kombination av dessa strategier för att uppnå klimatneutralitet och anpassa sig till miljömässiga hållbarhetsmål. En framgångsrik implementering av ELsA är beroende av djup processkunskap, särskilt när det gäller radikala processinnovationer, som kräver en grundlig förståelse för ömsesidigt beroende och sammankopplade processer. Samarbete med externa kunskapskällor, inklusive universitet och intressenter, är avgörande för att driva innovation och anpassa sig till föränderliga energisystem. Ledarskap spelar en viktig roll för att navigera i dessa komplexiteten och säkerställa ett strategiskt tillvägagångssätt för implementering av ELsA.

Denna avhandling bidrar till forskningen om energiledning på olika sätt: i. ompröva energihushållningens roll i det aktuella sammanhanget av övergången till hållbara energisystem, ii. främja teoretisk och praktisk förståelse för energiledning i tillverkande organisationer, iii. förbättra kunskapsskapande perspektivet inom energiledningsaktiviteter för att förbättra antagandet av både energieffektivitet och processinnovation, och iv. förbättra fördjupad teoretisk förståelse av kunskapsskapande perspektivprocessen för energiledning genom utveckling av ett kunskapsbaserat ramverk.

List of publications

This thesis is based on the work described in the papers listed below. In the thesis, five papers are referred to by Roman numerals, and the papers are appended at the end of the thesis. A co-author statement for each paper is presented in sub-section 1.3.

I. Andrei, M., Thollander, P., Sannö, A. (2022) Knowledge demands for energy management in manufacturing industry - A systematic literature review. Renewable and Sustainable Energy Reviews, 159, 112168 https://doi.org/10.1016/j.rser.2022.112168 Published under the CC BY license

II. Andrei, M., Rohdin, P., Thollander, P., Wallin, J., Tångring, M. (2023) Bottom-up analysis of decarbonization measures for an automotive paint shop – experiences from a longitudinal case study. *Under review in Renewable and Sustainable Energy Review Journal*

III. Andrei, M., Thollander, P., Inge, P., Gindroz, B., Rohdin, P. (2021) Decarbonization of industry: Guidelines towards a harmonized energy efficiency policy program impact evaluation methodology, Energy Reports, 7, 1385–1395 https://doi.org/10.1016/j.egyr.2021.02.067 Published under the CC BY license.

IV. Andrei, M., Thollander, P., Rohdin, P., Bertoldi, P., Mac Nulty, H. (2023) Analyzing voluntary initiatives from the transition management perspective – bridging the ambition gap for industrial decarbonization? *Under review in Energy Reports Journal*

V. Andrei, M., Johnsson, S. (2023) Digital technologies for energy efficiency: Maturity and Challenges in Swedish manufacturing industry. *Manuscript to be submitted to the International Journal of Manufacturing Systems.*

Other publications not included in the thesis

i. Andrei, M., Thollander, P., 2019. Reducing the Energy Efficiency Gap by Means of Energy Management Practices. Published in Conference Proceedings 2019 ACEEE Summer Study on Energy Efficiency in Industry. Inspiring Action for a Sustainable Future, Panel 2: People pp. 1–16.

ii. Lawrence, A., Thollander, P., Andrei, M., Karlsson, M., 2019. Specific energy consumption/use (SEC) in energy management for improving energy efficiency in industry: Meaning, usage and differences. Energies, 12 (2), 247.

iii. Jalo, N., Johansson, I., Andrei, M., Nehler, T., Thollander, P., 2021. Barriers to and drivers of energy management in Swedish SMEs. Energies, 14 (21), 6925.

iv. Varvne, H., Andrei, M., 2022. Organizing interdisciplinary energy system research, at EGOS Sub-theme 51: [hybrid] Organizing for Interdisciplinarity to Tackle Grand Challenges, Session VII: Breaking conventions and new perspectives on interdisciplinarity.

Pentru dragul meu Tata,
care a plecat de langa noi

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Doing a PhD was a dream come true!

Abbreviations

AI	Artificial Intelligence
AR	Augmented reality
ARo	Autonomous robots
A SIM	Automated production simulations
BAT	Best available technologies
BD	Big Data
BDA	Big Data Analysis
CPS	Cyber Physical Systems
EC	Edge Computing
EED	Energy efficiency directive
EEM	Energy efficiency measure
EEU	Energy end-use
EII	Energy intensive industry
EnM	Energy management
EnMP	Energy management practice
EnMMI	Energy management in manufacturing industry
GHG	Greenhouse gas
IEnM	Industrial energy management
IIoT	Industrial Internet of Things
IoT	Internet of Things
KPI	Key performance indicator
NEII	Non-energy intensive industry
OECD	Organisation for Economic Co-operation and Development
SEA	Swedish Energy Agency
SME	Small and medium enterprise
UNFCCC	United Nations Framework Convention on Climate Change
VA	Voluntary agreement
VI	Voluntary initiative
VR	Virtual Reality

Definitions

In this thesis several energy-related expressions are used interchangeably. These are *energy consumption* and *energy use*. Although the term energy consumption is widely used and accepted in the scientific literature, according to the first law of thermodynamics, it is technically wrong, since energy can neither be created nor destroyed, it can only change form (Çengel, 2021). *Energy use* is used instead of *energy consumption* and refers to the amount of energy supplied to a process or system.

Decarbonization refers to the process of reduction or elimination of carbon dioxide or all greenhouse gas emissions related to the use of fossil fuels by different means, e.g. using technologies, as well as mandatory and voluntary measures (Dupont and Sebastian, 2015). The ultimate end state of this process would be a 'decarbonized' global economy in which no fossil CO_2 is emitted to the atmosphere. In this thesis, it is in the context of the EU's objective to reduce GHG emissions by 2050 that the term 'decarbonization' is used (Butler et al., 2015).

Climate-neutrality is a term that describes a state in which the activities of EU countries as a whole result in annual net-zero greenhouse gas emissions (European Commission, 2021a). This means that the activities release no greenhouse gas emissions, or every ton of emissions emitted is compensated with an equivalent amount of emissions removed (Butler et al., 2015).

Energy efficiency is defined in the Energy efficiency Directive /2012/27/EU) as the "ratio of output of performance, service, goods or energy, to input of energy" (European Commission, 2012).

Energy efficiency improvements are achieved by reducing the energy use while maintaining the output or by maintaining the energy use but increasing the output by ways of technological, behavioral and/or economic changes (European Commission, 2009).

Energy savings is an absolute figure and refers to a reduction in the use of energy, so being an absolute amount of 'not used' energy (Pérez-Lombard et al., 2013).

Energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states (e.g., lighting, space heating) (Fell, 2017).

Energy conservation indicates that a reduction in energy use corresponds with a reduction in the amount or quality of service provided. In relation to energy efficiency, there are three different types of energy conservation measures: (1) Saving energy without changing energy efficiency, by maintaining constant the decrease in energy input and services output; (2) Enhancing energy efficiency and conserving energy by decreasing energy use more than the drop in service output, and (3) Experiencing a decrease in energy efficiency while conserving energy due to a greater reduction in energy input compared to the drop in the demand of energy services (Pérez-Lombard et al., 2013).

Energy transition refers to a shift in the way energy carriers are produced and used. It involves moving from traditional, often fossil-fuel-based energy sources, such as coal, oil and natural gas, toward more sustainable and environmentally friendly alternatives, such as renewable energy sources

Incremental innovations are gradual and continuous improvements of existing technologies and processes, containing a low need for new knowledge (Dewar and Dutton, 1986)

Radical innovations entail a fundamental change in the technological regime that involves a high degree of new knowledge (Dewar and Dutton, 1986)

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PART 1

THE KAPPA

A good theory explains, predicts and delights (Weick, 1995)

1. Introduction

This chapter begins with an introduction to the thesis, describing the context and the motivation of the research, followed by the aim and the research questions. Further, the scope and delimitations are presented and discussed. The chapter ends with an overview of the appended papers together with the co-author statement.

Mitigating climate change represents one of the most pressing challenges of our times. The historic Paris Agreement was endorsed at the end of 2015, when signatories pledged to curb CO_2 emissions to keep the rise in temperatures well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C (UNFCCC, 2015). In 2009, the EU responded to climate change through a long-term climate policy objective to reduce greenhouse gas (GHG) emissions by 80-95% by 2050, compared to 1990 levels (European Council, 2009). In 2021, the European Climate Law made the 2050 deadline for the EU's climate-neutrality objective legally binding (European Commission, 2021a).

Limiting global warming to below 2°C requires significant energy system changes in the next 30 years (IPCC, 2022). This includes reduced fossil fuel use, increased supply of low- and zero-carbon energy sources, increased use of electricity and alternative energy carriers, and more efficient use of energy than today (IPCC, 2022). The objective of the low-carbon energy transition is to establish a sustainable energy system that fosters growth, innovation, and job opportunities and at its core provides sustainable, secure, competitive and affordable energy (European Commission, 2015). A sustainable energy system plays a key role in mitigating the environmental impact of energy supply and use by being designed to harness renewable energy sources (European Commission, 2015). A low-carbon energy system transition supported by measures to increase energy efficiency is aligned with the United Nations' Sustainable Development Goals, in particular SDG 7 Affordable and clean energy (United Nations, 2023).

Despite the need to reduce global CO_2 emissions and reach the goal of net-zero emissions by 2050 (European Commission, 2019; IPCC, 2018; Rockström et al., 2017), anthropogenic carbon emissions are constantly rising (IPCC, 2018). To achieve the 1.5°C scenario, it is necessary to increase current commitments for GHG emissions reduction by more than five times (UNEP, 2019). In the early 2000's, climate change governance has become increasingly transnational (Jagers and Stripple, 2003; Pattberg and Stripple, 2008;

Widerberg and Stripple, 2016), transitioning toward a more diverse, multi-level and polycentric approach (Widerberg and Stripple, 2016). One such approach gaining more popularity is the climate-relevant international voluntary initiatives (VIs) that supports the Paris Agreement ambition (see e.g., Falkner et al., 2010; Widerberg and Stripple, 2016). Bottom-up voluntary initiatives encourage organizations to step up their contribution to climate neutrality goals. These initiatives for reducing CO_2 emissions are considered to complement traditional multilateral policymaking and appear in debates on how to 'bridge the gap' between GHG mitigation pledges by governments and the decarbonization pathway needed to halt global warming (see, e.g., Blok et al., 2012; Widerberg and Stripple, 2016). In such VIs, an increasing number of companies are committed to achieving net-zero GHG and have set science-based targets[1] for e.g., energy efficiency and emissions reduction improvements.

Energy efficiency is considered the 'first fuel' of a country, playing a crucial role in achieving a cost-effective energy transition (International Energy Agency, 2018) and contributing to Europe's energy self-sufficiency (European Commission, 2012; European Parliament and the Council of the European Union, 2018). Furthermore, it is necessary to reconceptualize energy efficiency as an energy source in its own right, valuing saved energy and competing equally with generation capacity (European Commission, 2015). However, the rate of energy efficiency improvement is less than half of what is required to meet the climate targets (International Energy Agency, 2021). The scaling up of solar and wind energy is cited as being equally important as energy efficiency for the energy transition mainly due to its declining costs (IPCC, 2022). Energy efficiency, along with industry-specific actions, material efficiency, and grid decarbonization constitute the essential 'pillars' of industrial decarbonization, providing a comprehensive and integrated approach (Worrell and Boyd, 2021).

The transition of the manufacturing industry is essential in reaching the EU vision since industry is one of the highest energy-using sectors accounting for about 25% of the total final energy use and approximately one-fifth of EU total GHG emissions (Eurostat, 2020). In Sweden, industry accounts for even

[1] Targets are considered 'science-based' if they are in line with what the latest climate science deems necessary to meet the goals of the Paris Agreement (SBT, 2020)

more energy use, at 38% of the total final energy use (SEA, 2022a) and around 31% of the national total greenhouse gas emissions (SCB, 2023). The industrial sector is undergoing a transformation driven by the requirements of the 'Fit for 55' package, and new ways of working with energy efficiency and energy management are being explored. Due to the high complexity of industrial energy systems, and due to its great diversity, improving energy efficiency is a difficult task (Schulze et al., 2016). Knowledge, especially extensive knowledge (Dewar and Dutton, 1986), is a key factor for adopting radical and incremental innovations. Prior knowledge in the form of a more highly educated workforce (Solnørdal and Thyholdt, 2019), as well as practical knowledge (Backman, 2018a) are determinants for increasing the adoption of innovations in energy efficiency (Solnørdal and Thyholdt, 2019) and the implementation of energy efficiency measures (Backman, 2018a).

Energy audits are a first step in the implementation of energy efficiency measures (Backlund and Thollander, 2015) and diffusion of energy efficient technologies (Paramonova et al., 2021), thus supporting companies to become more energy efficient and contribute to reaching the climate goals. Historically, several generations of energy efficiency policy programs have promoted public energy audit programs for industry and voluntary agreement (VA) programs with energy management components (Thollander et al., 2020). When designing public policies on energy-efficiency, it is important to understand the potential of energy efficiency in various industries. Policy evaluations are important for the successful implementation of policy programs, since they can provide useful information regarding the status of the programs' goals and objectives (Janus and Brinkman, 2010). The design of policy evaluation is one way to further develop, streamline and improve program implementation. Evaluation studies of different national energy efficiency policy programs (e.g., Price and Lu, 2011; Tanaka, 2011) and VAs (Price, 2005) have been conducted. A study of the comparability of energy audit program evaluations conducted by Andersson et al. (2017) shows that there is a lack of consistency in how evaluations are performed and how the measures are categorized, leading to difficulties in comparing the energy efficiency potentials across programs.

Furthermore, the untapped potential of energy efficiency, particularly offered by the adoption of digital technologies, presents significant opportunities for further advancements in sustainable practices within the industry (IEA, 2017). Digital technologies, e.g., sensors, internet of things, robotics, and artificial intelligence, can help mitigate climate change by enhancing energy efficiency, improving energy management, and facilitating the adoption of low-emission technologies, including decentralized renewable energy, while fostering economic opportunities (IPCC, 2022). Even more, digital technologies are expected to enhance the global connectivity, efficiency, reliability, and sustainability of energy systems (European Commission, 2022; IEA, 2017).

An earlier paradigm regarding industrial energy efficiency potential was focused mainly on the diffusion of new and more efficient technology (Jaffe et al., 1999). However, more recent studies show that the energy efficiency potential is larger when focusing on the wider system (not only on technology), where the operator and users play a major role in the use of the motor, not only on the motor itself (Waide and Brunner, 2011). Therefore, by including energy management practices (EnMP) alongside energy efficient technologies, it is possible to exploit the full potential of energy efficiency (Sandra Backlund et al., 2012a; Schulze et al., 2016). There are several definitions of EnM (see e.g., Ates and Durakbasa, 2012; Capehart et al., 2016; Kannan and Boie, 2003; Schulze et al., 2016), but what they have in common is the efficient use of energy and, in many cases, a whole system perspective in order to examine all interconnected activities (Rouhani and Beheshtian, 2006).

Furthermore, the energy saved by the implementation of EnM practices (EnMPs) is considered the most economical source of 'new' energy, releasing the pressure on economics and environment, and providing time to develop new energy sources (Capehart et al., 2016; Rouhani and Beheshtian, 2006). Currently in literature EnMPs are defined as

> *"a technique, method, procedure, routine or rule adopted at a precise stage of the industrial energy management setting in order to achieve the company's energy efficiency objectives. It acts on technological, non-technological, or of support aspects, by improving the energy performance directly or indirectly in a specific area of the company."* (Trianni et al., 2019, p. 1619)

This definition establishes the scope of EnMPs around energy efficiency objectives. However, what this thesis is claiming and set forth to explore is that EnMPs during the energy transition include activities beyond energy efficiency. Specifically, they incorporate activities related to the decarbonization of industrial processes, including energy supply (own and purchased) and fuel conversion, at the very least. And possible in the future can also incorporate flexibility solutions related to electricity, e.g., batteries, supply chain energy management and energy resilience.

Given the significant role of EnM in industrial energy systems and their inherent complexity, it is essential to view industrial EnM from an extended system perspective, employing bottom-up and top-down approaches. This will provide a 'reality-fit' on industrial energy management, accounting for the social context that is constantly changing in relation to policies, industrial practices, knowledge demands, and technologies. This approach is deemed necessary for gaining a deep understanding of EnM in the current context, both for academic purposes and for energy professionals, and can support and contribute to a comprehensive understanding of EnM during the transition toward a sustainable energy system.

1.1. Aim and research questions

The aim of this thesis is to explore the role of industrial energy management in the transition toward sustainable energy systems, using an extended system approach. The thesis employes top-down and bottom-up approaches and specifically focuses on three key aspects: energy management practices in manufacturing industries, knowledge creation in energy management and design of policy evaluation and industry-related voluntary initiatives. The aim has been broken down into the following research questions:

1) What types of energy management practices are implemented in manufacturing industries and how do they contribute to the transition toward sustainable energy systems?
2) How is knowledge created and applied in industrial energy management practices to facilitate the transition toward sustainable energy systems?
3) What design strategies should be employed in policy evaluations and voluntary initiatives to facilitate the implementation of industrial energy policy programs?

By addressing these research questions, the thesis seeks to explore industrial energy management practices implemented during transition and how they support the transition toward sustainable energy systems. Furthermore, the thesis seeks to contribute to the understanding of the knowledge dynamics in industrial energy management practices and explore the processes and mechanisms through which knowledge is created to drive the transition toward sustainable energy systems. Additionally, the thesis seeks to uncover how design and effectiveness of policy evaluations is enabling the implementation of industrial policy programs in the context of energy transition. By addressing these questions, the thesis will provide insights and recommendations on enhancing industrial energy management practices in alignment with the goals of sustainable energy systems. The connection between the appended papers and the research questions is illustrated in Table 1.

Table 1. Connection between the research questions and appended papers

	PAPER I	PAPER II	PAPER III	PAPER IV	PAPER V
RQ 1	x	x		x	x
RQ 2	x	x			x
RQ 3			x	x	

1.2. Scope and delimitations

The scope of this thesis entails energy management practices in the manufacturing industry during transition toward sustainable energy system. *Energy management practices during energy transition* refers to a series of activities connected with the supply and use of energy, which industrial organizations employ to achieve their objectives related to energy efficiency and GHG emissions reduction in alignment with the climate policies and regulations.

The understanding of an energy system follows the definition given by the Graduate School in Energy Systems (FoES), as follows:

> *Energy systems consist of technical artefacts and processes as well as actors, organizations and institutions which are linked together in the conversion, transmission, management, and utilization of energy. The view of energy as a sociotechnical system implies that also knowledge, practices and values need to be taken into account to understand the on-going operations and processes of change in such systems. (Palm & Karlsson, 2007, p. 12)*

The view of energy systems adopted by FoES takes in humans and their interaction with the technologies, services, and solutions, as well as with policies, laws, and other social institutions. This view is a good mirror of the complexity of the energy system embedding parts that at the same time can counteract each other but also need to interact to reach climate goals and the objectives of the energy policy. Therefore, there is a great need for knowledge and actors who can understand and manage multiple perspectives and complex relationships within energy systems.

However, due to the climate change challenge, the energy system needs to transform in a sustainable direction. In this thesis, the meaning of sustainability follows the well-known Brundtland definition put forward in the 1987 report 'Our Common Future' as development that *"meets the needs of the present without compromising the ability of future generations to meet their own needs"* (WCED, 1987). Hence, the transition to a sustainable energy system refers to implementing sustainable ways to meet the present energy demands while reducing CO2 emissions to meet the climate-neutrality objective, while addressing economic, social and environmental dimensions. Hence, in this thesis, a sustainable energy system is understood as

> *a sociotechnical system made up of technical artefacts, processes, actors, organizations, but also the knowledge, practices and values embedded in the on-going operations and processes of change toward climate neutrality.*

The studied industrial sector in this thesis is the manufacturing sector, referring to a segment of the economy where raw materials are converted into products through the addition of value. The manufacturing industry is an intricate object of study, mostly due to the high complexity of the production processes, as well as the diverse materials used and end products.

For research question 1, the industrial EnMPs in the manufacturing industry were studied from a global perspective with a top-down approach (in Papers I and IV) and from a Swedish perspective by employing a bottom-up perspective (in Papers II and V). In Paper II, the Swedish manufacturing of machinery and equipment sector (NACE 28.92) was studied through a case study. The manufacturing of machinery and equipment is of interest for several reasons. First, the *manufacturing of machinery and equipment* industry is the world's largest manufacturing activity (Womack et al., 1990) and second, is a complex and energy-intense process which uses a significant quantity of raw materials (Giampieri et al., 2020). This industry is of major importance for Sweden in particular, due to being the largest export industry in 2016 and holding a 21% share of industry investments (Vinnova, 2017). In Sweden the *manufacturing of machinery and equipment* is estimated to account for 3% of industrial final energy use. Paper II examines the allocation of energy use and greenhouse gas emissions at the process level, but these factors are not essential to the aim and research questions of this thesis, and they are not addressed further in the following chapters. The same holds for the conservation supply curves (CSCs) and the marginal abatement cost curves (MACCs) developed in Paper II. The prices per fuel, investment costs and emission factors for the system and economic analysis performed have been retrieved from Swedish sources. In Paper V, a global perspective was applied, with a primary emphasis on the manufacturing sector as illustrated in Table 2.

Table 2. Studied sectors

Manufacturing sector categorization	NACE codes
Food products, beverages, tobacco	C10-C12
Textile, clothing, and leather	C13-C15
Wood	C16
Pulp and paper	C17
Printing and reproduction of recorded media	C18
Chemical (chemicals, pharma, rubber and plastic)	C20-C22
Non-metallic mineral products	C23
Iron and steel	C24.1-C24.3
Non-ferrous metals (aluminum)	C24.4-C24.5
Mechanical engineering	C25-C30
Other engineering (furniture, other manufacturing)	C31-C32

For research question 2, the knowledge dynamics in the manufacturing industry were studied from a global perspective with a top-down approach (Paper I), and from a Swedish perspective through a bottom-up approach in Papers II and V. And for research question 3, a top-down approach was employed, and the manufacturing sector is indirectly covered through the energy efficiency policy programs deployed in Europe (in Paper III), and directly covered in Paper IV. Utility companies were identified in Paper IV, but due to their low representation in the results, this thesis has a limited contribution on the practices of utilities. Since these are not essential to the aim and research questions of this thesis, they are not addressed further in the following chapters. The system studied in this thesis is illustrated in Figure 1.

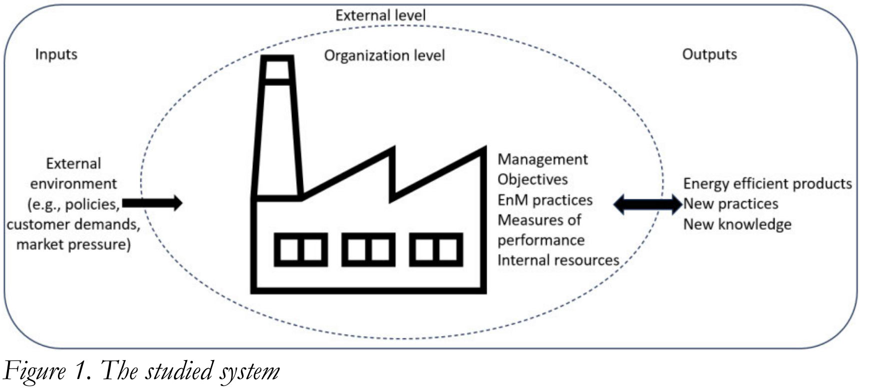


Figure 1. The studied system

1.3. Papers overview and co-author statements

This thesis is based on five appended papers. A brief description of the papers, together with a co-author statement, is found below.

Paper I

Andrei, M., Thollander, P., Sannö, A. (2022) Knowledge demands for energy management in manufacturing industry - A systematic literature review Renew. Sustain. Energy Rev. 159.

In this paper, I developed a knowledge-based framework consisting of three broader forms of knowledge and specific knowledge attributes that can capture the knowledge employed in industrial energy management. The framework was applied in a systematic literature review, analyzing the forms of knowledge and main aspects of energy management in manufacturing industries from 157 articles published between 2010 and 2020 in various academic journals. Besides the framework, the results show that the technical form of knowledge is the primary type of knowledge employed in energy management and that a paradigm shift -changing toward Industry 4.0. is under way. Another employed form of knowledge employed is process knowledge, which is concerned with the prerequisite information needed to implement energy management. Finally, leadership knowledge is also employed in energy management and a blend of in these three forms of knowledge might move us beyond traditional knowledge toward new forms of knowledge that maximize the potential for energy management in manufacturing industries.

The author of this thesis has written the entire manuscript, developed the framework, conducted the review, and performed the analysis. The valuable experience of Patrik Thollander and Anna Sannö helped to enhance the value of the discussion section, as well as the paper as a whole. They provided continuous supervision and comments during the progress of the paper. The initial idea is based on Patrik Thollander's experience and the curiosity of the author of this thesis.

Paper II

Andrei, M., Rohdin, P., Thollander, P., Johanna Wallin, Magnus Tångring. (2023) Bottom-up analysis of decarbonization measures for an automotive paint shop – experiences from a longitudinal case study. Currently under review in Renewable and Sustainable Energy Reviews.

A bottom-up approach was employed in this paper to conduct a longitudinal case study of an automotive paint shop between November 2019 and March 2023 working toward decarbonization. To achieve the study's aim, a bottom-up methodology was developed comprising several steps: i) analysis of decarbonization measures, ii) mapping of process energy use and CO_2 emissions, and iii) economic analysis. The data-based methodology is flexible and can be applied in different automotive paint-shops. The main findings show that i) incremental energy efficiency measures have the fastest adoption level, with relatively high savings potential, and most of these are cost effective; ii) radical process innovation measures have a higher savings potential, but long-term adoption levels due to the radical innovations required in the supply chain, and the highly specialized knowledge needed in the pre-treatment process; and iii) the primary drivers for implementing the measures are to achieve the climate targets and establish a leading position in the sector, rather than focusing primarily on the cost-effectiveness of the measures.

The author of this thesis wrote the manuscript in its entirety, except for the system analysis section, which was written together with Patrik Rohdin. The analysis of the measures and the allocation of energy and GHG emissions was performed by the author of this thesis, together with Patrik Rohdin. Johanna Wallin and Magnus Tångring helped with data collection and validated the results and analysis. The economic analysis was conducted by the author of this thesis. The valuable knowledge of Patrik Rohdin and Patrik Thollander helped to enhance the paper as a whole. Patrik Thollander and Patrik Rohdin provided continuous supervision and comments during the progress of the paper.

Paper III

Andrei, M., Thollander, P., Inge, P., Gindroz, B., Rohdin, P. (2021) Decarbonization of industry: Guidelines towards a harmonized energy efficiency policy program impact evaluation methodology. Energy Reports 7, 1385–1395.

This paper builds on the research gap regarding a harmonized methodology for industrial energy efficiency policy program evaluation. The lack of a harmonized methodology leads to difficulties in i) comparing energy efficiency and cost saving potentials throughout different programs, and ii) providing necessary information that supports the improvement of the policy program. A set of five-step guidelines that lay the foundation for an ex-ante energy efficiency policy program evaluation methodology has been developed, as follows: (s1) define key issues, (s2) set the objectives for each key issue, (s3) identify the options for each key issue, (s4) analyze options from an energy and environmental perspective, and (s5) compare options and select the recommended one. The proposed guidelines can support policymakers and evaluators in answering questions such as: i) how can the objectives of the policy program be achieved? And ii) is there any need to change the policy program?

In this paper, I was responsible for writing the entire manuscript, conducting the review, developing the framework, and conducting the analysis. The valuable knowledge of Patrik Thollander helped to enhance the value of the discussion section. Patrik Thollander and the other co-authors were involved in developing the initial idea of the paper.

Paper IV

Mariana Andrei, Patrik Thollander, Patrik Rohdin, Paolo Bertoldi, Hannes Mac Nulty. (2023) Analyzing voluntary initiatives from the transition management perspective – bridging the ambition gap for industrial decarbonization? Under review in Energy Reports journal.

In this paper I built on the socio-technical transition processes literature and applied the transition management framework in a novel way. First, I developed an analytical framework based on transition management literature complemented with voluntary initiatives literature, and second, I applied the framework to analyze a set of eighty-three industry-related voluntary initiatives. I conducted a system level analysis of eighty-three industry-related voluntary initiatives led by state and non-state actors to identify their theoretical potential to bridge the ambition gap for industrial decarbonization. They were identified based on the report of Mac Nulty et al. (2021) and by cross referencing with the data-bases: UNFCC Global Climate Action portal of cooperative initiatives (UNFCCC, 2021) and the UNEP Climate Initiatives Platform (UNEP, 2014). The voluntary initiatives were categorized based on a system level consisting of VIs arena, agenda, operationalization, and accountability. The main findings emphasize, first, the need for more measurable targets, higher-level commitments, and stronger accountability mechanisms, particularly for non-state actors (industry); and second, the challenges faced by industry in terms of access to significant resources.

In this paper, I was responsible for writing the manuscript, developing the framework, conducting the review and analysis of the voluntary initiatives. The experience of Patrik Thollander and the other co-authors plus the curiosity of the author of this thesis (since the topic appeared in previous studies) led to the initial idea for the paper. The author of the thesis has further developed the idea and grounded it in the transition literature. Patrik Thollander provided continuous supervision and comments during the progress of the paper. Patrik Rohdin helped to enhance the paper as a whole. Hannes Mac Nulty together with Paolo Bertoldi provided a partial initial investigation of several initiatives. However, the investigation found in the appended paper was entirely redone by the author of the thesis.

Paper V

Mariana Andrei and Simon Johnsson. (2023) Digital technologies for energy efficiency: Maturity and Challenges in Swedish manufacturing industry. Manuscript to be submitted to the Journal of Manufacturing Systems.

This paper developed a maturity model to evaluate the implementation of Industry 4.0's digital technologies for energy efficiency in Swedish manufacturing companies. The model allows the quantification and qualification of maturity levels based on three dimensions and five maturity levels. An online questionnaire was developed to explore the following aspects in the manufacturing companies: i) their energy efficiency practices; ii) whether the adoption of digital tools is part of the company's strategy or goals to increase energy efficiency, and iii) the type of digital tools currently used in the support and production processes, and iv) the challenges identified for the adoption of digital technologies. . The results reveal that the aluminum- and iron and steel industries exhibit higher maturity levels in adopting digital tools for energy efficiency. Furthermore, it shows that the highest adoption rate of digital tools is in relation to energy use monitoring and data collection through the Internet of Things and Cyber-physical Systems. The most common challenge reported by the surveyed companies is 'lack of knowledge'. The study provides recommendations for manufacturing organizations to evolve into mature entities regarding the adoption of digital tools for energy efficiency.

In this paper, the writing, model development, questionnaire development and survey analysis was a shared effort together with Simon Johnsson. The author of this thesis had the initial idea based on the results from Paper I, which was further developed with Simon Johnsson. Students Wilma

Gustafsson and Erica Dellin submitted the questionnaire to companies that reported their energy audits in 2017–2020, while the authors of the article re-submitted the questionnaire to non-respondent companies and submitted to companies which reported their energy audits in 2021.

1.4. Research journey

During my PhD studies at the Division of Energy Systems at Linköping University, I have been involved in the research project "Towards a theory of energy management through contrasting case studies from the shipping and the manufacturing sectors". The project is supported by the Graduate School in Energy Systems (FoES) and financed by the Swedish Energy Agency. The project is implemented as a partnership between Energy System division, Linköping University and Gothenburg Research Institute, University of Gothenburg. The project team consists of Professor Patrik Thollander and the author of this thesis from Linköping University and Professor Ulla Eriksson-Zetterquist, Dr. Hannes von Knorring and another PhD student Hanna Varvne from GRI. The aim is to analyze how energy management is conducted in the Swedish manufacturing industry and in the shipping industry. The research project aims also to identify how energy management can be developed in order to contribute to the industry's transformation into sustainable energy systems and long-term competitiveness. This has provided an overall aim of the thesis, while at the same time allowing the freedom to ground the research in the most context-appropriate theories and methods and design the research strategy based on the latest research on industrial energy management and the author's research interest. Therefore, the content of the appended papers has not been influenced by the research school to which the author of this thesis belongs.

The research started from the hypothesis that industrial energy management during energy transition goes beyond the deployment of technology and the current energy management models, and it is influenced by external factors such as the decarbonization goals, which put pressure on innovation deployment and new ways of working. The focus was first on exploring ex-ante energy efficiency policy programs evaluations. The chosen perspective was that of a policymaker that needs to bridge the decarbonization goals with the results from the evaluations of the energy efficiency policy programs and is faced with the decision of either changing/improving the program or stopping it. During the same time, the thesis' author started contacting Swedish manufacturing companies in order to obtain approval for participatory observations of their energy management practices. At the same time, on the invitation of the author's main supervisor, the thesis' author began participating in the national Swedish Energy Management Network meetings, where around twenty manufacturing companies active in their energy management work are meeting yearly to share best practices and learn from each other. This opened the way to promoting the research project, and participatory observations were commenced in two engineering organizations. Later, an international review study on industrial energy management in the manufacturing industry was conducted with a knowledge framework developed to categorize the practices based on three most common forms of knowledge. This study led to two more studies: a review of the potential for industry-related voluntary initiatives to bridge the ambition gap for industrial decarbonization, and a survey study on the adoption of digital technologies for energy efficiency by the Swedish manufacturing industry.

The timeline for the five papers included in this thesis is illustrated in Figure 2, where the dotted lines represent the timeline of each study, and the dotted arrows represent the journey of how individual papers led to the development of other papers.

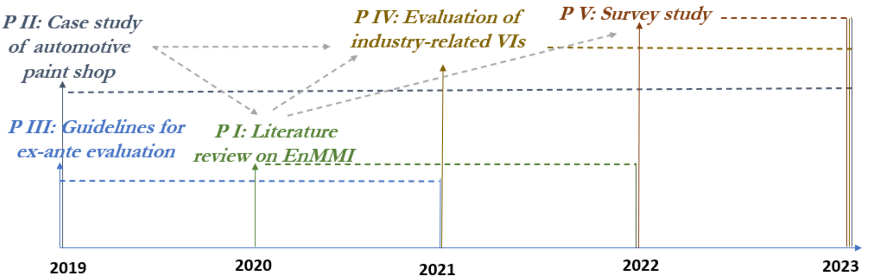


Figure 2.Timeline of the paper's initiation

2. Industrial energy management

This chapter gives the industrial energy management background connected to this thesis. It starts by presenting industrial energy use in EU and Sweden and continues with an introducing the broader field of energy management. Next, major energy policies at European and Swedish level are being presented, followed by an overview of the major energy efficiency policy programs. Policy evaluation follows, and the chapter ends with presenting industry-related voluntary initiatives.

2.1. Industrial energy use

In the EU, energy end-use (EEU) reached its peak in 2006 with 11513 TWh and by 2021 it had fallen by 5.1% (Eurostat, 2021), while in 2021, the EEU was 10 930 TWh, with a slight 6.2% increase compared to 2020. In the EU, the industrial sector accounts for 25.6% of EEU. In Sweden, the industrial sector accounted for 38% of total Swedish EEU in 2020, amounting to 136 TWh/year, and circa 31% of national total GHG emissions (SCB, 2023; SEA, 2022a). While EEU has remained quite stable over the last 20 years, a slight decrease has been noted in the last four years. The trend for the industry's EEU in Sweden between 1970 and 2020 is shown in Figure 3.

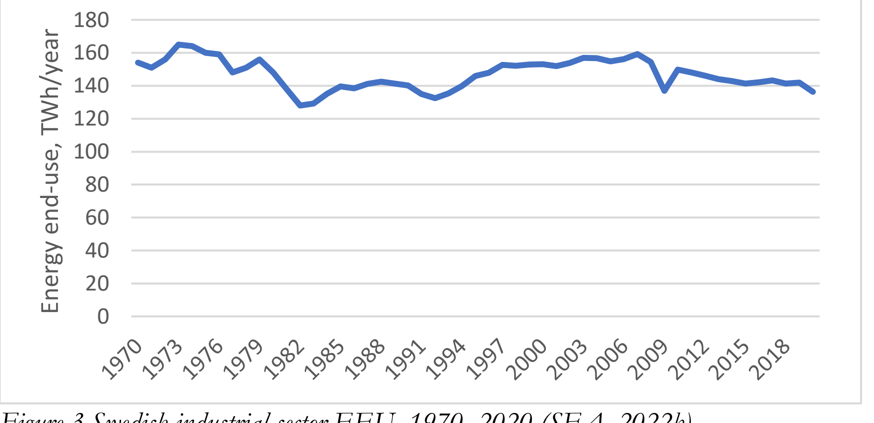


Figure 3.Swedish industrial sector EEU, 1970–2020 (SEA, 2022b)

During the same period, the supply of biofuels in industry doubled, while petroleum products decreased from 74 TWh in 1970 to 8 TWh in 2020. However, coal and coke use in industry stayed quite constant during this period, with a dip in 2009 around the time of the global financial crisis, as illustrated in Figure 4.

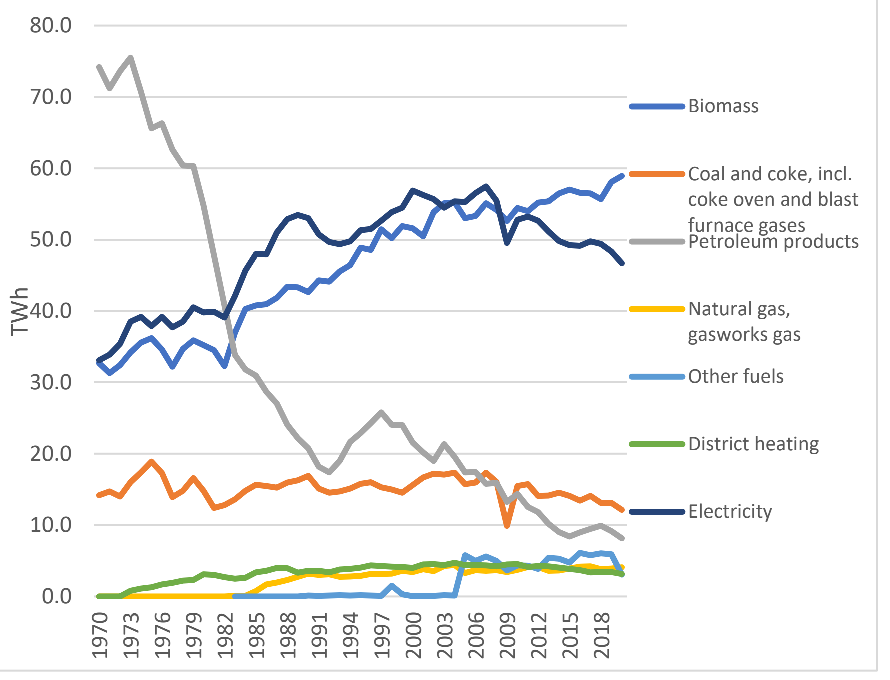


Figure 4.Swedish industrial sector EEU per energy carriers between 1970–2020 (SEA, 2022b)

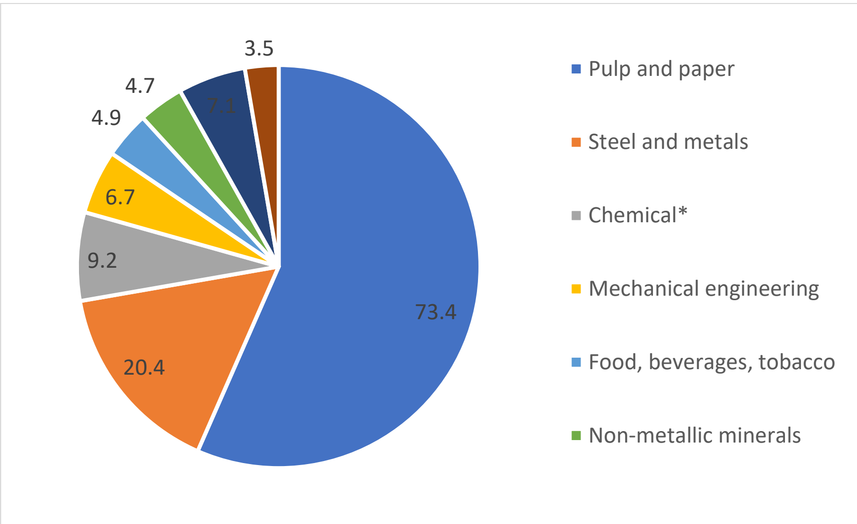
The manufacturing sector in Sweden follows the national Nace Rev. 2 (Eurostat, 2008) standards and is categorized as illustrated in Table 3. All the industries have been addressed in this thesis to a certain extent, except for the NACE C33.

Table 3.Classification of manufacturing sectors in Sweden

Manufacturing sector categorization	NACE codes
Food products, beverages, tobacco	C10-C12
Textile, clothing, and leather (Others)	C13-C15
Wood	C16
Pulp and paper	C17
Printing (Others)	C18
Chemical (coke and petroleum products, chemicals, pharma, rubber, and plastic)	C19-C22
Non-metallic mineral products	C23
Iron and steel	C24.1-C24.3
Non-ferrous metals (aluminum)	C24.4-C24.5

Mechanical engineering	C25-C30
Other engineering (furniture, other manufacturing, repair and installation of machinery and equipment)	C31-C33

Industrial companies can also be categorized by their energy intensity. A company can be categorized as energy intensive if its energy costs in relation to added value exceed 3% (Thollander and Palm, 2013). In Sweden, pulp and paper, iron and steel, chemical, mining, and mineral manufacturing are energy-intensive sectors. The pulp and paper industry accounts for the highest proportion of the total industrial energy use, with a figure of 54% in 2020, for example. Next comes the iron and steel and metals industries, which account for 15% of the total industrial energy use, as illustrated in Figure 5.



**Chemical industries here include NACE C20-C22*

*** Small industries and others include NACE 13-15, 18, 31-33*

Figure 5. Final EEU for the manufacturing industries in Sweden in 2020, by industry, TWh (SEA, 2022b)

Another important categorization of industrial EEU is related to the unit process concept, which is a way to divide the EEU of an industry into smaller units. The unit process concept is divided into two major categories (Söderström, 1996): production processes and support processes. Production processes are defined as the processes needed to produce the final product, while support processes are the processes which support the production process but are not directly needed for production. The concept is based on the activity of certain industrial processes, such as cooling or drying of products, producing compressed air and so on, and can be seen as the smallest categorization of an industrial energy system. Söderström (1996) divided the production processes into 11 categories: decomposition, mixing, cutting, joining, coating, forming, heating, melting, drying/concentration, cooling/freezing, and packing, while putting the support processes into 7 categories: lighting, compressed air, ventilation, pumping, space heating and cooling, hot tap water, and internal transport. Since the unit process categorization may be general across industries, it allows for the development of KPIs, and comparison of a given process across industries. More recent has developed sector specific production process categories (Thollander et al., 2021).

2.2. Introduction to energy management

Understanding energy management in practice requires first understanding what energy management is. There is increasing activity in regard to energy management in industrial practices, and many definitions of energy management are found in the literature, comprising contributions from a variety of scientific disciplines, such as Bunse et al. (2011), Capehart et al. (2016), Kannan and Boie (2003), and O'Callaghan and Probert (1977). A definition of EnM quite close to this thesis is given below:

> *Energy management (EM) is considered a combination of energy efficiency activities, techniques and management of related processes which result in lower energy cost and CO2 emissions* (Ates and Durakbasa, 2012, p. 81).

However, the most comprehensive definition of industrial energy management is given by Schulze et al. (2016), as seen below:

> *Energy management comprises the systematic activities, procedures and routines within an industrial company including the elements strategy /planning, implementation/operation, controlling, organization and culture and involving both production and support processes, which aim to continuously reduce the company's energy consumption and its related energy costs* (Schulze et al., 2016, p. 3704).

This definition of energy management is applied in this thesis. Schulze et al. (2016) developed a conceptual framework for energy management based on the five essential key elements of energy management identified in literature: strategy/planning, implementation /operation, controlling, organization and culture, which in turn comprise a total of 30 practices. According to the framework developed by Schulze et al. (2016), the starting point for the implementation of energy management is set by a strategic management decision. Following this, a responsible energy management team needs to be established and an energy manager appointed. Next, an initial energy audit needs to be performed in order to determine the energy-related status quo of the company.

After these initial steps, the five key elements come into force. The *strategy/planning* element consists of developing an energy policy/energy strategy including long-and short-term energy targets. The *implementation* element is focused on the operationalization of energy management based on the action plan developed in the strategic process. The *controlling* element ensures that energy-related data is constantly collected within an energy information system that apart from energy use, monitors related energy costs within the company. Furthermore, key performance indicators are established to enable performance evaluation and benchmarking. The fourth element, *organizational*, comprises the governance structure within the company (e.g., formal lines of authority and responsibility), where the role of energy manager and procedures addressing all aspects of the corporate energy value chain are essential. And the final element, *culture*, includes aspects such as the involvement of top management in the energy-related decision-making process, rewards at individual and group level, and energy-related education and training.

2.3. Energy management practices

Energy management practices are the component of energy management (Sa et al., 2015; Schulze et al., 2016). Previous research on energy management in industry reveals that for manufacturing companies, implementing in-house energy management practices can enhance energy efficiency by 4 to 40% (Caffal, 1996). Furthermore, the potential of EnMPs from the Swedish program for Improving Energy Efficiency in Energy Intensive Industries was studied by, e.g., Paramonova et al. (2015), showing that they accounted for at least 35% of the total deployed energy efficiency potential among the participating energy-intensive companies. This improvement is attributable to a combination of technology and management operations. Therefore, it is recommended to incorporate both technology and organization-related actions in in-house energy efficiency initiatives. The *energy management gap* concept was introduced by Backlund et al. (2012). The energy management gap concept complements the energy efficiency gap and implies that the management of energy is part of the energy efficiency potential and energy management practices include more than the technical approach, in particular engineering skills, management and housekeeping (Kannan and Boie, 2003).

A series of comprehensive studies of industrial companies' implementation of energy management practices have been conducted (Abdelaziz et al., 2011; Brunke et al., 2014; May et al., 2017; Thollander and Ottosson, 2010). Trianni et al. (2019) conducted a review of industrial EnMPs, describing the fundamental attributes that characterize EnMPs, an their relation to the overall work on energy management. Energy management practices can take different forms, such as a technique, method, procedure, routine, or a rule that a company applies in order to improve its energy efficiency performance, and their relationship with energy services needs to be considered (Trianni et al., 2019). EnMPs were categorized as illustrated in Table 4.

Table 4. Types of EnMPs in manufacturing industry (Trianni et al., 2019)

Type of energy management practice	Description
Technology-related	Practices related to the development, implementation, functioning and optimization of the technologies
Non-technology-related	Practices related to managerial and organizational activities
Administrative	Practices related to the management of energy efficiency investments and energy costs
Energy-performance-related	Practices related to the calculation and analysis of the company's energy performance and targets
Informative	Practices related to the energy related information flow both within and outside the company
Procurement	Practices related to the energy efficiency principles in internal and external procedures and interactions
Staff-related	Practices related to the energy efficiency awareness, motivation, training, and management of people
Support	Practices related to the adoption of support services for the internal energy management
Engineering	Practices related to the support concerning the design of the intervention
Financial	Practices related to support regarding external financing of the intervention and incentives

Managerial	Practices related to generic support for the management or improvement of energy efficiency performance

Energy management has not been considered a core activity in energy-intensive industry (Thollander and Ottosson, 2010). However, due to a combination of rising energy costs and energy policies requirements, energy management started to be considered one of the main functions of industrial management since the 1970s (Abdelaziz et al., 2011; Petrecca, 1993). Nevertheless, although energy management potential has been highlighted in literature (Caffal, 1995), its contribution differs depending on the size of the organization, production type and energy intensity (Backlund et al., 2012). For example, in a study conducted by Backlund et al. (2012a) on a number of energy-intensive companies from a region in Sweden, the results show that the energy-intensive firms are more successful in adopting EnMP.

The number of industrial companies implementing an energy management system (EnMS) has increased in the last years. This is mainly attributed to the recognition of energy management as an effective tool for optimizing production systems and operations in pursuit of improving energy efficiency (Schulze et al., 2016), but also to reduce the use of valuable energy resources (Capehart et al., 2016; Rouhani and Beheshtian, 2006). It is important to highlight that energy management needs to be seen as separate from an energy management system, which is a tool used to implement energy management in a company as proposed by the ISO standard 50001:2011, revised in 2018. The standard defines the energy management system as a "set of interrelated or interacting elements to establish an energy policy and energy objectives, and processes and procedures to achieve those objectives" (International Organization for Standardization, 2011, p. 2). It comprises the organizational and informational structures as well as the technical tools (e.g., hardware and software) needed to implement an energy management system. However, the way energy management is implemented in an organization depends on the specific characteristics of the organization. For example, it is more important to have knowledge on the internal energy-using processes in an energy-intensive industry with complex production processes than it is in a non-energy-intensive industry, since energy efficiency improvements in relation to process knowledge can yield higher cost savings (Thollander et al., 2020).

2.4. Success factors for energy management

The highest energy efficiency potential is reached when energy efficient technology is implemented alongside successful energy management practices (Thollander and Palm, 2015). In industrial energy systems, research is not only conducted on technical aspects, but also encompasses the development of models and methods for strategic decision-making and management practices, which are vital for continuously enhancing energy efficiency. Energy management has been studied in terms of practices (May et al., 2017; Trianni et al., 2019) and success factors which can guide energy managers toward achieving the full potential of energy efficiency (Johansson and Thollander, 2018). In order for the full potential to be reached, a set of success factors for energy management have been discussed by Johansson and Thollander (2018). These are i) top management support, ii) long-term energy strategy, iii) a two-step energy plan, iv) an energy manager position, v) correct energy cost allocation, vi) clear energy KPIs, vii) energy controllers among floor-level staff, viii) education for employees, ix) visualization, and x) energy competition.

Apart from these factors, Sannö et al. (2019) identified several more when conducting participatory observations of in-house energy management program adoption at a multinational company. These are leadership, speed of execution, and cultural transformation on a corporate level. Building on the theory of absorptive capacity in connection with energy efficiency, Svensson and Paramonova (2017) show that the knowledge and skills acquired by industrial personnel working with energy efficiency, maintenance and production processes can be readily applied to suggest improvements. Other success factors for energy management fostering a company's commitment to EE innovation are identified by Solnørdal and Thyholdt (2019), who relate these factors to prior knowledge (i.e., educated workforce) and knowledge development (i.e., R&D and collaboration with external knowledge sources including universities). A model of knowledge creation through practice has been applied by Backman (2018a) to study the collaboration between SMEs and municipalities through industrial energy efficiency networks (IEENs). The results show that supporting knowledge creation in SMEs through practice can increase the amount of implemented energy efficiency measures. This approach to knowledge creation is referred to a 'co-production of knowledge' or 'co-creation of knowledge' and it is claimed that research addressing sustainability challenges is most effective when it is co-produced by academics and non-academics (Norström et al., 2020).

Furthermore, Guy and Shove (2000) highlight that the production and use of technical knowledge and energy-related expertise is a social process that affects actors in such a way that the energy efficiency choices are made as a response to changing opportunities and internal and external pressures. Adequate knowledge of energy use across the production and support processes is needed in order to implement successful energy management. Creating an energy balance through e.g., an energy audit (Schulze et al., 2016) could therefore be the first step in implementing industrial energy management. An energy audit provides information on the energy use throughout processes for different energy carriers and appropriate measures for improved energy efficiency (Thollander et al., 2020). The benefits of conducting energy audits are plentiful, from reducing specific energy use and GHG emissions, to reducing operational costs through systematic analysis, and improving overall performance of the total system and the profitability and productivity of the facility (Abdelaziz et al., 2011). Information regarding energy use is also needed for reporting purposes. Energy management has become increasingly prominent in industries today, with top management actively involved in planning regular energy management projects. Annual reports of companies now include comprehensive information on energy conservation activities and the company's accomplishments in energy management/efficiency projects (Abdelaziz et al., 2011). Training of personnel is another important way to increase awareness and develop the competences of the people involved in industrial energy efficiency. One approach is to have specific courses for engineers working in industry and energy management courses at university level, all providing a foundation for the legal, technological, environmental, social and economic dimensions of energy efficiency (Abdelaziz et al., 2011). Another approach is to train those staff at a company who work on energy issues (Thollander et al., 2020).

2.5. Digital technologies for energy efficiency

Digital technologies enhances the flexibility and efficiency of energy systems (Heymann et al., 2023), have the potential to improve energy efficiency (Lin and Huang, 2023) and are enablers for the clean energy transition (Dekeyrel and Fessler, 2023). By enabling data collection and analysis, digital technologies make devices smarter, while connectivity of digital technology also facilitates intelligent automation, enhancing energy efficiency in systems. However, scholars have different opinions on the impact of digitalization on energy. One category argues that digitalization has a positive impact on energy use while another group of scholars claims that digitalization has a negative impact on energy use. In the first camp, Ishida (2015) for example, has shown that digitalization of manufacturing, operation and management has reduced energy use and eliminated outdated production capacity; and Xu et al. (2022) claim that digitalization optimizes industrial structure, fosters technical innovation, and enhances production efficiency, thereby effectively promoting energy efficiency improvement. In the other camp, Haseeb et al. (2019) for example, claim that digitalization increases the energy use, Ren et al. (2021) argue that digitalization has increased China's energy use, and Lange et al. (2020) show that while energy efficiency improvements throughout the economy are dependent on digital technologies, overall, digitalization increases energy use, due to the rebound effect. However, none of these scholars have focused on the impact of digitalization on energy use or energy efficiency in the manufacturing industry.

With regard to the adoption of digital technologies for energy efficiency, it is claimed that technologies such as Internet of Things (IoT) and cyber physical systems (CPS) provide opportunities for detailed management and monitoring of energy use, as well as energy efficiency and monitoring of KPIs (Thollander et al., 2020). Furthermore, digital technologies support awareness, proper visualization and structured data thanks to the use of smart sensors and smart meters at the machine and production line level, which collect large amounts of data on energy use (Shrouf and Miragliotta, 2015). As a result, real-time energy consumption data from manufacturing processes can be readily collected and analyzed, enabling enhanced energy-aware decision-making (Shrouf and Miragliotta, 2015). Digital technologies which provide storage in the cloud or on site (such as edge computing) and enable analysis of data are also very useful in energy management work. Particularly in the industrial sector, digital technologies are claimed to boost energy efficiency through the use of smart sensors, machine learning, industrial robots, data analytics and improved connectivity (Dekeyrel and Fessler, 2023). For example, in a smart factory, digital twins simulate e.g., various production scenarios in factories, allowing virtual modeling of production processes. When combined with artificial intelligence, this enables energy and resource-efficient experimentation that would otherwise require substantial resources in a physical industrial plant (Dekeyrel and Fessler, 2023). However, for digitalization to truly contribute to a sustainable and clean energy transition, it is important to enhance the energy efficiency of digital technologies also and reduce their climate footprint (Dekeyrel and Fessler, 2023).

2.6. Energy efficiency – a critical view

Industrial energy efficiency improvements increase productivity, stimulate economic growth, and improve competitiveness (Brockway et al., 2021). However, the criticism regarding energy efficiency revolves around the so-called *rebound effect* (Brännlund et al., 2007; Greening et al., 2000; Herring, 2006; Saunders, 2000). The rebound effect was first raised by Daniel Khazzoom (1980) and ever since has been the focus of much research (Greening et al., 2000), especially by energy economists. Definitions of the rebound effect vary in the literature. However, the overall rebound effect refers to behavioral responses to improved energy efficiency that offset part of the potential energy and emissions savings (Sorrell et al., 2018). In short, the claim is that economically justified energy efficiency improvements at microlevel, lead to higher levels of energy use at the macro level (Saunders, 1992). The rebound effect can be divided into two major categories:

- The *direct* rebound effect: a price effect where a technological improvement in fuel use reduces the price of energy services[2] by decreasing the amount of fuel required to produce them, thus leading to an increased demand for the service (Greening et al., 2000).
- The *indirect* rebound effect: energy efficiency lowers overall energy costs, which leads to spending the cost savings on other goods and services that also require energy (Sorrell et al., 2018).

The long-running dispute among energy economics researchers, beginning with Khazzoom (1980), is how large the magnitude of the rebound effect is considered to be. However, for industrial processes, is challenging to estimate the economy-wide rebound effects, although there is growing research suggesting they may be considerable (Brockway et al., 2021). For example, the direct rebound effect for industrial processes was found by Greening et al. (2000) to be a little under 20% and the indirect rebound effect about 0.5%. This assessment was based on established facilities that have undergone energy audits or participated in similar programs, as a response to the claim of Nadel (1993) and Eto et al. (2000, 1994) that direct measurements of the direct rebound effect for industrial firms are extremely limited. In a later study conducted by Bentzen (2004) using data covering the period 1949-1999, the

[2] Energy services refer to the commodity, which is actually used, i.e., hot water, process heat, lighting, cooling. Apart from fuel, the production of these commodities requires the input of capital, labor, and management expertise (Greening et al., 2000).

rebound effects for the US manufacturing sector are found to be approximately 24%. A study conducted by Broberg (2015) analyzed the economy-wide rebound effect from increased energy efficiency in industrial energy use in Sweden and put the rebound effect within the 40-70% range, and even higher (75%) for energy-intensive production. The literature suggests that in the case of strong rebound effects, the energy efficiency measures may require additional carbon and energy taxes to achieve savings and environmental improvements (Brännlund et al., 2007; Broberg et al., 2015; Hanley et al., 2009; van den Bergh, 2011). The review conducted by Brockway et al. (2021) emphasizes that the wide range of estimates and limitations due to the shortcomings of the modelling approach limit the confidence in the results. However, it notes that the evidence base is growing in quality, quantity, and diversity, and various studies draw broadly similar conclusions.

3. Energy policies during transition to sustainable energy systems

This chapter gives the policy context connected to this thesis. It starts with the major energy policies at European and Swedish level and is followed by an overview of the major energy efficiency policy programs. Policy evaluation is presented next, and the chapter ends with a presentation of industry-related voluntary initiatives.

3.1. Energy policies

The 2015 Paris Agreement on Climate Change, the United Nation's Sustainable Development Goals and the Special Report of the Intergovernmental Panel on Climate Change together calls for increased and decisive actions to reduce greenhouse gas emissions. The 2015 Paris Agreement, with its goal to limit 'the increase in global average temperature to well below 2° C above pre-industrial levels', and pursue efforts to limit the increase to 1.5°C, is a landmark in the multilateral climate change process because it brings nations into a common cause to undertake ambitious efforts to combat climate change (UNFCCC, 2015). The European Parliament adopted the EU Climate Law in 2021, which has set the legally binding target of achieving climate neutrality by 2050 (European Commission, 2021a). And as an intermediate step toward climate neutrality, the emissions reduction objective for 2030 has been raised, taking it from 40% to 55% (European Commission, 2021a). This upward amendment implies revising and updating existing energy and climate-related legislation through the so-called 'Fit for 55' package (European Commission, 2021b), under which, current laws are aligned with the 2030 and 2050 ambitions for climate neutrality.

In order to reach the ambitious targets for 2030 regarding GHG emission reductions, the European Parliament and the Council reached a provisional agreement to raise the binding renewable energy target to at least 42.5% by 2030 (European Comission, 2023) and, in pursuit of energy efficiency, proposed to increase the level of ambition to a 9% reduction in energy use by 2030, compared with the forecasts made in 2020 (European Commission, 2021b). In 2017, Sweden's government set out to implement the Paris Agreement with the introduction of a Climate Policy Framework, accompanied by a Climate Act setting the target of zero net emissions of greenhouse gases into the atmosphere by 2045, with intermediary milestone targets for 2030 and 2040, and a climate policy council (MOE, 2020). By 2030, energy use shall be 50% more efficient than in 2005 and in the year 2040 electricity production shall be 100% from renewables (Swedish Government, 2020).

The major types of currently available policies for promoting energy efficiency in the EU that have an impact on industry and energy transition are: i) the Energy Efficiency Directive (EED) from 2012, as amended in 2023, ii) the Renewable Energy Directive 2018/2001 revised in 2023 (RED III), iii) the Industrial Emissions Directive (IED) adopted in 2010, iv) the Non-Financial Reporting Directive (NFRD) amended in 2014, v) the EU Emissions Trading System (EU ETS), and vi) the Energy Taxation Directive (ETD) adopted in 2003. The 2012 EED amended in 2023 promotes 'energy efficiency first' as the overall principle of EU energy policy, in regard to both policy application and investment decisions. Furthermore, it increases the energy efficiency target, making it binding for EU countries to collectively reduce energy use with additional least 11,7 % by 2030, compared to the projections of the 2020 EU Reference Scenario, so that the Union's final energy consumption amounts to no more than 763 Mtoe (European Parliament and the Council of the European Union, 2023). The RED III directive increased the minimum share of renewable energy sources in final energy use to 42.5% by 2030, accompanied by sectoral targets.

A considerable share of the overall pollution in Europe comes from industrial production processes, and the main EU instrument overseeing pollutant emissions from the industrial facilities is the 2010 IED. The aim of the IED is to protect human health and the environment by reducing harmful emissions through the better application of Best Available Technologies (BAT). Therefore, the IED provides a list of around 50,000 installations that are required to operate in accordance with a permit that contains conditions set in accordance with the principles and provisions of the IED. The NFRD is another important policy in the decarbonization arena as it lays down the rules on disclosure of non-financial and diversity information. EU rules on non-financial reporting apply to large public-interest entities with more than 500 employees, covering approximately 11,700 large companies and groups across the EU. The EU ETS is a tool that puts a quantity limit and a price on emissions and establishes a scheme for GHG emission allowance trading with the EU. And finally, the ETD developed the framework conditions for the taxation of energy products such as electricity, motor fuel and heating fuel. However, a new proposal for the ETD was submitted in 2021. The revised proposal aims to support the transition toward clean fuels by linking the minimum tax rates on fuels and their energy content in order to reflect the EU's ambitious targets on the reduction of greenhouse gas emissions and energy savings.

3.2. Energy efficiency policy programs

An important discussion around energy efficiency policy is related to the 'energy efficiency gap'. In an ideal market, according to market economic theory, assets are freely exchanged between actors maximizing benefits and minimizing costs, while consumers and business have full information about market prices and no transaction costs exists (Thollander et al., 2020). When one of these conditions does not function fully, it is perceived as a market failure or a market barrier. Such market barriers might slow the diffusion of energy-efficient technologies leading to non-implementation of energy efficiency measures, therefore leading to a gap between the optimal level of energy efficiency and the actual level (Thollander et al., 2020). This is known as the energy efficiency gap (Jaffe and Stavins, 1994). The reason for this unexploited potential is commonly explained by the existence of different barriers to energy efficiency (Jaffe and Stavins, 1994) varying between different sectors, regions and countries (Sorrell et al., 2004). A market failure, e.g., information asymmetries or imperfections, or a market barrier might justify policy intervention through governmental policy programs (Thollander et al., 2020; Thollander and Palm, 2013).

Energy efficiency policies can be categorized as i) administrative policies (e.g., regulations or performance standards), ii) economic policies (e.g., taxes or subsidies), iii) information policies (e.g., voluntary guidelines), and iv) research and development policies (e.g., advancing technological development). The first three categories are geared toward removing the market barriers to energy efficiency, and policy programs are usually a combination of these categories (Thollander et al., 2020). Raising industry awareness of the positive impacts of energy efficiency measures can be achieved through energy audits, which quantify energy use and drive actions for improvement. Energy audits prove to be a valuable tool for expediting investments in and implementation of energy efficiency measures, aiding companies in becoming more energy efficient and contributing to CO_2 emissions mitigation (Backlund and Thollander, 2015). Industrial energy audit programs are put forward as a means to overcome e.g., information barriers and can be categorized into i) programs for stand-alone energy audits, and ii) integrated policy programs with energy audits.

The first generation of energy efficiency policy programs for industry are the stand-alone public energy audit programs. These programs are voluntary and are established by the national governments to increase the demand for energy audits, especially from SMEs, offering to facilitate free-of-charge audits or subsidies to partially cover the costs of energy audits (Price and Lu, 2011). An example of such a policy program in Sweden was the Swedish Energy Audit Program, implemented between 2010 and 2014 and designed mostly for SMEs with an annual energy use of more than 500 MWh (Lublin and Lock, 2013). The companies were able to apply for a subsidy to cover half the cost of an energy audit, up to a maximum of SEK 30,000. Although the program was primarily aimed at SMEs, larger companies could also apply for the subsidy if the financial support for an energy audit came before the Law for Energy Audits entered into force and if they were not already participating in the Swedish program for Improving Energy Efficiency in Energy Intensive Industries (which is an integrated VA discussed below).

Integrated industrial energy-efficiency policy programs include energy audits as a key component combined with other policy measures, such as VA schemes and mandatory regulations. VAs are agreements signed between industry and governments and are the most popular programs. VAs are a form of voluntary approach in which industry may first negotiate standards of behavior with other firms or private groups and then allow third parties to monitor compliance (IPCC, 2007). VAs are claimed to be one of the most effective policy instruments for energy efficiency improvements, when set up under the right institutional framework, delivering cost-effective energy savings (Rezessy et al., 2015). VAs are seen as a second generation of industrial policy programs, which include energy management components and energy efficiency networks (Thollander et al., 2020).

Mandatory regulations are legal requirements set by national governments and require facilities apart from conducting energy audits to meet energy efficiency improvement targets or deploy a certified energy/environmental management system (Price and Lu, 2011). Based on the specific conditions of the countries, policy makers decide whether they will use either voluntary or mandatory programs and which measures to include, such as certified energy or environmental management systems with established energy efficiency improvement targets, energy action plans, energy and/or CO_2 tax exemptions, threat of energy or CO_2 tax if goals are not reached, financial support for investments or subsidies for energy audits (Price and Lu, 2011).

In Sweden, an example of an integrated VA program was the Swedish program for Improving Energy Efficiency in Energy Intensive Industries. This program was launched in 2004 and was deployed over two five-year periods, ending in 2014. Under this VAP, energy-intensive companies received an exemption from the electricity tax of EUR 0.5/MWh, while in return companies were expected to: i) implement and certify and energy management system, ii) conduct a thorough energy audit, iii) implement cost-effective energy efficiency measures for electricity, and iv) implement routines for including energy in procurement (SEA, 2016). The results from the first period highlight the implementation of an energy management system as a critical factor for the success of the program (Stenqvist and Nilsson, 2012).

3.3. Policy evaluation

Fleiter et al. (2012a) conducted an impact evaluation of the stand-alone German energy audit program with a view to supporting more efficient policy design as well as ex-ante policy evaluation. Using a bottom-up approach, an evaluation of energy savings, CO_2 mitigation, and cost-effectiveness was conducted and the impact in terms of energy savings and costs was compared to evaluations of similar stand-alone audit programs in the USA, Australia, and Sweden. Although some main indicators are comparable, program characteristics, such as scope (firm size and sectors), auditor obligations, and the maturity and degree of standardization differ.

Andersson et al. (2017) conducted a study on international policy program evaluation, focusing on the comparison of energy audit policy program evaluations and their presentation of results. The study revealed variations in evaluation methods and result presentation. Inconsistencies were found in the categorization of measures, making it challenging to compare energy efficiency and cost-saving potentials across different programs within the same category.

Weiss (1998) emphasizes the importance of similarity in measures, goals, and activities for conducting a proper comparison of multiple energy efficiency programs. Evaluations are primarily utilized to inform program improvement decisions, with only limited use in determining whether to proceed or terminate a program. Even when an evaluation indicates program failure, the information is employed to make subsequent attempts more successful. Paradoxically, evaluation methods are well-suited for assessing the overall impact of a program, which is relevant to the infrequent 'go–no go' decision. However, they are less developed as tools for understanding the mechanisms and factors behind a program's success or failure and identifying areas for improvement. Evaluation is expected to guide constructive change by providing essential information that facilitates program modifications (Weiss, 1998). The role of ex-ante evaluation is extremely important, especially during energy transition, when evaluation of the trends in results is key to the success of the program. An ex-ante evaluation has to determine the likelihood of the program goals being of the program to be fulfilled, as well as to providing e information that will enable further development and improvement of the program (Parsons, 1995).

Randomized controlled trials (RCTs) are one method used by analysts to evaluate industrial energy efficiency programs and they are considered the 'gold standard' for credible evaluations (Gillingham et al., 2018). RCTs are performed every year and comprise a simple comparison of energy use before and after an intervention or 'deemed savings' – approaches that use engineering estimates for the energy savings taken in response to an intervention (Gillingham et al., 2018). This approach involves 'ex-ante' calculations, where energy savings are determined by calculations made prior to the program, rather than measurements from after the program (i.e., 'ex-post' evaluations). However, it has been shown that engineering deemed-savings estimates tend to overestimate the energy savings from energy efficiency measures (Gillingham et al., 2018).

3.4. Industry-related voluntary initiatives

According to the IPCC, voluntary actions are one of the prevalent approaches for promoting energy efficiency in industry (IPCC, 2015). The IPCC describes voluntary actions as informal programs, self-commitments, and declarations where the organizations entering into the action set their own targets and do their own monitoring and reporting (IPCC, 2015). Organizations and NGOs, including industry associations, have launched a variety of initiatives to address GHG potential and energy efficiency.

Voluntary Initiatives (VIs) are efforts that go beyond the existing legal requirements in order to improve corporate environmental performance. Action from the private sector is perceived as an important source of climate change mitigation. VIs have become a key element in the mix of public policies and corporate strategies for managing industrial impacts on the environment. There is a broad range of VIs addressing environmental concerns, from greenhouse gas mitigation to waste management.

It is argued that the industrial transition to decarbonization is supported by voluntary initiatives, such as the Science Based Targets initiative[3] for industries (Gebler et al., 2020). This is an international initiative launched in 2014 that encourages organizations to commit to carbon emission reduction targets that are in line with the level of decarbonization required to meet the goals of the Paris Agreement. A science-based target method takes into consideration the emission reduction trajectories to net-zero emissions by 2050 required to limit global warming to 1.5°C. The SBT initiative provides industrial organizations with a target-setting framework for net-zero target setting in line with the latest climate science. It includes methods, guidance, criteria, and recommendations, and it independently assesses and approves companies' targets. More and more industrial organizations have joined the SBT initiative and committed to a target of net-zero greenhouse gas emissions by no later than 2050, alongside interim science-based targets to reach this objective. The SBT initiative is especially focused on welcoming organizations from the highest-emitting sectors which play a critical role in ensuring the transition to a zero-carbon economy. (SBT, 2020; SBTi, 2019). Once organizations commit to setting a SBT, many experience difficulty in gathering data and setting targets (Giesekam et al., 2021).

Other well-known types of industry related VIs are e.g., voluntary agreements (Paton, 2000). Voluntary agreements are used to describe different industry actions, spanning from industrial covenants (Suurland, 1994), negotiated agreements (Bressers et al., 2007) and self-regulation (Lyon and Maxwell, 2003) to eco-contracts (Storey et al., 1999) and voluntary actions (Price and Lu, 2011; Storey et al., 1999). While VAs initially started to be deployed in only a few countries, e.g., Japan (Wakabayashi and Arimura, 2016), they are now used extensively around the world, e.g. the EU (Rezessy and Bertoldi, 2011), Sweden (Stenqvist and Nilsson, 2012), and the USA (Glachant, 2007), particularly to deal with industrial greenhouse gas emissions and waste. The OECD defined the term 'voluntary agreements' as:

> *An agreement between government and industry to facilitate voluntary action with a desirable social outcome, which is encouraged by the government, to be undertaken by the participant based on the participant's self-interest.* (OECD, 1997, p. 5)

[3] Please see https://sciencebasedtargets.org/about-us for more info on the topic

According to this definition, VA do not include actions that are implemented without government initiative or implemented solely as the result of a government mandate. Therefore, the use of the term 'voluntary' has been disputed for a long time since many agreements are in fact established under the threat of an alternative legislative intervention, such as the UK climate change agreements and the Dutch 'covenants' (Glachant, 2007). Regarding the voluntary status, the IPCC clarifies that not all VA are truly voluntary, since some include rewards and /or penalties associated with joining or achieving commitments (IPCC, 2015). In this matter, Price (2005) divided VAs into three broad categories: i) VA completely voluntary, ii) VA with implied future threat of regulation or taxation, and iii) VA implemented within existing energy or greenhouse gas emissions tax policy.

Apart from the degree of regulatory (or fiscal) threat, there are other key characteristics of VAs, such as the manner of setting the target, the nature of the commitment, and the mix of incentives. Based on these characteristics, the OECD (1997) identified the four types of VA as: i) target-based, ii) performance-based, iii) co-operative research and development, and iv) monitoring and reporting. The target-based alternatives are legally binding negotiated targets which can pre-empt future regulatory requirements, while performance-based ones are negotiated performance goals which are not legally binding nor explicitly designed to pre-empt future regulatory requirements. Co-operative R&D focuses on the development of new technology. And finally, monitoring and reporting is a part of most VAs, but can take the form of a VA in its own right (OECD, 1997). There is an increasing number of comprehensive reviews and assessments on the effectiveness of VAs. However, they use different metrics and evaluative criteria, making it difficult to compare them (Price, 2005). Furthermore, evaluating the effectiveness of VAs is challenging, due to the so-called selection bias for comparison, where the best-performing organizations that enter into a VA are used to measure the performance and then their performance is compared to that of a typical non-participating organization (IPCC, 2007). The energy use of companies may also affect the evaluation where lower energy using companies may not join a VA meaning the evaluation in turn becomes difficult since it then means one may have to compare between companies of different sizes (Ottosson and Petersson, 2007).

4. Theoretical framework

This chapter discusses the theoretical concepts that contributed to the understanding of industrial energy management during the energy transition using an extended system perspective. Such concepts as philosophy of energy, system approach (system thinking, complex systems), absorptive capacity and knowledge dimensions are described below.

4.1. Epistemology of energy in EnM context

The notion of energy comes from Aristotle. In his *Metaphysic Treatise,* Aristotle combined *en* (term translated in English as 'in') with *ergon* (term translated in English as 'work', 'product', 'task') and concluded that every object is maintained by *energeia* ('activity') (Coopersmith, 2010). *Energeia* is described as the state of being engaged in an act or the carrying out of a deed *(ergon)* (Bartlett and Collins, 2011). When used with a technical meaning – 'activity' (*energeia*) together with 'capacity' or 'power' (*dynamis*) – it refers to the 'power', or 'potential' for 'activity'. Later on, the concept of *energeia* is used in relation to kinetic energy, while *dynamis* relates to potential energy (Bartlett and Collins, 2011). The most widely known definition follows the first law of thermodynamics, which states that *energy cannot be created nor destroyed.*

Energy management can be connected to Aristotle's concept of *dynamis* through the understanding of potentiality and actuality. *Dynamis* refers to potentiality or the inherent capacity for something to become actualized. In the context of energy management, *dynamis* can be seen as the untapped potential for energy conservation, energy efficiency improvements, and the integration of renewable energy sources. Energy management involves identifying and harnessing the potential within energy systems to achieve desired outcomes. It focuses on maximizing the actualization of energy potential by implementing measures and strategies that optimize energy use, reduce waste, and enhance efficiency.

Similar to Aristotle's concept of dynamis, energy management recognizes that energy possesses inherent potential that can be transformed into actual energy services, such as electricity, heating, or mechanical work. This potential can be realized through effective energy management practices, enabling the efficient utilization and allocation of energy resources. Furthermore, the concept of *dynamis* highlights the dynamic nature of energy management, acknowledging that energy potential can vary across different contexts, technologies, and systems. Energy management seeks to identify and unlock the dormant potential within energy systems through the application of knowledge, innovation, and strategic decision-making.

In summary, the connection between energy management and Aristotle's *dynamis* lies in the recognition and activation of the untapped potential within energy systems. Energy management aims to transform the potentiality of energy resources into actual energy services by implementing measures and strategies that optimize energy use and enhance efficiency. By leveraging the concept of dynamis, energy management endeavors to actualize the inherent potential within energy systems, contributing to sustainable energy practices and the achievement of energy system transition goals.

4.2. Philosophy of energy in the energy transition context

The philosophy of energy in the context of energy transition explores the fundamental principles, values, and beliefs that underpin the understanding and approach to energy and the process of transitioning toward a more sustainable energy system (Heurtebise, 2020). It delves into the ethical, metaphysical aspects of energy, everyday phenomenology of energy and its values in contemporary society. By examining the philosophy of energy, deeper insights into the underlying concepts and ethical considerations associated with energy transition can be reached.

- Justice and ethical considerations (Sovacool et al., 2016): the energy transition might raise important ethical questions related to the moral dimensions of energy production, distribution and use. This can include nuclear waste, involuntary resettlement, energy pollution, energy poverty and the responsibility to mitigate climate change. It invites reflections on justice centered on availability, affordability, due process, transparency and accountability, sustainability, equity, and responsibility.
- Metaphysical considerations (Heurtebise, 2020): traditional philosophical history emphasizes the opposition between materialism and idealism, but introducing the concept of energy into this debate can offer a new perspective on the ontology of energy. Energy transcends the limitations of both materialism and idealism, suggesting that ontologically there are only energies, connecting or disconnecting entities in transformative processes. From a metaphysics of energy standpoint, the idea of energy shortage becomes meaningless, as energy is abundant, even threatening human existence. Our current relationship with energy involves capturing

and utilizing it through technology, but this approach may overlook its inner-transformative essence in favor of its disposable kinetic power.

- Phenomenology of energy (Heurtebise, 2020; Ihde, 1990): The goal of phenomenology of energy is to reveal how we engage with energy in our daily lives through technological devices by examining the structures of experience and consciousness involved in these interactions.
- Values in contemporary 'petrocultures' (Ewing, 2019; Heurtebise, 2020): An energy transition entails more than just switching energy sources; it also involves reevaluating and adjusting our expectations and lifestyle related to energy. A post-postcolonial perspective on the geopolitics of energy is needed, especially when the European Union's reliance on Russian energy resources becomes problematic as Moscow constructs new pipelines bypassing Ukraine. Similarly, China's Belt & Road Initiative reflects Beijing's aim to guide international society toward a new world order, highlighting the interconnectedness of geopolitical and geo-economic issues.

The challenges during the Anthropogenic age regard the climatic and ecological consequences of exploiting nature (Hickel, 2019). Overexploitation – exemplified by the mining of minerals for the transition to green energy – exacerbates deforestation, ecosystem collapse, and biodiversity loss worldwide (Hickel, 2019). The crisis lies not in resource scarcity but in the damaging effects of over-extraction. Even before fully exhausting fossil fuels or achieving equitable exploitation, the planet's habitability is at risk due to the inability of ecosystems to absorb excessive carbon, nitrogen, and waste. Paradoxically, contemporary civilization may face extinction not due to energy resource depletion, but rather from the consequences of excessive energy use (Heurtebise, 2020). This is particularly relevant for manufacturing industries since manufacturing often involves resource-intensive processes and energy use, which can contribute to environmental problems such as over-extraction, deforestation, and biodiversity loss. These challenges highlight the need for sustainable practices in industries, including manufacturing, to mitigate the negative environmental impacts.

4.3. Knowledge for energy management

4.3.1. Forms of knowledge

This section explores the interplay of Aristotelian knowledge forms in the context of energy management. Aristotle defined three forms of knowledge: Technē, Epistēmē, and Phronēsis. *Technē,* a technical art or craft, is understood as the 'technical knowledge' used to produce an artifact, such as shoes, tables, a building, and the knowledge that goes with it, hence the art of shoemaking, of carpentry, and of architecture. *Technē* is bound up with 'making' and therefore has an end other than its own activity (Bartlett and Collins, 2011). *Epistēmē* is referred to as 'scientific knowledge' or 'science' and is related to the possession of 'scientific' knowledge, i.e., knowledge in the strict sense, as opposed to knowledge acquired in some other way. *Epistēmē* knowledge is in most cases already successfully dealt with in today's national educational systems, e.g., technical school, high school, college, technical institute, university. Aristotle also introduced practical thinking as distinct from theoretical thinking and as necessary for action and discussed the intellectual virtue responsible for good practical thinking. *Phronēsis* or 'practical wisdom', as it is interpreted, is such an intellectual virtue – a state of soul accompanied by reason that makes possible the sort of thinking necessary for good action. Furthermore, *phronēsis* is the capacity for intellectual perception. More specifically, it is a way of perceiving that is at the same time articulate enough to be sensitive to the particulars of the situation in which one must act and discerning of the ethical features, and flexible and open enough to be determined by deliberation (Rabinoff, 2018).

Taking these common types of knowledge are discussed by Aristotle, in what follows I will describe them in the context of energy management in the manufacturing industry. But first, I will explain what I mean by theoretical and practical knowledge in this context. The general idea behind theoretical knowledge is that I do not mean knowledge in the strict sense, e.g., the mechanical or electrical principles on which a machine relies, but the learning process that gives a deeper understanding of a concept or method through seeing it in context and through the experience of others, not one's own. This gives a theoretical understanding, for example, of why one technology is more successful than another, or why one method of operating is better than another, and so on. However, the practical knowledge in operating a machine, for example, helps to improve technical skills and knowledge. Practical knowledge can even lead to a deeper understanding of a technology or process through the act of personal experience. Like most other types of knowledge, it often improves over time and is gained through sometimes years of practice and training, with mistakes and feedback from more skilled persons helping the individual to improve much faster than if they were just left to their own devices.

Hence, in this thesis, *technē*, or 'technical knowledge', is seen as a tacit mode of knowledge and reflects the theoretical and practical knowledge that leads to the development of technical skills in a certain technology, installation, machine, or tool. Tacit knowledge is gained through experience rather than formal education, exists in people and organizations with a shared knowledge base (Tranfield et al., 2004), is embedded in routines (Menghi et al., 2019) difficult to articulate or document (Ford et al., 2003) and context dependent (Clegg et al., 2006). Therefore, technē is understood as the type of knowledge – theoretical and practical – that directly informs technical skills, particularly in a certain technology, installation, machine, or tool (Bartlett and Collins, 2011). Technical skills vary depending on the field of work. For example, a mechanical engineer may list as technical skills design calculation, simulation, and testing, but also big data analysis, structural analysis, statistics, 3D design, and knowledge of the machining systems, all of them connected in different ways to the technology used in the production process.

Epistēmē, or scientific knowledge, often gained through education programs, is the knowledge that informs process knowledge allowing for process optimization and control. Hence in this thesis it is translated as 'process knowledge' and represents the scientific knowledge that leads to a better understanding and operation, but also, improvement or change in a production process. Epistēmē is an explicit mode of knowledge being easily documented (Tranfield et al., 2004) and context independent (Clegg et al., 2006). Knowledge that informs process knowledge can take several forms, ranging from tools for studying processes, e.g., modelling, optimization, manufacturing simulation, pinch analysis, that improves and transforms production processes, to methods and performance indicators that allow one process to be benchmarked against another, or methods for monitoring and analyzing the energy use in the process, not to mention education programs in manufacturing processes. For example, if thinking about the complexity levels of current welding methods, such as metal arc welding, tungsten arc welding and so on, and the need to better understand and improve the quality of the welding process, the source of knowledge that creates specific knowledge about the welding process may be found in technical schools and training courses, but also in a whole scientific body of literature, technical papers, and textbooks. Therefore, process knowledge is the knowledge of one's own processes that leads to improvement, optimization, and advances process control.

Phronēsis, as a third form of knowledge (often translated as 'practical wisdom' e.g., how to act as a leader) can come with practically very little *epistēmē* and *technē* but with years of experience in leadership. Phronēsis as knowledge is of course a must for every good leader to possess and even though age naturally brings a great advantage in relation to *phronēsis*, it still does not exclude young leaders with years of practice in social environments such as school and other social activities. As with other forms of knowledge, *phronēsis* also improves with training or practice if one is so inclined. When it comes to energy management, leadership knowledge might be key to successful implementation of energy management strategies. Energy managers are constantly surrounded by change, as their job is to includes the deployment of new and innovative technologies, new business processes, and enlightened energy management strategies. While *epistēmē* knowledge aligns well with traditional educational systems, *technē* and *phronēsis* knowledge thrive through close relationships with experienced individuals, mentors, or trainers.

4.3.2. Absorptive capacity

External knowledge is vital for innovation across organizational levels. The ability to utilize external knowledge is crucial for innovation, and it depends on the existing level of prior related knowledge. This ability is referred to as absorptive capacity and includes a set of procedures that an organization implements in order to acquire, understand, transform and apply external knowledge (Zahra and George, 2002). The concept of absorptive capacity assumes that prior related knowledge is necessary for an organization to *assimilate* and utilize *new* knowledge effectively. Prior knowledge can exist at the most basic level, but it may also include knowledge of the most recent scientific or technological developments in a given field, thus enabling the recognition, assimilation, and application of new information for commercial purposes.

Research on memory development indicates that accumulated prior knowledge improves the acquisition, retention, and application of new knowledge (Cohen and Levinthal, 1990). Cohen and Levinthal (1990) argues that problem solving and learning capabilities share similar developmental processes, and their distinction is not significant. While the content learned may vary, learning capabilities involve assimilating existing knowledge, while problem-solving skills involve creating new knowledge. Furthermore, Cohen and Levinthal (1990) claim that the richness of preexisting knowledge enhances the ability to assimilate information and has two implications:

learning is cumulative, and learning performance is highest when the new knowledge is related to existing knowledge. Learning becomes more challenging in unfamiliar domains, while expertise and diverse knowledge contribute to learning. In uncertain contexts where valuable information may come from various domains, a diverse background provides a stronger foundation for learning by connecting incoming information with existing knowledge. Knowledge diversity not only enhances assimilation, but also fosters innovation by enabling novel associations and connections.

An organization's absorptive capacity relies on the absorptive capacities of its individual members. The development of organizational absorptive capacity is built upon prior investments in individual absorptive capacities, and it tends to accumulate over time. However, organizational absorptive capacity is not simply the sum of individual capacities. It encompasses not only the acquisition and assimilation of information but also the organization's ability to *exploit* it (Cohen and Levinthal, 1990). Organizational absorptive capacity is influenced by knowledge transfers both across sub-units within the organization and between the organization and the external environment. Understanding the sources of absorptive capacity requires examining the communication structure between the organization and its external environment, as well as within different sub-units of the organization. However, the capacity to absorb knowledge and the underlying decision-making process is influenced by the specific circumstances of an event and the individuals participating in it (Thollander and Palm, 2015).

4.3.3. Knowledge creation

Knowledge dynamics refers to the variation of knowledge at the individual, group or organizational levels within a specific context and arises from the processes of knowledge creation, knowledge acquisition, or knowledge loss (Bratianu and Bejinaru, 2020). Knowledge dynamics are connected with the absorptive capacity (Cohen and Levinthal, 1990) of the internal energy systems and the production processes, as discussed by Paramonova et al. (2021). Knowledge creation for energy management is intricately connected to the utilization of external knowledge and co-creation of knowledge. The capability to acquire, understand, transform, and apply external knowledge is crucial for innovation in energy management. This process relies on the existing level of prior related knowledge, which enables the recognition, assimilation, and application of new information. Researchers claim that a change is needed in how energy efficiency research is conducted, arguing that earlier policy initiatives are missing the context of energy-saving actions and how such actions are connected with the technical sphere (Backman, 2018b; Shove, 1998). Technical change should not be perceived as a one-way, linear process of knowledge transfer from one actor to another (Backman, 2018b). People do not absorb abstract knowledge and then implement optimal energy efficiency measures (Shove, 1998; Sorrell et al., 2004). The adoption of energy-saving strategies is anything but standardized, individualized or economically determined (Backman, 2018b; Guy and Shove, 2000). Rather, energy-related practices are socially situated, specific, localized in terms of time and a context built on knowledge, routines, and established methods (Guy and Shove, 2000). Hence, this shift in perspective is based on how knowledge is perceived, since knowledge is not a mix of undeniable facts or objective truths; rather, knowledge is enacted and depends on context and actors (Guy and Shove, 2000; Latour, 1987). Furthermore, knowledge creation is strongly related to explicit and tacit knowledge (Tranfield et al., 2004). In order to create knowledge a blend of both tacit (e.g., personal experience, practice and sharing of best practices) and explicit (e.g., documented information) mode of knowledge is needed.

4.4. Systems approach

The study of industrial energy management during energy transition requires a solid theoretical framework to capture the complex interactions and dynamics at play. One such framework that proves valuable is system theory. Churchman (1968) is the founder of the systems approach, a way of thinking about systems and their components by considering the interrelationships and interactions among them. Churchman (1968, p. 11) defined systems as "made up of sets of components that work together for the overall objective of the whole". Churchman (1968) discusses several system approaches, however this thesis will focus on the *efficiency* approach and the *management scientific* approach. However, Churchman (1968) claims that the best system approach is to live in them and react to them in terms of one's experience.

4.4.1. The efficiency approach

Efficiency of operations takes into consideration Churchman (1968) approach related to efficiency. According to the efficiency approach, trouble spots and waste need to be identified, followed by a process to remove inefficiencies. In industrial EnM this approach refers to the strategic and coordinated efforts undertaken by organizations to optimize their energy-related processes through energy efficiency practices. From a policy perspective, this approach is connected with energy efficiency programs, such as the energy-audit programs. However, Churchman (1968) claims that the efficiency approach *per se* may be an inefficient approach to manage a system from an overall system point of view, and that a broader view of the system is needed. Merely focusing on efficiency improvements in areas, such as support and production processes or energy use, without considering their *interdependencies and interactions* with the broader manufacturing system, for example with reference to the supply chain, the operator or the energy infrastructure outside the plant (transmissions and distribution systems), can lead to suboptimal outcomes, while neglecting the systemic effects and potential trade-offs might hinder the successful outcome of energy management. Furthermore, IEnM during energy transition involves multiple factors beyond efficiency, such as decarbonization goals, cost-effectiveness, and product quality. Such non-efficiency factors need to be approached in a holistic manner. Transitioning toward sustainable energy systems entails change in energy sources, technologies, and processes. Hence, system adaptability is another important consideration, relating to the system's capacity to adjust to changing circumstances. And, finally, an efficiency-driven approach may lead to trade-offs between various dimensions, leading to an inadequate balance of factors energy costs, environmental goals, production efficiency and product quality. Therefore, effective energy management during transition requires an understanding and optimization of these value trade-offs to achieve a system that meets the objectives and aligns with the goals of the energy transition. Understanding how all these factors are interconnected and influenced by the overall system is crucial for effective decision-making.

4.4.2. The management approach

4.4.2.1. The total system objectives and measures of performance

According to Churchman (1968), the way we think about a system will guide how we describe the system. The scientific management approach refers to a system in terms of its *function* or *objective* and should disrupt typical mental processes by suggesting radical approaches to thinking. Furthermore, care is to be given to move away from vague objectives to precise and specific measures of performance that allows for evaluation of the system's performance against clear and stated objectives.

4.4.2.2. The system's environment

According to Churchman (1968), a system's environment is the 'fixed' or 'given' constraints that are outside the system, but belong to and influence the system, and cannot be changed. The *external environment* in the form of policies and policy programs can be seen as being outside the system, but they definitely serve as crucial factors that influence EnMPs during the energy transition. First of all, the main external pressure comes from the policies related to the decarbonization of industry. These policy interventions play a critical role in shaping the direction, pace, and success of the transition toward sustainable energy systems. Climate policies such as carbon pricing mechanisms, renewable energy targets, emission reduction commitments, and regulations provide a regulatory framework and incentives for organizations to prioritize energy efficiency, renewable energy adoption, and emissions reduction. These policies create a supportive environment for the development and implementation of energy management practices that align with the broader objectives of mitigating climate change and reducing greenhouse gas emissions. Policy programs (e.g., VAs), including financial incentives, grants, subsidies, and research and development initiatives, further influence energy management practices by providing support and resources to organizations undertaking energy transition efforts. These programs help overcome barriers to adoption, facilitate technology transfer, and promote innovation in energy management practices.

Hence, as Churchman (1968) points out, the external environment determines how the system performs. Therefore, it can be claimed that the *external environment* influences EnM, for example, by: i) setting clear goals and targets which provide a clear direction for organizations to orient their EnMPs and strategies, ii) creating market signals by incentivizing clean energy technologies and penalizing high-emission practices (e.g., the PFE program in Sweden), thus encouraging organizations to adopt practices in line with the policy objectives, and iii) providing a regulatory framework that organizations must comply with, such as requirements for energy audits, reporting emissions and implementing energy efficiency measures. Another feature of the system's environment, according to Churchman (1968), is the need for systematic and continuous revision. This is particularly specific to legislation and climate-related policies, which are updated with milestone targets on the path to reaching the 2045 target for decarbonization, and which are themselves reflected in the goals and objectives of the organizations.

4.4.2.3. The resources of the system

The resources of the system are contained within the system itself and include the means for the system to do its job and perform. These resources, such as man-hours and technologies, can be changed, and used to the system's advantage (Churchman, 1968). The system can decide the allocation of men for each job and also the budget and the timeline for various kinds of activity. Although companies perform a thorough analysis of resources, in terms of inventory, this type of approach to what a resource is leaves out many of the important resources of a system (Churchman, 1968). Inventories cannot register the educational background and personal capabilities and skills of the personnel. Another flaw of the inventory approach to resources is that it misses how resources are used. In particular, it fails to capture the lessons learned from missed opportunities, the potential that went unrealized due to the allocation of resources to other endeavors, all this being related to the lack of leadership vision. Another aspect of resource determination is connected with the technological advances to which companies should pay special attention, especially during energy transition. However, when looking at the resources of a system, particular attention also needs to be allocated to the manner and means by which current system resources can be further developed and increased to create better resources – research and development for technologies; training and education for personnel; and political activities for the budget. The part of the system that focuses on increasing resources is actually the most important component of the system (Churchman, 1968).

4.4.2.4. The components of the system

Component thinking involves identifying those components whose measures of performance are connected with overall system performance (Churchman, 1968). The components of the system represent the specific activities and objectives within the system boundary which are driven by the mission of the system and support the performance metrics of the system. The separation of the system into components is for analytical purposes, providing an opportunity to assess system performance. However, this approach is not very popular, hence leading to difficulties in assessing large systems (Churchman, 1968). In the context of EnM during energy transition, the specific activities of the system components refer to the various actions and tasks undertaken to optimize energy use, adopt renewable energy sources, and implement sustainable practices. The objectives of system components pertain to the desired outcomes and targets set for the transition of the individual organization. These objectives could include reducing carbon emissions, increasing the share of renewable energy in the energy mix, improving energy efficiency, achieving cost savings, and so on. Looking at the system in terms of the respective components enables the use of measures of performance that can serve as indicators to assess the effectiveness and progress of the system. Such key performance indicators can include specific energy use, carbon emissions intensity, renewable energy penetration rate, and energy cost savings. Measuring the system performance in terms of output per unit cost enables monitoring of the system's total performance increase.

4.4.2.5. The management of the system

The management of the system is connected with the actions needed for effective management of that system and considers all four of the abovementioned elements (Churchman, 1968) – the goals, the environment, the utilization and development of resources, and the components. The management of the system establishes the goals, allocates the resources, controls system performance, and verifies if plans are being implemented according to the strategy and pathways developed. Feedback is particularly important for the management of the system since changes will need to be made if a concept within the system is not working properly. Feedback plays a crucial role in the management of the system during the energy transition, allowing for continuous assessment and improvement of EnM strategies and practices. If certain aspects of the system concept are not functioning effectively or are not yielding the desired outcomes, feedback mechanisms help identify the need for change and adjustments. This enables the management to adapt and optimize the energy management approaches to ensure the successful progression of the energy transition.

According to Churchman (1968), building models of the reality in order to simplify it and explain it is common. The 'input-output' model for example, described as a black box, is used to illustrate the inputs of resources (e.g., energy flows) and outputs (e.g., products and waste), and the processes inside the box are invisible. It is common to use such an input-output model in industrial energy management, since the energy system in this context is composed of complex production systems connected with other systems. Therefore, using a system approach for industrial energy management is helpful due to the ability to increase awareness of the flows, specificities, and problems within such models. This highlights the need for an extended system approach, based on two layers– internal and external. The internal one includes technologies, processes, practices, human knowledge and collaboration, while the external one includes policies and policy programs.

Another way to think about system is in terms of their degree of complexity. Boulding introduced the general system movement in the early 1950s, and his research and writing centered around the quest for fundamental governing principles, rules, and system structures. Boulding's (1956) 'Skeleton of Science' consists of nine levels of organization with a hierarchical progression of increasing complexity, from the static mechanics at the first and least complex level to the human and the interaction between humans at higher order levels the most complex system to study. Boulding (1956) describes general systems as follows:

> *General Systems Theory is a name which has come into use to describe a level of theoretical model-building which lies somewhere between the highly generalized constructions of pure mathematics and the specific theories of the specialized disciplines.* (Boulding, 1956, p. 197)

General systems theory is essential in the current sociological situation in science. Knowledge is not an abstract entity but a product of human organisms and social organization. Knowledge is what individuals know, and its growth relies on receiving meaningful information that can reorganize their existing knowledge (Boulding, 1956).

5. Methodology

This chapter starts by introducing the research design and the guiding philosophical paradigm of the thesis. It is followed by an overview of the methods. Next, the research approach, analytical frameworks, methods for data collection and analysis are presented in relation to each paper.

5.1. Exploratory research design

Qualitative research is characteristically exploratory and flexible, with data playing a central role in guiding decisions and understanding, while remaining sensitive to the unique context of the study (Mason, 2002). However, the flexibility characteristic does not mean an absence of direction (Mason, 2002), but rather it entails an initially broad focus that gradually narrows as the research advances. This thesis aims to explore the role of industrial energy management in the transition toward sustainable energy systems using an extended system level, and thus requires a research design that is flexible and adaptable to change as new results and insights unfold throughout the study. Hence, an exploratory research design was chosen. Furthermore, by using an exploratory approach, the theory arises organically from the data collected, and such theoretical findings may serve as a foundational basis for potential future quantitative investigations (Kelly and Bowe, 2011).

5.2. Philosophical stance

Pragmatism as the philosophical paradigm of this research

This research aims to explore the role of industrial energy management in the transition toward sustainable energy systems by using an extended system approach. This system is in a state of perpetual motion and change, driven by the overarching goals of society related to the transition to sustainable energy systems, as well as the values of the companies involved. So, this research is highly grounded in a changing reality aiming to achieve desired results.

The reality connecting the organizations and the energy transition is the foundation for how this research is understood and addressed (Kuhn, 1970) and for defining the research paradigm. The approach of this research is founded in the philosophical school of pragmatism, which embraces plurality of methods. The school of pragmatism was developed in the late 1800s by a group of sociology scholars who challenged the traditional empiricist notion by focusing on the subjective experience of the social world (Savin-Baden and

Howell Major, 2013). Their belief was that the world should be researched by the most sensible and practical methods for the research questions and rejected the idea that the 'truth' is accessed through the virtue of one scientific method (Mertens, 2005). Researchers who adopt this approach fall somewhere between realists and idealists, adopting an open orientation to what they are studying by choosing a range of research approaches such as grounded theory and action research, and striving for unobtrusive observation of the environment (Savin-Baden and Howell Major, 2013).

There are different perspectives on how to conduct pragmatic research. Researchers can adopt an interpretative (subjective) approach, which requires an explanation of theoretical influence as well as an analytical framework that situates the interpretation, but also a descriptive (objective) approach to describe the data. However, the kind of pragmatic approach applied in this research is in line with Savin-Baden and Howell Major (2013) and is situated somewhere between a purely interpretative approach and a purely descriptive approach. This allows the pragmatist researchers to take a practical approach to their research and focus on the 'what' and 'how' of the research problem by applying different approaches to understanding the problem (Creswell, 2009). Applying a pragmatic approach is well suited to providing the descriptive information that can inform professional practices (Savin-Baden and Howell Major, 2013). Pragmatism argues that reality is a process or experience, and claims that truth may be interpreted in terms of the practical effects of one's own beliefs and, particularly, the usefulness of these effects (Savin-Baden and Howell Major, 2013).

Two of the main themes of pragmatism – radical contingency and unpredictability, and plurality and constructive dialogue – align with the research of this thesis. Pragmatism acknowledges that our universe and lives are characterized by radical contingency, meaning they are subject to unpredictable and unforeseen events (Elder-Vass, 2022). Pragmatism recognizes the existence of multiple traditions, perspectives, and philosophical orientations. Embracing pluralism, pragmatism advocates for open and constructive dialogue with other viewpoints (Elder-Vass, 2022). It encourages a genuine effort to understand opposing arguments rather than dismissing them. In Paper III and IV, a top-down perspective was applied that is connected with policymakers directly (Paper III) and indirectly (Paper IV). In this thesis, the plurality of perspectives is used to comprehensively address the research questions from different viewpoints. In Papers I, II and V, EnMPs are viewed, as defined in practice theory (Reckwitz, 2004), as a routinized collection of physical and mental actions taking place in the manufacturing organizations in order to achieve the goals related to energy efficiency and decarbonization. In Paper III, EnM is viewed as a tool that supports the design of an ex-ante policy evaluation for energy audit policy programs. Together, these different perspectives reveal uses and methodological considerations regarding EnM that provide a more comprehensive answer to the research questions. In Paper IV, EnMPs are viewed as internal and external activities conducted by industrial organizations, based on the design or prerequisites of a voluntary initiative aiming to contribute to the transition toward a sustainable energy system through energy efficiency and decarbonization activities.

The way pragmatism describes ontology, that is the belief system about the form and nature of the world (Biesta, 2010), is that reality is grounded in individuals' environment and personal experiences, acknowledging the inherent limitations in fully understanding it. Consequently, researchers select a particular understanding of reality based on how effectively it leads to anticipated or desired outcomes. Pragmatism's rejection of fixed realities and its emphasis on practical consequences aligns well with the dynamic and evolving nature of energy systems in transition. By adopting an ontological perspective rooted in pragmatism, I can explore the complex interplay between the policies, technologies, actors, practices, and social dynamics that shape energy management practices. This approach recognizes that energy management is not a static concept but a fluid process that requires continuous adaptation and learning. Pragmatism's focus on the practical implications of knowledge allows for a nuanced understanding of how different approaches to energy management contribute to the desired outcomes of a sustainable energy system. Based on that, this research employs different theories, analytical frameworks, and methods and energy management is seen, for example, as an 'practice' in Papers I, II, IV and V and as a 'tool' in Paper III.

From an epistemological standpoint, pragmatism operates on the premise that research can avoid delving into metaphysical discussions concerning the essence of truth and reality. Instead, it emphasizes the importance of cultivating 'practical understandings' that are grounded in tangible, real-world problems (Patton, 2002). Although this approach aligns well with interpretivist perspectives that emphasize the socially constructed nature of reality, its primary focus lies in examining the practical outcomes and implications of research data (Morgan, 2014). It involves interrogating the value and significance of the data by exploring its tangible consequences. This approach proves especially valuable in contexts where practice and knowledge production are deeply intertwined. Classical pragmatists have even shifted their focus to the dynamic processes of 'knowing' and 'learning'. By employing pragmatism, researchers can delve into exploring and comprehending the intricate links between knowledge and action within specific contexts (Biesta, 2010). In this sense, the act of 'knowing' possesses the transformative power to reshape and improve practice (Biesta, 2010; Kelly and Cordeiro, 2020). Pragmatism, in its epistemological stance, regards knowledge from an instrumental perspective. It sees knowledge as a tool or instrument that serves the purpose of problem-solving and facilitating human actions (Bush, 2007). In line with this, research question 2 focuses on knowledge as an instrument for further developing practices that can enable the energy transition and Papers I, II, IV and V explore this theme.

5.3. Research overview

When designing and implementing the studies for this thesis, I was faced with many choices on how to frame and design the studies. Choosing the phenomenon of study, also referred to as the 'unit of analysis' in quantitative research, and the 'who' or 'what' that is central to the phenomena, is one of the most important choices since it will determine the research questions, which data will be collected and how the analysis will be conducted. In this research, choosing the phenomena was quite a straightforward decision due to the research project I was a part of, which had a focus on industrial energy management practices. Based on this, I have positioned the research in the context of transition to sustainable energy systems and identifying the 'who' or 'what' was an iterative process.

According to Savin-Baden and Howell Major (2013), the choices that researchers make stem from their values and beliefs, rather than from a rational or even conscious process. However, by engaging in thoughtful and deliberate decision-making processes, researchers can establish a conceptual model that helps them navigate the interconnectedness of their choices and illuminates the framework through which data is interpreted. Such a model aids in recognizing and understanding personal biases and the underlying motivations driving those choices. The essential choice moments for this thesis are described in Table 5, alongside the several approaches and methods employed to answer the research questions.

Table 5. Essential choice moments

Category	Essential choice moments	Section
Choosing a position	Philosophical stance	5.2
Framing the study	The 'who' and 'what' of study	5.3
	Aim and research questions	1.2
	Literature review	2 and 3
	Theoretical and conceptual frameworks	4
The research approach	Systematic literature review (PI)	5.4.1
	Case study with participatory action research approach (PII)	5.4.2
	Evaluation studies (PIII and IV)	5.4.3
	Survey study (PV)	5.4.4
Data collection	Literature review (PI, PII and PIII)	5.6.1
	Interviews (PII)	5.6.2
	Observations (PII)	5.6.3
	Documents (PII, IV)	5.6.4
	Data bases (PIV)	5.6.5
	Questionnaire (PV)	5.6.6
Data analysis	Content analysis (PI)	5.7.1
	System analysis (PII and IV)	5.7.2
	Domain analysis (PIII)	5.7.3
	Sector and cluster analysis (PV)	5.7.4

The studies are influenced by system thinking and take a cross-disciplinary approach. Comprehensive answers to complex and multifaceted problems, called 'wicked' problems (Thollander et al., 2019), require a cross-disciplinary approach involving integrating, interacting, or overlapping different disciplines to analyze a common problem (Stock and Burton, 2011). In this research, both interdisciplinary and multidisciplinary approaches were applied. The interdisciplinary approach is rooted in collaboration between disciplines and the focus is on problems from the 'real world'. Based on this approach, boundaries between disciplines are erased and new integrative knowledge is created (Ma et al., 2014). This is seen throughout all five papers, which embrace different disciplines to answer the research questions. Furthermore, a transdisciplinary approach was applied in Papers II and III. The transdisciplinary approach involves collaboration between academic researchers from different disciplines and non-academic actors, creating new knowledge and theories when studying a real problem (Stock and Burton, 2011). The transdisciplinary approach is the most complex and most desirable approach, since it combines scientific research with generating new knowledge and capacity for decision-making by the non-academic actors involved (Stock and Burton, 2011). The general research framework for the studies conducted in this thesis is illustrated in Table 6.

Table 6. General research framework for the studies

Paper	I	II	III	IV	V
Plan					
Research paradigm: Pragmatism					
Theoretical or conceptual framework	Knowledge-based analytical framework (Conceptual)	System approach (Theoretical)	EnM and policy evaluation (Conceptual)	Transition management (Theoretical)	Maturity level (Conceptual)
Phenomenon	EnM in manufactu-ring industry (Process)	Transition process in automotive paint shop (Process)	Energy-audit policy program evaluations (Structures)	Design of industry-related VIs (Structures)	Adoption of DT in manufactu-ring industry (Process)
Research approach	Systematic literature review	Case study with participatory action research approach	Evaluation: Utilization-focused evaluation	Evaluation: Traditional evaluation	Survey
Contribution to RQs	RQ1 & 2	RQ1 & 2	RQ3	RQ 1 & 3	RQ1 & 2
Main software tools	Web-based survey tool and excel	Web-based survey tool and excel	Microsoft office package	Web-based survey tool and excel	Excel and Minitab
Design					
Objective	Investigate the forms of knowledge employed in EnMMI	Explore the transition process in automotive paint shop	Develop a methodolo-gy for ex-ante evaluation of EE policy programs	Evaluate the potential of VIs to bridge the gap for decarboni-zation	Assess the adoption of DT for energy efficiency in Swedish manufactu-ring sectors

Design research approach	Descriptive	Descriptive	Predictive	Predictive/ descriptive	Descriptive
Data collection					
Input	Literature review	Interviews, observation, documents, literature review	Literature review	Documents: articles, reports, VIs' official public documents. Databases	Questionnai-res
Data analysis					
Data handling	Coding, Categorize, convert into themes, descriptive tables, integrative figures	Coding, categorize, convert into themes, descriptive tables, integrative figures	Cutting the data into meaningful segments	Coding, categorize, convert into themes, descriptive tables, integrative figures	Categorize, convert into themes, descriptive tables, integrative figures
Data analysis	Content analysis: Constant comparison, domain analysis, thematic analysis	System analysis: Measures analysis, Energy and GHG analysis, and Economic analysis: CSC & MACC	Domain analysis	System analysis: Constant comparison, content analysis, thematic analysis	Questionna-ire analysis, sector analysis, cluster analysis, descriptive statistics
Results					
Deliverables	Categorization of EnMPs based on knowledge domains; Framework for knowledge creation process (theoretical)	System level analysis. Analytical framework for decision making	Guidelines for conducting ex-ante industrial EE policy program evaluation	System level analysis of industry related VIs. Analytical framework for VIs evaluation at system level	Maturity model for evaluating the adoption of DT for energy efficiency

Dissemina-tion	Journal article	Journal article	Journal article	Journal article	Journal article

5.4. Research approach

5.4.1. Literature review study

In this thesis, a literature review was conducted in Paper I by following a systematic method, as illustrated in Figure 6. The literature review holds a significant role in research, as it aids in mapping pertinent and established intellectual information regarding the phenomenon under study (Tranfield et al., 2003). Moreover, it serves to enrich the existing knowledge base on the subject matter. Literature reviews serve different purposes. A simple literature review entails aiming to argue a position about the current state of knowledge on a topic. On the other hand, a complex literature review seeks to identify a research problem for further study (Machi and McEvoy, 2016). Systematic reviews diverge from traditional narrative reviews through their adoption of a replicable, scientific, and transparent process – a comprehensive methodology that seeks to minimize bias (Tranfield et al., 2003). This involves exhaustive literature searches encompassing published studies, while also providing an audit trail of the reviewer's decisions, procedures, and ultimate conclusions.

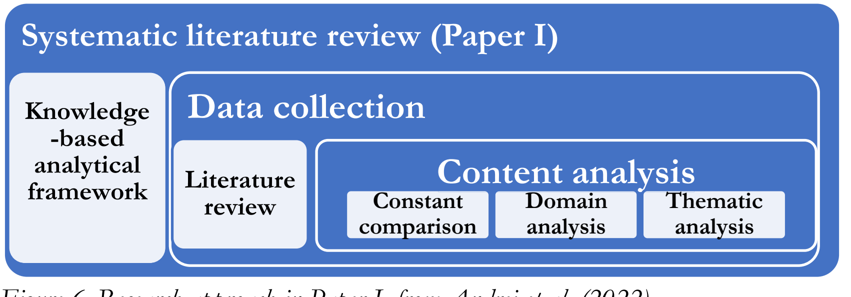


Figure 6. Research approach in Paper I, from Andrei et al. (2022)

Because of the exploratory nature of the systematic review, a research aim and objectives were formulated instead of a hypothesis, as recommended by Yin (2018). In order to fulfill the aim and the objectives of the systematic literature review, the answers were searched for in all the peer-reviewed scientific articles (original and reviews) on industrial energy management in the manufacturing industry published between 2010 and 2020 that fulfilled the chosen search criteria. Studies which did not fulfill the criteria were excluded based on a pre-determined exclusion criterion. The literature was reviewed following a six-step process, and a knowledge analytical approach was applied to the review. A knowledge-based framework was developed to understand the model for knowledge that has developed industrial energy efficiency to current levels, and to enable analysis of the model in the current context of transition. The generalizations and conclusions were based on the content of the reviewed articles.

5.4.2. Case study with participatory action research

Case studies are a qualitative method commonly used in research methodologies in the energy field (Schulze et al., 2016). According to Yin (2003) case studies are an "empirical inquiry that investigates a contemporary phenomenon within its real-life context (…)"(Yin, 2003, p. 13). The distinctive need of case study research arises out of the desire to understand complex social phenomena. When designing a case study, the rationale, purpose, and research approach are essential. In this thesis, the case study research approach from Paper II is illustrated in Figure 7.

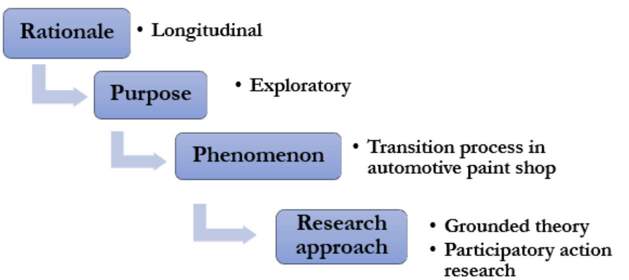


Figure 7. Case study research approach employed in Paper II

In case study design, a fundamental differentiation is made between single-case and multiple-case study designs. The single-case study proves suitable under various circumstances, with longitudinal single-case as one rationale (Yin, 2018). In this thesis, a longitudinal case study (Paper II) was conducted in a Swedish automotive paint shop in order to explore the transition process by focusing on the implementation of energy efficiency and decarbonization measures. Figure 8 illustrates the longitudinal timeline for investigating the process of implementing decarbonization measures in the studied automotive paint shop. The investigation started in November 2019 and continued until March 2023. Over this period, three main stages of the research took place.

The longitudinal case involved examining the case at multiple points in time, choosing predefined time intervals to follow the developmental course of interest, as suggested by (Yin, 2018), for exploratory cases which aim to clarify relationships between variables.

Figure 8. Timeline for studying the process of implementing decarbonization measures (from Paper II)

Another classification of case studies is by method, an approach often overlooked in qualitative research due to the fact that researchers view case study as a methodology in its own right (Savin-Baden and Howell Major, 2013). Therefore, case studies can have different research approaches, e.g., grounded theory and action research (Savin-Baden and Howell Major, 2013). When a case study is blended with different methods, it creates a more holistic, contextual, descriptive, and concrete approach. The methodology approach for the case study is illustrated in Figure 9.

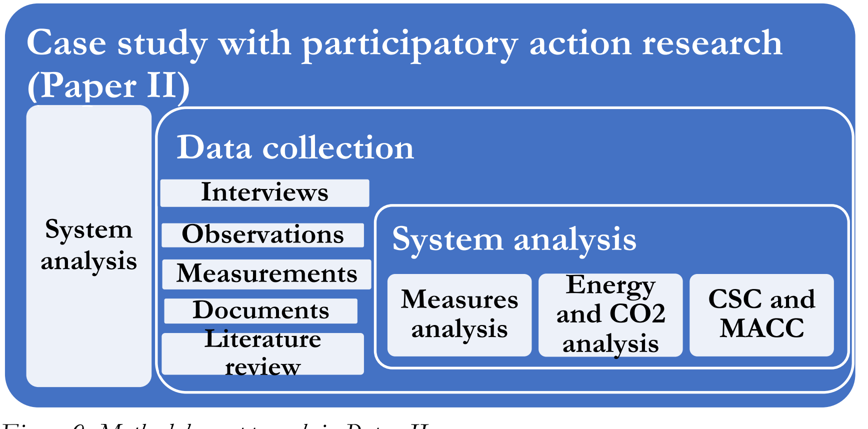


Figure 9. Methodology approach in Paper II

In Paper II, a grounded theory and participatory action research approach was applied. Participatory research is a research approach connected with knowledge co-production or co-creation research which has become prominent over the past 40 years (Norström et al., 2020). Knowledge co-production research emerged as a response to the complexity and social relevance of climate change challenges (Norström et al., 2020). This approach was applied in order to understand the processes in the Paint Shop, the possible decarbonization measures for paint shops in particular, and to ground the analysis in the data itself (Strauss and Corbin, 1990; Wertz et al., 2011), not in theories. Grounded theory and case studies have been used in combination by several authors, in different disciplines, see, e.g., Halaweh et al.(2008) and Al Adwan (2017).

Action research is a collaborative type of research aiming to "*engage in problem solving through a cyclical process of thinking, acting, data gathering and reflection*" (Savin-Baden and Howell Major, 2013, p. 245). It is a useful tool for researchers who want to solve real world problems in a collaborative fashion by examining a practical situation, make a change and explore the consequences of that change (Savin-Baden and Howell Major, 2013). In a pragmatic research paradigm, like the one employed in this thesis, the researcher and practitioners work together to identify the primary problems, defining the problem after dialogue through reaching a common understanding (Savin-Baden and Howell Major, 2013). Participatory action research is a method of intervention, development and change conducted with groups, and involves exploring an issue systematically from the perspective of the members most affected by the issue (Savin-Baden and Howell Major, 2013). Therefore, the research approach is conducted with people and not on people, and challenges that notion that legitimate knowledge lies only with the dominant knowledge of the privileged experts. It acknowledges that knowledge should be developed in collaboration with expert knowledge and the voices of the 'knowers' (Savin-Baden and Howell Major, 2013). Participatory action research is applied to generate knowledge that informs action. Negotiated participation and the development of shared understanding are central to this method.

5.4.3. Evaluation studies

In this thesis, two papers (Paper III and Paper IV) deal with evaluation: the evaluation of energy efficiency policy programs and of the industry-related voluntary initiatives. The methodology approach in Paper III is illustrated in Figure 10. Evaluation is a process of studying an activity in order to improve or change it, and can take several forms, such as utilization-focused evaluation (as seen in Paper III) and traditional evaluation (as seen in Paper IV) (Savin-Baden and Howell Major, 2013).

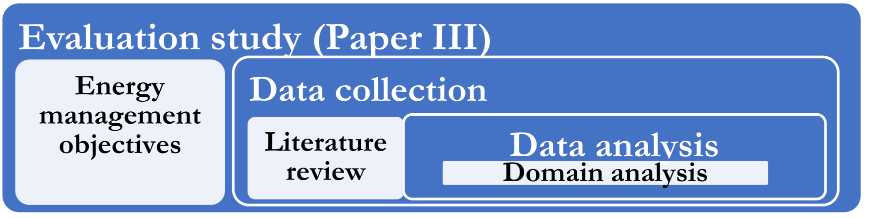
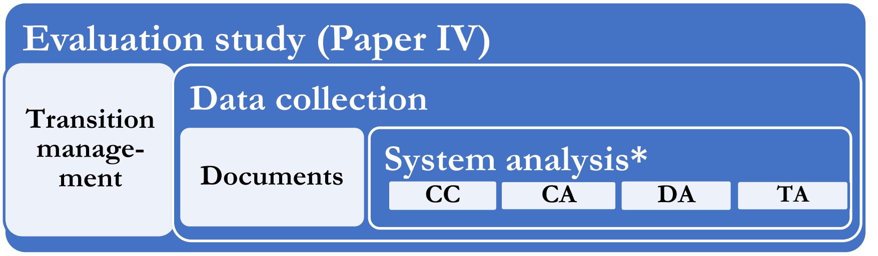


Figure 10. Methodology approach in Paper III, from Andrei et al. (2021)

In Paper III, guidelines for utilization-based evaluation were developed. Utilization-focused evaluation was developed by Patton (1997), who argued that evaluation is "…done for and with specific, intended primary users for specific intended uses" (1997, p. 23). Hence, the characteristic of this approach is that it must have impact, not just usefulness, and thus utility and decision-making are the most important parts of the evaluation (Savin-Baden and Howell Major, 2013). The guidelines for the ex-ante evaluation developed in Paper III involved gathering information about energy efficiency policy programs, policy process and policy evaluation. This started with establishing the framework for the guidelines, based on corporate and energy management. The guidelines for evaluation were developed with the aim of supporting policymakers and evaluators in identifying whether the policy program needs to be changed and how the objective of the policy program can be achieved. Paper IV applied a traditional evaluation, and the approach is illustrated in Figure 11.



**CC=constant comparison; CA = content analysis, DA=domain analysis; TA= thematic analysis*

Figure 11. Methodology approach in Paper IV

Traditional evaluation is frequently used today both in qualitative and quantitative approaches (Savin-Baden and Howell Major, 2013) and involves setting goals and objectives, developing measurement instruments, measuring achievement of goals and objectives, and then comparing them and making recommendations (Stark and Lattuca, 1997). In Paper IV evaluation of the theoretical potential of industry-related voluntary initiatives to bridge the ambition gap for industrial decarbonization was conducted. Based on the transition management framework, eighty-three global industry-related state- and non-state actors-led voluntary initiatives are analyzed according to the following criteria: establishment of VI's arena, establishment of VI's agenda, implementation of VI's activities, and VI's accountability mechanisms.

5.4.4. Survey study

Surveys are a research method concerned with gathering information from a population on a specific subject (Thiel, 2014). In this thesis, Paper V conducted a survey study on the adoption of digital technologies for energy efficiency in the Swedish manufacturing industry. The methodology approach is illustrated in Figure 12.

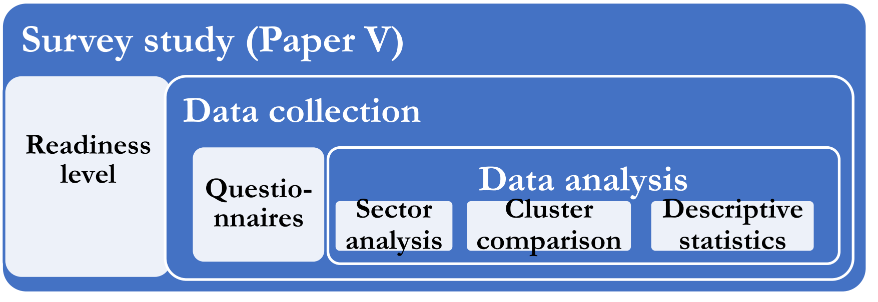


Figure 12. Methodology approach in Paper V

The targeted companies are large companies (NACE C.10-C.33) subject to the requirement to undergo an energy audit every four years according to the Energy Efficiency Directive (European Commission, 2012) and which reported their audit to the Swedish Energy Agency during the period 2017–2021. The sectors are listed in Table 7. The total number of manufacturing companies that reported their energy audit to the Swedish Energy Agency between 2017 and 2021 is 532. Below are company populations for each surveyed sector, categorized by their predominant activity within the sector.

Table 7. Surveyed sectors in Paper V

Sector categorization for analysis	NACE codes	Population number
Textile, clothing, and leather	C13-C15	7
Printing and reproduction of recorded media	C18	7

Manufacture of basic precious and other non-ferrous metals and casting of metals	C24.4-C24.5	10
Pharma	C21	11
Furniture	C31	12
Iron and steel	C24.1-C24.3	18
Manufacture of other non-metallic mineral products	C23	22
Wood	C16	29
Plastics and rubber	C22	43
Pulp and paper	C17	45
Chemical	C20	49
Food and beverages	C10-C11	64
Engineering	C25-C30, C32	215

The study used a mixed methodology, combining analysis of the literature to build a maturity model, plus a survey study for implementing the model. The maturity model followed a methodology inspired by De Bruin et al. (2005), involving a design phase and an implementation phase, where a survey based on the resulting model was conducted among manufacturing companies.

5.5. Analytical frameworks

In this thesis, several analytical frameworks were developed in order to analyze the data. In Paper I, a knowledge-based framework was developed with inspiration from the main Aristotelian concepts of knowledge. In Paper IV, a conceptual framework inspired by the transition management theory was developed and, in Paper V, a maturity model was developed to assess the readiness level for Industry 4.0 digital technologies for energy efficiency in the manufacturing sector.

5.5.1. Knowledge based framework

Paper I involved the development of a knowledge-based framework that enables the understanding of the model for knowledge that has taken industrial energy efficiency to current levels, and the analysis of the model in the current context of industry transition. Addressing the current industrial transformation requires moving beyond traditional knowledge toward new forms of knowledge that maximize the potential for adopting new and radical innovations. Doing so requires, first, an understanding of the model for knowledge that has taken industrial energy efficiency to current levels, and then an analysis of the model in the current context of transition, but also for the future. The framework consists of three broader forms of knowledge and specific knowledge attributes that can capture the knowledge employed in industrial energy management. The framework is applied in a systematic literature review, analyzing, and categorizing the forms of knowledge and key aspects of energy management in manufacturing industries. The framework was developed by the thesis author and is illustrated in Table 8.

Table 8. Main attributes of the knowledge-based framework used for analyzing the articles on EnMMI, from Andrei et al. (2022)

Attributes of knowledge	**Translation of Aristotelian concepts for EnMMI**		
	Technē Technical knowledge	***Epistēmē Process knowledge***	***Phronēsis Leadership knowledge***
Type	Descriptive: *practical 'know-how' and 'know-what'*	Procedural: *theoretical 'know- how'*	Reasoning: *practical and theoretical 'know-why'*
Mode	Tacit	Explicit	Tacit and Explicit
Characteristics	Pragmatic, variable, context dependent. Oriented toward production	Universal, invariable, context independent. Oriented toward universal truths about processes	Pragmatic, variable, context dependent. Oriented toward action
Rationality	Based on practical rationality governed by a conscious goal	Based on analytical rationality	Based on practical value rationality

5.5.2. Framework for assessing VI's potential

In Paper IV, an analytical framework is developed for scrutinizing the VIs through the transition management framework (TMF). The system-level analysis provided by the TMF is the main contribution in the evaluation of the VIs' potential. TMF provides the analytical lens that enables assessment of complex societal issues at different levels and development and implementation of strategies that influence the direction and speed of transitions toward decarbonization. The framework enables the analysis of the theoretical potential of industry-related voluntary initiatives to bridge the ambition gap for industrial decarbonization and is illustrated in Table 9. The framework was developed by the thesis author.

Table 9. Framework and main criteria for VI system level analysis, based on the work of Loorbach (2010, 2007), as illustrated in Paper IV

TM framework levels	***Translation of TMF into VIs framework for system analysis***		***Analysis outputs per each level***
	VIs main activities	**Main criteria for VI analysis**	
Strategic	Establishment of VIs arena	• Dominant organizations • Focus area • Geographical focus • Vision • Goals • Membership • Focus sector • Types of funding	• Overview of VIs arena
Tactical	Establishment of VIs agenda	• VIs characteristics • Pathways • Level of commitment	• A high/low evaluation of commitments*
Operational	Implementation of VIs activities	• Operationalization • Concrete activities	• Models of VIs operationalization and activities
Reflexive	VIs accountability mechanisms	• Monitoring • Reporting • Evaluation	• A strong/weak evaluation of accountability mechanisms**

* Measurable commitments (e.g., including % and deadline for all members) are marked as high, with the rest as low
** Transparent and goal-oriented accountability frameworks are marked as high, with the rest as low

5.5.3. Maturity model

In Paper V, a maturity model was developed to assess the maturity level for the adoption of digital technologies for energy efficiency in the Swedish manufacturing sectors, as illustrated in Figure 13.

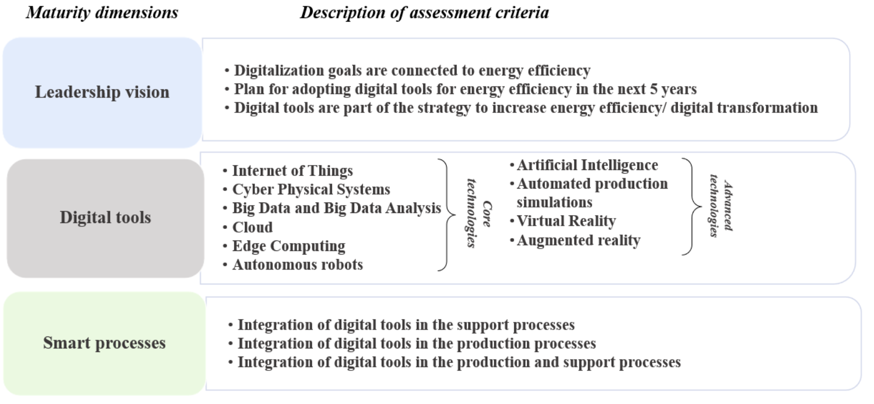


Figure 13. Maturity model for assessing the adoption of digital technologies for energy efficiency (from Paper V)

The model targets manufacturing companies involved in energy efficiency and digital transformation that aim to increase their awareness of digital technologies and maturity levels, as well as academic researchers interested in the manufacturing sector's digital transformation. It is designed for evaluation by academia and for self-evaluation by companies. The maturity model quantifies and qualifies maturity levels using three dimensions: leadership, digital technologies, and smart processes, plus a total of eight assessment criteria. Maturity dimensions represent key aspects of adopting Industry 4.0 digital technologies for energy efficiency and group the assessment criteria. The leadership aspect includes the strategic plan that a company adopts regarding digital technologies for energy efficiency. The digital technologies dimension reflects the adoption of core and advanced digital technologies for energy efficiency, and the smart processes dimension refers to the implementation of digital technologies in support and production processes. Assessment criteria are identified for each dimension. The criteria are adapted to achieve different development levels and serve as a foundation for providing recommendations for manufacturing organizations on how to evolve into mature entities regarding the adoption of digital tools for energy efficiency.

5.6. Mixed methods for data gathering

5.6.1. Literature review

In this study, Papers I, II and III have used literature review as the method for data collection. In Paper I, data was gathered through a systematic literature review approach. The search was conducted in Web of Science and Scopus databases by using the search strings illustrated in Paper I. After applying the search strings, selection criteria were established as described in detail in Paper I. The search process is illustrated in Figure 14.

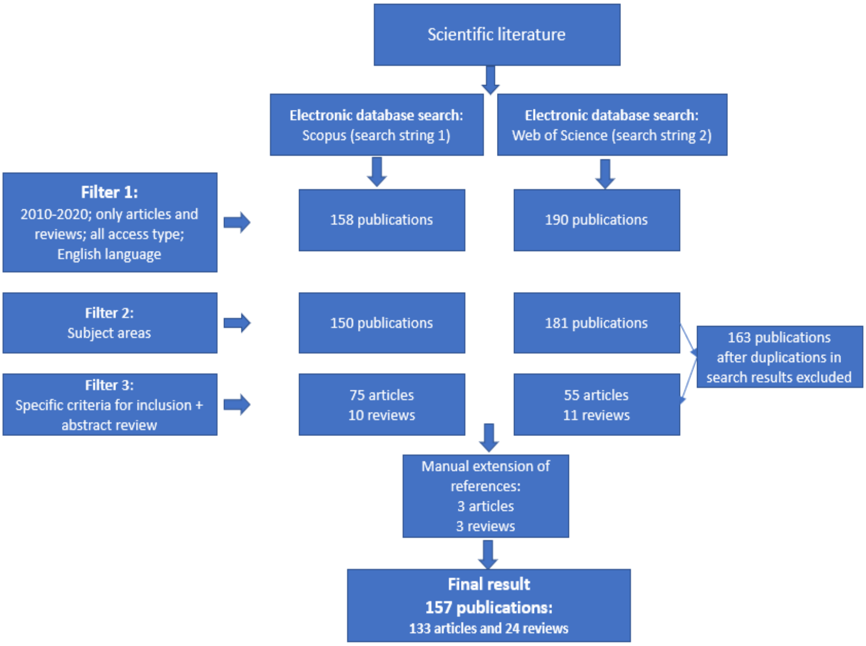


Figure 14. Search process applied in Paper I, from Andrei et al. (2022)

In Paper II data regarding potential energy efficiency and decarbonization measures for the paint shop was sourced through literature review. Searches were conducted in Web of Science and Scopus and 24 articles were found suitable for analysis. A series of search strings was used in order to identify the articles.

Paper III involved a literature study regarding the types of energy efficiency policy programs, energy audit standards, and policy process and evaluation. Data was collected on the most commonly deployed policies for energy audits and on the energy efficiency programs implemented in Scandinavia. Data for the policy process was focused on the common model of input-output and on the following type of analysis:

- analysis of policy process: how it is being implemented, how problems are defined, agendas are set, and policies are formulated and evaluated.

- analysis in and for policy process: the use of analytical techniques and research in problem definition, decision- making, evaluation and implementation.

Information was gathered about the types of policy evaluation: summative (ex-post) and formative (ex-ante) policy program evaluations. Furthermore, a review of energy management objectives was conducted in order to gain an understanding of the principles and how they can support the development of guidelines for ex-ante policy impact evaluation. This data laid the foundation for developing the guidelines for ex-ante policy impact evaluation.

5.6.2. Interviews

In Paper II, interviews were conducted for collecting data. Interviews are the main research approach in qualitative research and the central method for data collection (Savin-Baden and Howell Major, 2013). The interviews were conducted with stakeholders from the organization, in particular with the members of the energy team. Between November 2019 and June 2022 (during the stage 1 of the longitudinal case study), nine interviews (as seen in Table 10) were carried out with the members of the energy team responsible for the work with energy management and decarbonization of the Paint Shop. All interviews were held on the site, in English, and notes were taken during the interview. The interview guide provided questions and structure, while allowing follow-up questions. All the interviews were conducted by the author of this thesis.

Table 10. Data collection (interviews) in Paper II

#	Date	Type	Role of the interviewee
1	October 2020	Interview	Responsible for the energy group: production engineer
2	October 2020	Interview	Responsible for real estate– external
3	October 2020	Interview	Manufacturing engineer in welding
4	October 2020	Interview	Head of Finance
5	October 2020	Interview	QES Manager
6	October 2020	Interview	Preventive maintenance
7	October 2020	Interview	Responsible for the energy group: EHS engineer
8	December 2021	Interviews	Responsible for the energy group: production engineer
9	December 2021	Interviews	Responsible for the energy group: EHS engineer

5.6.3. Participatory observations

Paper II included participatory observations, also referred to as active participations, carried out between November 2019 and March 2023 in an automotive Paint Shop. As a data collection method, observation is considered the best way to gain an understanding of the context (Savin-Baden and Howell Major, 2013) and it is considered the "fundamental base of all research methods" (Adler and Adler, 1994, p. 389). Following Savin-Baden and Howell Major's (2013) classification, the active participation conducted in Paper II is categorized as illustrated in Table 11.

Table 11. Categorization of observations conducted in Paper II, based on Savin-Baden and Howell Major (2013) classification

Categories	Criteria	Description	Application in Paper II
Extent of the observation	Focused observation	Participant's responses from interviews guided the research	• Meetings with the members of the energy team took place in order to explore and discuss the challenges and the measures for decarbonization • The interviews offered a focused theme that was explored throughout the study
	Selective	Focus on specific types of activities	Specific focus on the regular energy team meetings, where the current measures under implementation were discussed by all the members involved
The way in which it is conducted	Structured	Predetermined observation protocol derived from theory or research	A combination of these two forms of observation was employed. It was structured in the sense that it had a predetermined observation protocol, but it was constantly updated based on the evolution of work on the topic. The
	Unstructured	Observation is based upon what stands	

		out to the researcher	Paint Shop is characterized by a fast pace of events and decisions related to energy management work for decarbonization.
Duration	Years	Common for ethnographic research	November 2019 – March 2023

The data collection took place in multiple ways: through fieldwork visits and meetings with members of the Energy Group. During these visits, participation in the Energy Group meetings was one way to collect data. Furthermore, meetings with the personnel in charge of the Energy Group took place in a collaborative manner in order to gain insights into their work and collect data for study. Table 12 provides an account of all the visits when data was collected in multiple ways.

Table 12. Data collection Paper II (meetings and participatory observation)

#	Date	Type	Participants involved
1	November 2019	Meeting for data collection	Responsible for the energy group: production engineer and Environment & Health & Safety (EHS) engineer
2	December 2019	Energy group meeting	Members of the energy group
3	October 2020	Fieldwork visit and participatory observation in the energy group meeting	Responsible for the energy group: production engineer and EHS engineer; Members of the energy group
4	December 2021	Fieldwork visit and participatory observation in the energy group meeting	Responsible for the energy group: production engineer and EHS engineer; Members of the energy group
5	February 2022	Online meeting for data collection	Responsible for the energy group: production engineer and EHS engineer

6	February 2022	Online meeting for data collection	Responsible for the energy group: production engineer and EHS engineer
7	August 2022	Fieldwork visit for update and data collection	Responsible for the energy group: production engineer and EHS engineer;
8	October 2022	Online meeting for data collection	Responsible for the energy group: production engineer and EHS engineer
9	March 2023	Online meeting for update and data collection	Responsible for the energy group: production engineer and EHS engineer;

5.6.4. Documents

In this thesis, Papers II and IV gathered data from different types of documents. The data from documents can provide a richer and more accessible source of information for understanding the studied participants and the research context (Savin-Baden and Howell Major, 2013). Data gathering from documents can be the sole method applied or it might be combined with other forms of data. Hence, in Paper II, data gathering from documents was conducted in combination with data gathering from observations, interviews, and literature. The types of documents may include public documents (e.g., articles, published strategies, reports), practical documents (e.g., those written by members of a community or organization), and files (e.g., statistical records, computer files)(Savin-Baden and Howell Major, 2013).

There were two types of documents collected for Paper II, external and internal documents. The external type of document comprises company's annual report and sustainability roadmap, as well as its roadmap for sustainable operations. With regard to internal documents, the following types were collected: energy reports conducted for the period 2017–2021, reports regarding energy use, energy management work, energy efficiency measures, key performance indicators; own logging of energy use, actions and measures undertaken under the energy management group; reports regarding the production processes. The author of this thesis has had open access to all these types of documents throughout the entire period of study. In Paper IV, data was gathered from academic literature, reports, VIs' webpages, and VIs' official public documents, such as initiative reports, adherence, and commitment declarations.

5.6.5. Databases

In Paper IV, data gathered for each voluntary initiative was triangulated with the data existing in two data bases: the UNFCC Global Climate Action portal of cooperative initiatives (UNFCCC, 2021) and the UNEP Climate Initiatives Platform (UNEP, 2014), in order to develop a comprehensive understanding of and information on the phenomena.

5.6.6. Questionnaire

In Paper V, data regarding the adoption of digital technologies for energy efficiency by the Swedish manufacturing industry was collected using an online questionnaire. Questionnaires offer an organized and quick way to gather data about a phenomenon from a specific population (Groves et al., 2004). The questionnaire was sent to 358 manufacturing companies. Eight questions were developed to explore the following aspects in manufacturing companies: i) the adoption of digital technologies in their strategy or goals for energy efficiency, and ii) the types of digital technologies used in the support and production processes. The questionnaire included three open-ended questions. This allowed for coherence and consistency in validating the answers. There were also five multiple-choice questions, with one of them using a Likert scale ranging from 1 (unimportant) to 5 (important). The online questionnaire was sent via e-mail to organizations in two rounds.

5.7. Mixed methods for data analysis

5.7.1. Qualitative content analysis

In Paper I, qualitative content analysis was applied to analyze the data collected through systematic literature review. Content analysis is the process of examining the content of a text with regard to the patterns, frequency, and use of terms or phrases (Savin-Baden and Howell Major, 2013). In Paper I, the data gathered from 157 articles was first categorized between original articles and review articles. Next, the data was categorized, coded, and classified in themes and domains. The process for category development and selection was carried out in an inductive way, where papers were read again and again, and categories were developed during the coding process to allow identification of main aspects of EnM in manufacturing. Similar main aspects and categories were gathered into three overarching themes: technical knowledge, process knowledge and leadership knowledge. In order to clarify the content analysis communicatively, the categorization of papers on each form of knowledge was based on the main aim of the studies. After all the relevant articles were identified, a data extraction form was constructed in a Microsoft Excel worksheet, where articles were coded according to i) knowledge themes, ii) categories, iii) main aspects of EnM in manufacturing industries, iv) year, v) journal, vi) sector, and vii) database. The articles were compared and further categorized on manufacturing system levels: machine, process, line/multi-machines, and factory/organization, inspired by the works of Apostolos et al. (2013) on levels for EE in manufacturing systems and Duflou et al. (2012) on the decomposition of manufacturing systems.

5.7.2. System analysis

In Paper II, a system analysis was conducted. The system represents the paint shop, and the analysis was conducted in three steps: measures analysis, energy and GHG analysis and economic analysis. During the measures analysis, potential and specific energy efficiency and decarbonization measures were identified and their potential application for the paint shop was assessed. The measures were categorized as i) energy efficiency measures, ii) process optimization measures, iii) process innovation measures, iv) fuel conversion measures, v) local electricity production measures and vi) mixed measures. To understand the technological change taking place in the Paint Shop, the measures were analyzed, and categorized based on the innovation level and knowledge attributes. Furthermore, the analysis is built on the knowledge framework for energy management described under sub-section 5.5.1. which makes a distinction between three types of knowledge forms for the adoption of radical and incremental innovations: epistēmē, phronēsis and technē.

During the second step of analysis, the production and support processes were categorized based on the unit process concept (1996), and a taxonomy was developed for automotive paint shops at a general level. The taxonomy of processes has enabled assessment of the EEU at the processes level and technologies within the studied system, as well as analysis of energy flows among different processes. An energy mapping at process level has been compiled based on the previous energy audit report and collected data (Rohdin et al., 2022). The energy use was divided into current energy carriers: liquefied petroleum gas (LPG), electricity (EL), and district heating (DH). The allocation of GHG emissions was performed following the taxonomy for production and support processes using the attributional approach.

The third step analyzed the cost of conserved energy (CCE) and cost of carbon reduction (CCR) for energy efficiency and fuel switching measures implemented between 2014 and 2023 in the Paint Shop. Both energy efficiency and carbon reduction measures were illustrated within their specific processes. Data was illustrated using energy conservation supply curves (ECSC) and marginal abatement cost curves (MACC), per process and energy carries. Furthermore, the data regarding CCE and CCR was illustrated using quality management tools, such as the Pareto chart, where the percentage of accumulated energy and carbon savings for the implemented measures was plotted against the goal.

ECSCs and MACCs have been widely used to study energy efficiency and GHG mitigation options for different industry sectors. ECSC is a helpful tool for visualizing the economic and technical potential of energy efficiency (Huang et al., 2022). ECSCs illustrate the cost associated with mitigating one unit of energy. The curve is shaped like a ladder, where each step represents one conservation measure, showcasing those conservation options with the lowest costs and the highest savings potential (Fleiter et al., 2009). The conservation options with negative costs mean that their implementation would generate net-profits and are referred to as cost-effective measures (Huang et al., 2022). The CCE is estimated as shown in equation (1) based on Fleiter et al. (2009) and Huang et al. (2022).

$$CCE = \frac{(I \times CRF + O\&M - B)}{\Delta E} \qquad [1]$$

I represents the investment cost [EUR] for a given energy efficiency measure (EEM); *CFR* represents the capital recovery factor calculated using Equation (2) and *O&M* indicates the annual operating and maintenance costs. *B* is the annual benefit [EUR] determined using Equation (3) and ΔE represents annual energy savings [MWh/year].

$$CRF = \frac{(1+r)^L \times r}{(1+r)^L - 1} \qquad [2]$$

where *r* is the discount rate and *L* is the lifespan of the EEM

$$B = [(\Delta E \times P_e) + (\Delta C \times P_{CO2})] \qquad [3]$$

B is determined by implementing EEM based on P_e (the price of electricity, LPG, or DH) plus the sale of CO_2; and ΔC indicates the annual reduction in carbon emissions [$tCO_2eq.$] determined as in Equation (4) and PCO_2 represents the current market value of CO_2 [EUR/$tCO_2eq.$].

$$\Delta C = \Delta E \times ELEF \quad [4]$$

ELEF represents the EF for electricity, LPG, or DH in tCO_2eq.

The MACC is calculated for the same set of energy efficiency and carbon reduction measures and follows the same underlying concept as that of the ECSC. The specific costs of a carbon reduction (CCR) measure can be calculated as follows (Huang et al., 2022):

$$CCR = \frac{(I \times CRF + O\&M - B)}{\Delta C} \quad [5]$$

where ΔC indicates the annual reduction in carbon emissions [$tCO_2eq.$] determined in a similar way as in the case of ECSC.

In Paper IV, a system analysis was conducted on the design of voluntary initiatives with respect to the theoretical potential to bridge the ambition gap for industrial decarbonization. The analysis was conducted based on a framework developed from and inspired by the transition management theory. After the data collection, for analytical purposes, the types of leading organizations are aggregated into two main categories: state actors (including governments and intergovernmental organizations – IGOs) and non-state actors (such as industry and non-governmental organizations - NGOs). VIs led by more than one organization are categorized under the main leading organization. A data extraction form was developed in a Microsoft Excel file, where VIs started to be categorized based on the initiative name, leading organization, focus area and year of establishment. The data extraction form was then further developed to include the necessary content for VI evaluation. VIs were categorized based on the main criterion from the analytical framework. However, in order to enable VI analysis, first, the VIs' main characteristics and pathways were gathered into overarching themes, such as commitments, collaborations and standard and certifications. The system level analysis of the eighty-three industry-related voluntary initiatives was performed in line with criteria related to the creation of an arena and agenda, operationalization, and accountability. Their content was analyzed using the constant comparison method. The data handling and analysis was conducted by the author of the thesis.

5.7.3. Domain analysis

Domain analysis was applied in Paper III. Domain analysis is a data analysis method whereby the domain includes various categories that share a relationship (Savin-Baden and Howell Major, 2013). The process of data analysis in Paper III started with dividing the categories of the guideline for ex-ante policy evaluation into meaningful segments, based on the objectives of energy management as proposed by Capehart et al. (2016):

- To improve energy efficiency and reduce energy use and costs
- To reduce GHG emissions
- To cultivate good communication on energy issues
- To develop and maintain effective monitoring, reporting and management strategies for wise energy usage.

This was followed by a process of developing guidelines using an abductive approach.

5.7.4. Sector and cluster analysis

In Paper V, the data analysis of the questionnaire responses was conducted at both sector and cluster level. The measurement and determination of each company's maturity was conducted per sector, following five steps. Step 1 evaluated the assessment criteria, while step 2 established the weighting factor for each dimension: leadership vision, digital technologies, and smart processes. Under step 3 data sets for dimensions with different scales were normalized to a range of 0 to 5 to allow for calculation of maturity levels. In step 4, the maturity level was calculated for each company and sector. To minimize the impact of potential misunderstandings in the survey responses, the free-text answers were compared with the ratings given by companies for different statements. If there was a discrepancy between the free-text answer and the corresponding rating question, the rating answer was adjusted based on the free-text response. Step 5 involved visualizing maturity levels via a heat map chart, bar charts and cluster analysis. At sector level the data was analyzed using a heat map chart in order to illustrate the adoption rates of digital technologies in different sectors, and the color scale indicates how each industry compares to the average adoption rate. Bar charts were used to analyze and illustrate the adoption of core and advanced technologies per production and support processes, and to illustrate the maturity level score of each sector. This cluster analysis was conducted to group companies based on their maturity level. Cluster analysis resulted in the identification of four homogenous groups, allowing us to distinguish four clusters: traditional, learners, achievers, and leaders. Descriptive statistics were conducted for each cluster and the scores for each cluster were illustrated via boxplots.

5.8. Adapting research methods

This research partly took place during Covid-19 pandemic, which has influenced the possibilities to conduct field work. When conducting field work, the researcher needs to be prepared to adapt the context of the field and adjust to the changing reality. However, the Covid-19 has forced this research to take a different path than the initially planned one. In early 2019 the plan was to conduct multiple case studies in Swedish manufacturing industry using participatory research. For this, companies have started to be contacted and the author of this thesis started joining the national Swedish Energy Management Network meetings in order to identify cases and negotiate access. Three companies from the automotive, metalworking and petroleum sectors were identified, and access was granted at two of them. In November 2019 the first study visit started at the automotive paint shop followed by the first visit at the metalworking company in December 2020. In spring 2020, though, the visits to the companies had to stop due to the pandemic restrictions and were replaced with online meetings.

This has influenced the possibilities for data collection, hence changing the data collection methods and the overall research approach. This has led to adopting an exploratory approach where the next studies were based on the current findings. After some time, the company from the automotive sector has given access to their internal documents related to energy use and energy management work. This collaboration and access to their internal loggings and documents lasted until March 2023. Participatory research at the metalworking company also changed to online meetings, however these research findings not turned out to be part of this thesis. Getting access to the petroleum company took more than a year and succeeded after many rounds of negotiations where the other PhD student part of the project was the driver. Only one interview was possible to conduct there and took place with the energy manager and the process engineer and a conference paper was written which belongs to the "other publications" of this thesis.

5.9. Reflections on quality of research

In this thesis data was collected from interviews, questionnaires and documents that expressed the subjective views of involved people, including the author of this thesis, so there might be an inherent bias that could affect the analysis. To minimize this possible bias, methodological triangulation (Miles and Huberman, 1994) was used as much as possible. Methodological triangulation was also used to develop a comprehensive understanding of the phenomena under study (Patton, 1999) and to obtain reliable and valid results.

The use of interviews for data collection has enhanced the idea that interviews are a mutual dialogic creation of understanding (Kvale, 2007). This concept of mutuality was applied between the interviewee and the interviewer. In the use of the interviews, the understanding of Silverman (2013) prevailed, who claimed that interviews can be seen as manufactured data, acknowledging the significance of interpretation and analysis when considering the accounts provided by the interviewees. Furthermore, it is important to be aware that interviews do not provide a true depiction of the event but rather only how people account for that event. Interviews should be perceived as observations of interactions between two individuals: the interviewer and the person being interviewed, as described by Czarniawska (2014). Therefore, I argue that interviews should be viewed as observations involving all participants. And knowledge is generated through the dynamic interactions not only between interviewers and interviewees, but also between the researchers themselves.

When performing the analysis of documents, databases and articles, the view of Patton (2002) prevailed, that analysis is both an art and a science. The 'art' aspect involves creatively applying methods to solve analytic problems and constructing coherent theories from data. The 'science' aspect entails grounding interpretations in data, with varying levels of analysis, from superficial to in-depth, which develop concepts based on properties and variations. During the interview, notes were taken to complement the audio recording. During the analysis the original recording was listened to over-and-over again and the notes of the meeting were read, and coding was conducted. Initial coding was done around the initial concept followed by looking for explanations. Furthermore, an iterative process of correcting was followed where different sources of knowledge were compared (Sandberg, 2005).

When conducting participatory action research, the practical problem to study was identified in the design phase. The problem and the findings were further investigated with theory in a literature review. Participatory action research means researching with companies rather than on companies, hence it requires good collaboration and relationships in order to get access to the particular phenomenon of study as well as to understand the tacit knowledge available in the case study (Sannö, 2017).

The case study conducted in this thesis is in line with the "information-oriented selection" strategy for selecting cases discussed by Flyvbjerg (2006). This means that this case was selected because of the expected informational content. Although a stream of researchers claim that the focus on the particular and the use of intrinsic case study is too narrow, authors such as Stake (1995) argue that this dependence on a single case study is important for theory building. This is in line also with Flyvbjerg (2006), who states that one can often generalize from a single case study and the case study may be central to scientific development via generalization, as supplement to other methods. However, Flyvbjerg (2006) also claims that formal generalization is overestimated as a source of scientific development, while "the force of example" and transferability are underestimated. Furthermore, one key strength of single case study is the use of multiple sources and techniques for data gathering and data analysis. This applies to the case study conducted in this thesis, where data was collected through interviews, observations, measurements, documents, and literature review and several data analysis methods were employed.

Doing participatory research also entails ethical reflections. The access that the research gains is not limited to the data that are tacit, such as hard facts, but also to people's feelings and own thoughts, therefore confidentiality is very important.

6. Results

This chapter presents the main findings of this thesis's papers. The presentation of the results is structured based on the three perspectives applied in this thesis: EnMPs, knowledge dynamics, design of policy evaluation and voluntary initiatives evaluation.

6.1. Industrial EnMPs supporting the energy transition

This section presents the results regarding the industrial energy management practices based on Papers I, II, IV and V, classified as follows: internal industrial energy management practices (from Papers I, II, and V) and external practices (from Paper IV).

6.1.1. Internal industrial EnMPs

The results from Papers I, II and V regarding EnMP enable further analysis that offers a detailed picture of EnMP in manufacturing industries by highlighting the characteristics of the EnMPs as illustrated in Table 13), as previously was somehow similarly conducted also by (Fleiter et al., 2012b; Trianni et al., 2019), as follows:

- *Category of EnM practice*, referring to energy conservation, energy efficiency, fuel conversion, energy supply, GHG emissions reduction
- *Type of EnM practice*, referring to the different dimensions of the practice, i.e., technology-related, process-related, and leadership-related, fuel conversion, local production
- *Area of the EnM practice*, i.e., production process, support process, organization
- *Level of implementation in the manufacturing system*, i.e., machine level, process level, line/multi-machine level, factory level
- *Type of innovation*, i.e., radical, incremental.

Table 13. Synthesis of EnMP from Papers I, II and V based on their key characteristics

EnMP Category[1]	EnMP description	EnMP type[2]	EnMP area[3]	System level[4]	Innovation type[5]
EC	Behavioral measures	Tec/Pro	PP,SP	F, P, M	Inc

	Reduce idle losses	Tec/Pro	PP,SP	F, P, M	Inc
	Program time control acc. to production	Tec/Pro	SP	F, P, M	Inc
EE	Real-time energy data monitoring, collection, and analysis	Tec	PP, SP	F, P, M	Inc
	Deployment of technology	Tec	PP	F, P, M	Inc, Rad
	Scheduling optimization	Tec	PP	F, P, M	Inc
	Optimization of robotics operation	Tec	PP	P, M	Inc
	Enhanced process efficiency	Tec/Pro	PP	P	Inc
	Discrete event simulation	Tec	PP	P	Inc
	Predictive and/or preventive maintenance	Tec	PP	M	Inc
	Data-driven tool wear models	Tec	PP	M	Inc
	Enhancing control and awareness of energy usage patterns and dynamics	Tec	PP, SP	F, P	Inc
	Optimizing tool settings and machining conditions	Tec	PP	M	Inc
	Energy performance related (e.g.,	Tec	PP, SP	M, L, P, F	Inc

	KPIs, benchmarking)				
	Machine design and selection	Tec	PP	M	Inc
	Change to LED	Tec	SP	F	Inc
	Variable speed drive	Tec	SP	P	Inc
	Analysis of efficiency potentials	Pro	PP, SP	F, P	Inc
	Energy audit	Pro	PP, SP	F, P	Inc
	Energy-aware production scheduling	Pro	PP	P, M, L	Inc
	Operational measures	Pro	PP	P	Inc
	Process modelling and optimization	Pro	PP	P	Inc
	Process planning and scheduling	Pro	PP/SP	P	Inc
	Maintenance of baths	Pro	PP	M	Inc
	Reducing temperature in baths	Pro	PP	M	Inc
	On-site data processing and analysis	Pro	PP	P, M, L	Inc
	Models and calculations for	Pro	PP	P	Inc

	understanding own processes				
	Operational efficiency, productivity, and automation	Pro	PP	P	Inc
	Control and awareness of energy usage patterns and dynamics	Pro	PP	P	Inc
	Planning and implementation of EnM	Lead	Org	O	Inc
	Strategies for improving and advancing EE	Lead	Org	F, P	Inc
	Energy strategy	Lead	Org	F	Inc
	Investment criteria for EE technologies	Lead	Org	F, P, M	Inc
	Promotion of behavioral changes	Lead	Org	F	Inc
	Training operators	Lead	Org	P	Inc
PI	New coating technology	Pro	PP	P	Rad
	Thin film technology	Pro	PP	P	Rad
	Low-curing powder	Pro	PP	P	Rad
FC	Alternative fuels	Tec/Pro	Org	F	Inc
	Electrification of furnaces	Tec/Pro	Org	F	Inc

OS	Local CHP[4]	Tec/ Pro/Lead	Org	F	Inc/Rad
CCS/CM	Specific measures for reducing GHG emissions (CCS and compensation measures)	Tec/ Pro/Lead	PP, SP, Org		Inc/Rad

Legend: (1) EC = Energy conservation; EE = Energy efficiency; PI = Process innovation; FC = Fuel conversion; OS = Own supply; CCS/CM = CCS and Compensation measures; (2) Tec = Technology-related; Pro = Process-related; Lead = Leadership-related; (3) PP = Production process; SP = Support process; Org = Organization. (4) F = Factory; P = Process; L = Line; M = Machine. (5) Inc = Incremental; Rad = Radical

In Paper I, the results show that the internal EnMPs are technology-related, processes-related, and leadership-related. Most of the focus was found to be around technology-related practices and a paradigm shift towards Industry 4.0 was identified. Manufacturing organizations have a demand for interconnected, automated, adaptive, and flexible solutions that are shaping the manufacturing system towards Industry 4.0 which encompasses internet of things (IoT), cyber-physical systems (CPS), big data, additive manufacturing, and digital simulation. The digital technologies are being implemented at the plant and production processes level, but also on manufacturing cell, robot, and tool level, showing that advanced information technology (AIT) applications are being constantly updated in order to reach the complexity of manufacturing system.

At the factory level, AIT applications enable different EnMPs which improve energy efficiency. For example, *real-time energy data collection and analysis* via IoT, CPS and big data analytics allows for monitoring and collecting real-time energy data, which is essential for EnMPs. This data enables setting measures of performance such as key performance indicators for own processes and energy use. *Scheduling optimization* based on IoT, and big data provides real-time data on machine status and production processes, allowing for dynamic

[4] Combined Heat and Power (CHP)

scheduling adjustments to optimize energy use during production. *Energy-efficient strategies* in connected virtual factories is enabled by CPS through the integration of energy-efficient manufacturing modules and assessment of technical capabilities and energy use. Another type of practice at the factory level is the *planning and implementation of EnM in organizations.* This includes integrating EnM into a company's business plan and production management, as well as developing sustainable EnM programs and assessing the performance of the EnM systems. Furthermore, *development of strategies for improving and advancing EE in manufacturing*, through different practices such as *behavior changes*, *developing corporate energy policy* and *establishing investments criteria for energy-efficient technologies* are other implemented practices.

At process level, *optimization of robotics operation* is enabled via IoT and CPS through real-time and control of robotic systems, ensuring they operate efficiently and use energy only when necessary. *Enhanced process efficiency* as well as *improvements in energy efficiency at machine and factory level* are enabled by cyber physical energy system (CPES) which integrates CPS with existing energy technologies and AIT-led innovations in the fields of machine learning, manufacturing big data analytics, cloud manufacturing, and IoT. *Discrete event simulation* helps identify bottlenecks and inefficiencies in production processes, allowing for adjustments to improve energy efficiency as well as to reduce resource and energy waste. Practices such as *operational measures, process modelling and optimization, process planning and scheduling* are common employed practices enabling solutions for energy-efficient production, as well as for improvements to performance in terms of productivity and related cost savings.

At machine level, *predictive and/or preventive maintenance* is enabled by the application of AIT. By analyzing data from sensors and IoT devices, maintenance needs can be predicted, reducing downtime and energy waste associated with unexpected equipment failures. Furthermore, *data-driven tool wear models* help predict maintenance or replacement needs in tools, reducing energy waste associated with inefficient tools. *Energy-aware production scheduling* based on machine planning is a common practice enabling energy-efficient production planning, while considering factors such as production time, machine workload, and environmental sustainability indicators, thus being an effective way to improve EE and reduce energy costs. *Optimizing tool settings and machining conditions* is a practice that reduce energy use at machine level. This is done through the use of *optimization models for cutting parameters* which determine the most efficient cutting parameter for CNC machining.

Furthermore, KPIs for *evaluating the energy performance of machine tools*, *designing and selection of machine,* and for *systematic energy use analysis and evaluation of CNC machining* are other employed practices.

In Paper II, internal industrial energy management practices are connected with the identification and analysis of energy efficiency and decarbonization measures that will help achieve the sustainability objectives of the automotive paint shop, as presented below. The EnMP are illustrated in Figure 15.

- 2021-2040
  - Minimum 2% annual energy efficiency
  - Idle 10%
- 2025-2030: Commitments to SBTs
  - 50% reduction of CO2 emissions for Scope 1 and 2
  - 30% reduction for Scope 3
- 2040: Commitments to SBTs
  - Net-zero emissions in full value chain by 2040

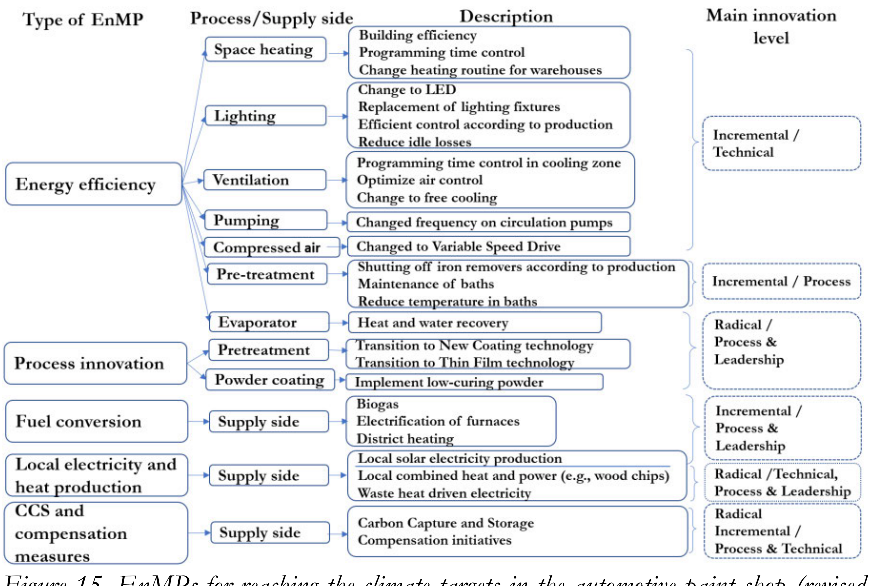


Figure 15. EnMPs for reaching the climate targets in the automotive paint shop (revised from Paper II)

The studied paint shop focuses on improving energy efficiency, aiming for an annual minimum 2% increase. Energy efficiency measures target support processes (e.g., space heating, lighting, ventilation) and production processes (e.g., pre-treatment). Initial steps include *behavioral changes* such as optimizing heating, lighting schedules, and using free cooling. These save about 4% of total energy yearly with zero investment costs. Technology-related measures in the support processes, such as using variable speed drive compressors, have yielded ca. 44% energy savings of the total energy savings per year, but required substantial investment. Energy efficiency measures in the production processes are implemented in the pre-treatment and involve *maintenance of baths* and *reducing temperature in baths*, but also *behavioral* type of measures, e.g., shutting off machines and devices according to production, working to reduce idle losses, and shutting down iron removers according to production. The energy savings from the maintenance of baths are quite low, below 0.5% of the total energy savings per year, while temperature reduction of baths saves ca. 24% of the total energy savings per year, with zero investment cost.

Process innovation type of measures represent a key area in the EnMPs in the paint shop and are connected with the pre-treatment and powder coating processes. These process innovations are radical innovations and involve collaboration among paint shop personnel, researchers, and supply chain partners. They require research, testing and scale-up. In pre-treatment, two major innovations are being explored: transitioning from electrodeposition (ED) coating technology to a more energy-efficient new coating technology that also reduces water usage, and shifting from zinc-phosphate to thin film technology which offers faster processing, less heat and chemical usage. Yet, transitioning to thin film technology in the pre-treatment process poses two significant challenges. First, there is a lack of prior knowledge within the organization about this technology, requiring a higher level of competence. Second, there's a need for better understanding and expertise in rebuilding the equipment to enhance resource and energy efficiency without compromising quality. Such a change requires deep process knowledge, strong relations with the supplier, the support of the management group, and personnel ownership. In powder coating, the focus is on implementing a low-curing powder that requires lower temperatures, but this depends on supplier innovation and product quality tests. Challenges include developing new paint characteristics and addressing high temperatures in the paint shop.

To further reduce carbon emissions in the paint shop, fuel conversion measures are available, such as switching to biogas or electrifying furnaces. Biogas is a market-ready alternative to LPG, while furnace electrification requires substantial infrastructure changes. Another option is local combined electricity and heat production using e.g., wood chips, potentially meeting current heat demands. However, it's capital-intensive with challenges like lock-in effects, fuel price uncertainty, permit testing, and ongoing monitoring of highly pressurized systems. Carbon capture and storage (CCS) can help reduce unavoidable emissions, while compensation initiatives serve as a "last resort" to mitigate emissions throughout a factory's life cycle.

In Paper V, the results regarding the EnMPs implemented with the support of digital technologies show that the focus is on *online monitoring* of energy usage, to identify areas with the highest potential for savings, establish key performance indicators, and identify abnormal energy use patterns. *On-site data processing and analysis* is another practice seen in pharma, pulp and paper, and iron and steel sectors. *Training operators* to utilize the process computers' control capabilities for paper machines is another practice in the pulp and paper sector. The iron and steel industry aims to *understand its own processes* through thermodynamic models and calculations, given the complexity of its manufacturing processes. Other practices are related to *enhancing control and awareness of energy usage patterns and dynamics*, *conducting analysis to identify efficiency potentials*, and *improving the monitoring of energy performance*. Furthermore, in sectors such as pharma, iron and steel, and aluminum their practices goes beyond energy efficiency into continuous efforts to achieve *higher levels of operational efficiency, productivity, and automation*.

6.1.2. External industrial EnMPs

Paper IV extends the idea of EnMPs in an external context. The results show that companies have new ways of working in order to achieve climate goals. Participating in a voluntary initiative (VI) which aim to increase energy efficiency and reduce CO_2 emissions is a common practice for manufacturing organizations. The analysis of the initiatives main objectives shows that the VIs led by IGOs, and NGOs focus on emission reduction, followed by energy efficiency, and more than half deployed at a global level, while the governmental and industry-led VIs focus on energy efficiency, energy productivity and emissions reduction mostly at national level. The results show that the popularity of VIs increased from 2009 until 2022, as illustrated in Figure 16.

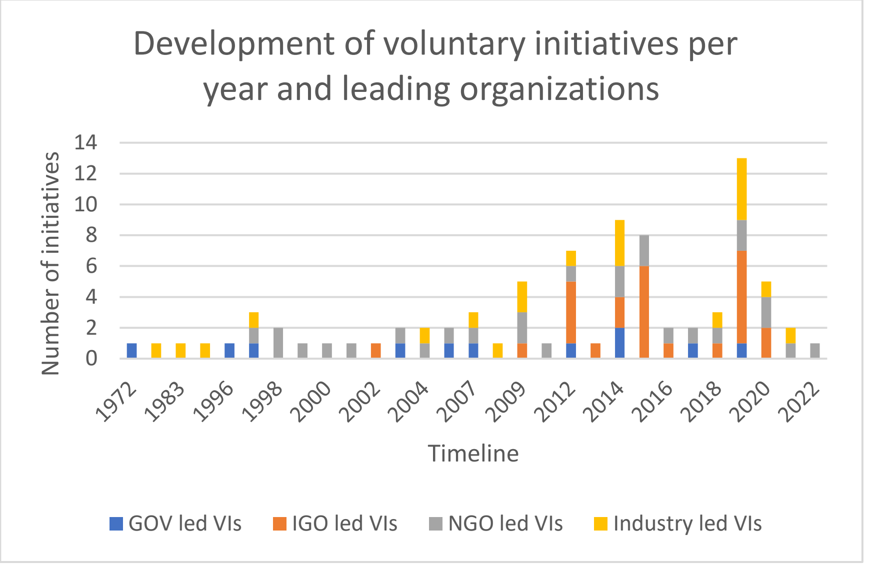


Figure 16. VIs established between 1972 and 2022(based on the analyzed initiatives, categorized per main leading organization) (from Paper IV)

Operationalization of state-led VIs can be conceptualized in three types of models: hierarchy model, direct model and impact recognition model as illustrated in Figure 17. Non-state actors-led VIs can be conceptualized in two models as illustrated in Figure 18.

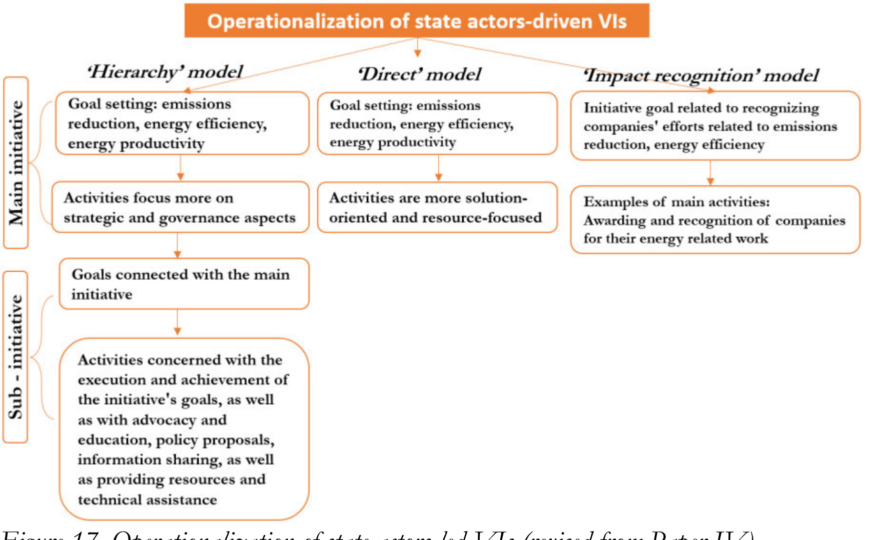


Figure 17. Operationalization of state actors-led VIs (revised from Paper IV)

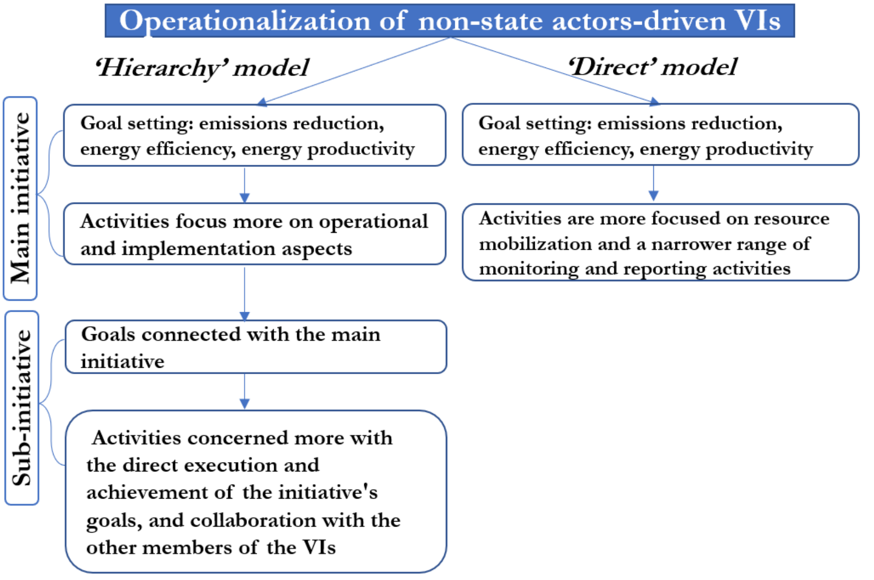


Figure 18. Operationalization of non-state actors-led VIs (revised from Paper IV)

The “hierarchy” model operates in a similar way in state and non-state actors-led VIs. In this type of VI, the primary initiative involves establishing a goal, such as emissions reduction, energy efficiency, or energy productivity, and gathering resources to support the actions of participating organizations within designated sub-initiatives. The activities of the main initiative focus on the successful management of the initiative. The participating organizations commit to VI’s overarching goal in a manner specified by the VI's design.

While activities in the main VIs, led by both state- and non-state-actors involve elements of goal setting, collaboration, implementation, and reporting, they also differ. For example, in the state-led VIs the main initiatives have more of a strategic and governance approach, such as development of policy frameworks, development of governance structures, systems and processes for monitoring and reporting, as well as review and revision of activities deployment. While the non-state-driven VIs, especially industry-led VIs, focus more on operational and implementation aspects. Activities can involve development of networks, support frameworks and structures, and monitoring and reporting frameworks.

The activities of the sub-initiative also focus on goal setting, collaboration, and reporting, but the state actors-led VIs places a stronger emphasis on policy instruments, information sharing, while the industry-led VIs focus more on the execution and achievement of the initiative's goals. Examples of activities in the state driven VIs deployed under specific sub-initiatives consists of e.g., adoption of carbon pricing, emission reporting, sharing best practices, providing resources (information) and technical assistance.

The "direct" model is operationalized in the same way between state and non-state actors led VIs. Activities are related to strategy development, stakeholder engagement, collaboration, and the implementation of initiatives or programs, but they differ in terms of their overall focus and specific components. Examples of activities are e.g., strategy development, implementation of activities aligned with the initiative's goal, monitoring and reporting requirements, sharing real-world examples and best practices, and collaboration-activities. A difference in activities was seen, however. In the state-actors-led VIs, activities have an emphasis on comprehensive initiative management, including policy and advocacy aspects, and it seeks to create a supportive ecosystem for initiative success. Hence, they are more solution-oriented and resource-focused, e.g., technology deployment and climate financing. Leading organizations provide various resources, including technical assistance and support, to businesses.

In the non-state actors (NGOs)-led VIs, activities, for example, can include a combination of benchmark development for specific plants, outlining best practices for energy efficiency. Subsequently, these VIs directly engage with other plants to encourage and support them in adopting these benchmark practices. This may involve upgrading equipment to enhance energy efficiency. The progress of plants in meeting VI benchmarks is closely monitored and reported. Successful plants receive public recognition for their efforts, which not only helps build a positive reputation but also encourages other plants to adopt similar energy-efficient practices. Under industry-led VIs, the direct model concentrates on specific aspects such as resource mobilization and a narrower range of monitoring and reporting activities. Industry-led VIs are operated by an executive team solely under the control of the member companies. The process of implementing and carrying out activities are initiated and driven by private sector actors. Two specific activities for this type of VIs are: stakeholder engagement and mobilizing resources.

And in the "impact recognition" model identified in the governmental-led VIs, companies implement a specific energy-related project with measurable objectives, and based on the third-party evaluation they are awarded and certified for a number of years.

6.2. Knowledge dynamics in industrial EnMPs

This perspective aimed to investigate the forms of knowledge applied and created in energy management and how knowledge for energy management supports the transition to sustainable energy systems. First, the results regarding the forms of knowledge applied in industrial EnM in manufacturing industry from Paper I are provided together with the knowledge creation process. Second, the results from Paper II regarding the knowledge creation in practice during energy transition follow. And, finally, the results are complemented by results from Paper V which are connected with knowledge creation based on the information provided by digital technologies.

6.2.1. Forms of knowledge applied and created in EnMMI

Paper I, included in this thesis, conducted a systematic review of 157 peer-reviewed articles on EnMPs in manufacturing industry, published between 2010 and 2020 in a variety of journals, and applied a knowledge-based framework to analyze the forms of knowledge applied in energy management practices. In the context of energy transition, EnM knowledge dynamics are evolving. The main forms of knowledge (as described in Paper I and in this thesis in sub-section 4.3.1) used for the analysis of the EnMPs are technē (technical knowledge), epistēmē (process knowledge) and phronēsis (leadership knowledge).

The interplay between these knowledge streams raises questions about the potential blending of process and technical knowledge and the need for cross-disciplinary collaboration. The maturation of digitalization in EnM may lead to more complex process knowledge, necessitating multi-disciplinary teams with diverse skills and expertise. These teams could operate not only at the company level but also at the sector level, as knowledge for the energy transition is highly sector specific. One important result from this paper is that a blend in these three forms of knowledge is needed in order to implement EnMMI during energy transition when the adoption of incremental and radical innovations in terms of practices and technologies are needed to enable the energy transition. This is illustrated in Figure 19.

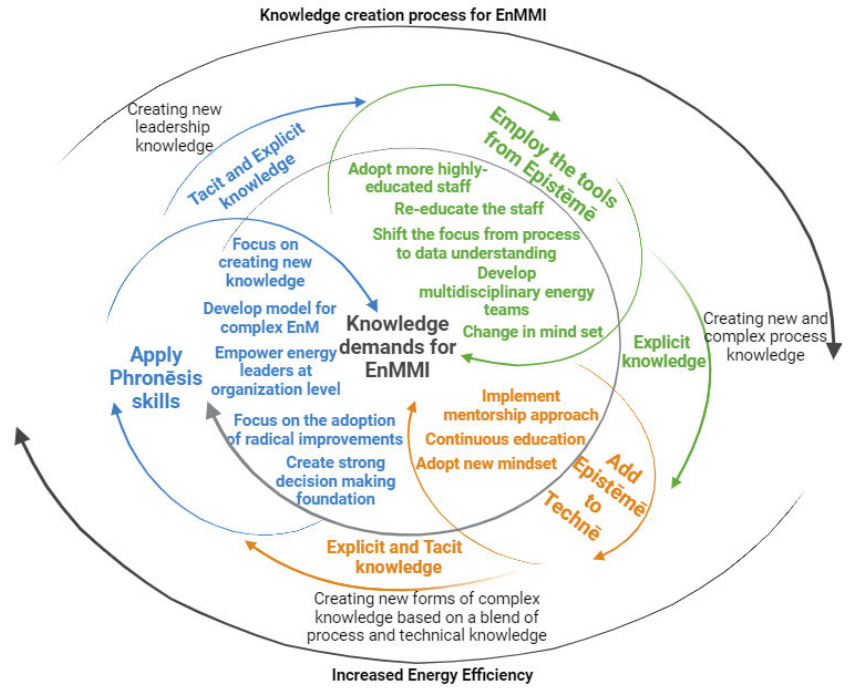


Figure 19. Knowledge creation process and knowledge demands for the adoption of radical and incremental innovations in EnMMI, from Andrei et al. (2022)

Overall, knowledge creation in EnMMI is a dynamic and evolving process influenced by the changing landscape. It involves the acquisition of specialized knowledge, the adaptation of traditional expertise, and the fostering of leadership to navigate the complexities of energy management in manufacturing industries.

6.2.2. Knowledge creation for EnM in practice

In Paper II, a bottom-up system level analysis has enabled the development of a framework which support knowledge creation for EnM during energy transition and beyond. This framework was applied in the case study. The knowledge creation framework is illustrated in Figure 20.

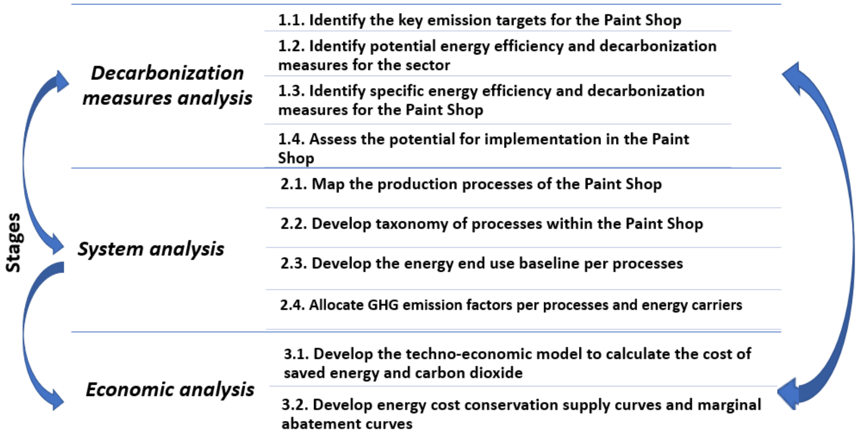


Figure 20. Overview of the knowledge-development framework based on a system level analysis for manufacturing organizations (from Paper II)

Stage One: Measures Analysis, started with mapping the sustainability objectives of the Paint Shop (as described in sub-section 6.1.1. under Paper II). Next, a series of steps have been conducted: i) identifying potential energy savings measures and decarbonization options for the sector; ii) identifying potential energy efficiency measures and decarbonization options suitable for the Paint Shop; and iii) assessing the potential of implementing these measures in the Paint Shop. This was conducted through a literature review and analysis of previous energy reports conducted for the paint shop. This has led to a list of potential measures which were analyzed together with the personnel in charge of the EnM work in the paint shop. To understand the technological change taking place in the Paint Shop, the measures were analyzed and categorized into main groups based on their characteristics, innovation level and knowledge attributes (as illustrated in Figure 15 in sub-section 6.1.1).

The **Second Stage: System Analysis**, started with the mapping of the paint shop production processes. This has enabled the development of a taxonomy based on the workflow in the production processes of the paint shop. Energy end-use (EEU) and CO_2 emissions were then possible to allocate per production and support processes. The results of the EEU allocation show that production processes have the highest EEU per year (84%), while the support processes EEU is 16%. Electricity accounts for 46% of the EEU per year, followed by LPG with 44% and DH with 9%. Of the total electricity use, about two thirds goes to production processes and about one third to support processes. The primary area of use of LPG is as fuel for ovens (ED and powder oven).

The results of the CO_2 emissions allocation show that in the production processes, *Powder oven* accounts for the largest GHG emissions (556 kton CO_2eq/year), followed by the *ED oven* with 379 kton CO_2eq/year. Regarding the allocation of GHG emissions for support processes, ventilation and space heating account for the largest share of GHG emissions (78 kton CO_2eq/year). These results show that the primary focus of the Paint Shop is to streamline and convert the use of LPG to furnaces.

In the last stage, the **Third Stage: Economic Analysis**, a set of measures implemented during 2014 and 2022 have been analyzed. This approach enabled ex-post evaluation of implemented measures while increasing awareness and understanding of the methodology needed to apply during the analysis. The list of measures are illustrated in Figure 21.

Figure 21. Timeline of implemented energy efficiency and greenhouse gas abatement measures (from Paper II)

In this stage, the conservation supply curves (CSC) have been plotted to estimate the quantity of energy that was saved by the Paint Shop and the cost of conserved energy (CCE) per unit of energy. The results show that the greatest potential for electricity savings (44%) comes from the compressed air system (CAS) and is a cost-efficient measure. The lowest potential for electricity savings comes from the evaporator (0.2%). Regarding DH savings potential, the measures implemented in the pretreatment have the highest energy-saving potential (24%) and have the lowest CCE. It is also important to mention that all the measures from pre-treatment process have zero investment costs, since they are included as normal maintenance and operations (e.g., reduce temperatures in baths, improve method for cleaning the heat exchanger for phosphate bath). Another important result is connected to the fuel conversion measure, which in this case involves changing the LPG boiler to DH, which has only 6% potential for energy saving, and had a positive CCE. The CSC is illustrated in Figure 22.

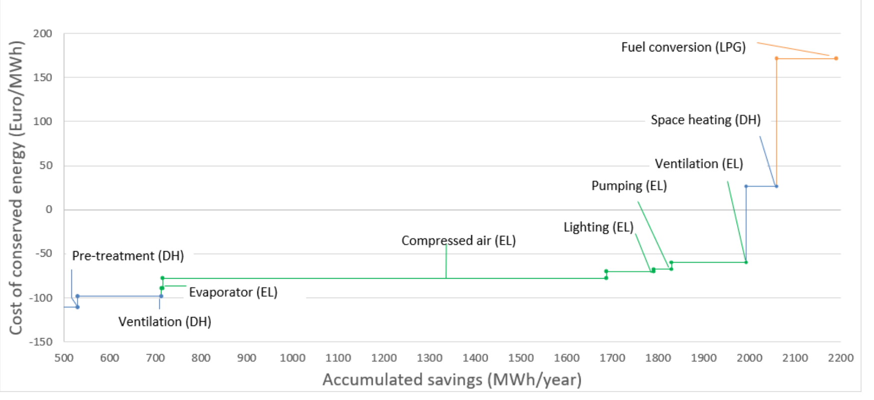


Figure 22. Conservation supply curve, per process and energy carries, for the measures implemented between 2014 and 2022 (from Paper II)

The Pareto analysis of the studied measures, shown that the measures accounting for 80% of energy efficiency potential (with the lowest CCE) are the ones related to pre-treatment, ventilation, evaporator, compressed air, and lighting, as illustrated in Figure 23.

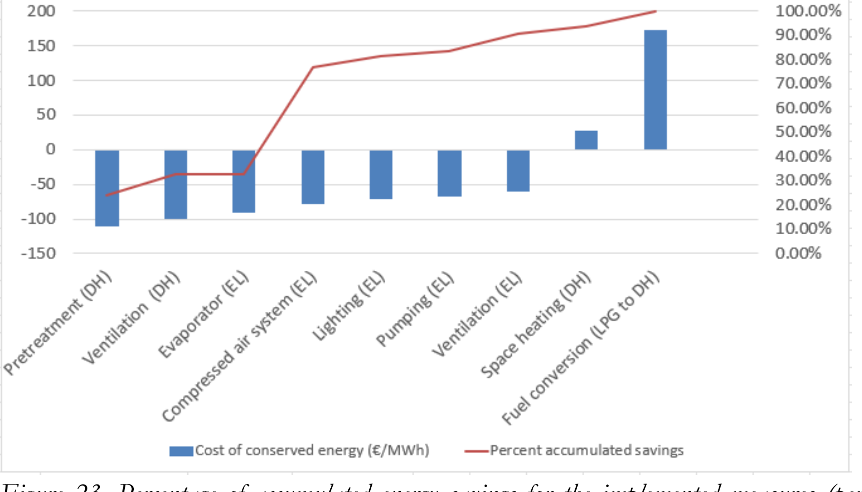


Figure 23. Percentage of accumulated energy savings for the implemented measures (per process and energy carrier) (from Paper II)

The CO_2 reduction potential is closely related to the quantity of saved electricity, DH and LPG. The analysis shows that by switching to DH, the CO_2 emissions will be reduced significantly, as it stands for about 40% of the

CO_2 abatement potential. CAS has the second highest CO_2 reduction potential, accounting for about 34% of the total. DH measures are divided between cost effective and non-cost effective. The rest of the measures that are cost effective are connected with the pre-treatment process (10% of the potential) and ventilation (3% of the potential), while the measure related to space heating (windows replacement) has the highest MAC and a potential of about 1% for reducing CO_2. With regard to electricity, pumping has the lowest CO_2 reduction potential (about 1%) and a negative MAC. Taken together, these measures could reduce emissions by 359 tCO_2/year (as seen in Figure 24). And, as in the case of energy efficiency measures, in general, as the degree of carbon mitigation increases, each additional unit of reduction will become more expensive.

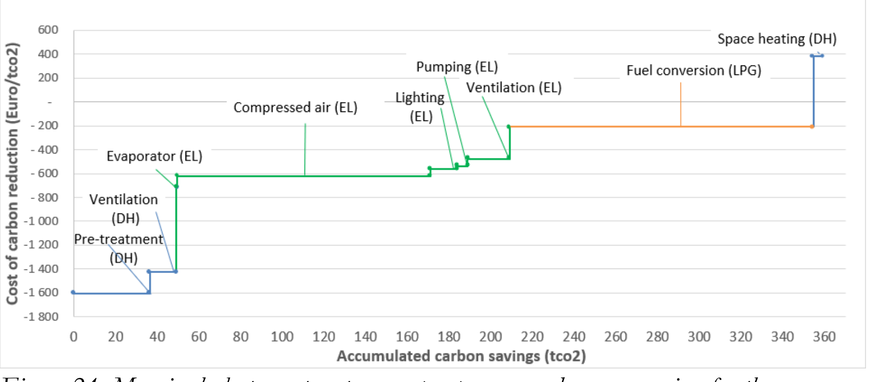


Figure 24. Marginal abatement cost curve, per process and energy carries, for the measures implemented between 2014 and 2022 (from Paper II)

The Pareto analysis (Figure 25) show that in order to achieve 80% of the CO_2 abatement potential, all the measures regarding pre-treatment, ventilation, evaporator, CAS, lighting, ventilation, and fuel conversion need to be implemented.

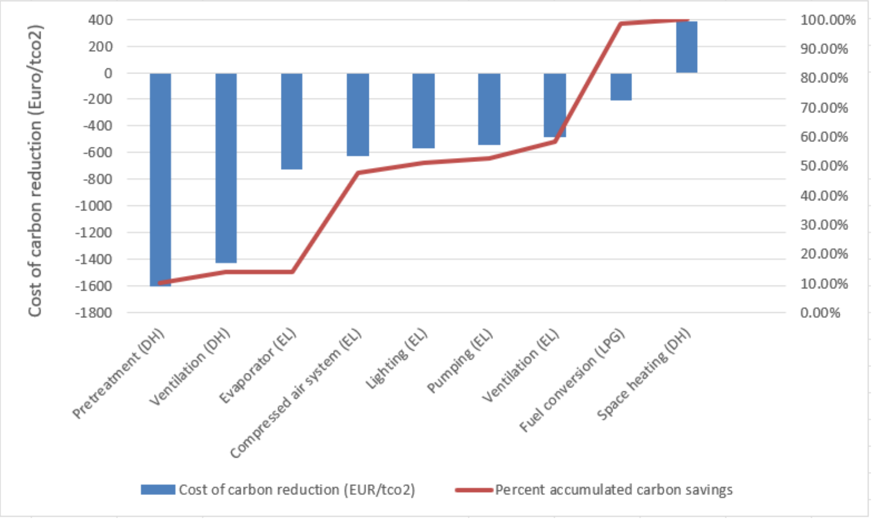


Figure 25. Percentage of accumulated carbon savings for the implemented measures (per process and energy carrier) (from Paper II)

Furthermore, the analysis shows that all implemented measures are incremental innovation and the highest energy savings (MWh/year) lie in the support processes entailing technical knowledge type, as illustrated in Figure 26. The measures focused on production process entail process type of knowledge represent the second highest energy savings in the Paint Shop, including the fuel conversion measure, and the measures with the lowest energy savings are the measures focused on support processes entailing leadership type of knowledge.

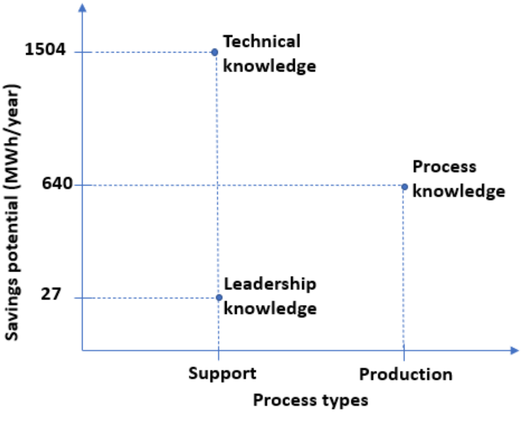


Figure 26. Savings potential per process and knowledge type (from Paper II)

6.2.3. Knowledge creation based on digital technologies

In Paper V, the adoption rate of digital technologies (DiTech) for energy efficiency has been assessed for the Swedish manufacturing sectors based on a maturity model which takes into consideration the following dimensions: 1) leadership: whether the adoption of DiTech is included in the energy efficiency strategy or companies have specific digitalization goals connected to energy efficiency, 2) the type of DiTech adopted by companies, and 3) the transition to smart processes based on the integration of DiTech in the support and production process. The adoption of digital technologies for EE work is explored from a knowledge creation perspective.

The maturity level for energy efficiency and Industry 4.0 was assessed at both sector and company levels using the developed maturity model. Figure 27 presents the maturity level scores for each sector, calculated as the average score of individual companies within each sector. Notably, the iron and steel and aluminum sectors stand out as the only industries reaching maturity level 3. These sectors demonstrate a higher adoption of both core and advanced digital technologies.

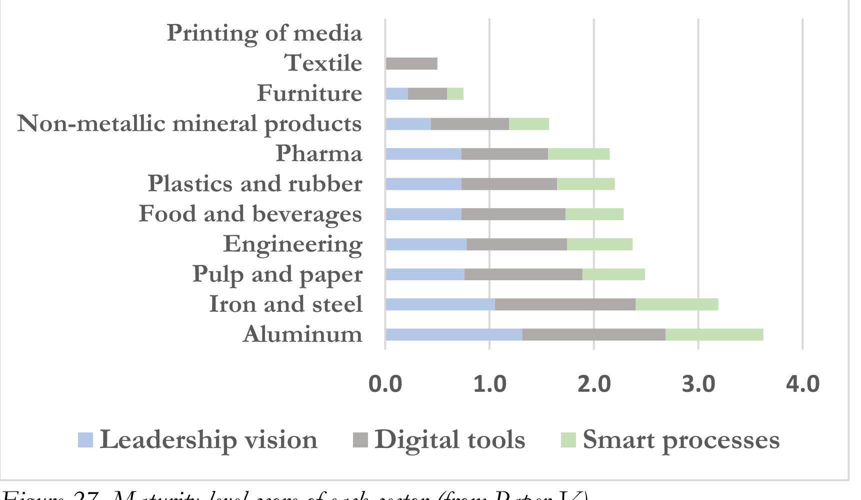


Figure 27. Maturity level score of each sector (from Paper V)

The overall results show that more than half of the companies align their digitalization goals with energy efficiency, and one third plan to adopt or continue using digital technologies for energy efficiency within 5-10 years. Over 50% of these companies see DiTech as essential to their energy efficiency and digital transformation strategies. The most common digitalization goals related to energy efficiency in pulp and paper, iron and steel, aluminum and engineering sectors include online monitoring of energy usage in carriers and manufacturing processes, to identify areas with the highest potential for savings and establish key performance indicators. In the pulp and paper sector, the focus is on online energy monitoring, operator training due to complexity of their processes, and enhancing data collection. The iron and steel industry aims to understand its own complex processes and develop technologies such as VR/AR and AI for widespread deployment in operations. The pharmaceutical sector's long-term plan includes implementing virtual 'operating technicians' for energy monitoring and anomaly detection.

DiTech which provide information and can support knowledge creation, have the highest adoption rate, as illustrated in Figure 28 per surveyed sectors. These are mostly connected to monitoring and data collection of energy use (i.e., Internet of Things - IoT and cyber physical systems - CPS). DiTech which provide data storage, either on cloud or on-site (edge computing), and enable information sharing, provide support, and enable big data analysis, are the next adopted tools. Adoption of BD analysis and AI follows, highlighting the sector work for operational efficiency, productivity, and automatization, as well as the importance of AI techniques. The lowest adoption rate is among autonomous robots (ARo), augmented reality (AR), and virtual reality (VR), highlighting the potential for further adoption of digital technologies which support energy efficiency.

Sectors	IOT	CPS	BD	Cloud	EC	ARo	AI	A SIM	VR	AR
Engineering	59%	7%	17%	24%	17%	14%	10%	14%	0%	7%
Aluminum	50%	25%	25%	50%	25%	0%	50%	25%	25%	0%
Iron and steel	60%	30%	60%	50%	40%	20%	30%	30%	20%	30%
Non-metallic minerals	17%	0%	17%	33%	17%	0%	0%	0%	0%	0%
Plastics and rubber	50%	0%	0%	0%	33%	0%	17%	17%	0%	0%
Pharma	50%	17%	50%	33%	50%	0%	17%	0%	17%	0%
Pulp and paper	47%	33%	20%	53%	40%	13%	7%	0%	7%	0%
Food and beverages	33%	8%	0%	42%	25%	0%	8%	0%	0%	0%
Average adoption rate among sectors	46%	15%	24%	36%	31%	6%	17%	11%	9%	5%

Figure 28. Adoption of core and advanced digital technologies, per sector (from Paper V)

With regards to transition to smart process through the implementation of digital technologies for energy efficiency in support and production processes, Figure 29 illustrates that core technology digital technologies are most often implemented in both support and production processes, while for advanced technology digital technologies it is more common with implementation in only production processes. The iron and steel and aluminum sectors are exceptions to this. In those two sectors advanced technology digital technologies are more commonly implemented in both support and production processes.

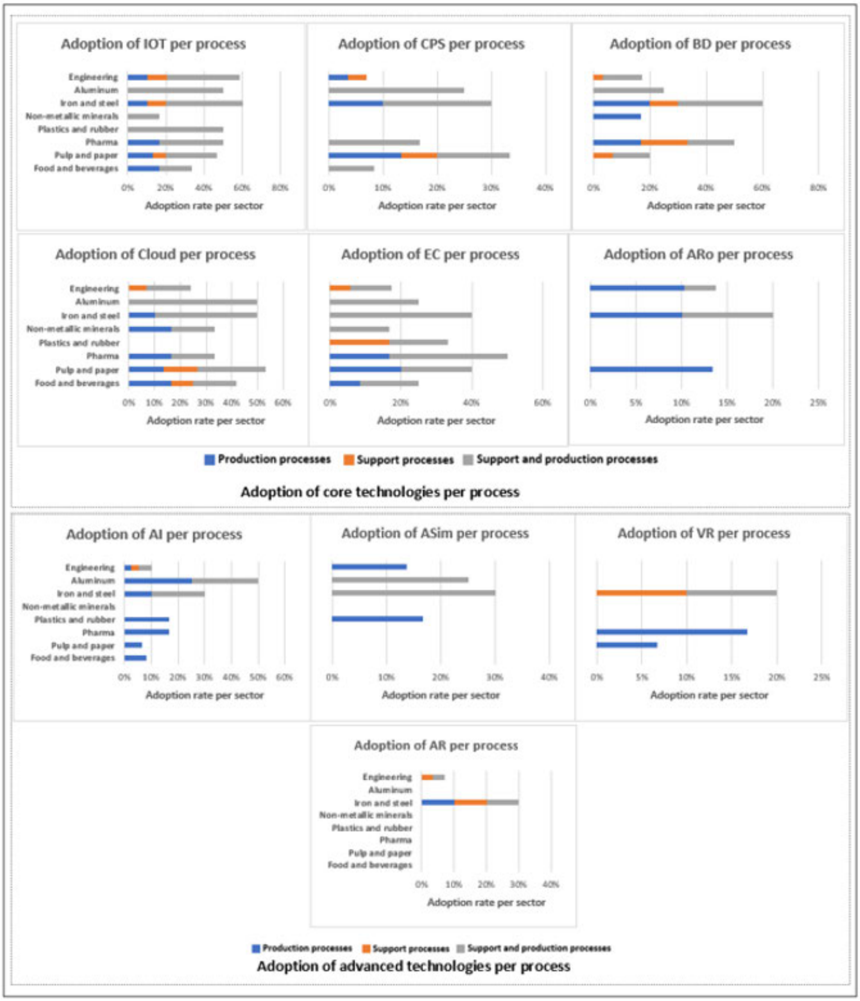


Figure 29. Adoption of core and advanced digital technologies, per process (from Paper V)

Although the adoption of digital technologies can be seen connected directly with the techne form of knowledge, the results from both Paper I and Paper

V indicate that digitalization is perceived to enable an increase in process, technical and leadership knowledge.

6.3. Design of policy evaluation and voluntary initiatives

6.3.1. Design of ex-ante EE policy program evaluation

In Paper III, guidelines for the design of ex-ante EE policy program evaluation (EEPPE) were developed. Regarding the contributions of evaluation, it has been shown historically that, by providing objective information about the implementation and outcomes of the program, policymakers can make rational and wise decisions on program planning and budgeting. The result of this paper is a set of guidelines consisting of five steps (as illustrated in Figure 30) which can contribute to the development of a harmonized methodology for an ex-ante evaluation of energy efficiency policy programs that can support the industry's transition towards decarbonization.

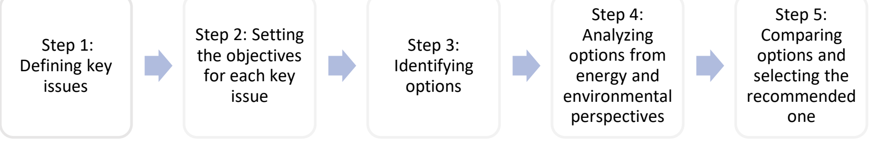


Figure 30. Five steps guidelines for conducting an ex-ante energy efficiency policy program evaluation, from Andrei et al. (2021)

The proposed steps, together with the subsequent activities, can be performed in two different phases of program implementation, i.e., the planning phase and the operational phase, as presented in Table 14. The guidelines for developing a harmonized methodology for EEPPE are illustrated in Table 14. Steps 1 and 2 will help answer the question regarding *how to achieve the objectives of the program*, and steps 3, 4 and 5 will help determine whether there *is a need to intervene in the program*. With a harmonized methodology for evaluation, policies can be compared and a higher degree of learning from other policies may be reached. Furthermore, the energy efficiency measures deployed can also be monitored, compared, and evaluated.

Table 14. The steps for conducting ex-ante EEPPE (revised from Andrei et al. 2021)

The five steps for conducting ex-ante industrial EEPPIA	General description of each phase and key issues to be addressed	Implementation phase
Step 1: Defining key issues	• Energy and GHG estimation: primary energy factors, methodology for carbon footprint calculation (attributional or consequential), reporting under Scope 1-3, emission factors for energy carriers, energy use for production and support processes • Target group estimation: annual energy use per energy carriers, number of companies and program's expected total annual energy use • Energy efficiency estimation: based on existing data or pilot studies • Non-energy benefits estimation • Policy program's costs estimation and estimated deployment rate	Phase 1: Planning
Step 2: Setting the objectives for each key issue	• General objectives • SMART objectives • Operational objectives	Phase 1: Planning
Step 3: Identification of options	Several main options should be presented, ideally at least three, differing factors such as costs, resource availability, problem magnitude, and potential energy efficiency impact. The latter could be categorized as major, minor, or moderate. These options should be compared to a 'status quo option', which serves as a baseline for comparison.	Phase 2: Operational

Step 4: Analyzing options from an energy and environmental perspective	Step 4 is crucial and focuses on evaluating the strengths and weaknesses of all identified options, including the status quo, in terms of their economic, social, and environmental effects and their long-term sustainability impact.	Phase 2: Operational
Step 5: Comparison of options and selection of the recommended one	This step involves comparing identified policy options as well as “used” policy options to recommend the most effective one to policymakers. This comparison considers the advantages and disadvantages of each option identified in step 4 to determine which options is perceived as the most effective. Qualitative and quantitative tools such as multi-criteria analysis, scenario analysis and cost-benefit analysis, can be used in this phase.	Phase 2: Operational

The results from phases 1 and 2 support the policy makers and evaluators in the third phase, i.e., post-operational phase, in deciding whether the objectives of the program can be achieved from an energy and environment perspective and if there is any need to intervene in the program.

6.3.2. Design of industry-related VIs

In Paper IV, the design of industry-related VIs was analyzed on a system level using the transition management framework in order to evaluate the theoretical potential to bridge the ambition gap for industrial decarbonization. Their goals have been analyzed and categorized in terms of quantitative and qualitative goals. Among all types of leading organizations, industry-led VIs have more than half of their goals as quantitative, and less than half qualitative. The goals in the IGOs-, NGOs- and governmental-led VIs are mostly qualitative. The results show that a relevant number of initiatives do not have clearly defined and measurable goals and, apart from this, they do not provide sufficient information on their activities, implementation and achieved impact. This adds to the difficulty in assessing whether the initiatives have reached their declared goal.

The VIs agenda, which refers to the VIs commitments, were assessed for each main group of VIs by using a high/low evaluation criterion. Measurable commitments, with clear percentage and deadline are considered high-level commitments, while the rest are considered low-level commitments. Figure 31 below illustrates the level of commitment in each leading type of VIs. There are noticeable differences in the level of commitment between state-driven and non-state actors-driven initiatives. The VIs with the highest level of commitment are the ones driven by NGOs and IGOs, while the industry-led VIs have the lowest level. The high commitments under the governmental-led VIs are mostly under voluntary agreements programs.

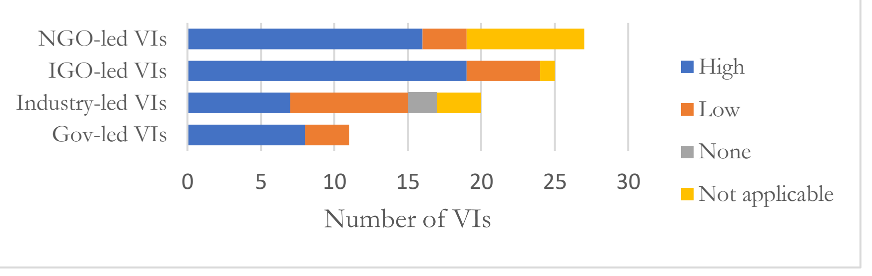


*Figure 31. Level of commitments per each type of leading organization(*Not applicable means that the scope of the initiative is not for commitments per se, but more e.g., for support and assessment frameworks for companies) (from Paper IV)*

A similar situation holds for the accountability mechanisms. Transparent and goal-oriented accountability frameworks are considered high-level, while the rest are low. Figure 32 illustrates the differences in the accountability mechanisms employed in the state actors-driven and non-state actors-driven initiatives.

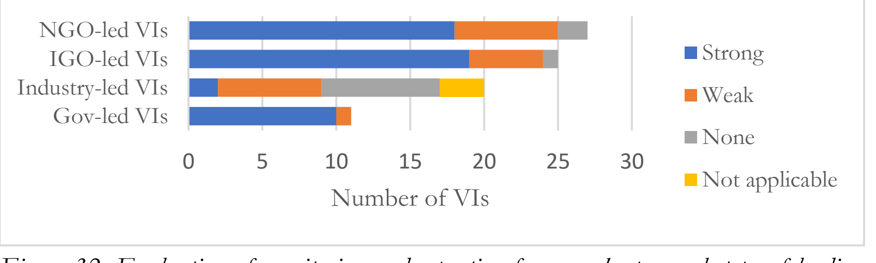


*Figure 32. Evaluation of monitoring and reporting frameworks per each type of leading organization (*not applicable means that the scope of the initiative does not necessarily require an M&R mechanism) (from Paper IV)*

The results show that most of the IGOs-, NGO-s and governmental-led initiatives have strong monitoring and reporting (M&R) frameworks. Companies report publicly progress against both interim and long-term targets, as well as the actions being taken, at least annually, consistent with standards and best practices of measurement. In the case of industry-led initiatives, some of them do not have a M&R system publicly advertised, while some report under a joint reporting mechanism, and some have softer forms of M&R, where companies are urged to determine their baseline for Scopes 1-3. Figure 33 illustrates some key differences between state-driven and non-state driven VIs.

System level	Key differences	State actors led VIs		Non-state actors led VIs	
		IGOs	GOV	NGOs	Industry
Strategic	Focus	More on emissions reduction at global level	More on emission reduction and energy efficiency at regional level	More on emissions reduction at global level	More on emissions reduction for specific sectors, supply chains, or corporate practices at regional level
	Goals	Most of them more qualitative, less measurable	Most of them more qualitative, less measurable	Most of them more qualitative, less measurable	Most of them more quantitative and measurable
	Memberships	Higher number of members	Lower number of members	Higher number of members	Lower number of members
	Decision making	More formal decision-making process through e.g., inter-/governmental negotiations		More decentralized decision-making processes, through e.g., consultation or consensus-building	
Tactical	Types of funding	Multiple sources	Mostly governmental	Multiple sources	Mostly from members
	Level of commitment	More formal and binding	More formal and binding	More formal and binding	More flexible and informal
Operational	Resources	Access to significant resources: legal frameworks, and institutional support		Access to significant resources: legal frameworks, and institutional support	Rely mostly on partners' support
Reflexive	Accountability	Subject to greater accountability from the public and other governments		More accountable to their stakeholders	
	Monitoring & reporting	Stronger monitoring and reporting frameworks		Stronger monitoring and reporting frameworks	Weaker monitoring and reporting frameworks

Figure 33. Key differences between state-driven and non-state-driven -VIs at system level (from Paper IV)

7. Discussion

This chapter provides a discussion about the major outcomes of this thesis. It starts by revisiting the aim and research questions and a discussion on each research question follows. It continues with reviewing energy management through the lens of the main theoretical framework. The major contributions and implications of the thesis are outlined.

This thesis has joined the field of research on energy management that has extended the classical way of studying energy management, not limiting research by solely studying technical aspects of energy management. Through the use of qualitative and quantitative research methods, such as case study research, participatory observation, literature review and survey, knowledge of industrial energy management during energy transition has been extended. By doing so, the degree of system complexity (Boulding, 1956) has increased to the higher system levels, incorporating practices, industrial energy programs, knowledge dynamics and, of course, individuals and organizations. This extended system perspective has strengths, but also limitations. The former refers to the capability of providing an enhanced understanding of the research topic, while the latter refers to the possible uncertainties due to its increased system complexity. However, such widened system approach enables policy makers to formulate effective industrial energy end-use efficiency policies and supports practitioners in their energy management work.

The research aim has been to explore the role of industrial energy management in the transition towards a sustainable energy system through an extended system perspective focused on practices, knowledge dynamics and design of policy evaluation. This was conducted through top-down and bottom-up approaches. In order to fulfill the aim of this thesis, three research questions have been responded to:

RQ1: What types of energy management practices are being employed in manufacturing industries and how do they contribute to the transition towards sustainable energy systems?

RQ2: How is knowledge created and applied in industrial energy management practices to facilitate the transition towards sustainable energy systems?

RQ3: What design strategies should be employed in policy evaluations and voluntary initiatives to facilitate the implementation of industrial energy policy programs?

The answers to these questions are discussed in sub-sections 7.1, 7.2 and 7.3. Building on a refined system-approach understandings, the role of EnM in the transition to sustainable energy systems is described in section 7.4.

By addressing these research questions, the thesis has explored the industrial energy management practices implemented during transition and how they support the transition towards sustainable energy systems. The thesis contributes to the understanding of the knowledge dynamics in industrial energy management practices and explored the processes and mechanisms through which knowledge is created to drive the transition towards sustainable energy systems. Additionally, the thesis has uncovered how design and effectiveness of policy evaluations is enabling the implementation of industrial policy programs in the context of energy transition. By addressing the three research questions, the thesis has provided insights and recommendations for enhancing industrial energy management practices in alignment with the goals of sustainable energy systems.

7.1. EnMPs and their role in the transition toward sustainable energy systems

The Energy Management practices identified in this thesis, based on the system approach described in sub-section 4.4., are connected with the system objectives and measure of performance, with the components, i.e., the internal and external practices, as well as with the external environment influencing the EnMP.

7.1.1. Energy Management objectives

The European Commission, driven by its goal to reduce GHG emissions by at least 55% by 2030 and attain climate neutrality by 2050, along with the establishment of interim targets for energy efficiency and renewable energy (European Parliament and the Council of the European Union, 2023) stands as a primary external catalyst for the adoption of EnMP in manufacturing companies, as seen also by e.g., Bunse et al. (2011). As seen in Papers II and IV, environmental regulations have empowered the manufacturing sector to actively pursue reductions in GHG emissions and increasing energy efficiency. One of the main findings of this thesis is the direct and indirect influence of climate objectives on EnMP, leading companies to set specific objectives and targets for energy efficiency and GHG reduction, while engaging in new practices. Furthermore, companies are actively engaged in monitoring activities and the development of key performance indicators. The development of measures of performance facilitate the evaluation of progress towards achieving energy efficiency and greenhouse gas reduction objectives. Such activities helps to move away from vague objectives to specific measures of performance (Churchman, 1968). The actors integrated within these organizations play pivotal role as agents of change across different organizational levels, as seen also by Child and Breyer (2017). Organizational leadership has an important role in achieving the company's goals (Nixon et al., 2012), particularly when it demonstrates commitment to energy efficiency (Johansson, 2015) and reduction of GHG emissions.

Environmental awareness and companies' ability to innovate have a strong impact on attaining the objectives regarding climate change mitigation, as was seen also by Costa-Campi et al. (2015). Furthermore, the findings suggest that the decision of manufacturing organizations are driven not only by environmental reasons, but also by environmental management practices (Ates and Durakbasa, 2012; Thollander and Ottosson, 2010). Such environmental practices, e.g., organizational routines and managerial actions, are generating environmental awareness and putting environmental issues at the top of the strategic agenda. The formulation of sustainability strategies and clear goals by the top management regarding energy efficiency and GHG emissions reduction are being transferred down to the personnel and contribute to developing a culture for sustainability change, as seen also by Salim et al. (2019). When environmental values become integral to organization culture, employees are more inclined to adopt energy-efficient behaviors (Sorrell et al., 2000).

7.1.2. Energy Management practices

The EnMPs identified in this thesis (Papers I, II, IV and V) are comprised of energy conservation measures (behavior-related), energy efficiency measures (technology, process and leadership-related), process innovation measures, energy supply measures (fuel conversion, local production, and CCS-related) as well as compensation measures. As seen in Papers I, II and V, organizations are considering and implementing a combination of these measures, indicating that achieving climate neutrality requires a blend of strategies, as discussed also by Giampieri et al. (2020). This is also in line with the findings of Holechek et al. (2022), which argue that for reaching climate neutrality, the combination of several pathways is needed, such as renewable energy sources, improving energy efficiency, increasing energy conservation and carbon taxes. As seen in Papers I and II, energy conservation practices have an important role since they are directly connected with the concept of energy sufficiency[5]. In order to reduce energy use effectively, energy conservation is also required rather than just relying on energy efficiency measures, as claimed also by Herring (2006). From a cost perspective, implementing energy conservation measures is of high importance, since measures such as the behavioral ones or working with idle energy have zero investment costs.

Energy efficiency is an effective countermeasure to rising energy needs and unsecure energy supplies (IEA, 2008; Tanaka, 2008), and plays an important role in mitigating GHG emissions, as seen also by, e.g., Fernando and Hor (2017) and Bunse et al. (2011). Energy efficiency aligns with the strategies of incumbent organizations, as it reduces production costs and emissions while increasing productivity and competitiveness in the long run, also discussed by e.g., Brunke, Johansson and Thollander (2014) and Worrell et al. (2003). Furthermore, Papers I and V have shown that a paradigm shift towards Industry 4.0 digital technologies for energy efficiency takes place in manufacturing organizations. For example, a high share of Swedish manufacturing industry have a strategic approach related to digital technologies and energy efficiency. The adoption of digital technologies in energy efficiency work is often linked to the presence of a strategy focused on improving energy efficiency through digital transformation. This strategic approach can serve as a driver for adopting digital technologies for energy efficiency, as seen in the studies of Rohdin and Thollander (2006) and Thollander and Ottosson (2010) which highlight that having a long-term energy strategy plays a crucial role in driving efforts to reduce energy use and enhance energy efficiency.

Notably, a common finding from Papers I, II and V is that the majority of energy efficiency measures are incremental innovations relying upon already established measures, while some measures demand a radical innovation step

[5] Energy sufficiency concept recognizes the need to achieve an absolute decrease in the total energy use for reaching high levels of development (Burke, 2020)

by the company. This is supported by the findings of Wesseling et al. (2017), who claims that when companies embrace incremental process innovation aligned with established technological pathways aimed at boosting productivity are more likely to initiate partial investments. As seen in Paper II, most of the incremental innovations in energy efficiency are cost efficient, however, as the degree of energy efficiency potential increases, each additional unit of reduction is likely to become more expensive. Energy efficiency measures implemented for the support processes have the potential to make a significant impact on the energy use of the company, at least in the beginning of the energy efficiency work. However, high savings potential in terms of energy and greenhouse gas emissions in many firms lies in the production processes, also discussed by Paramonova et al. (2021) and process innovation plays a critical role. Both incremental and radical process innovations can yield high savings. In particular, radical process innovations can provide co-benefits such as material recycling, reduced water usage, fewer chemicals, and an improved working environment, as seen in Paper II.

Another finding from Paper II shows that process innovation, whether incremental or radical, hinges on deep process knowledge. Deep process knowledge is especially critical when considering radical process innovations, which often requires a substantial investment of time, spanning several years, and a high level of operational maturity. However, the deep process knowledge required to implement radical process innovation also necessitates a deep understanding of the interdependencies with the broader manufacturing system, which includes e.g., the supply chain. It has been seen that energy systems can be quite difficult to change due to interdependent relationships, as shown also by Geels and Kemp (2007) and Nykamp et al. (2023). For example, in the automotive paint shop industry, the successful change to a low-curing powder (a radical process innovation), hinges crucially on supplier involvement. This is because the innovation begins with product innovation at the supplier level. And research and development in chemicals are seen as risky, expensive, challenging to implement, and sometimes unable to compete with established technologies. This can help explain the extended time required for the technology to mature and scale up its life cycle (Nemet et al., 2018; Wesseling et al., 2017).

Furthermore, Paper II has shown that when it comes to radical process innovations, the main challenge is connected with prior knowledge of specific technology and own processes. This is in line with the findings of Solnørdal and Thyholdt (2019)'s study which has shown that a firm's knowledge characteristics are determinant for increasing that firms' innovations in energy efficiency. These knowledge characteristics are i) prior knowledge in the form of a higher educated personnel, ii) the ability to cultivate knowledge through research and development, and iii) collaboration with external source of knowledge, including universities and competitors. In the realm of incremental innovations, it's a common practice for organizations to operate within multi-disciplinary teams. However, when it comes to radical process innovation, the imperative is to establish multi-disciplinary teams comprehending scientific knowledge (e.g., academia), process knowledge (e.g., specialists in specific processes) and technical knowledge (e.g., technology experts). These diverse teams have the potential to leverage existing knowledge effectively, ensuring ongoing education to meet the increased need for new knowledge while actively fostering improved multi-disciplinary collaboration. The increased need for more collaboration is highlighted also by Rotmans et al. (2001), who emphasize that driving the transition requires the involvement of multiple actors.

Understanding the energy system infrastructure of the manufacturing organizations is directly connected with the implementation of energy supply measures. As seen in Paper II, energy supply measures are connected with the fuel conversions, e.g., alternative fuels and electrification of processes, as well as own combined heat and power production plant (CHP). Alternative fuels (e.g., biogas) are a practice that can be implemented in combination with process innovations and energy efficiency, as discussed also by Giampieri et al. (2020). However, access to biogas in the future and how biogas will be valued in terms of carbon dioxide emissions are challenges that need to be considered. A change, such as conversion to carbon-free electricity is dependent on available external infrastructure and adaptation of production processes. If considering conversion to carbon-free electricity, from a system perspective awareness is to be given to the fact that all other sectors will be competing for carbon-free electricity and there are technical difficulties in achieving electrically powered industry, as discussed also by Beard et al. (2010) and Parker et al. (2019).

As seen in Paper II, own supply of electricity, such as local electricity production (photovoltaic) is a common practice, however despite its technological potential, power generation by solar energy does not guarantee meeting the SBT for all company's cases, and investigations on a case basis needs to be conducted, seen also by Abdoli et al. (2020). Local CHP is a large-scale and capital-intensive measure that moves beyond the core business operations of manufacturing organizations, but the added value is that it enables a reduction of the production costs and of the environmental impact particularly for manufacturing processes with year-round demand for heat (Galitsky et al., 2008; Giampieri et al., 2020). However, this type of measure requires extensive investigative work to determine whether there are technical, economic, and environmental benefits that outweigh the operation of a facility of this type locally.

And lastly, in Paper II was seen that the manufacturing industry can achieve a complete decarbonization if these complex technological transformations are complemented by emission reduction practices, i.e., compensation mechanisms, CCS or compensation initiatives, as discussed by Gebler et al. (2020). However, emission reduction practices raises several important questions related to (i) the availability and compatibility of low global warming potential alternatives, (ii) the extent to which demand can be met by these alternatives, (iii) the quality and effectiveness of these substitutes, and (iv) defining the system boundaries with awareness to prevent problem shifting (Gebler et al., 2020).

The combined adoption of all above-mentioned practices in the manufacturing industries have a direct contribution to the 2030 and 2050 targets as they address energy efficiency and reduction of GHG emissions. However, the order for the implementation of EnMP is also very important. An 'optimum' order for the adoption of EnMP is illustrated in Figure 34. The novelty of this approach, as compared with, e.g., Gebler et al. (2020), is the introduction of the process innovation step, which can entail high savings potential depending on the complexity of the process.

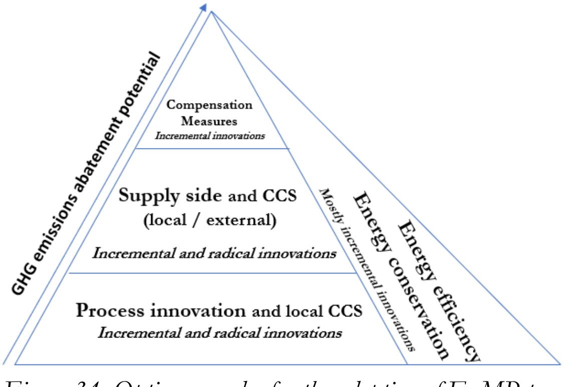


Figure 34. Optimum order for the adoption of EnMP to contribute to the 2030 and 2050 targets (revised from Paper II)

The maturity and feasibility of the specific measures within these practices vary from case to case, as does the timing for potential implementation. Furthermore, the empirical data from Paper II shows that these measures can lead to trade-offs between the company's environmental goals, i.e., the target to reduce energy efficiency versus the target to reduce CO_2, to not be adequately balanced as discussed also by Churchman (1968). The trade-offs need to be approached in a strategic manner, and the role of leadership is very important.

7.1.3. The implementation process for EnMP

One central finding from Paper II regarding the decision-making process for the adoption and implementation of EnMPs can be summarized as follows: when it comes to decisions concerning the adoption of energy efficiency measures, the process tends to be rather linear, as seen also by Cooremans (2012), and they require mostly internal and technē knowledge. Decisions regarding energy efficiency measures predominantly draw upon internal expertise and readily available technology solutions. In contrast, decisions related to process innovation take on a more iterative approach. In this context, the analysis, innovation, and evaluation phases, as illustrated in Figure 35 entail a pivotal innovation step characterized by transdisciplinary collaboration, as well as epistēmē, phronēsis and technē knowledge creation. This collaboration involves active engagement between industrial plants, academic institutions, and suppliers, aimed at fostering the adoption of radical process innovations and the development of customized products. Lastly, decisions pertaining to supply-side measures exhibit a dynamic interplay between choice and analysis, involving iterative cycles of deliberation and assessment.

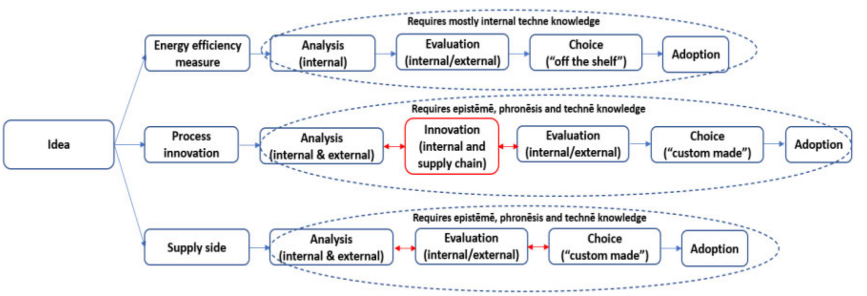


Figure 35. Decision-making process for different types of decarbonization measures (revised from Paper II)

7.1.4. Integrating new practices in Energy Management

Paper IV has emphasized that a new category of EnMP, 'external' EnMP, such as the participation in and implementation of voluntary initiatives (VIs), is increasing in popularity, as seen also by e.g., Falkner et al. (2010) and Widerberg and Stripple (2016). Voluntary initiatives are claimed to be essential for reaching the climate goals due to their potential to bridge the gap for industrial decarbonization as highlighted by, e.g., Blok et al. (2012). Hermwille et al. (2015), UNEP (2019, 2015) and Widerberg and Stripple (2016). These practices should be seen as integral part of the energy management work since they are directly connected with the goals related to energy efficiency and reduction of GHG emissions. Such practices consist of e.g., strategy and/or roadmap development, development of support frameworks for goals implementation, planning and implementation of activities, monitoring and reporting of activities and mobilization of resources necessary for the implementation of the goals set under the VI. Furthermore, collaboration with different stakeholders and groups at different levels in order to raise awareness, share information and best-practices and support knowledge creation are also common practices.

7.1.5. The influence of external environment on EnMPs

In this thesis various external factors have been identified in Papers II, IV and V to exert pressure on the adoption of EnMP. These factors encompass climate policies, environmental considerations, customer demands, market forces and technologies, as seen also by, e.g., Child and Breyer (2017), Arena et al. (2009) and Ellen et al. (2006). The influence of external environment can differ from organization to organization, depending on the sector, type of organization (e.g., energy intensive, non-energy intensive), category (e.g., large, SMEs), as well as the organizational culture. The implementation of EnMP in the context of transition require a change in the organization. The change process implies a shift from traditional EnMP to new and complex ones which require structural change in the use of resources and processes, as well as in managing the change.

Environmental pressure can have an impact on the need to adopt change in a production process. For example, in the case study from Paper II, a driver for changing from phosphate to thin film technology in the pre-treatment process comes from phosphate being a limited resource.

In Papers II and IV was seen that increasingly environmentally-conscious public and customers are pressuring firms to adopt energy management practices to reduce carbon emissions (Fernando and Hor, 2017). Customers changing their purchasing behavior with regard to more sustainable products are influencing how companies view the environmental impact of a product (Bunse et al., 2011). Organizations today need to show accountability and responsibility with regards to climate challenge, but also due to the fact that customers demand accountability. This is significant since companies have noticed that superior environmental performance can give a reputational and competitive advantage (Jovane et al., 2008) and efficient manufacturing is a major factor in reducing a product's overall environmental impact and is a significant driver for competitiveness (Bunse et al., 2011).

And in Paper V was seen that the integration of digital technologies emerges as a transformative enabler of energy efficiency practices. Digital technologies enhance safety, productivity, and achieve various benefits, e.g., reduced downtime, lower costs, energy efficiency, and improved product quality (International Energy Agency, 2017). Digital technologies can bridge the gap between data and knowledge, enabling the adoption of EnMPs.

7.2. Knowledge creation for Energy Management

In this thesis, knowledge is considered one of the main inside resources for the implementation of EnMP. The resources refer to knowledge, education, personal skills, and leadership. And, as Churchman stated, the increase of resources is the most important component of the system (1968). Knowledge creation play a critical role in the continuous development of industrial energy management. The energy transition entails a fundamental shift towards more sustainable and cleaner energy sources, necessitating the adoption of novel technologies and practices. Information has a role to play in the implementation of EnMP. Moreover, insufficient information is often stated to be the most common barrier to energy efficiency (Thollander et al., 2007). Hence, public policy interventions are often in the form of energy audits, since they provide information regarding the energy flows in the organization (Schleich, 2004).

A first step in understanding the process in terms of energy flows is conducting energy audits. An energy audit serves as a valuable tool for identifying opportunities, assigning value to energy use (Fernando and Hor, 2017), accelerating investments in and implementation of energy efficiency measures (Backlund and Thollander, 2015) thus justifying resource allocation for energy efficiency projects and helping companies to become more energy efficient and contribute to CO_2 emissions mitigation. However, energy audits are not enough for gaining deep process knowledge, especially in mature organizations which have been conducting energy audits for years and have complex production processes, as discussed also by Paramonova et al. (2021). Furthermore, knowledge creation requires more than just collecting and disseminating information. It requires the use of both explicit and tacit mode of knowledge.

This thesis has shown that explicit mode of knowledge for EnMPs can be obtained through the use of system level frameworks (Paper II), as well as through the adoption of digital technologies equipping and guiding company personnel with pertinent information (Paper V). By leveraging system level frameworks, organizations can systematically dissent complex EnM challenges, enabling them to identify key insights and opportunities for improvement. In Papers I, II and V was argued that explicit knowledge can be created by employing tools and methods for energy analysis of production and support processes. These methods enable learning about own processes, about the energy use in the processes, the energy flows, and what types of energy efficiency improvements are possible.

Furthermore, Papers I and V claim that digital technologies support the creation of explicit knowledge. Digital technologies connected with the monitoring and data collection of energy use (i.e., IoT and CPS), data storage, either on cloud or on-site (i.e., EC), information sharing, and big data analysis are technologies that provides useful information. The adoption of technologies for energy analysis through real-time energy monitoring, data collection and analysis, identification of abnormal energy use patterns and quantification of energy efficiency gaps, was seen also by Tan et al. (2017). By empowering individuals within the company with real-time access to critical data, informed decision-making is facilitated.

Of course, if and how this information is used in the decision-making process depends on the leadership of the organization and the skills of the staff in handling and making sense of the data. The process of equipping individuals with valuable data not only facilitates their decision-making processes but also serves as a catalyst for the creation of new knowledge within the organization when the organization is equipped with experienced and qualified personnel. The training of operators in handling digital technologies and using advanced models to understand their own processes are needed in order to further enhance both explicit and tacit knowledge creation. However, successful adoption of digital technologies requires a carefully structured strategy, underpinned by digital transformation maturity and readiness (Mittal et al., 2018; Santos and Martinho, 2020). Maturity models offer a structured approach to assessing an organization's digital capability and guiding it towards higher levels of maturity (Santos and Martinho, 2020).

Paper II has shown that tacit modes of knowledge can be obtained through co-creation. Co-creation plays an important role in the adoption of EnMPs, in particular when radical process innovation needs to take place. The role of transdisciplinary collaboration is essential for the co-creation process since the skills and knowledge of industrial actors and researchers complement in a harmonious way in practice. This is discussed also by Tranfield et al. (2004). Co-creation of knowledge based on internal multidisciplinary teams, as well as transdisciplinary teams is needed since having the staff and people with right competence is essential especially when the complexity to change the technology and the production is higher, and new skills and technology are required to better understand the change and the overall process. However, building competence and relationships happens over time (Huy, 2001).

7.3. Design strategies for policy evaluation and voluntary initiatives

As seen in Paper III, various policy initiatives and market-oriented regulations, such as taxes, subsidies, tradable emission permits, and green certificates, have been implemented in several countries (Bunse et al., 2011; de Groot et al., 2001; Unger and Ahlgren, 2005). Companies that enhance their energy efficiency and reduce their carbon footprint can better position themselves to address the challenges and costs associated with existing and future CO_2 regulations (Bunse et al., 2011). Companies are therefore joining national energy efficiency policy programs, such as voluntary agreement programs (VAPs). An ex-ante evaluation of energy efficiency policy programs should be designed in such a way to enable policy makers to evaluate the program against the goals and, when needed, to improve it (Weiss, 1998). Hence, paper III highlights the importance of the design of ex-ante methodologies for evaluating energy efficiency policy programs in alignment with the climate goals, relying on attributes associated with energy management. These elements encompass, e.g., how to improve energy efficiency and reduce energy use, how to reduce GhG emissions, develop and maintain effective monitoring, reporting, and management strategies for wise energy use. The importance of data collection and the indicators used for evaluation are key for the successful planning and implementation of energy efficiency policy programs.

Paper IV has highlighted several important aspects regarding the design of VIs which are key for the successful implementation and contribution to the climate goals. From a strategic point of view, the number of manufacturing organizations should increase in the industry and governmental-led VIs in order to contribute to reaching the climate goals, as shown also by Pattberg (2010). In particular, the participation of companies from the energy intensive sectors such as chemicals and aluminum should increase, as seen also by Otto and Oberthür (2022), due to their complex production processes and the subsequent difficulty in innovation and reducing GhG emissions. This can be facilitated through support frameworks where information, administrative support and best practices are shared. Furthermore, clearly defined and measurable goals need to be established in order to assess whether the initiatives have reached their declared goal, as shown also in the study of Fenhann et al. (2018).

Another key finding from Paper IV is connected with the commitment level of manufacturing organizations. The commitment level is more flexible and informal in the industry-led VIs, as compared to the commitment level from the IGOs, NGOs and governmental-led VIs. However, this can be connected with how the VIs are designed in terms of rule structures for ensuring that participating companies adhere to VIs obligations, seen also by Prakash and Potoski (2007). Another reason regarding the low commitment level in industry-led VIs may be attributed to the fact that, when companies are confronted with the decision to implement climate-related initiatives, the managerial choice plays a pivotal role. In other words, the decision to commit to such initiatives and the extent of that commitment hinge on the individual prerogatives of managers and the corporate leadership, as outlined by Griffiths, Haigh and Rassias (2007).

Non-state actors-led VIs are more accountable to their stakeholders, while the state actors-led VIs are subject to greater accountability from the public and governments. The accountability mechanisms need to improve in order for the VIs to contribute to climate governance as discussed also by Bäckstrand (2008) and Widerberg and Pattberg (2015). Weak monitoring and reporting frameworks challenges the data collection needed to fairly estimate the contribution of VIs to the climate goals contribute to bridging the ambition gap for decarbonization, as discussed also by Widerberg and Stripple (2016). Moreover, assessing the effectiveness of such initiatives becomes even more complicated when there is no established standard baseline against which to evaluate voluntary actions (Paton, 2000; Schiavi and Solomon, 2006).

Hence, this thesis claims that enhancing industry-led VIs accountability necessitates a design which enables the increase in the number of industrial members, involving measurable goals to establish shared expectations among members. Additionally, clear commitment level as well as monitoring and reporting frameworks are crucial to track member progress in achieving initiative goals, enabling goal evaluation, and identifying areas for improvement. Consideration of external stakeholder tracking and public disclosure of member progress, akin to state-actor-led VIs, could further bolster the potential of industry-led initiatives to contribute to climate goals.

7.4. The role of EnM in the transition toward sustainable energy systems

As seen in the appended papers, the requisites for energy management have evolved in response to the dynamic reality and context. This evolution has prompted reflection on the role and purpose of energy management within industrial organizations. Consequently, within this thesis, the overarching role identified for industrial energy management in the energy transition is to

> *facilitate the achievement of the company's energy efficiency and CO_2 emissions reduction goals, through the implementation of customized practices that enhance long-term competitiveness, foster resource development, while simultaneously allowing for adaptation to external factors, in the form of policies, regulations, technologies and market dynamics.*

7.5. Thesis contributions

➢ Theoretical contributions

This thesis contributes to energy management research by providing an enhanced understanding of the role of energy management in the transition toward sustainable energy systems. It makes a theoretical contribution to the field of industrial energy management in the context of energy transition since it sheds light on the changing role and purpose of energy management.

Furthermore, this thesis makes key contribution by shifting the focus from a primarily technology-oriented perspective to a knowledge-based approach in the field of energy management. As a result, it introduces a knowledge-creation framework, marking an advancement in energy management research within the manufacturing industries. While previous research, e.g., Svensson and Paramonova (2017), Backman (2018a), and Solnørdal and Thyholdt (2019), have extensively examined various aspects of knowledge creation for energy management, there has been a gap in understanding and classifying the forms of knowledge utilized in this domain from a knowledge perspective. The novelty of this contribution lies in the development of a comprehensive knowledge-based framework that encompasses primary forms and attributes of knowledge relevant to EnMMI. This framework serves as an analytical tool, enabling the systematic analysis, comprehension, and categorization of the diverse forms of knowledge employed in the field. This knowledge analytical approach addresses the evolving knowledge demands required for effective energy management and the adoption of energy efficiency and process measures and contributes to a deeper understanding of how knowledge shapes and influences energy management practices in manufacturing industries.

- **Methodological contributions**

In Paper I, an analytical knowledge-based framework was developed based on three broader forms of knowledge and specific knowledge attributes. This analytical framework can be applied to analyzing and categorizing the forms of knowledge and key aspects of energy management in manufacturing industries. This framework, for example, was used by Ibn Batouta et al. (2023) to conduct a systematic literature review and classify the current status of research on energy efficiency in the manufacturing industry between 2016 and 2022 based on the three overarching forms of knowledge.

In Paper IV, an analytical framework for facilitating a system level analysis of the design of voluntary initiatives was formulated, incorporating key principles from the transition management framework. The primary contribution of this analytical framework lies in enhancing the evaluation of voluntary initiatives' potential to contribute to climate neutrality. It adds depth and explanatory power to their design by providing a systematic assessment at the system level.

In Paper V, a maturity model for assessing the adoption of digital technologies for energy efficiency within the manufacturing industry was developed. Currently, no maturity model evaluates digital technologies adoption for energy efficiency in manufacturing industry. The model targets manufacturing companies engaged in energy efficiency and digital transformation, with the goal of enhancing their awareness of digital technologies and maturity levels. It also serves as a tool for academic researchers focusing on digital transformation within the manufacturing sector. The model has been structured to accommodate evaluation by academia and self-assessment by companies.

7.6. Thesis implications

➢ **Implications for energy management work in manufacturing organizations**

The knowledge creation model holds significant implications for practitioners. It underscores the importance of leadership in utilizing this model for effective energy management implementation. Additionally, practitioners should be mindful of the synergies that exist among the three broader forms of knowledge - technical, process and leadership – especially when dealing with the implementation of both incremental and radical innovations in EnMP.

The evolution of energy management practices, as seen in the appended papers, highlight the need for a proactive and adaptive approach within manufacturing organizations. In light of these findings, the overarching role of energy management in the context of the energy transition becomes clear: it is a pivotal driver for the achievement of energy efficiency and CO_2 emissions reduction targets in manufacturing organizations. Moreover, it plays a vital role in enhancing long-term competitiveness, fostering resource development, and enabling adaptation to external factors such as policies, regulations, and market dynamics.

This thesis offers practical insights into the development of comprehensive energy management strategies, emphasizing the importance of combining diverse EnMP, including energy conservation, efficiency, process innovation, and supply-side measures. Furthermore, it identifies a paradigm shift towards Industry 4.0 digital technologies for energy efficiency, offering practical implications for manufacturing companies aiming to leverage digital technologies for energy management. Additionally, it emphasizes the necessity of multidisciplinary and transdisciplinary teams, incorporating scientific, process, and technical expertise, in facilitating innovation and knowledge creation within organizations. This insight can guide practical efforts to enhance collaboration and innovation. And, lastly, introduces the concept of 'external' EnMP, specifically voluntary initiatives (VIs), and outlines the need for their integration into energy management practices. This provides guidance on aligning internal goals with external sustainability initiatives.

- **Implications for industrial energy-efficiency policies development**

It is important to ensure that scientific results serve policymakers in reality. In this thesis the issue of inconsistent categorization and evaluation of measures among different policy programs was addressed. Inconsistent categorization and evaluation of measures hampers cross-program comparisons of energy efficiency and cost-saving potential. To bridge this gap, an ex-ante evaluation approach for energy efficiency policy programs rooted in energy management principles becomes imperative. Such an approach should enable policymakers to assess program effectiveness against climate objectives and, when necessary, make improvements. Hence, in this thesis a set of guidelines were developed based on the energy management principles that can support policy makers to create a harmonized energy-efficiency policy evaluation methodology.

8. Conclusions

This chapter wraps up the thesis' main findings and briefly presents the answers to the research questions.

When conducting research, the researcher approaches the object of study with a set of ideas about the nature of reality i.e., ontology, which leads to specific set of questions about the relationship with the known i.e., epistemology, that are studied in specific ways i.e., methodologic approach. This thesis relates to ontology i.e., the way we understand and view energy management and its role in the transition, epistemology i.e., how we acquire, validate, and apply knowledge about energy management, and finally methodology i.e., how to study energy management.

The hypothesis that industrial energy management practices incorporate activities beyond energy efficiency has been validated. The theoretical insights from the fields of knowledge management, system research, action research, transition research, and science and technology studies have been combined and served as a pillar to develop an understanding of the role of energy management in the transition toward sustainable energy systems. The methodology employed in this thesis has been based on these theoretical insights.

Based on this, the answers to the research questions have been provided:

RQ1: Regarding energy management practices in manufacturing industries, it has been shown that a comprehensive approach, encompassing energy conservation, energy efficiency, process innovation, energy supply measures, compensation measures, and participation in energy policy programs and voluntary initiatives, is essential for achieving sustainability goals. Furthermore, it has been shown the need to incorporate process innovation as a significant component of energy management practices where multi/transdisciplinary collaborations are critical for success.

RQ2: The thesis emphasized the significance of knowledge creation in industrial energy management practices. Knowledge creation, combining both explicit and tacit knowledge, which are acquired in different ways, is vital for adapting to the evolving energy landscape. Multi and transdisciplinary collaboration is key to harnessing the full potential of knowledge creation in the context of EnMPs.

RQ3: In terms of policy evaluations and voluntary initiatives, the thesis has highlighted the importance of meticulous design. Ex-ante assessment methodologies for energy efficiency policy programs should consider energy management components and a systems perspective, while VIs must define clear, measurable goals and enhance accountability through robust monitoring and reporting frameworks. VIs can contribute to climate goals if well-defined designs and transparent tracking mechanisms are in place but may need to be complemented by public policy programs in order to enhance even stronger accountability.

This updated view of energy management in manufacturing industries sets the foundation for new theoretical model development that more accurately describes the EnM role and practices in the current context of energy transition.

In summary, this thesis offers valuable insights into the multifaceted world of energy management, knowledge dynamics, and policy design, providing a holistic understanding of the role of energy management in the transition towards sustainable energy systems in the manufacturing sector.

9. Future research

Developing energy management models based on the role of EnM during the transition for various manufacturing sectors, both discrete and process manufacturing, would be of interest. Additionally, studying the implementation of energy management to achieve efficiency and CO_2 emissions reduction targets, as well as the relationships between policies, voluntary initiatives, and the actual implementation of energy management in reaching these targets, will provide further insights on the topic.

How companies handle the trade-offs and the conflicts between targets, i.e., energy reduction versus CO_2 emissions reduction in the long term would be another important area of research. How tacit and explicit knowledge are combined in order to enhance knowledge creation for energy management during transition would bring further insights that can strengthen and support practitioner's work.

There is also a need to strengthen the research methods of energy management to support the practitioners with practical guidance. In order to manage the complex process of transitioning towards climate neutrality, researchers should include a mix of methods, from longitudinal in-depth studies to surveys.

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PART 2

APPENDED PAPERS

Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

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