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Navigating the market of thermal energy storage for steam decarbonization

Exploring the thermal energy storage technological innovation system through the lenses of heat-intensive industry representatives in the European Union

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Finally, I would like to thank all the participants in this research who gave their time and insights to be part of this project.

Abstract

Currently, industries are actively pursuing heat decarbonization solutions, yet face challenges in identifying and understanding suitable options for their facilities. Thermal energy storage (TES), systems that capture and store renewable energy for prolonged periods to provide superheated steam, are presented as a promising but relatively recent solution for decarbonizing heat-intensive industries. This thesis aims to explore how these industries navigate the TES market for superheated steam decarbonization and identify factors influencing the technology deployment. Using the Technological Innovation System Framework, the research gathered data through interviews, questionnaires, and analysis of grey literature such as reports, media articles, and corporate websites. The findings reveal a nursing TES market with limited information availability, leading to uncertainty and prolonged decision-making among potential users. Challenges such as grid connection issues and fluctuating fossil fuel prices impact the business case for TES deployment. To address these challenges, technology developers are recommended to enhance transparency, collaborate on research to strengthen the business case and promote the added values of TES systems. Policymakers should integrate TES into existing policies, ease grid connections, and provide financial support to incentivize adoption. Meanwhile, industries are encouraged to prioritize long-term decarbonization goals and adopt a more innovative mindset. This research contributes valuable insights to an underexplored academic area, offering practical recommendations to drive market maturation and accelerate the transition to cleaner industrial processes in the European Union. By bridging the gap between technology developers and potential users, this study aims to provide tools to facilitate the deployment of TES and support the decarbonization efforts of heat-intensive industries.

Keywords: Thermal Energy Storage, Heat-intensive Industries, Technology Innovation System, Steam Decarbonization, Industrial decarbonization, European Union.

Executive Summary

Currently, societal and political pressures are pushing all stakeholders, especially industry, to take action on climate change. Heat-intensive industries face one of the greatest challenges - trying to reduce greenhouse gas emissions while ensuring continuity of operations, in a market where decarbonization technologies are just being developed. In the European Union, heat-intensive industrial processes consume around 65% of the region's thermal energy demand (Kauko et al., 2022). In that context, Thermal Energy Storage (TES) is a promising technology that could support heat-intensive industries to decarbonize the generation of superheated steam.

The problem this thesis addresses is the market navigation of heat-intensive industries when looking at TES solutions. Heat-intensive industries tend to have low resources, limited knowledge, as well as time and budget restrictions which affect their experience finding, analyzing, and making decisions about new decarbonization technologies. This experience is connected to systemic barriers and facilitating factors that influence directly the deployment of new technologies, in this case, TES.

This master's thesis is focused on exploring and understanding the state of the market of TES for superheated steam decarbonization in the European Union (EU), with a special focus on the perspectives of heat-intensive industries seeking to decarbonize superheated steam processes. This research utilizes the Technological Innovation Systems (TIS) framework (Bergek et al., 2008) to collect, analyze and present data including the heat-intensive industry perspectives, market dynamics and the challenges related to TES deployment in industrial settings.

Research questions

> **RQ1:** *How do heat-intensive industries navigate the complex market of new solutions for decarbonizing their superheated steam process with thermal energy storage solutions?*
>
> **RQ2:** *What are the inducement and blocking mechanisms that impact the deployment of TES in heat-intensive industries in the European Union?*
>
> **RQ3:** *What activities and strategies key stakeholders can implement to accelerate the deployment of TES for industrial superheated steam processes in the European Union?*

Methodology

The study is of a qualitative nature and utilizes the TIS framework to frame the data collection and analysis. The collection of data is via interviews and written questionnaires to three key stakeholders: heat-intensive industries, energy storage associations, and manufacturing associations. Also, some grey literature was included in order to complement the primary data collection. The interview questions sought to cover the TIS framework functions and structural components (Bergek et al., 2008). Similarly, the code for data analysis included the same elements of the framework.

Key findings and analysis

The research findings highlight the complexity of the market dynamics for TES adoption. The market is in its early stages and there is a degree of uncertainty about processes, technology, business models, and other issues.

Participants' perceptions of the knowledge that is available varied. While some found the information clear, others expressed uncertainty and confusion, particularly about the practical application and economic aspects of TES. Academic resources were not seen as useful in the decision-making process, as they tend to focus on technical details rather than business models. Participants generally believed in the growth potential of TES for decarbonization, although opinions varied on its readiness for commercial adoption. Market conditions, such as the price of energy using this technology compared to fossil fuel alternatives, are hindering the uptake of TES.

Several pilot projects and commercial demonstrators for TES in the EU were identified, but the participants believe is not enough experimentation in industrial settings to take the risk of adopting TES. Direct outreach from technology developers is the primary channel through which industries find TES as a solution for superheated steam decarbonization. Overall, TES has a degree of legitimacy but is still considered an immature market for industrial applications.

Financial resources, mainly from venture capital, are being mobilized for TES development. However, there are concerns about the energy infrastructure readiness in Europe. The emergence of external economies related to TES remains limited, reflecting the nascent stage of the market and technology.

The work also identifies inducement and blocking mechanisms. On one hand, there is an overall positive perception of TES as a decarbonization technology from the media and various stakeholders, providing initial legitimacy. Regulatory pressures are driving industries towards decarbonisation and, then, finding TES. Meanwhile, outbound sales efforts by technology developers are driving adoption. Finally, the use of non-critical materials in TES solutions strengthens their business case.

On the contrary, TES deployment is hindered by several challenges. Complex and long grid connection processes and the competitive price of fossil fuels are the main blocking mechanisms that delay adoption. Limited awareness among heat-industry representatives, centralized knowledge sources, and incomplete understanding of the TES value chain are other negative factors constraining market development. Finally, there is a strong conservatism in heat-intensive industries that further hinders the integration of innovation for decarbonization.

Understanding the market situation, as well as the drivers and barriers, is essential to think about what the necessary actions are to accelerate TES deployment.

The study recommends targeted strategies for technology developers, policymakers, and industry stakeholders to facilitate TES adoption. For technology developers, the focus of the recommendations relies on providing transparent and high-quality information on TES, collaborating on experimentation projects in industrial settings, improving sales efforts, and promoting the benefits of TES that are beyond energy storage to effectively engage potential users. These recommendations aim to accelerate the market maturity and acceptance of TES systems.

Meanwhile, policymakers are encouraged to promote TES as a viable decarbonization solution through incentives and the integration of TES into existing policies. Also, it is urgent to develop policies that facilitate the grid connection by TES systems. If taking action, policymakers can significantly facilitate the uptake of TES in heat-intensive industries. Finally, recommendations for heat-intensive industries include prioritizing long-term decarbonization strategies such as TES adoption for superheated steam generation, as well as a culture favorable towards innovation. Together, these efforts promote a shift towards greener industrial processes and stimulate innovation in decarbonization technologies within heat-intensive sectors.

Conclusion

In conclusion, the MSc thesis offers valuable insights into the challenges and opportunities associated with TES adoption in heat-intensive industries within the EU. The study emphasizes the need for collaborative efforts among stakeholders to address market barriers, improve the information available, and accelerate the green transition toward sustainable industrial processes. The findings contribute to a broader understanding of the thermal energy storage innovation system and provide actionable recommendations for promoting TES as a viable solution for industrial decarbonization.

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1 Introduction

The world is already experiencing the effects of climate change, and all actors in our society are responsible for taking relevant action to reduce Greenhouse Gas (GHG) emissions. Since the year 2000, industrial GHG emissions have grown exponentially faster than any other sector, making them one of the stakeholders with more responsibility for climate action (Intergovernmental Panel On Climate Change, 2023). Simultaneously, the political pressure is growing year by year with new regulations, agreements, and policies on national, regional, and international levels. This institutional pressure, coupled with a growing awareness of society, urges the industries to act for the climate.

Combining industry and energy, the industry is the world's largest energy consumer, accounting for nearly 30% of final energy consumption (Intergovernmental Panel On Climate Change, 2023). In the European Union (EU), industry accounted for around 25% of the region's total energy consumption in 2019 (Kauko et al., 2022). Industrial processes that use heat consume roughly 65% of the European Union's thermal energy demand (Kauko et al., 2022). However, firms are starting to take ownership of their role in the transition to a greener future. Currently, over 6,800 companies around the world are committed to reaching net-zero and Science Based Targets (SBTi) for GHG emissions reductions (Companies Taking Action, n.d.). In this paper, the reduction of GHG emissions will be known as **decarbonization**, defined as "the process of stopping or reducing carbon gases, especially carbon dioxide, being released into the atmosphere as the result of a process, for example, the burning of fossil fuels" (Cambridge Dictionary, 2024). The industrial facilities that consume heat at high temperatures, will be named in this document as **heat-intensive industries**, which represent different manufacturing sectors, such as food, beverages, paper, pulp, rubber, plastics, chemicals, and refineries. Even if not committed to the SBT initiative, a lot of companies and industrial facilities are looking for solutions for cost-effective and effective decarbonization. Particularly, the heat-intensive industries, which consume large amounts of energy, are looking into reducing costs and energy consumption, while increasing energy safety. As decarbonization is an XXI Century need, heat-intensive industries are facing the challenge of finding adequate solutions for doing so, especially concerning heat for industrial processes.

Some industrial heat processes utilize steam, which can be considered superheated steam when its temperature exceeds the boiling point corresponding to the operating pressure (Superheated Steam | Britannica, 2024). To produce steam, the common practice is to use a fossil fuels boiler to heat water, see Figure 1-1 for reference. There are alternative solutions in the market, including commercially available options such as biomass energy, geothermal energy, heat pumps, and electric boilers. Nevertheless, other promising solutions are being developed and matured, such as Thermal Energy Storage (TES), which is the focus of this thesis. TES can be defined as "systems (that) can store heat or cold to be used later" (LDES Technologies | LDES Council, n.d.)[1]. These promise stable, flexible, and cost-effective storage of energy from renewable sources for superheated steam generation, see in Figure 1-1 the conceptual process flow of TES.

[1] See chapter 3 for further information on TES

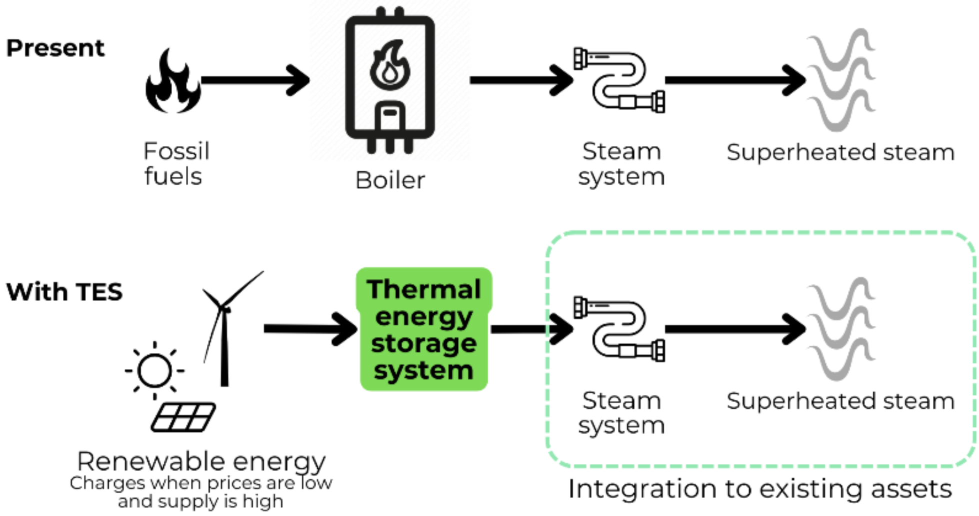

Figure 1-1 Simplified superheated steam industrial process and Thermal Energy Storage application.

Source: own elaboration inspired LDES Council & RB (2023).

The technology developers of TES are mainly startups in different statuses of maturity, but there are a few big companies that, as part of one of their initiatives or branches are also developing TES ("Worldwide Overview of High-Temperature Energy Storage System Providers," 2024 & *Electro-Thermal Energy Storage (MAN ETES)*, n.d.). Nevertheless, the deployment of these solutions can be generally considered in the very early stages. This is reflected in the low presence of TES for industrial use currently installed and operating – only nine pilot or commercial demonstrators in countries under the European Union ("Worldwide Overview of High-Temperature Energy Storage System Providers", 2024 & *HEINEKEN and CSIN Open World's Largest Solar Thermal Plant with Innovative Fresnel Technology for Industrial Use in Spain*, 2024). Technology developers are trying to bring to market different types of TES (explained further in Chapter 3) with diverse use cases and applications, but the demand is evolving slowly, and the industries seem still reluctant to incorporate TES in their processes. All this, in a context where the renewable energy supply is growing (Renewable Energy on the Rise: 37% of EU's Electricity - Products Eurostat News - Eurostat, 2022) and solutions like TES can reduce risks related to the intermittency of renewables. The slow progress puts the energy transition on hold.

This thesis will focus on the connection between heat-intensive industries located in the European Union member states looking for non-fossil-based steam processes and TES technology developers trying to mature and prove their solutions, their challenges, and how this can be eased for accelerating the energy transition of industrial steam.

1.1 Problem definition and relevance

Currently, heat-intensive industries face the challenge of searching for solutions that can support the decarbonization of their superheated steam processes, while continuing with complex operations and navigating an emerging market of mature and new solutions. Industries need to find solutions, understand them, and select them according to their specific needs, which ends up in delays and extensive sales processes between technology developers and industries. If the industries do not invest and work with TES technologies, these will not be mature and commercially deployable anytime soon, delaying technology substitution, innovation diffusion, and climate action.

The challenge of navigating an emerging market of innovative solutions is not unique to TES technology, this situation is common for many innovations. There is a wealth of examples and literature that aim to explain and understand how some technologies thrive while others struggle to gain market acceptance. TES represents just one example of this broader phenomenon, highlighting the intricacies between technological advancement, market readiness, and industry adoption.

The problem to be explored in this thesis is the complex experience of heat-intensive industries while navigating the TES market, as well as the inducement and blocking mechanisms that impact the deployment of TES solutions, with a special focus on heat-intensive industries perspectives in the European Union, in the context of accelerating the decarbonization of superheated steam processes while promoting the maturation of TES as a clean solution for it.

The significance of this research topic relies on the practical use of the potential results of the study, which can be incorporated into business and management plans in technology developers. This importance was identified not only in an initial literature review but also in talking with technology developers representatives who are struggling with attracting and retaining potential customers (known in this text as heat-intensive industries) when offering clean tech solutions for superheated steam.

The relevance of the academy is because it is not a very explored niche. Most of the research available is related to the technical characteristics and applications of the TES. Two examples are Zanganeh et al. (2015), a paper that presents how to optimize the design and use of a rocks-based TES, and Kenisarin (2010), who evaluates alternatives of storage materials – specifically phase change materials – and their usability for TES. Meanwhile, there is no exploration about the heat-intensive industries – potential users of TES – perspective and experience navigating the market. This thesis will complement existing knowledge in academia and look into this very specific conjunction of topics.

Finally, the author has a personal interest in understanding the market dynamics of TES and emissions reduction within industries. Also, this problem definition acknowledges the personal interest and limitations of the author, focusing on market dynamics, relations between actors, and business strategy issues, since is her area of study and experience.

1.2 Aim, RQs and objectives

This MSc thesis aims to explore the state of the market of TES for the decarbonization of superheated steam in the European Union (EU) from a number of heat-intensive industries' perspectives and utilizing the Technological Innovation System (TIS) framework (Bergek et al., 2008). The exploration will focus on three key aspects: (a) the experience of heat-intensive industries in navigating the market of TES, (b) inducement and blocking mechanisms that impact the deployment of TES for clean industrial superheated steam processes, (c)and how stakeholders could overcome those challenges. The perspective of interest is from a group of heat-intensive industry representatives that have scrutinized TES for the decarbonization of their steam needs and are located within the European Union.

Based on the previous sections, as well as the aim and knowledge gap stated, it was formulated the following Research Questions:

RQ1: *How do heat-intensive industries navigate the complex market of new solutions for decarbonizing their superheated steam process with thermal energy storage solutions?*

RQ2: *What are the inducement and blocking mechanisms that impact the deployment of TES in heat-intensive industries in the European Union?*

RQ3: *What activities and strategies key stakeholders can implement to accelerate the deployment of TES for industrial superheated steam processes in the European Union?*

1.3 Scope and delimitations

In this thesis, the focus relies on heat-intensive industries that have superheated steam processes between 200 °C to 600 °C. This selection is mostly for simplification purposes and to scope TES applications. The current state of TES technologies covers from around 100 °C to up to 1500 °C, including more industrial processes and pure heat ("Worldwide Overview of High-Temperature Energy Storage System Providers," 2024). In that sense, the author decided to focus on superheated steam, to exclude heavy industries such as steel, iron, and cement that mostly use heat above 900 °C, but that does not mean that TES can't be a solution for those applications. Lastly, the temperatures below 200 °C can be more easily decarbonized by other solutions such as industrial heat pumps, which currently can provide around 80 °C to 180-230 °C steam and are a promising solution that is already commercially available and could represent lower costs and risks than TES emerging solutions.

Regarding the geographical scope, the author aimed to focus on heat-intensive industries located in Germany in order to have a single political background and more comparable cases. Also, Germany is one of the strongest European countries with a wide important presence of heat-intensive industry. However, while scouting for interviews the author faced the challenge of an extremely low response rate. From over 50 contacted professionals working in industrial facilities in Germany, the author did not get a single interview. In that context, the decision to broaden the scope to the European Union (EU) member states was taken. This thesis by no means represents the entire heat-intensive industry' perspective, in reality presents a few specific cases and tries to find commonalities and differences, while looking at diverse types of literature. More regarding this will be explained in Chapter 3 about methods.

1.4 Audience

The main audience for this thesis is business developers from technology developers working on TES solutions. Furthermore, it is relevant for professionals working with superheated steam processes in heat-intensive industries (food, beverages, paper, pulp, rubber, plastics, chemicals, and refineries) in the EU that are looking for innovative solutions to replace fossil fuel-based steam systems and reduce their GHG emissions. Lastly, the research is relevant for the academic audience, and anyone interested in the energy transition and innovation.

For business developers and professionals within TES developers, this thesis offers valuable insights about their potential customers and the barriers impeding the widespread adoption of their technologies. It also presents a deeper understanding of market demands and provides actionable recommendations to navigate challenges effectively, facilitating more efficient customer engagement and market penetration strategies.

In the context of heat-intensive industries, this thesis serves as a resource for understanding the current market landscape and available TES solutions. It aims to inspire investment considerations or partnership discussions with emerging firms developing TES technologies, fostering innovation and sustainability within these industries.

From an academic point of view, this thesis contributes a systems perspective on the market dynamics and deployment challenges associated with TES—an aspect that has been relatively unexplored until now. This thesis highlights the intersection of technology, industry, and sustainability, laying a foundation for future research, and encouraging further academic investigation into the acceleration of TES technologies within the context of decarbonization and energy transition strategies.

1.5 Ethical considerations

The author works in the deep-tech startup Hyme Energy, based in Copenhagen (Denmark) which is developing a TES solution for steam decarbonization. Even though the position of the researcher in this company is focused on communications, the topic emerged after debating with colleagues and university teachers, as well as for pure interest in the energy transition innovation market. However, it is important to note that it was independent research. This was not collaborative research, Hyme Energy has not sponsored, influenced, or had any access to the raw data or privileged information.

The interviews performed were voluntary. The author approached different individuals via email, social media, or phone calls, explaining the thesis project and inviting them to an interview. The author informs that every participant will be anonymized and that the main results of the interviews will be available in the final text. No sensitive information is shared during the interviews. The interviews are recorded with the purpose of being transcribed and analyzed more comprehensively, and the recordings were deleted from every digital space by the end of June.

Data was stored in the author student's Microsoft 365 cloud account and in a hardware protected with a password where a backup was done every week.

1.6 Disposition

This thesis is structured into six chapters, each with respective sections and subsections, organized to follow academic conventions and the logical progression of the research and analysis.

Chapter One serves as the introduction to the research problem under analysis, detailing the aim, research questions, and related aspects.

Chapter Two provides a comprehensive review and analysis of existing research on TES and its market. This review not only presents recent research but also brings light to fundamental concepts crucial for understanding the thesis's scope.

Chapter Three outlines the research design and methodologies employed for data collection and analysis. This includes the use of the Technological Innovation System framework to guide and frame the research.

Chapter Four presents the primary research findings, along with the respective analysis. This chapter constitutes the core of the thesis, synthesizing results from preceding chapters and data collection efforts.

Chapter Five takes a step back and engages in a higher-level discussion, revisiting research questions, acknowledging limitations, and exploring implications for future research within the subject area.

Finally, Chapter Six offers concluding thoughts summarizing the research, and presents recommendations tailored for key system stakeholders. These recommendations aim to provide strategic guidance and tools for overcoming challenges and accelerating the adoption of TES for superheated steam decarbonization.

2 Literature review and analytical framework

This chapter serves as a comprehensive exploration and analysis of existing research related to TES and its market context. This review not only offers an overview of the latest research but also clarifies key concepts essential for understanding the current thesis. Besides, this chapter outlines the selected theoretical framework, establishing a solid foundation for the next chapter on methods. Through this literature review, the author aims to contextualize the research within the existing academic literature.

2.1 Setting the scene on thermal energy storage

In this section, the author presents the key concepts related to TES and its current state of research.

2.1.1 Key concepts

In this subsection, the author outlines the key terminology essential to understanding the thesis work. The concepts are rather technical but provide a basis for the subsequent sections.

Electrification as an approach to decarbonization

When looking at the decarbonization of industrial heat, including superheated steam, the literature suggests that there are four alternatives to explore: "(1) zero-carbon fuels, (2) zero-carbon heat sources, (3) electrification of heat, and (4) better heat management" (Thiel & Stark, 2021, p. 531). The current research focuses mostly on the electrification of heat (Son et al., 2022; Grieco & Palou-Rivera, n.d.; and Rightor et al., 2020). Electrification means generating steam with electricity, rather than with a fuel – including fossil fuels and biomass. The common and *off-the-shelf* solutions for electrification are heat pumps and electric boilers (Son et al., 2022).

Electrification is one of the emerging strategies to mitigate GHG emissions in industry (IPCC, 2023) because it is a cleaner way of producing heat. Madeddu et al. (2020), developed a bottom-up analysis of the EU's heat demand and calculated the CO_2 potential reduction. In the article, they present that electrification towards a net-zero industry by 2050 should take place in three stages and that this would halve industrial CO_2 emissions (Madeddu et al., 2020).

There are a lot of aspects to have in mind when talking about electrification, as for example if the electricity comes from fossil fuels and not renewable sources, these solutions are useless (Rightor et al., 2020) and might increase GHG emissions (Madeddu et al., 2020). Also, the grid currently does not have the capacity for a transition into complete electrification of heat processes, meaning that even more renewables must be deployed, along with other infrastructure developments (Thiel & Stark, 2021). Another relevant aspect is cost, heat-intensive industries are willing to decarbonize or change their processes at the lowest cost possible. In that sense, electrification can be challenged by unstable energy prices, geopolitical conflicts, unfavorable policies towards renewables, and more. An additional constraint is the limited capability of heat pumps, covering temperatures only up to 180-200°C, posing challenges for heat-intensive industries with higher temperature processes (Dumont et al., 2023).

Energy Storage

Energy storage is a system that holds energy charged at one point in time, to use it later (*Energy Storage*, n.d.). This is mainly used in the context of renewable energy because it can provide stability and flexibility to renewable energy when the sun is not shining, or the wind is not blowing. A complete facility of energy storage includes all the components to do the following three functions:

a) Charge: energy storage charges energy. Usually, the energy charged is in the form of electricity, especially from renewable sources.
b) Storage: the unit holds the energy as electricity, heat, or any other type of energy. So, from the charging process to the storage, sometimes an energy conversion is necessary.
c) Discharge: when needed or continuously, the energy is unloaded for whatever is needed. Sometimes another energy conversion is needed here, including extra equipment (Sterner & Stadler, 2019).

Energy storage systems can be classified based on a set of characteristics (Guney & Tepe, 2017; Sterner & Stadler, 2019):

- Storage technology: electrochemical, mechanical, thermal, fuels and chemical.
- Duration: depending on how long they store energy. There is not a clear and common understanding but mainly can be short-duration and long-duration.
- Energy output: electricity, heat, or other.
- Scale: these can be from portable lithium batteries to big facilities at industrial or grid scales.

In this thesis, the energy storage selected is based on two main characteristics: its technology and duration.

Long Duration Energy Storage (LDES)

There is no agreement on the exact definition of Long Duration Energy Storage (LDES) in academia or industry. The main factor determining what is an LDES and what is not is the number of hours of storage and discharge when the system is not charging. Twitchell et al. (2023) did a review of the current definitions of different organizations and research, and the consensus identified is that LDES can be any storage that holds energy for at least 10 hours.

Within the LDES technologies, there are several under development, including TES which will be explained in a separate section below. Other alternatives to LDES are electrochemical, mechanical, and chemical storage.

- Electrochemical Storage: this type of storage converts the electricity into chemical energy which can be converted into electricity again when required. The electrochemical batteries store energy in electrodes connected to an electrolyte conductor and a chemical reaction is needed to convert the energy. One example of long duration electrochemical storage is flowing batteries, which store the energy in a liquid electrolyte that is contained in external tanks. This type of battery-only discharges electricity (Sterner & Stadler, 2019).
- Mechanical Storage: this type of storage can store energy in potential or kinetic energy, following physics basic principles. A known technology is Compressed Air Energy Storage which stores compressed air in tanks and discharges it when needed. Pumped-Hydro is another typical example, these are usually water reservoirs at higher altitudes and when the energy is needed it will be pumped into a turbine to generate electricity. Lastly, Flywheel storage stores kinetic energy into a mass that is rotated when electricity is required (Sterner & Stadler, 2019).

- Chemical Storage: represents storage that uses chemical compounds to store energy and then generate electricity or heat. The main example is Hydrogen storage which has currently a lot of attention in media and policies. Hydrogen can be produced from renewable energy and then be stored in gas or liquid form until when is needed for producing heat and power (Sterner & Stadler, 2019).

Thermal Energy Storage

LDES is just a classification based on the duration of the storage capacity, but the other type of category is based on the storage technology. Thermal Energy Storage (TES) is one of those, which means that the energy is stored as heat in a specific material (Sterner & Stadler, 2019). Generally, the TES solutions offer storage in heat, but storing in cold is also possible. The main implication of TES is that an energy conversion is needed if the energy charged is electricity, which implies some energy losses. However, TES can also charge heat from diverse sources, including what is known as *waste heat* from other processes in a manufacturing facility.

There are three types of TES, summarized in simple words, based on Sterner & Stadler (2019):

- Sensible TES: in this type, the storage medium has to be heated and/or cooled, having a perceptible change in temperature. The temperature change varies depending on the storage medium material characteristics, particularly boiling and solidification points. Some examples are molten salts, rocks, cement, and others. This is the most common type of TES in the market ("Worldwide Overview of High-Temperature Energy Storage System Providers," 2024).
- Latent TES: is similar to sensible TES, but this type includes a change in phase for the storage material, meaning that when charging and discharging, the temperature change is so strong that the material will change from solid to liquid, liquid to solid, or liquid to gas. The materials with these characteristics are known as Phase Change Materials (PCMs) and usually are a mix of more than one component, including wax, silicon, and metal alloys. However, this type of TES is less common in real life.
- Thermochemical TES: this is the least common of the TES under development. This technology involves a chemical reaction to separate components, store them, and then reverse the reaction to unload energy. This process reduces energy losses, but its complexity is higher than in the other systems. An example of this is CO_2 emissions as a storage medium (*Electro-Thermal Energy Storage (MAN ETES)*, n.d.).

The key selling point of TES is that provides stability and flexibility because it can store electricity and use it later when the sun is not shining and the wind is not blowing, but also because it helps to shave peaks of energy demand, stabilizing the grid. TES and other types of energy storage are key infrastructures that need to be developed to provide more security and stability to the electrical grid powered by intermittent renewable sources (Papadis & Tsatsaronis, 2020).

The integration of TES into superheated steam processes is a form of direct electrification as shown in Figure 2-1 the electricity from renewables – either from an own renewable installation, or from the grid via green power purchase agreements (*How Corporate PPAs Can Help Drive Europe's Green Recovery*, 2020) – is stored in the TES, and then directly provides superheated steam. However, there is another type of application where TES is coupled with other solutions (i.e. an electric boiler) and provides indirect electrification to superheated steam processes (Beck et al., 2021; Li et al., 2022; Miró et al., 2016; and Kuravi et al., 2013). This is one of the main applications covered by the academic literature, but it is an older perception of TES. Besides, the market has evolved enough to have several technology developers offering direct electrification.

Figure 2-1 Direct and indirect electrification with TES

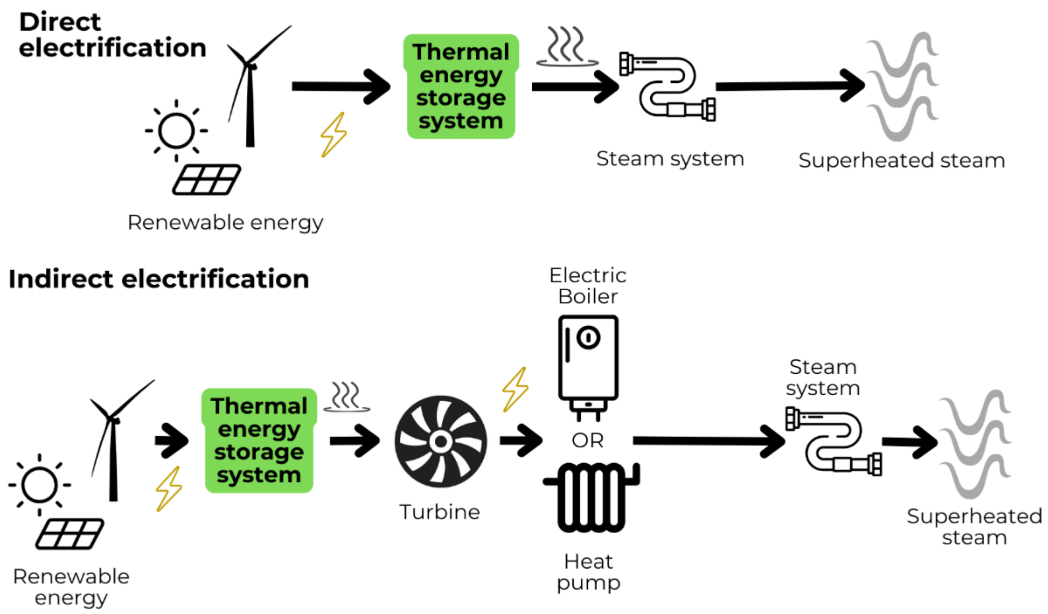

Figure 2-1 Direct and indirect electrification with TES

Source: own elaboration

Electrothermal Energy Storage

Electrothermal Energy Storage (ETES) is another classification of TES, but a less known and popular term. This means that the TES is charged by electricity only, stores the energy as heat, and delivers heat or electricity (SystemiQ, 2024). The author decided to simplify the language and use TES because is more well-known in both academic and grey literature. Every ETES is a TES, so for this thesis, it was selected the broader term.

2.1.2 Current research on thermal energy storage for decarbonization of industrial steam

The current academic understanding of TES for industrial heat decarbonization is in its very early stages of development. Generally, the academic literature concerning TES mostly focuses on its characteristics, diverse technologies, and technical aspects. The technology developers are bringing to the table innovations that cover more temperatures or that use other storage medium materials. In that sense, academia is still learning and understanding those innovative technologies.

However, a few articles present more information about its applications, particularly about industrial superheated steam generation. Among the ones that discuss TES in industrial settings, most of those focus on different cases not studied in this thesis, such as waste heat recovery, coupling with Concentrated Solar Power (CSP), and coupling the TES system with a power generation turbine and other electrification technologies such as electric boilers and heat pumps – also known as indirect electrification (Beck et al., 2021; Li et al., 2022; Miró et al., 2016; and Kuravi et al., 2013). Similarly, an article studies how TES can be integrated into industrial parks for heat – with indirect electrification – and power generation (Klasing et al., 2018). Besides, even if those academic articles present these applications, they focus on modelling for optimization or other technicalities related to the technological development of TES to offer a cost-effective alternative for heat-intensive industries (Geissbühler et al., 2016 & Zanganeh et al., 2015).

In terms of decarbonization potential, there isn't a consensus in academia on how much CO_2 reductions TES represents. This is mostly because the applications commonly presented in the literature are related to reusing industrial waste heat, TES coupled with other solutions or TES for power generation. However, to have an estimation, when integrating TES for industrial waste recovery, depending on the geographical location and the process, the CO_2 reductions can go from 70% to 93% less emissions of the same process without TES (Miró et al., 2016, p. 298). Similarly, when a CSP plant incorporates TES, this technology replaces the fossil fuel-based backup for when there is not enough solar supply, which can represent 43% in CO_2 savings (Cabeza et al., 2015).

2.2 Analytical framework

As mentioned, the thesis aims to understand the state of the market of TES from a system approach with a special focus on the heat-intensive industries perspective, and users of this technology. To do so, the author analyzed different theories and analytical frameworks that have been used in similar research for other topics. In that sense, one theory and two main frameworks were analyzed: Diffussion of innovations (Rogers et al., 2008), the Multilevel Perspective (MLP) – particularly the technological substitution pathway (Geels & Schot, 2007) – and the Technological Innovation System (TIS) (Bergek et al., 2008).

A theory commonly used to understand similar topics is *Diffusion of innovation* by Rogers et al. (2008). This theory is widely utilized in market research and presents how new technologies spread in new or existing markets. Rogers et al. (2008) introduced to academia a number of key elements which contribute to an understanding of the diffusion of innovations. These include the different categories of adopter types, the diffusion curve, and the decision-making processes of adopters in relation to whether they incorporate or do not incorporate an innovation. In this context, the theory can be considered a metatheory, given that it encompasses business-to-business and business-to-customer relations, as well as a wide range of dynamics between users and technology developers. In this context, the thesis employs one of the analytical tools developed by Rogers to present findings in a structured and logical manner. However, it should be noted that the thesis does not attempt to present the entire theory as a framework.

The Multilevel Perspective (MLP) examines the interactions and dynamics between different levels of a socio-technical system, and how transitions can occur. The considered levels are the landscape, regime, and niche, providing a comprehensive understanding of transitions and disruptions in technology and markets (Geels & Schot, 2007). Furthermore, within those levels, some different actors and functions play a role in the transition from business as usual to novelties (Geels & Schot, 2007). This framework is a valuable tool that has been widely employed in the field of sustainable transitions, as evidenced by the numerous studies that have utilized it. For instance, Grünewald et al. (2012) employed the MLP framework to investigate the distributed use of energy storage for electricity within the United Kingdom. However, for the current thesis, the MLP framework provides a more comprehensive perspective than the specific one being investigated. Consequently, it was decided not to utilize this framework for the research. Wesseling et al. (2016) take elements of Geels & Schot (2007) and other literature to analyze how energy-intensive processing industries are navigating the transformation of their businesses to decarbonize. They present, utilizing some elements of the multilevel perspective, structural components elements from the entire value chain of energy-intensive processing industries that influence the uptake or not of new technologies for decarbonization (Wesseling et al., 2016).

In contrast, the Technological Innovation System (TIS) framework, developed by Bergek et al. (2008), focuses on the systemic context in which innovation occurs, how this influences the actors involved, and how the diffusion of innovation is functioning. This framework enables the researcher to gain a comprehensive understanding of the current state of the technology diffusion process and to identify the inducement and blocking mechanisms that are influencing its maturation. For these reasons, it was deemed more appropriate for the research conducted in this thesis. The author will subsequently present the framework in greater detail and the current research conducted using the TIS framework.

2.2.1 The Technological Innovation System analytical framework

The TIS framework comprises six analytical steps for investigating technological innovation systems interactions. It also incorporates a comprehensive set of elements, referred to as *functions*, to evaluate dynamics between actors within a specific TIS and interactions between different TIS.

In this research, a TIS is defined as "socio-technical systems focused on the development, diffusion, and use of a particular technology (in terms of knowledge, product, or both)" (Bergek et al., 2008, p. 408). The key steps for a TIS analysis are:

1) Define the TIS under analysis.
2) Define the structural components – actors, networks and institutions.
3) Identify the state of the functions, denoted as *key processes* with a direct impact on technology development, diffusion, and use – knowledge development, resource mobilization, market formation, influence on the direction of research, legitimization, entrepreneurial experimentation, and development of external economies
4) Assessment of the achieved functionality
5) Identification of inducement and blocking mechanisms
6) Recommendations (Bergek et al., 2008).

This framework is presented again in Chapter 3, where it is also shown its alignment with the research.

2.2.2 The Technological Innovation System framework in practice

The IPCC Working Group 3 utilizes the TIS framework functions to explain factors that are inhibiting or promoting the technological development and cooperation in innovation for a low 1.5 °C future (IPCC, 2023). This is just an example to showcase the importance of the TIS framework for the analysis of sustainable technology diffusion. In this section, the author will present different examples of how the TIS framework was used in research.

Hekkert & Negro, (2009) perform five case studies utilizing the TIS framework to understand the technological changes in different biomass and biofuels innovation. After that, they scrutinize if all the functions presented by Bergek et al., (2008) are relevant. The results indicate that the functions are, in fact, relevant for analyzing the diffusion of innovations for sustainable transitions. Also, they encountered that the functions are interconnected between each other and that they interact in reinforcing and balancing cycles (Hekkert & Negro, 2009).

Several researchers are working with the TIS framework within the renewable energy area. Most focus on solar PV, including distributed generation (van Noord et al., 2024), comparative cases (Vasseur et al., 2013), circularity (Godinho Arriolli, 2021), and more (Esmailzadeh et al., 2020; Hanson, 2018). While some others focus on wind generation with differences between offshore (Wieczorek et al., 2013) and onshore cases (Bento & Fontes, 2015).

The TIS framework has been utilized in the energy storage topic area. Wicki & Hansen (2017), take a TIS perspective when analyzing the deployment of a type of energy storage: flywheels, a short time energy storage solution that utilizes kinetic energy and can be used in the automotive industry. The main results suggest that flywheel energy storage would be a mature technology ready to be commercially available.

2.2.3 Current understanding of the diffusion of thermal energy storage

The main progress on TES literature is reflected in **grey literature** in the form of media articles, or reports made by associations and consultancies. None of these analyze the innovation diffusion of TES in industrial settings but provide some information that contributes to the overall understanding of the state of TES in the market, recent updates on projects, comments on new developments, actors that show interest in the subject area, producer information, and other related information is typically a one-way process. This information is often technical and may include opinions and claims that are difficult to control. Consequently, it lacks the same level of credibility as peer-reviewed articles. Nevertheless, it can serve as a valuable supplement to findings from interviews, provide a context for information from interviews, or simply introduce new perspectives when used in a critical manner.

A recent report developed by SystemiQ in collaboration with the US-based venture investment firm Breakthrough Energy (2024) presents an overall approach to the market of ElectroThermal Energy Storage and provides recommendations to crucial stakeholders for accelerating the deployment of solutions in industrial settings. The report estimates that the deployment will occur in two and potentially three steps. The first one will cover processes with lower temperature steam (200°C-400°C) "The global potential for this first wave is estimated to be 3,100 TWh, covering 2% of global energy-related GHG emissions and 8% of gas use in terms of direct on-site impact" (SystemiQ, 2024, p. 15). The second wave covers processes of steam and heat above 400°C, with more than double of potential emissions abatement (SystemiQ, 2024). There is a potential third step covering the market of processes below 200°C that is now addressed by heat pumps which are more cost-efficient (SystemiQ, 2024). Regarding challenges, the report presents a comprehensive list of policy-related challenges that hinder the affordability and accessibility of ETES solutions in the world, information that will be used in the content analysis of this thesis, complementing the interviews and other grey literature. Lastly, the report claims that the technological readiness level (TRL) of the technologies for temperatures below 400°C is TRL 7 or above, while for temperatures above 400°C the TRL is between 4 and 6[2] (SystemiQ, 2024).

Another report elaborated by the European Association of Storage of Energy [EASE] (2023), presents that the type of TES with higher TRL is sensible heat and some latent heat using Phase Change Materials related to salts with a TRL 7-9, followed by the rest of latent heat technologies and thermochemical heat solutions with a TRL 4-6. The report analyses several real-life business cases, including three related to the decarbonization of industrial superheated steam in the food & beverages, pulp & paper, and brewery industries. Lastly, they provide recommendations to policy stakeholders (EASE, 2023).

Solrico, an agency of solar market research, analyzed the current TES systems under development in the market. They consulted with startup technology developers, and they identified and contacted 31 companies from 12 countries developing diverse TES for different applications: electricity generation, superheated steam production, district heating, and reuse of waste heat in industries. They also present where the startups are located geographically, the materials utilized in the different solutions, and what they present as the "level of commercialization" based on the number of pilots and commercial demonstrators under construction or finished ("Worldwide Overview of High-Temperature Energy Storage System Providers," 2024). Further information will be presented in Chapter 4, because this source is part of the grey literature collected and utilized in the analysis.

In conclusion, these inputs present an optimistic perspective on the opportunities and potential of TES, as well as an overall understanding of the current technologies. Besides, they showcase the main challenges and action points to overcome those to accelerate the deployment and development. The use of the TIS framework allows, in a systematic way, to complement the grey literature and to assess the potential of TES to take a role in the energy transition, or if it will fade out along with other solutions that are in development nowadays.

Other relevant grey literature in thermal energy storage

Besides the above-mentioned technical reports, additional media articles, and corporate websites were used. This grey literature brings updated information from recent events in the market, recent technical developments, news about projects taking place in the system, and some diverse perspectives. This grey literature is difficult to control and prove, particularly because opinions can be disguised as facts. However, grey literature can complement the findings from the data collection, put some of the interviewees' claims into perspective, and provide news about the latest updates on TES.

Some of the data utilized to complement the findings in Chapter 4 include updates on investments made towards TES technology developers (Colthorpe, 2024; *Germany's Kraftblock Raises €20M Series B for Sustainable Thermal Storage Technology*, 2023; & Viaintermedia.com, 2023) as well as about financial stakeholders involved in projects deploying TES (*Balancing CST Production Gives Sustainability Boost to Tape Factory*, n.d.; *EDP & Rondo Energy Partner to Decarbonize Industrial Heat Production*, 2024; & *Nasce la prima CER in area industriale*, 2023).

Other grey literature included in the analysis refers to legislations that influence the system, such as ISO 50001, the European Green Deal, the Corporate Sustainable Reporting Directive of the EU, and more (Directive (EU) 2023/1791 of the European Parliament and of the

[2] TRL: these levels go from 1 to 9, being 1 the lowest and 9 the closest to maturity (*Technology Readiness Levels - NASA*, n.d.)

Council of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955, 2023; *How It Works*, n.d.; *ISO - ISO 50001 — Energy Management*, 2023; & *The European Green Deal - European Commission*, 2021).

Lastly, some media articles, consultancy reports and corporate websites just present information about the technologies available, its technicalities and applications, as well as information about competing technologies, providing a broad understanding of the market, especially of the perspectives from technology developers and the overall discourse in media and reports regarding this technology (*Electro-Thermal Energy Storage (MAN ETES)*, n.d.; *Heatcube*, n.d.; *HEINEKEN and CSIN Open World's Largest Solar Thermal Plant with Innovative Fresnel Technology for Industrial Use in Spain*, 2024; *How It Works*, n.d.; Importer, 2022; EASE, 2023; *Molten Salt Energy Storage (MAN MOSAS)*, n.d.; R*edefining Industrial Heat*, 2023; & SystemiQ, 2024).

3 Research Design & Methods for data collection and analysis

This study is qualitative and employs a specific theoretical framework, as outlined in the preceding chapter, to guide the entire research process. The following three sections present the research design, data collection, and analysis.

3.1 Research Design

The researcher proposes a qualitative study. There are several reasons behind this approach, one of them based on Creswell & Creswell (2018) “If a concept or phenomenon needs to be explored and understood because little research has been done on it or because it involves an understudied sample, then it merits a qualitative approach” (p. 57). As mentioned in the problem definition, the knowledge gap requires exploring and understanding a topic not been explored enough. Additionally, the data collected include perspectives and opinions mainly from heat-intensive industry representatives for later finding commonalities and differences. The aim is to gather a diverse range of insights from heat-intensive manufacturing representatives. Through interviews and questionnaires, a nuanced understanding of this crucial stakeholder perspective was obtained. By analyzing these perspectives, the study intends to inform strategic decision-making and innovation among stakeholders of the TES TIS.

Regarding the worldview perspective, the author finds this thesis in the constructivist worldview. The reasoning behind this is that the topic has not been explored in academic literature previously, it is necessary to understand the situation, including diverse perspectives and experiences (Creswell & Creswell, 2018). Moreover, there is also an element of transformative worldview as it brings the aspect of change to the table, which is studied in this thesis throughout the TIS framework (Creswell & Creswell, 2018).

3.2 Data collection

Data was collected from a wide range of sources, including non-academic publications, social media content, mainstream media, questionnaires via email, and semi-structured interviews. This comprehensive approach ensures a rich dataset for analysis and varied perspectives.

3.2.1 Semi-structured interviews

As the focus relies on understanding the energy-intensive industries' perspectives, the main data collected was via semi-structured interviews, being the researcher the main instrument for this exercise (Creswell & Creswell, 2018). The author contacted and interviewed ten professionals from (a) heat-intensive industries – food & beverage, packaging, and plastics with superheated steam processes (between 200°C-600°C) located in the EU –, (b) Energy storage associations, and (c) manufacturing industry-related associations. Even though the goal was to perform interviews via call, some participants just answered a written questionnaire (see Appendix 1) due to personal preferences. The approach to contacting the interviewees was rather exploratory because the author did not have direct contacts or previous experience in the area. In that sense, the author approached it in different ways:

1. Looked for manufacturing companies in the database Orbis (accessible via the Lund University Library) and identified relevant ones. After, tried to find direct contacts with sustainability or energy-related employees using Apollo.io, a sales management platform that provides email and phone information of companies’ employees. If no data was found in the platform, the author would contact them via the generic email or phone available on the website.

2. Posted on LinkedIn and Facebook to leverage personal networks.
3. Contacted manufacturing industry-related associations and, apart from requesting an interview, asked if they could provide contact information of their members.
4. Snowball technique: after each interview, the author asked the interviewee for contacts.

The people who accepted interviews and answered questionnaires were contacted mainly by the first approach. However, in most of the cases, the person initially contacted referred to someone else, who provided the interview or questionnaire answers. The questionnaire was the second resource, when the participant could not access a formal interview or a phone call, but still wanted to contribute to the research. The author looked for representatives of heat-intensive industries that are considering, have considered, or have implemented TES solutions for the decarbonization of superheated steam processes. In the process of contacting interviewees, the author explained the aim of the project and ethical considerations.

Each participant was assigned a code to anonymize their responses. The interview guide was framed by the TIS framework functions, to collect the needed data in a structured way. All the interviews were recorded and lasted around 25 to 40 minutes, depending on the time availability and personality of the interviewee. The recordings were stored in the local computer and storage hardware, until the end of the research.

3.2.2 Grey literature

As mentioned in Chapter 2, the current understanding of TES for superheated steam decarbonization is not explored in academic literature other than for the technical aspects of the technology. However, the author could utilize grey literature as a supplement as it provides up-to-date insights, market analysis, and news that complement the primary data collected. The purpose is to validate the interview results, as well as to understand more perspectives of the TES market from heat-intensive industries, associations, technology developers, and other key stakeholders at a higher level. This also supports the completion of information for some functions of the TIS framework.

This grey literature includes content from diverse media such as newspapers and websites. Also, reports from associations and consultancy firms are considered grey literature. The author finds the grey literature by browsing the internet and social media, utilizing keywords such as "Thermal Energy Storage" "heat decarbonization" and "Electrification with TES".

3.3 Data analysis

The data analysis uses the technique of content analysis, to find themes, patterns, commonalities, differences, and gaps (Bryman, 2016 & Schreier, 2012). In order to perform this content analysis, the author builds a code of themes, categories, and subcategories where the data is distributed and analyzed, following the guidance of Schreier (2012) in her book titled *Qualitative Content Analysis in Practice.*

The data analysis was conducted in parallel to the data collection. Immediately after the interview, the audio was transcribed using Microsoft Word. After, the author summarized and processed the responses into a Microsoft Excel sheet to locate all the questions and diverse answers in the same place. This was to give a first sense of the responses, similarities, differences, and aspects to explore. Also, this was a handy resource when coding the data into the framework of analysis.

Later, the author built a code in Microsoft Excel, which is theory-driven by the functions outlined in the TIS framework. Nevertheless, the author wanted to leave room for spontaneity and added new code categories based on the interviews and questionnaires (Schreier, 2012). The columns in that Excel sheet represented different themes, categories, and subcategories, while rows represented the interviewees and grey literature. The author processed the transcriptions with support of the previous Excel sheet mentioned above and included relevant grey literature.

All this data was analyzed in two main steps: locating it in the different parts of the code (a) and then identifying the current state of the functions (b) (Bergek et al, 2008). In that way, it took the extra step needed to assess the functionality of the functions. After that, based on the assessed weaknesses of the market, the author identified the key blocking and inducing mechanisms, that support the development of recommendations for diverse stakeholders.

In the following Figure 3-3 is possible to see the TIS framework aligned with the Research Questions and the methods.

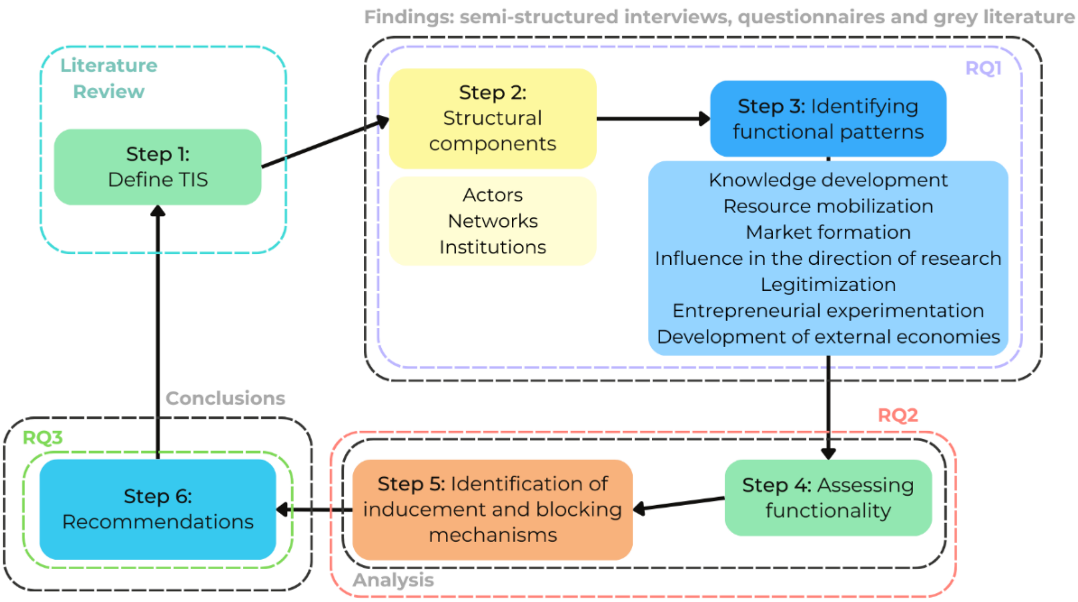

Figure 3-3 – TIS Framework alignment with the research

Source: own elaboration based on Bergek et al., (2008)

The figure showcases how the framework and the research align. The TIS framework is a step-by-step process, and the research builds up similarly. The first step was to define the TIS under analysis, which was defined during the literature review chapter. The second and third steps are part of the data collection and analysis, in the sense that the author utilized the functions and structural components when designing the interview guide and when researching grey literature. Also, the author utilized the functions and components to build the code for data analysis. As mentioned, the data analysis also includes two other steps: 4. Assessing functionality; and 5. Identification of inducement and blocking mechanisms. The key insights, assessment of the functions, and the inducement and blocking mechanisms are all presented in the next chapter "Findings and Analysis". Steps 2 and 3 aim to answer RQ1, while step 5 responds to RQ2. Lastly, the final step in the original TIS framework is about recommendations for policymakers, but in this thesis, the aim is to provide recommendations to relevant actors for the TIS under study, so that's why the term was simplified for a broader version. The recommendations are presented in the last chapter of "conclusions and recommendations" and answer the RQ3.

4 Findings and Analysis

This chapter presents the results and key findings of the data collection and analysis process. As mentioned in the methodology chapter, the main data collected was via semi-structured interviews and written questionnaires, as well as a review of grey literature. In Figure 4 it is possible to see the numbers of the contacted individuals and final interviews.

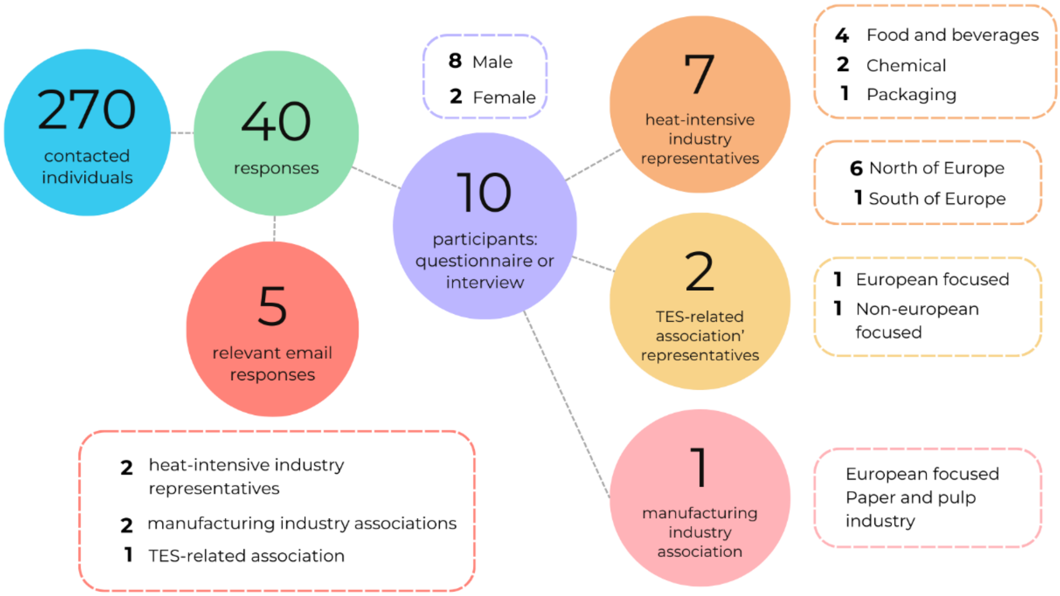

Figure 4 – Data collection

Source: own elaboration.

As is possible to see above, the conversion rate from contacted individuals to effective interviews or questionnaires is low. This is, as explained in Chapter 3, due to the nature of the exploratory approach, it was a challenge to find the interviewees. Besides, the participants who participated in the research have already considered, even shortly, the deployment of TES for decarbonizing their superheated steam processes, which can create some biases in their responses. The participants represent their personal and company views only. This does not make it possible to generalize results to the entire manufacturing industry in the European Union. The purpose of using the TIS framework in the data collection and analysis was to integrate the diverse results from the interviews, questionnaires, and grey literature, supporting the research in identifying common and divergent perspectives.

The chapter is split into three sections, the first being a brief presentation of the structural components of the Technological Innovation System under analysis in this thesis. In the second section, the author will describe the different TIS functions and assess their functional pattern. Finally, the third section presents the identification of inducement and blocking mechanisms that influence the deployment of TES deployment for superheated steam decarbonization. The first two sections aim to provide an answer to RQ1 of this thesis, while the third section responds to RQ2.

4.1 Structural components of the TIS under analysis

The structural components of a TIS are actors, networks, and institutions (Bergek et al., 2008). The author identified and analyzed the structural components of the TIS from the personal interviews and interviews through email using the same questionnaire and supported by data, comments and other information derived from the grey literature, including media articles, reports, and the company's websites.

It is important to clarify that by no means this is an exhaustive list of the actors, networks, and institutions related to the deployment of TES for superheated steam within the European Union, the system is more complex in reality, but due to the research limitations and based on the data collected, these are directly relevant for the TIS under analysis in this thesis.

4.1.1 Actors

The actors include all the upstream and downstream involved stakeholders (Bergek et al., 2008) in the technological innovation system under analysis in this thesis. The main actors identified during the grey literature review and interviews are described in the following subsections.

Technology Developers

The technology developers in this TIS are defined as startups and established companies that are developing a TES that charges renewable electricity and delivers superheated steam for industrial processes. Overall, the main technology developers are startups, because they are small organizations that are still developing and proving the technology, trying to bring it to market and make it commercially available. For startups, developing the TES and, in the future, deploying it, is the core of their business. However, some established companies are developing TES as a smaller business unit within their existing and established broad range of operations. An example of the last type is MAN Energy Solutions which manufactures a variety of equipment and now is also developing two TES solutions, one utilizing molten salts as storage medium, and the other storing in CO2 (*Electro-Thermal Energy Storage (MAN ETES)*, n.d. & *Molten Salt Energy Storage (MAN MOSAS)*, n.d.). This case is interesting because it represents companies that have expertise and capital, see the potential of TES, and decide to prepare for the future market.

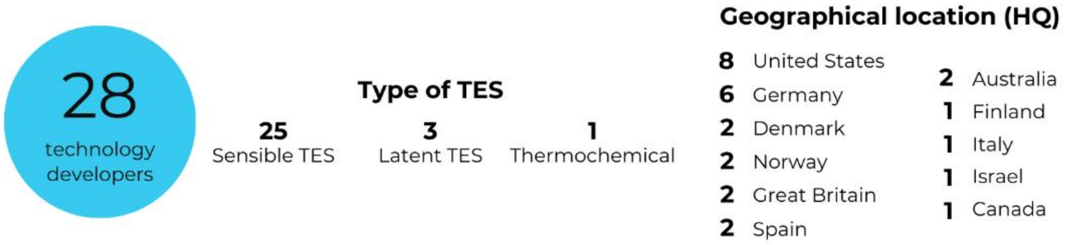

Figure 4-1 – Technology developers identified the types of TES they are developing and their geographical location by headquarters.

Source: own elaboration based on ("Worldwide Overview of High-Temperature Energy Storage System Providers," 2024; Electro-Thermal Energy Storage (MAN ETES), n.d. & Molten Salt Energy Storage (MAN MOSAS), n.d.).

As shown in Figure 4-1, there are 28 technology developers identified during the grey literature review. Recently, a consultancy published market research on TES, and they identified 27 companies developing different types of solutions for industrial heat decarbonization. Some of them also serve district heating and electricity generation. The 28th company identified by the author is MAN Energy Solutions. Of those, 29 technologies are being developed, including 25 sensible TES mostly using molten salts and cement or rocks. Three utilize Phase Change Materials as storage medium and just one of the identified solutions stores in CO2. The geographical focus of the developers is on the US, but also the north of Europe (P12, personal communication, 2024; "Worldwide Overview of High-Temperature Energy Storage System Providers," 2024; *Electro-Thermal Energy Storage (MAN ETES)*, n.d. & *Molten Salt Energy Storage (MAN MOSAS)*, n.d.).

Potential users

There are two potential types of users of TES for industrial superheated decarbonization in this TIS. The first and main type includes heat-intensive industrial facilities located in countries members of the European Union. The companies can be global, regional, or local, but the production facility that would use the TES is based in the EU (P1, P2, P3, P4, P5, P6, P7, P8, P9, personal communication, 2024). The second type of user is industrial parks located in the EU. These sometimes oversee providing heat and electricity to the different production facilities within the park (Klasing et al., 2018). This type of actor was contacted on diverse occasions, but the author could not get any response from them.

Associations

There are two types of associations considered in this TIS. One type is the energy storage associations, meaning associations that have TES and diverse energy storage developers as their members and promote activities to support the market development of TES. Two relevant energy storage associations are included in this study: the Long Duration Energy Storage Council (LDES) and the European Association of Storage of Energy (EASE).

The second type includes industrial manufacturing associations, these organizations represent the interests and issues of different industrial manufacturing sectors within the EU and its member states. Also, they work as a forum for companies to keep in touch with the latest trends, solutions, and innovations that might impact them. The author got one interview with this type of actor. The other two associations who answered a call or email mentioned that, even though they had the chance to host presentations on TES for their members, they did not have enough knowledge or expertise apart from what was presented to participate in the study (P13, P14, personal communication, 2024).

Financial stakeholders

The stakeholders that mobilize financial resources in the TES market are similar to other innovations, being the venture capital the most important (P11, P12, personal communication, 2024).

> *"Venture capital firms are investing directly in the technologies. I think they're willing to put money out there for companies that are interested in decarbonizing"* (P11, personal communication, 2024).

Also, some banks and financial bodies from the EU and other countries can provide financial resources to pilots and commercial demonstrators (*Balancing CST Production Gives Sustainability*

Boost to Tape Factory, n.d.). Lastly, some fossil fuel-related companies, such as Enel X, are investing in early development projects (*Nasce la prima CER in area industriale*, 2023).

4.1.2 Networks

The networks are considered formal or informal consortia, suppliers' groups, buyer-seller relations, and more (Bergek et al., 2008). Some of these networks are so formal and established that they overlap with some of the mentioned actors.

In the first place, within the more formal networks, we can find the LDES Council, EASE, and other associations where TES is a topic of conversation such as Renewable Collaborative. Other formalized networks are the projects that lead to pilot and commercial demonstrators, including usually private-public partnerships with public (either national or EU) funding.

Additionally, based on the interviews, it is relatively common for technology developers to do outbound sales and approach potential users to attract them (P2, P3, P5, personal communication, 2024).

> *"In most cases, because you are kind of a big player in the industry, they come to you"* (P3, personal communication, 2024)

Lastly, a go-to-market partnership that emerged recently and might mark a new path for the TES industry is the agreement between a technology developer and a company that produces, manages, distributes, and markets energy (*EDP & Rondo Energy Partner to Decarbonize Industrial Heat Production*, 2024)

4.1.3 Institutions

Institutions are defined by Bergek et al. (2008) as "culture, norms, laws, regulations and routines" (p. 413). The main institutions relevant to the scope of this study are regulations and standards from different levels. The selection of these is mainly based on the interviews and questionnaires.

At the international level, the key institutions identified are:

- Science Based Target initiative: this collaborative and voluntary effort supports companies establishing climate neutrality targets aligned with science. It represents a commitment and a framework to follow when decarbonizing operations (*How It Works*, n.d.).
- ISO 50001: this standard provides requirements and a framework for companies to follow to improve their energy management systems, identify energy-saving opportunities, and continually improve energy performance (*ISO - ISO 50001 — Energy Management*, 2023).

In the meantime, the key EU regulations for the TIS under study:

- European Green Deal: this is a comprehensive plan to lead the EU's economy to a more sustainable future. The main goal is to reach carbon neutrality by 2050. This plan also provides initiatives and policies for diverse stakeholders and activities, including industries and their energy use (*The European Green Deal - European Commission*, 2021).
- The energy efficiency Directive: a regulation that sets targets for energy consumption reduction in the EU, where the principle of "energy efficiency is to be treated as an

energy source in its own right" (Article 15 of the Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955, 2023).

- The Corporate Sustainability Reporting Directive (CSRD): is a recent regulation that establishes a strong and comprehensive set of requirements for corporate reporting on sustainability topics. This regulation influences because the transparency and compliance levels are strengthened and companies might investigate new solutions to prove that they are taking action (P3, personal communication, 2024) (*Corporate Sustainability Reporting - European Commission*, n.d.).

Finally, a strong culture was identified during the interviews. This is the conservative approach toward innovation in industries:

> *"The current risk is the conservative approach of the industry to enable and embrace the new technologies"* (P3, personal communication, 2024).

On a similar line, a manufacturing industry representative highlighted the need to raise awareness and advise their members on the technologies for decarbonization, because of this conservative approach (P15, personal communication, 2024). Lastly, in a research paper about the uptake of innovations for decarbonization of energy-intensive processing industries, Wesseling et al. (2016) present that the firms have a more conservative approach due to the high risk of incorporating something that is not proven yet, the capital expenditure needed, other operational costs that remain high until the technology is commercially scalable, and the complex and log-lasting decision cycles that delay investment.

On a similar line, a manufacturing industry representative highlighted the need to raise awareness and advise their members on the technologies for decarbonization, because of this conservative approach (P15, personal communication, 2024). The findings on the conservative approach support what Wessling et al. (2016) found on the uptake of innovations for decarbonization of energy-intensive process industries. They pointed out the high risk of incorporating something that is not proven yet, the capital expenditure (CAPEX) needed, other operational costs that remain high until the technology is commercially scalable, and the complex and long-lasting decision cycles that delay investment.

4.2 Functions and assessing the functionality of the TIS.

In the current section, the author presents the different TIS functions and the key findings from the data analysis. Also, at the end of each subsection, a summary of the function is presented, while providing a short analysis of the finding's significance. This is known as **assessing functionality**, which means "to describe the 'functional pattern' of the TIS. This aims at ascertaining to what extent the functions are currently filled in that TIS" (Bergek et al., 2008, p.414). In this sense, each function will follow the structure of introducing in one or two sentences the function, the core findings, and its respective analysis.

This section aims to answer RQ1 of this thesis, understanding how heat-intensive industries explore and navigate the TES market for superheated steam decarbonization. At the end, there is a subsection that aims to summarize the findings in relation to the RQ1.

4.2.1 Knowledge development and diffusion

This function aims to identify the status of the knowledge available and perceived by the diverse actors in the innovation system under analysis. As well, this function studies the types of knowledge available and who is the source of specific knowledge (Bergek et al., 2008).

From the direct data collection, it is possible to assess that there are diverse perceptions of the knowledge available. Some of the participants (P1, P2, and P6, personal communication, 2024) believe that is clear and comprehensive while being a very specific niche and in an early stage of development. Meanwhile, P3 and P6 believe that the information is not clear or certain enough. In particular, P3 claims:

> *"It's still hard to find, or to distinguish, what is science based, what is practical based and what it's based on nothing, sort to speak"* (personal communication, 2024).

Additionally, the participant highlighted that the academic information available is extremely focused on the science of the technology, the storage mediums, and how to optimize the technical aspects, but not so much on the business model or the economics of it in real life (P3, personal communication, 2024).

The types of knowledge most mentioned by the participants were related to the market and technology integration. The heat-intensive industry representatives claim to have mostly access to the information technology developers are sharing, this being the main source of knowledge in the TIS. The integration of TES in an industrial facility requires an extensive evaluation of several factors, from local regulations, physical footprint, steam requirements, and others, so the participants care a lot about researching if the technology can be integrated successfully (P1, P2, P3, P5, P6, personal communication, 2024).

When it comes to financial knowledge, overall, the participants focused on two aspects: (a) the energy prices with a TES system – which will be elaborated in Section 4.2.2 – and (b) the investment needed, developed in Section 4.2.6.

On the energy storage association side, the participant claims that heat-intensive industries know about TES and its potential because:

> *"they're looking at ways to make their operations more efficient, more effective, more profitable"* (P11, personal communication, 2024).

In the meantime, Participant 12, also from another energy storage association, believes that the information is available, but there is still a gap between people who are extremely informed and aware, and others confused with other TES applications or technologies (P12, personal communication, 2024). In that sense, there were a few potential respondents from heat-intensive industries who did not accept the interview, but it was possible to assess from the writing or conversations that they were outdated considering TES as a technology to couple with an electric boiler, or that they were confused with other types of Long Duration Energy Storage.

Lastly, a representative from a manufacturing association in the EU claims that the knowledge available is not clear, enough, or even trustworthy. As an association, they aim to raise awareness of the potential technologies for decarbonization, that might be useful for its members. However, P15 insists on the fact that heat-intensive industries receive mostly information from technology developers, which is constrained by their sales efforts.

"The thing is that our companies [association's members] are not experts. So, for them, it's really difficult to choose between molten salt or rock-based storage. And if a salesperson from those companies visits our industry, they always say, 'mine is good and the best'. Well, I think it's important that they are realistic and honest" (P15, personal communication, 2024).

Assessing functionality

This function is relevant since it lays the foundation where the actors can make decisions. If the knowledge is not available or is not clear, the actors find it difficult to make decisions about adopting the technology. Based on the participants, it can be stated that the knowledge available is still **insufficient** for the decision-making process. Besides, the information available is mostly focused on the commercial discourse of the technology developers, which generates some level of uncertainty and doubts for the potential TES users. There is a need for more scientific and based on real case information, especially concerning the business model, actual functionality of the technology in industrial settings, and economics around the use case.

4.2.2 Influence on the direction of research.

The function of influence on the direction of research mostly focuses on the perceptions of the technology potential, incentives to enter the TIS, and where the research within the TIS is going. The influence on the direction of research also explores the dynamics shaping the agenda for future research and what is guiding the allocation of resources towards specific areas of technological development (Bergek et al., 2008).

A finding from the participants' responses is that there is an overall and almost unified belief in a growth potential and interest in exploring this use of TES (P1, P2, P3, P4, P6, P11, P12, P15, personal communication, 2024). Only interviewee P5 expressed more doubts, claiming that:

"They (a technology developer who approached them) are not going to be successful in Ireland or Europe […] We are a decade away from proper technological development" (P5, personal communication, 2024)

The participant supports the claim by indicating that the energy market does not work in the way TES developers are saying, meaning that the difference in energy prices from when the supply is abundant to when is insufficient is not as big as they claim. This is challenged by all the other respondents who see this functionality of TES as an advantage:

"The second one [motivation to adopt TES] can be just the economic situation. Basically, you go to the market when the energy prices are lower, for instance during the night. And you buy electricity, you store the energy and then you transform that into thermal energy" (P6, personal communication, 2024).

Regarding the prices, the discussions with participants did not center on the prices of the TES system, but on the energy prices. Especially, in the context where a lot of countries of the EU natural gas is still more competitive than electricity:

"Today we have an issue in relation to fuel switching, which is that natural gas is, most of the time, way less expensive than electricity. This makes electrification of heat in industries very difficult" (P10, personal communication, 2024).

"Price of electricity is also a big barrier for electrification. It is way more expensive than gas." (P4, personal communication, 2024).

"I have access to cheap gas" (P5, personal communication, 2024).

An energy storage association claimed that governmental incentives are necessary, either via taxes towards fossil fuels, or subsidies to green electricity (P12, personal communication, 2024).

Based on the identification of technology developers in Section 4.1.1 above it is possible to assess that the current TIS is focused on sensible TES, representing over 85% of the solutions under development. This does not mean that the TIS will continue in that direction but marks a trend toward a type of TES more advanced in its development.

Both in the participants' responses and the grey literature it was possible to identify three key solutions that are perceived to be competitors to TES:

a) High-temperature heat pumps: solution also under development but with some success in lower temperatures (P1, P3, personal communication, 2024).
b) Hydrogen: can be a competitive technology but not in price, because hydrogen is still very expensive (P6, personal communication, 2024)
c) Lithium batteries: in some media articles they compare them highlighting that Lithium batteries cannot store for so long or provide industrial heat, but they still compare them (*Redefining Industrial Heat*, 2023).

On a curious note, electric boilers were not considered as an alternative, but only one respondent explained that in their perspective the electric boilers do not ensure flexibility or a constant supply of steam when the sun is not shining and the wind is not blowing (P6, personal communication, 2024)

Assessing functionality

The findings indicate that the influence in the direction of research brings together different aspects of what is going on in the market. Firstly, the **positive tone** towards TES as a crucial solution for superheated steam decarbonization could be biased by the small group of participants in the study. It can also be linked to knowledge development in two senses, (a) the heat-intensive industries receive information mostly from technology developers, which might condition their perspectives towards the solution; and (b) the only negative perspective can also be linked to the insufficient information available in the market. Secondly, the price of the steam generated by a TES is not known as **competitive** enough, because natural gas prices in Europe keep being more economical than electricity from renewables. Thirdly, the perspective regarding **competing technologies** varies and is still quite blurry, only three participants found other technologies as competitors.

4.2.3 Entrepreneurial experimentation

Entrepreneurial experimentation is the main way of reducing uncertainty in a TIS (Bergek et al., 2008). Future users need to see that the technology works as the technology developers claim, and that provides the steam for required needs. However, to experiment and test technologies, the system needs actors willing to take a risk and promote pilot plants, demonstrators, and other types of projects (Bergek et al., 2008).

Based on the review of grey literature, the author identified nine projects in the European Union that are constructing or have constructed a pilot plant and commercial demonstrators of TES for industrial superheated steam purposes, which are reflected in Figure 4-2-a. More projects were excluded because are focused on providing energy to district-heating grids and some of the interviewees mentioned that they prefer to know how the technology works in industrial settings (P3, P6, personal communication, 2024). Nevertheless, it is important to note that some technology developers claim their TES are useful for both applications ("Worldwide Overview of High-Temperature Energy Storage System Providers", 2024 & *HEINEKEN and CSIN Open World's Largest Solar Thermal Plant with Innovative Fresnel Technology for Industrial Use in Spain*, 2024).

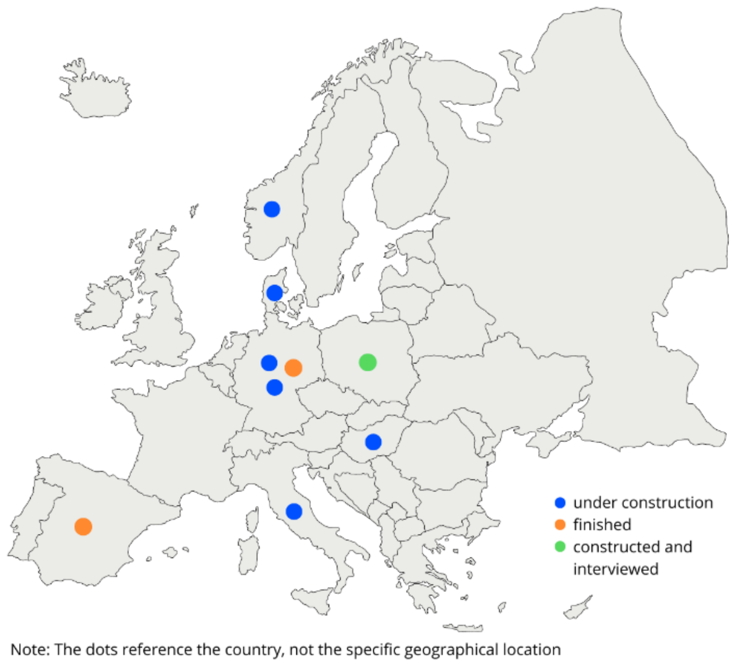

Figure 4-2-a – TES pilots and commercial demonstrators for superheated steam decarbonization purposes within the EU

Source: own elaboration based on "Worldwide Overview of High-Temperature Energy Storage System Providers" (2024) and HEINEKEN and CSIN Open World's Largest Solar Thermal Plant with Innovative Fresnel Technology for Industrial Use in Spain (2024)

On a similar aspect, the TRL is quite high according to the reports mentioned in Section 2.2.3 above. According to the EASE (2023), 55% of the technologies in the market are commercially available since they have a TRL of 7 to 9 which represents a strong background in entrepreneurial experimentation and testing.

Looking into the user perspective, it was possible to assess the potential **adopter type** of the participants following Rogers et al. (2008) theory of innovation diffusion. The adopter types of Rogers et al. (2008) present are based on the potential users' attitudes toward innovation and when they would adopt it – if they do so. The adopter types are innovators, early adopters, early majority, late majority, and laggards. In Figure 4-2-b below the author identified each respondent with a type.

Figure 4-2-b – type of adopter of TES within the interviewees.

Source: own elaboration based on the interviews and questionnaires

It is possible to see that one participant is considered an innovator, and that is because they already implemented a pilot plant in their facilities as part of a joint project that coupled a concentrated solar power plant with a TES to ensure 24/7, independent, and clean superheated steam. They are one of the first industrial facilities to have a TES in the EU. However, they do not own it, they have a Heat as a service agreement with the technology developer (P2, personal communication, 2024).

Besides, there were two participants whose positions were unclear, either because they did not state them directly or because it was complex to identify. On one hand, Participant 3 (personal communication, 2024) sounded very excited about the technology and mentioned that their team is already exploring the potential of integrating TES in a production facility in northern Europe, but also showed a very rational approach to waiting to see if the technology works or not, so it could be an early adopter or early majority. On the other hand, Participant 7 (personal communication, 2024) showed a very early understanding of TES, but a willingness to re-consider it in the future when the technology is more developed. In that sense, it could be a late majority or a laggard.

More pilots and commercial demonstrators impact the perception of the potential users of the technology. The manufacturing association representative explained that their members have a varied interests in TES and other technologies for decarbonization, but something is clean: when a member brings their story and shares their use case implementing any of these new technologies, a lot more members start looking into it (P15, personal communication, 2024).

Assessing functionality

This function assesses that there is experimentation with TES and some companies' **technology readiness is very high** (EASE, 2023). However, the small number of projects that aim to prove the technology on an industrial scale seems to be **insufficient** for the heat-intensive industry to feel that it is ready to take the risks. So, there is a **gap** between what technology developers claim and the potential user's perspective. Participants 3, 5, and 6 (personal communication, 2024) claim that there is a need for more testing to gain confidence. In addition, P6 and P1 (personal communication, 2024) highlight as a risk the **uncertainty** of what other technologies may emerge in the future and whether they will be better and cheaper than TES. Therefore, the decision to adopt TES may be delayed until there is more certainty about the solutions available, their associated costs, and efficiencies.

4.2.4 Market Formation

As the system has a brand-new technology that never existed before for the use cases claimed, the market is completely new or even inexistent. This function analyses the evolution and maturation of the market created by the innovation, including some aspects of the dynamics between actors that account for the market formation (Bergek et al., 2008).

In the case of TES, the participants agree that there is a market, it is just in a very early stage (all the participants, personal communication, 2024). There is an existent market because most of the participants (P1, P2, P3, P4, P5, and P6, personal communication, 2024) articulate the demand for a technology that provides flexibility and reliability to renewable energy for the decarbonization of superheated steam processes. However, no one claimed to demand a TES directly, is rather an explorative journey where they find out about the technology as one alternative and then evaluate it.

The TIS still does not have clear channels for potential users to find solutions. The main channel is direct contact from the technology developer that reaches out the potential users. However, P1 claimed that the discovery was through a networking event. Similarly, P4 and P6 received information from a third party, one from the local government-owned utility company and the other from a consultant advising them in their net-zero journey (personal communications, 2024).

Another aspect of the market formation is the types of agreement possible between the technology developer and the user. During the primary data collection, it was identified two key types of agreements: purchasing the TES plant and having a power purchase agreement (PPA), also known as Heat as a Service (HaaS), and only purchasing the heat needed. Two participants did not have a clear preference because it depends on the CAPEX size (P1, P3, personal communication, 2024), two preferred a traditional purchase of the plant (P5, P6, personal communication, 2024), and then one of them has already a Heat as a Service (HaaS) agreement with a TES company, where a third party financed the construction of the plant, and then the user buys the heat needed at the same price of natural gas (P2, personal communication, 2024). The manufacturing association presents to its members all the options, but tends to prefer the HaaS contract, because:

> *"Because I see that companies do that, they may, they actually move forward"* (P15, personal communication, 2024).

In parallel, the technology developers do not specify any type of agreement in their websites, if they do so, they tend to offer both options (*Heatcube*, n.d. &*How It Works*, n.d.).

The decision processes of the users in order to assess if the technology is adequate and to define if to go for a TES are extremely long and complex. The participants agreed on the fact that high-level management must be involved in several parts of the process, depending on the size of CAPEX (P1, P2, P3, P6, personal communication, 2024). The specific production facility employees using the superheated steam that needs to be decarbonized are also involved in the process because they know the technical requirements, limitations, and opportunities (P2, P3, P6, personal communication 2024). This results in an iterative process involving several parts. The only stakeholders recognized by participants are the local affected facilities, the high-level decision-makers within the company, and the technology developers (P1, P3, P6, personal communication, 2024), one participant recognized the third party who funded the TES construction (P2, personal communication, 2024).

Another aspect related to the market formation is an added value that technology developers offer, which is the opportunity to participate in the energy market by providing ancillary services. Having a TES allows you to store energy and provide some energy to the grid as a backup when the grid needs it, and the user does not. This helps to stabilize the grids, already at risk with the growing demand for renewables but not enough availability of them. Participation in the energy system relates to the interaction between this technology and integration with the overall system (P15, personal communication, 2024). However, there is still a lot of uncertainty around the topic. A participant found this as a motivation to adopt TES (P1, personal communication, 2024), meanwhile, association representatives think that some companies are putting too much focus on the topic and are not so relevant for the user (P11, personal communication, 2024).

Assessing functionality

Concluding this subsection and based on the data collection, the market of TES for superheated steam decarbonization in the EU is still in the **nursing stage**. The market exists but is still in a very early stage of formation. The channels of contact between technology developers and potential users are still under development. The **outbound** business development efforts from technology developers are the most effective in the view of the participants. There is still a lot **pending to define** regarding the types of agreements for deploying TES, the decision-making process of the companies that aim to integrate TES into their system, and the key parties involved in the deployment process.

4.2.5 Legitimization

It is a process for a technology to get legitimized, and a lot of factors come to play a role. The legitimacy represents social acceptance of the technology and the dynamics between the solution and the institutions of the TIS. In this sense, either if the institutions support the technology or if the technology supports the compliance of institutions, both dynamics are relevant to the technology's legitimization (Bergek et al., 2008).

When it comes to TES for decarbonization of superheated steam, the technology alone seems to have an overall legitimacy both among the interviewees and a number of reports that present it a suitable solution with rather high technology readiness (EASE, 2023 & SystemiQ, 2024). Also, media articles tend to speak positively on TES,

> *"Electrification of industrial heat has been called 'the next trillion-dollar market.' Recent studies have found that the decarbonized world will need twice as much heat battery storage as grid battery storage"* (Viaintermedia.com, 2023).

The technology per se has been academically studied for quite some time and counts with institutional legitimization, but its business case and application are not broadly studied or considered as completely mature, which was clear for some participants (P3, P6, personal communication, 2024 &, Importer, 2022).

Another form of legitimization is about the institutions of the TIS. As presented in section 4.1.3, the institutions identified are mostly initiatives and regulations that do not promote TES directly. The institutions identified rather focus on requirements towards energy efficiency and net zero for companies to comply, and to do so they need to find solutions like TES. There are two potential answers to why there are no policies directly promoting TES (at least at the EU level): the gap of knowledge within policymakers (a), it is still a very niche topic and is slowly taking attention out of lithium batteries, heat pumps and hydrogen, which are on the center of the discussion today (b) (P12, personal communication, 2024). Finally, the technology developers, mostly startups, do not have the resources to lobby for favorable policies, and that is when associations such as the LDES Council and EASE, became extremely relevant (P12, personal communication, 2024).

The participants of this study presented three tones toward TES for steam decarbonization: positive (P1, P2, P3, P6, P11, P12, P15 personal communication, 2024), confused due to lack of proper information (P4, P7, personal communication, 2024) and negative (P5, personal communication, 2024). However, is important to note that, even if the overall tone was positive, it was a very rational perspective. This means the respondents thought technology is a great solution with a future in the market, but not the ideal for their operations, or just in a very early stage of development. The negative view focused on the negative aspects of the use case: costs in comparison to fossil fuels, risks of implementing when is not commercially available, and energy losses due to energy conversions from power to heat (P1, P2, P3, P6, personal communication, 2024).

Assessing functionality

Assessing the status of the legitimacy of TES for superheated decarbonization is a challenging task. This is because in some aspects things signal in a positive direction, such as the tone towards TES, but in others, as the policy side, there is a lot of work to be done. It is possible to infer that the legitimacy of TES for superheated steam decarbonization is still in the very **early stages** of development.

4.2.6 Resource mobilization

The function of resource mobilization reflects all the different types of resources needed to develop, construct, and install a TES in an industrial setting. These include human capital, financial capital, and other complementary services and goods such as infrastructure and key materials (Bergek et al., 2008).

The participants of this study mostly focused on the financial resources needed for deploying TES (P1, P2, P3, P5, P6, personal communication, 2024). The money for financing the integration of TES in an industry aligns with the type of agreement preferred. If the heat-intensive industry wants to buy the plant, the resources come mainly from themselves. Nevertheless, some cases with a HaaS or PPA need a third party that finances the construction and installation of the TES system. From the TES association's perspective, the main actors financing the development and deployment of TES solutions are common for other emerging markets: venture capital, governmental funds, banks, and their technology developers (P11, P12, personal communication, 2024). This claim is supported by media articles that report on the funding rounds that technology developers have raised in the last few years.

> *"The Series B round, combined with a 2022 Series A, brings the startup's total attracted investment to more than US$230 million"* (Colthorpe, 2024).
>
> *"German climate tech firm Kraftbock has raised a Series B funding round of €20 million in a round"* (*Germany's Kraftblock Raises €20M Series B for Sustainable Thermal Storage Technology*, 2023)
>
> *"Rondo Energy, a leading provider of zero-carbon industrial heat and power, has raised $60 million"* (Viaintermedia.com, 2023).

Regarding the human capital, there are conflicting views. Most heat-intensive industry participants believe they do not need to train their workers, or that is not a big issue (P1, P2, P3, personal communication, 2024). However, one participant believes there is a need for someone knowledgeable on the decision-making of when to start to charge, store, and discharge the energy from the system depending on the prices and renewable supply (P6, personal communication, 2024). Meanwhile, when it comes to technology development, P12 (personal communication, 2024) highlighted the lack of a specialized workforce for the development of TES, especially women.

Lastly, the infrastructure aspect was only mentioned by Energy storage associations. The facilities that do not have their energy generation need a connection to the grid. This connection is a big cost and a long process. Also, in the EU the current grid is not prepared to handle the energy transition and needs to expand, resulting in a need for investment in the overall energy infrastructure (P10, P12, personal communication, 2024).

> *"The grid of the government is not strong enough to have enough electricity to make steam, so for us is not possible"* (P4, personal communication, 2024).

Assessing functionality

The resource mobilization function is one of the blurriest because the knowledge is spread and not clearly perceived by the participants. There is a strong and growing mobilization of **financial resources** for TES development, especially coming from venture capital and fossil-fuel-related companies. However, when it comes to the **grid infrastructure**, the case changes depending on the local conditions and regulations. As well, not every solution is modular or a product that comes and you just plug, which represents a wider supply value chain that is not clear or defined up to the current knowledge and depends on the local context where the plant would be deployed.

4.2.7 Development of positive externalities

In every market that scales and grows, different economies start to benefit from the emerging market. These economies could be labor-related – new talent needed to develop specific solutions and could also be related to the need for new goods or services, as well as new information flows between diverse industries (Bergek et al., 2008).

This function is the hardest to identify and find when collecting data. The main reason is that the technologies claim to use non-critical raw materials, and existing components with established value chains (P11, personal communication, 2024; Importer, 2022; *Redefining Industrial Heat*, 2023 & Viaintermedia.com, 2023). In that sense, it is considered that, only if the growth is extremely exponential, there will be a significant and positive effect on external economies (P11, personal communication, 2024).

Assessing functionality

Based on the participant responses and contributions from grey literature, this function accounts for the lowest development in comparison to the other functions. The research indicates this is not a real situation now due to the early state of the market. However, it is interesting to note that this topic is not a concern or interest of the participants, because they consider it would take **time** until the TES market reaches that point. Other participants did not have enough knowledge to answer, which also represents a lack of awareness of the current and future of external economies related to TES.

4.2.8 Summary of findings on the functions

After exposing the key findings and assessment of each function, an interesting way of summarizing the analysis is reflected in Figure 4-2-c below. The analysis brings to the conclusion that some of the functions have low or very low strength while a few are stronger.

The level of strength represents how is the function performing in the TIS under analysis and based on the data collection. The purpose of this figure is to summarize and simplify the identification of weak and strong functions within the system. The characteristics of the function define if the strength of the function is very low, low, medium, high, and very high.

Table 4-2-c – Assessment of the strength of the functions within the TIS under analysis

Function	Strength of the function
Knowledge development and diffusion	Low
Influence on the direction of research	Medium
Entrepreneurial experimentation	Medium
Market formation	Low
Legitimation	Medium
Resource mobilization	Low
Development of positive externalities	Very low

Source: own elaboration, inspired by Godinho Arriolli (2021).

Market navigation

As mentioned when introducing this chapter, the goal of the findings and the analysis was to answer RQ1 that guided this thesis. The aim of understanding how they navigate the market was mainly to explore how these industries find solutions, how they assess them, how they make decisions, and similar information. Based on the data collection, it is possible to partially answer the question. It is relevant to note that the findings cannot be generalized to the European Union or the heat-intensive industries in general. Although they reflect a fragment of the market situation the picture given from the various sources appears to be rather homogeneous.

The heat-intensive industry representatives found out about the TES as a solution for the decarbonization of superheated steam in different ways. Technology developers contacting potential users was one of the most common approaches, but also in events or by a third party who presented as a way of electrification (P1, P2, P3, P4, P5, P6, personal communication, 2024).

The potential users analyze the potential integration of TES in different ways, but there is no concrete criterion. Mainly they assess if the technology can provide the required steam and the costs of the heat, but since it is a new market, some criteria are still unknown (P2, P3, P4, P5, P6, personal communication, 2024). An important observation is that every investment decision represents a complex and long process including local facility workers and senior management at the company or even group levels (P1, P2, P3, P4, P5, P6, personal communication, 2024).

Regarding access to information, the actors' perception was somehow positive based on the early stage of the market. However, they still consider that it is insufficient and not sufficient quality information. This is mainly because the main information comes from tech developers, who know their technology better than anyone, but also are uncertain about the real applications, the market, and the business case because they are learning along the way.

In conclusion, the findings from this study provide valuable insights into how representatives of the heat-intensive industry navigate the emerging market for TES for the decarbonization of superheated steam. Nevertheless, it is an ongoing learning process for the heat-intensive industries, and their navigation in the market appears to be rather undefined, with some clarifications to be made when the market evolves.

4.3 Inducement and blocking mechanisms for deployment of TES for superheated steam decarbonization

After presenting the key findings for each function and assessing its functionalities, the author proceeds to present the inducement and blocking mechanisms that affect the deployment of TES for superheated steam decarbonization in the EU. These results are extracted from what was presented from the data collected and it has its limitations, such as the low number of participants in the study, so the results are not able to genialize and represent the EU. This subsection answers RQ2 of this research.

4.3.1 Inducement mechanisms

The main facilitator factors or inducement mechanisms that influence positively the deployment of TES are, as identified from the data collection, the following:

- Belief in growth potential: the overall trust in technology and that it has the potential of being the key solution in the context of the energy transition.
- Positive tone towards the TES technology: the positivity around the technological aspects of TES from diverse stakeholders and media provides an initial level of legitimation to build from.
- Regulatory pressures: the institutions (mentioned in Section 4.1.3) that urge the industries to take action and to find solutions for the decarbonization of their operations. Even if they do not promote TES directly, they force the industry representatives to go out and find solutions.
- Strong outbound sales activities from technology developers: the developers are approaching their potential users and introducing them to the technology. The efforts can improve but have been the main channel of contact between the interviewees and the solutions.
- Use of non-critical raw materials: the TES solutions under development do not utilize critical raw materials, which improves the business and sustainability case for when they scale up.
- 9 projects in the EU: the technology developers in partnership with suppliers, potential users, and other stakeholders are already experimenting in the region with 9 projects under construction and constructed. This is not enough, but a good precedent that is paving the way for commercialization.
- Venture capital: investors are risking and allocating resources to the development of technology. Some technology developers are already in Series A or B[3] of the scale-up funding, while most of them seem to be in the early stages of funding.

[3] Series funding is the result of fundraising efforts in different periods of a startup. The called *series A* represents the first bigger investment round after seed funding. Meanwhile, series B and C involve progressively more capital raised for the effective scale-up of the new firm (*Series Funding*, n.d.).

4.3.2 Blocking mechanisms

The challenges and risks that affect negatively, delay and even stop the deployment of TES solutions for the decarbonization of superheated steam are more than the inducement ones. However, this is common to an early-stage TIS. Also, the TIS framework insists on finding blocking mechanisms to suggest solutions and accelerate market development (Bergek et al., 2008).

- Lack of policies in place for an optimal grid connection: when the user does not have off-grid energy generation – i.e. their own solar PV plant or wind turbines – the grid connection process and cost delay the deployment and negatively affect the business case.
- Price of competing energy sources: fossil fuels are still more affordable than renewable energy, especially when we include the capital expenditure and risks of integrating a TES solution.
- The level of awareness is still limited: as mentioned by the participants from the study, the understanding of TES solutions is still limited with a focus on what the technology developers claim.
- Centralized source of knowledge: the participants mostly accessed the information the technology developers provided.
- Lack of unified and complete understanding of the value chain of TES: this might not directly affect the deployment, but the understanding of the market, making it hard to identify room for improvements.
- Insufficient financial support: there are investments towards the development of TES, but the experimentation on an industry scale is still considered low by the participants of the research, and one of the challenges is access to funding for these experimentation projects.
- Insufficient understanding of the types of agreements: there is no complete clarity of the types of agreements possible between the user and the technology developer, particularly about the implications of the different agreements. This is also delaying decision-making processes because the CAPEX and risks vary depending on the option selected.
- Conservative approach of the industry: the cultural aspect of the heat-intensive industries that are risk-averse and try to continue business-as-usual delays innovation.

These blocking and inducement mechanisms answer research question number two of this thesis and frame the recommendations presented in the last chapter of this text.

5 Discussion

This chapter takes a step back to look at the research performed more holistically. There are different purposes for the discussion. On one hand, the author showcases the alignment (or lack of it) between aim, RQs, method, and results. On the other hand, the author revisits and reflects on the limitations and implications of the research. Lastly, a few niches and topics are suggested for future research.

5.1 Revisiting the aim and research questions

As stated earlier in this thesis, the main objective of the research was focused on three key aspects:

a) the **experience** of heat-intensive industries in navigating the market of TES,
b) **inducement and blocking mechanisms** that impact the deployment of TES for clean industrial superheated steam processes,
c) and how stakeholders could **overcome** those challenges.

Those aspects were incorporated into three research questions respectively.

After the process of performing a literature review, a challenging data collection, its analysis and finally drafting the findings and analysis in text, the author finds evidence that all three research questions have been answered.

The presentation of findings and analysis of the structural components and functions of the TIS framework answered RQ1 (Sections 4.1 and 4.2). However, the TIS provides a comprehensive assessment of the market status of TES from a higher level, which made it difficult to focus solely on how heat-intensive industry representatives navigate the market. Nevertheless, the key elements of how industries navigate this specific market were presented. An interesting note is that the market is under development, which leads to some uncertainties or undefined processes related to the market navigation. This could be explored in future research, for example exploring and designing a customer journey for this specific technology and application.

In contrast, RQ2 and RQ3 are fully aligned with the TIS framework, as represented in steps five and six (see Figure 3-3). The inducing and blocking mechanisms were derived from the analysis of the functions and are presented in Section 4.3. Meanwhile, the recommendations are presented in Chapter 6 on conclusions and recommendations below. Although the TIS framework was originally designed to provide recommendations for policymakers, this thesis extends this to a wider range of stakeholders in the system, thus providing a more comprehensive tool for decision-makers.

Finally, it should be noted that the responses cannot be entirely representative of the entire European Union's heat-intensive industry, because are based on a relatively small number of participants, mainly with an interest in the TES sector.

5.2 Limitations and implications of this study

The main limitations of the study rely on the data collection process. As explained in Chapter 3, the author took an exploratory approach to contact potential participants, which led to a total of ten participants and five relevant email responses. This limits the generalization of the results, and to ensure validity the author introduced grey literature such as media articles, social media posts, and reports made by consultancy companies and associations. However, the generalization potential is limited to the available grey literature and common responses among the participants.

Another limitation was the focus selected in relation to the TIS framework. The author focused on finding heat-intensive industries that have analyzed TES for decarbonizing their superheated steam processes but also interviewed energy storage and manufacturing associations. The TIS framework is more comprehensive and does not aim to catch one single perspective, but the entire system and its actors. Some functions, such as the development of external economies, have limited findings which are mainly attributed to the focus on collecting one perspective.

On another hand, the implications of this thesis extend in different ways to academia and practitioners within the field. There are no previous studies on TES utilizing the TIS framework within the academic literature, especially not about the use case of TES for superheated steam decarbonization. In that sense, this research is already bringing a new analysis to academia utilizing the TIS framework. Another implication is related to the focus of the thesis. This research introduces a novel approach by focusing on a few actors within the TIS framework rather than in the entire ecosystem, which represents a curious contribution to the existing literature on innovation systems. This could promote further academic interest and exploration into the focus on specific stakeholders' perspectives when utilizing the TIS framework.

For practitioners, particularly those engaged in technology development, this thesis offers insights into the perspectives of potential customers that are of significant value. For them, it is relevant to gain an understanding of consumer needs and perceptions, so they can act strategically and accelerate negotiation processes for the deployment of TES. Moreover, heat-intensive industries could also benefit from this research. The thesis offers a valuable analysis of the TES market for the decarbonization of superheated steam, which could inform the decision-making process of their net-zero journey.

Finally, this research brings light to a novel topic that suggests being crucial for the energy transition. This understanding could be deepened and updated in the future depending on how the market evolves.

5.3 Suggestions for future research

Based on the findings of this study, several key topics emerge as promising for future research. These areas require further investigation and exploration and could not be covered during the present thesis project due to resources or scope limitations.

Firstly, a more detailed investigation of the value chain of TES systems would be beneficial. Despite the assumed familiarity of the TES value chain in the market, there remains a lack of explicit academic knowledge regarding its intricacies, including suppliers, funding partners, construction partners, and more. Research focusing on mapping and understanding this value chain can bring light to critical aspects of TES deployment and related challenges, including the development of external economies and the dynamics between different actors within the value network.

Secondly, it is of great importance to incorporate the perspective of technology developers to enrich future research. It would be interesting to perform research similar to the present one, but with a focus on the technology developers, for then comparing key findings. By directly collecting the technology developers' perspectives, the academia can gain a comprehensive understanding of their views, experiences, and challenges in TES deployment for superheated steam decarbonization. A comparative analysis can bring interesting findings on the differences between the actors' perspectives and a more comprehensive assessment of the blocking and inducement mechanisms affecting TES deployment and general decarbonization efforts.

Thirdly, as explained at the beginning of the discussion, further understanding of the market navigation it is encouraged, especially when the market increases its maturity in the upcoming years. This market navigation could be explored with other frameworks or tools in order to systematically find the specific and concrete data on that niche, rather than the context and system perspective provided by the TIS framework.

Finally, it would be highly beneficial to establish a robust set of criteria the end-users can utilize for analyzing TES as a viable decarbonization solution. The decision-making process surrounding TES adoption is still in its early stages, with numerous uncertainties and considerations. Developing a systematic framework or criteria for evaluating TES solutions from the user's perspective can assist heat-intensive industries in making informed decisions and accelerate the adoption of sustainable TES technologies.

In conclusion, future research should aim to enhance the comprehension of the TES value chain, incorporate the perspectives of diverse stakeholders, and develop comprehensive criteria for evaluating TES solutions for end-users. These research avenues will contribute to the advancement of the field of TES in academic literature from a market perspective.

6 Conclusions and recommendations

The last chapter of this thesis presents conclusions (6.1) and recommendations to relevant stakeholders (6.2). The conclusions are presented as a summary of the thesis with emphasis on the key findings and discussion. Meanwhile, the recommendations serve as the final piece of the thesis work and respond to RQ3.

6.1 Conclusions

The thesis aimed to research the state of the market of Thermal Energy Storage for the decarbonization of superheated steam in the European Union (EU) from a number of heat-intensive industries' perspectives. This qualitative study investigated the perspective of heat-intensive industries that are navigating the market to find solutions for decarbonizing superheated steam processes and, while doing so, they find TES as a solution and analyze it. The study takes a system-level perspective using the TIS framework, which guides the collection, analysis and presentation of data throughout the text.

RQ1: *How do heat-intensive industries navigate the complex market of new solutions for decarbonizing their superheated steam process with thermal energy storage solutions?*

This question aimed to explore the experience of the potential users of TES when seeking solutions, analyzing them, and deciding whether they implement or not the solution in their facilities. It also had the purpose of collecting their perspectives on the market. To answer RQ1, the author utilized the TIS framework to collect data and analyze it.

Overall, the assessment indicates that the functions of *knowledge development and diffusion*, *market formation*, and *resource mobilization* level of strength are low. In the case of the first function, this is because the knowledge available is perceived as insufficient and very centered on the technology developers' offerings and discourse by the participants of the study. Meanwhile, market formation is still in its nursing stage because there are no established clear types of agreements to incorporate TES by industrial users. The added values around the TES use-case are still blurry, unclear, and regulation-dependent; also, there are no specific decision-making processes established in the heat-intensive industries or specific channels where the potential users can find solutions and explore them. Regarding resource mobilization, even though there is a growing investment in the technology developers work to mature these solutions, not so much in other infrastructure requirements such as grid connection, which completely hinders the deployment of TES.

In parallel, the functions *influence in the direction of research*, *entrepreneurial experimentation*, and *legitimization* are assessed as medium level of strength, because they are more developed than other functions, but are still far from ready for market. Firstly, the cost of steam from TES is a key concern, particularly in the EU due to competitive natural gas prices, but there is an interest in exploring this solution for superheated steam decarbonization. Secondly, there are 9 projects in EU member states of TES for superheated steam decarbonization, but it is not considered enough for industries to yet trust in the technology. Lastly, the legitimation of this technology seems higher because of the overwhelmingly positive tone towards it; however, there is still work to do when it comes to the legitimation policies can provide, as well as a broader understanding of the technology.

The function that was assessed with a very low level of strength is *development of positive externalities*, and this is mostly because it is an unexplored and unknown area for users and other stakeholders. There is a common understanding that TES solutions do not require critical or new materials, so the demand for equipment relies on existing designs that are already being produced. However, further research is encouraged on this point.

Looking specifically at the experience of industries navigating the market, the insights could be summarized as follows:

- There are no clear or established channels where heat-intensive industries find the solutions.
- The decision-making processes involve high-level management and the local facility managers and operators but are long undefined processes.
- There are no specific criteria for analyzing the incorporation of TES, is a learning in progress.
- There is an overall positive view, but a clear request for more entrepreneurial experimentation to make more informed decisions.
- The available knowledge is mostly perceived as niche and technical. There is an agreement that it could be improved, particularly by diversifying the sources of knowledge to take a step aside from the technology developers' discourse.

The RQ1 could be further explored in future investigations as the market evolves and aspects get clarified. Currently, the market maturity leaves space for uncertainty on how the potential users explore and navigate it.

RQ2: *What are the inducement and blocking mechanisms that impact the deployment of TES in heat-intensive industries in the European Union?*

This question aimed to identify the factors facilitating or hindering TES deployment in industrial settings.

On the positive side, the inducement mechanisms identified were diverse. Overall, the study's stakeholders expressed confidence in the growth potential of TES, because they see it as a promising solution for the energy transition. Similarly, there was a favorable attitude towards TES technology, providing an initial level of legitimacy. Besides, regulatory pressures from the EU or member states that push industries to take climate action are contributing to the uptake of TES solutions. The proactive outbound sales efforts by technology developers play a significant role in introducing TES to potential users and educating them on this new development. Finally, venture capital investment in TES development is growing and building on legitimacy.

On the negative side, there are several blocking mechanisms that hinder the deployment of TES solutions for superheated steam decarbonization. There are big challenges related to grid connection policies and associated costs that delay deployment. Also, the price of fossil fuels is still more competitive than electricity, affecting the business case of TES technology. There is also quite limited awareness among stakeholders about TES solutions, which are primarily centralized on information provided by developers, which constrains the trustworthiness of the information. Similarly, the uncertainty about the types of agreement between users and technology developers delays decision-making processes. Finally, the prevalent conservative culture in heat-intensive industries delays innovation in TES and any other innovation.

The answer to this question was complete and effectively done based on the data collection and the constraints of this study. These inducement and blocking mechanisms are not exhaustive to the TES deployment topic, but they do cover the heat-intensive industries' perspective, as well as the views from two energy storage associations and a manufacturing association. The insights set a baseline for answering the final research question of the thesis.

RQ3: *What activities and strategies key stakeholders can implement to accelerate the deployment of TES for industrial superheated steam processes in the European Union?*

The development of recommendations is part of the research and aims to provide some suggestions and tools for different stakeholders to promote the deployment of TES in industrial settings. The author acknowledges that the recommendations will not solve the deployment of TES, but that they can provide a call to action for key stakeholders. These recommendations are based on the findings of this research, where weaknesses were identified in the functions, as well as inducement and blocking mechanisms. The list of recommendations is included in the following section.

6.2 Recommendations

The recommendations are split based on the stakeholder group: (1) technology developers, (2) policymakers, and (3) heat-intensive industries.

6.2.1 Recommendations for technology developers

Main recommendations

- Publicly available information: increase quality information available about the technology, how it works, the benefits, and tradeoffs, to promote transparency and understanding by the potential users.
- Collaborate for experimentation in industrial settings: Foster partnerships with academia and industry to conduct more experimentation in industrial settings and demonstrate real-world applications and business cases to gain acceptance and trust from heat-intensive industries.
- Enhance sales efforts: continue the strong outbound sales activities to engage potential users and build trust in TES technology.
- Identify and promote publicly the added values: identify and research the added values apart from providing flexibility and stability to the energy supply and promote them publicly so the potential users can see more than just storage.

Other recommendations

- Define the possible types of agreements: aim to define the types of agreements through which the technology can be deployed, as well as share publicly or with potential customers a detailed description of what is required and the implications of each option. This would ease the decision-making process and promote market maturity.
- Collaborate with research centers and universities: promote research with academic centers to enhance technology credibility. Particularly, collaborate in research about the market and business case aspect of the technology to diversify the current academic knowledge focused on technical aspects.
- Participate in outreach activities: increase efforts to educate and demonstrate the value proposition of TES solutions for superheated steam processes with policymakers, academia, potential users, and general audiences.
- Advocate: unite and collaborate with relevant policymakers and associations to advocate for supportive policies that incentivize the adoption of TES solutions.

The implementation of these recommendations would facilitate the adoption of TES by providing clear, high-quality information to potential users, fostering collaborative experimentation in industrial settings, and strengthening outbound sales efforts. The identification and promotion of the broader benefits of TES beyond energy storage, such as flexibility, the balancing of the energy market, and stability, could enhance the value proposition of the technology and facilitate its wider understanding and acceptance. The collective potential of these combined efforts is to accelerate the market maturity of TES systems for superheated steam decarbonization.

6.2.2 Recommendations for Policymakers in the EU and its member states

Main recommendations

- Promote TES as a valid decarbonization solution: develop policies that incentivize the adoption of TES systems, such as tax reductions or other incentives.
- Incorporate TES into existent policies: the incorporation of energy storage into the existing policies can provide incentives for heat-intensive industries to explore this solution towards their net zero journeys.
- Develop grid connectivity policies for TES systems: develop and implement policies that facilitate optimal grid connections that reduce processing times and costs for TES connecting into the grid to charge renewable electricity.

Other recommendations

- Develop information regarding TES for superheated steam decarbonization: provide clarity to the potential users and legitimation to the market by presenting reports on TES for industrial heat decarbonization.
- Provide financial incentives for experimentation: increase financial support and incentives for TES technology development and industrial-scale experimentation to accelerate market adoption.
- Raise internal awareness about TES: provide education and information among the employees of parties and political institutions so they can take informed decisions regarding new policies and regulations that can affect, negatively and positively, the deployment of TES in industrial settings.
- Collaborate with associations: work alongside energy storage and manufacturing associations to understand and address political challenges that hinder the deployment of TES, but also to unite efforts and raise awareness on the topic within diverse societal stakeholders.

These recommendations would significantly advance the uptake of TES within heat-intensive industries operating in EU member states. This would ease the decarbonization of these industries through the promotion of TES as a valid decarbonization solution, which could be achieved through the implementation of incentives and the incorporation of TES into existing policies. Furthermore, improvements in grid connection policies so it is easier to integrate TES systems would streamline the adoption of these systems. Besides, initiatives to enhance awareness, provide financial incentives for experimentation, and collaborate with associations will collectively foster a more supportive environment for TES deployment, accelerating market adoption and contributing to industrial decarbonization goals.

6.2.3 Recommendations for heat-intensive industries

Main recommendations

- Promote long-term thinking: prioritize long-term decarbonization activities, such as TES, rather than just focusing on the low-hanging fruits that represent an easier and quicker fix.
- Invest in research and development for decarbonization of production processes: allocate resources towards experimentation and pilot projects in collaboration with technology developers to accelerate the energy transition and development of decarbonization technologies.
- Engage in collaborative partnerships: seek partnerships with technology developers, academia, and relevant stakeholders to better understand TES applications and explore potential agreements that suit specific operational needs.

Other recommendations

- Promote innovation culture: foster a more innovative and risk-tolerant culture within heat-intensive industries to facilitate the adoption of new technologies like TES.
- Be open to diverse financial resources: explore financing options including third-party funding for TES deployment to minimize upfront costs and risks.

The implementation of these recommendations will result in a shift of focus towards long-term decarbonization strategies, such as TES, within heat-intensive industries. Furthermore, investments in research, fostering innovation, and then the formation of collaborative partnerships with technology developers and academia, allows firms to accelerate the adoption of TES and other decarbonization technologies. Such efforts will stimulate innovation and facilitate the transition towards cleaner and more efficient industrial practices.

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Appendix 1

Interview Questionnaire

7) What type of process are you aiming to decarbonize with Thermal Energy Storage? (please, only provide the generic name of the process: i.e. drying, coating).

8) Apart from Thermal Energy Storage, have you considered any other technologies for decarbonizing this process? If yes, which ones?

9) Where did you find out about Thermal Energy Storage as a solution for industrial steam?

    a) Internet
    b) Conference
    c) Networking event
    d) Social media
    e) Someone contacted me
    f) Someone recommended me Thermal Energy Storage
    g) Other.

10) Please, share three key motivations for adopting Thermal Energy Storage for the decarbonization of industrial steam.

11) Please, share three perceived risks in adopting Thermal Energy Storage for the decarbonization of industrial steam.

12) How do you perceive the information available in the market about Thermal Energy Storage for generating industrial steam using renewable energy?

13) In general lines, when considering solutions for steam decarbonization, what are the key steps on your decision-making journey? Which levels of management are involved?

14) What type of contractual agreement are you considering for adopting Thermal Energy Storage?

    a) Purchase
    b) Leasing
    c) Service agreement (i.e. Heat as a Service)
    d) Joint project/partnership

15) What potential challenges do you foresee in your workforce's skill set during the implementation of Thermal Energy Storage?

16) How do regulations and policies impact your organization's decision-making in adopting a new technology for decarbonizing your steam processes? Can you provide specific examples?