Universitat de Lleida

Development of Thermal Energy Storage for Increasing Renewables Penetration at Building and District levels

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Universitat de Lleida

TESI DOCTORAL

Development of Thermal Energy Storage for Increasing Renewables Penetration at Building and District levels

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Memòria presentada per optar al grau de Doctor per la Universitat de Lleida

Programa de Doctorat: Enginyeria i Tecnologies de la Informació

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Summary

World Economic Forum estimates in its 2023 report on likelihood and impact of global risks that in next ten years, six of ten global risks are associated with environment. To address challenges posed by climate change and to achieve sustainable development goals by United Nations Development Programme's (UNDP), global community has intensified its efforts towards sustainable development. One of the key strategies is to increase renewable energy resources' (RES) share in energy mix. The transition towards RES presents both opportunities and challenges, particularly in the realm of intermittent nature of RES and thermal energy management for buildings and districts. The motivation for this scientific study is derived from above mentioned facts and thesis is framed to analyse role of thermal energy storage and heat pumps in increasing RES share at building and district level. The first section of thesis employs bibliometric analysis technique to identify trends, patterns, and research gaps in the integration of heat pumps and thermal energy storage (TES) techniques in current energy system. The analysis also provides insights into energy policies of countries with highest research output in this field along with challenges posed in wide deployment of heat pumps and TES techniques. This section also provides a thorough literature review on the said topic and discusses role of heat pumps and TES in detail in context of sector coupling. The second section provides a numerical and experimental analysis of low global warming potential (GWP) heat pumps coupled to electrical and TES to increase share of renewables across Europe. Third section provides experimental evaluation of different designs for PCM storages for cooling applications. By addressing technical, economic, and environmental aspects, this thesis provides valuable guidance for policymakers, engineers, and stakeholders striving towards a sustainable energy future.

Resumen

El Foro Económico Mundial estima en su informe de 2023 sobre la probabilidad y el impacto de los riesgos globales que en los próximos diez años, seis de cada diez riesgos globales están asociados con el medio ambiente. Para abordar los desafíos que plantea el cambio climático y alcanzar los objetivos de desarrollo sostenible del Programa de las Naciones Unidas para el Desarrollo (PNUD), la comunidad global ha intensificado sus esfuerzos hacia el desarrollo sostenible. Una de las estrategias clave es aumentar la participación de los recursos de energía renovable (RES) en la combinación energética. La transición hacia las RES presenta tanto oportunidades como desafíos, particularmente en el ámbito de la naturaleza intermitente de las RES y la gestión de la energía térmica para edificios y distritos. La motivación para este estudio científico se deriva de los hechos mencionados anteriormente y la tesis se enmarca para analizar el papel del almacenamiento de energía térmica y las bombas de calor en el aumento de la participación de las RES a nivel de edificios y distritos. La primera sección de la tesis emplea una técnica de análisis bibliométrico para identificar tendencias, patrones y brechas de investigación en la integración de técnicas bombas de calor y el almacenamiento de energía térmica (TES) en el sistema energético actual. El análisis también proporciona información sobre las políticas energéticas de los países con mayor producción de investigación en este campo, junto con los desafíos que plantea el amplio despliegue de técnicas bombas de calor y TES. Esta sección también proporciona una revisión exhaustiva de la literatura sobre dicho tema y analiza en detalle el papel de bombas de calor y TES en el contexto del acoplamiento sectorial. La segunda sección proporciona un análisis numérico y experimental de bombas de calor de bajo potencial de calentamiento global (GWP) acoplado a electricidad y TES para aumentar la participación de las energías renovables en toda Europa. La tercera sección proporciona una evaluación experimental de diferentes diseños de almacenamiento PCM para aplicaciones de refrigeración. Al abordar aspectos técnicos, económicos y ambientales, esta tesis proporciona una guía valiosa para los formuladores de políticas, ingenieros y partes interesadas que se esfuerzan por lograr un futuro energético sostenible.

Resum

El Fòrum Econòmic Mundial estima al seu informe del 2023 sobre la probabilitat i l'impacte dels riscos globals que en els propers deu anys, sis de cada deu riscos globals estan associats amb el medi ambient. Per abordar els reptes que planteja el canvi climàtic i assolir els objectius de desenvolupament sostenible del Programa de les Nacions Unides per al Desenvolupament (PNUD), la comunitat global ha intensificat els seus esforços cap al desenvolupament sostenible. Una de les estratègies clau és augmentar la participació dels recursos d'energia renovable (RES) en la combinació energètica. La transició cap a les RES presenta tant oportunitats com desafiaments, particularment a l'àmbit de la naturalesa intermitent de les RES i la gestió de l'energia tèrmica per a edificis i districtes. La motivació per a aquest estudi científic deriva dels fets esmentats anteriorment i la tesi s'emmarca per analitzar el paper de l'emmagatzematge d'energia tèrmica i les bombes de calor en l'augment de la participació de les RES a nivell d'edificis i districtes. La primera secció de la tesi empra una tècnica d'anàlisi bibliomètrica per identificar tendències, patrons i bretxes de recerca en la integració de tècniques bombes de calor i l'emmagatzematge d'energia tèrmica (TES) al sistema energètic actual. L'anàlisi també proporciona informació sobre les polítiques energètiques dels països amb més producció de recerca en aquest camp, juntament amb els reptes que planteja l'ampli desplegament de tècniques bombes de calor i TES. Aquesta secció també proporciona una revisió exhaustiva de la literatura sobre aquest tema i analitza detalladament el paper d'bombes de calor i TES en el context de l'acoblament sectorial. La segona secció proporciona una anàlisi numèrica i experimental d'bombes de calor de baix potencial d'escalfament global (GWP) acoblat a electricitat i TES per augmentar la participació de les energies renovables a tot Europa. La tercera secció proporciona una avaluació experimental de diferents dissenys d'emmagatzematge PCM per a aplicacions de refrigeració. En abordar aspectes tècnics, econòmics i ambientals, aquesta tesi proporciona una guia valuosa per als formuladors de polítiques, enginyers i parts interessades que s'esforcen per assolir un futur energètic sostenible.

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List of symbols and abbreviations

COP	Coefficient of performance
DHC	District heating and cooling
EU	European Union
GHG	Greenhouse gases
GWP	Global warming potential
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
LCoE	Levelized cost of electricity
LTES	Latent thermal energy storage
PCM	Phase change materials
RES	Renewable energy sources
SDG	Sustainable development goals
SOC	State of charge
TES	Thermal Energy Storage
TTES	Tank thermal energy storage
UNDP	United Nations Development Programme

Chapter 1
Introduction and objectives

1.1. Introduction

1.1.1. Statement of problem and motivation

In recent years, the global community has intensified its efforts towards sustainable development, driven by a shared commitment to address climate change and achieve the United Nations Development Programme's (UNDP) Sustainable Development Goals (SDGs). These SDGs, adopted in 2015, provide a universal framework to address this challenge, especially SDG 7, which aims to ensure access to affordable, reliable, sustainable and modern energy for all by 2030 [1]. Moreover, the Paris Agreement, signed in 2016, sets the ambitious goal of limiting the global temperature rise to well below 2 °C, preferably to 1.5 °C, in the second half of this century [2]. The significance of this temperature threshold cannot be overstated, as surpassing it could lead to irreversible and catastrophic impacts on the planet. The global challenge of climate change requires a rapid and profound transformation of the energy sector, which is responsible for about three-quarters of the greenhouse gas emissions worldwide [3]. World Economic Forum released its report in 2023 on the likelihood and impact of global risks in next two and ten years as shown in Figure 1 [4]. For the next two years, five of the ten global risks are associated with environment. For the next ten years, six of the ten global risks are associated with environment. This explains the seriousness of the issue. It is need of the hour to address all climate related issues and take actions now to preserve the future.

One of the key strategies to achieve UNDP goals is to increase the share of RES in the energy mix, such as solar, wind, hydro, biomass, and geothermal. RES can provide multiple benefits for energy security, economic development, and environmental protection, by reducing the dependence on fossil fuels, creating new jobs and industries, and mitigating the impacts of climate change. However, the integration of high shares of RES in the energy system also poses significant challenges and opportunities, especially in the heating and cooling sector, which accounts for almost half of the global energy demand [3]. Some RES, such as solar and wind, are variable and intermittent, meaning that their availability depends on weather conditions and does not always match the demand of energy. Therefore, there is a need to balance the supply and demand of energy in a flexible and efficient way, by using technologies that can store excess energy when it is abundant and cheap and release it when it is scarce and expensive. Thermal energy storage (TES) in one of the technologies that can be used for fulfilling this purpose.

Electrification of heating and cooling sector is another solution to reduce greenhouse gas emissions. In the pursuit of electrifying the heating and cooling sector, the integration of heat pumps with thermal energy storage systems emerges as a transformative approach. This synergy enables the efficient utilization of stored thermal energy for both heating and cooling applications, contributing to the overall electrification of energy systems. The integration of heat pumps and TES not only enhances energy efficiency but also supports the broader goal of achieving a sustainable and resilient energy infrastructure.

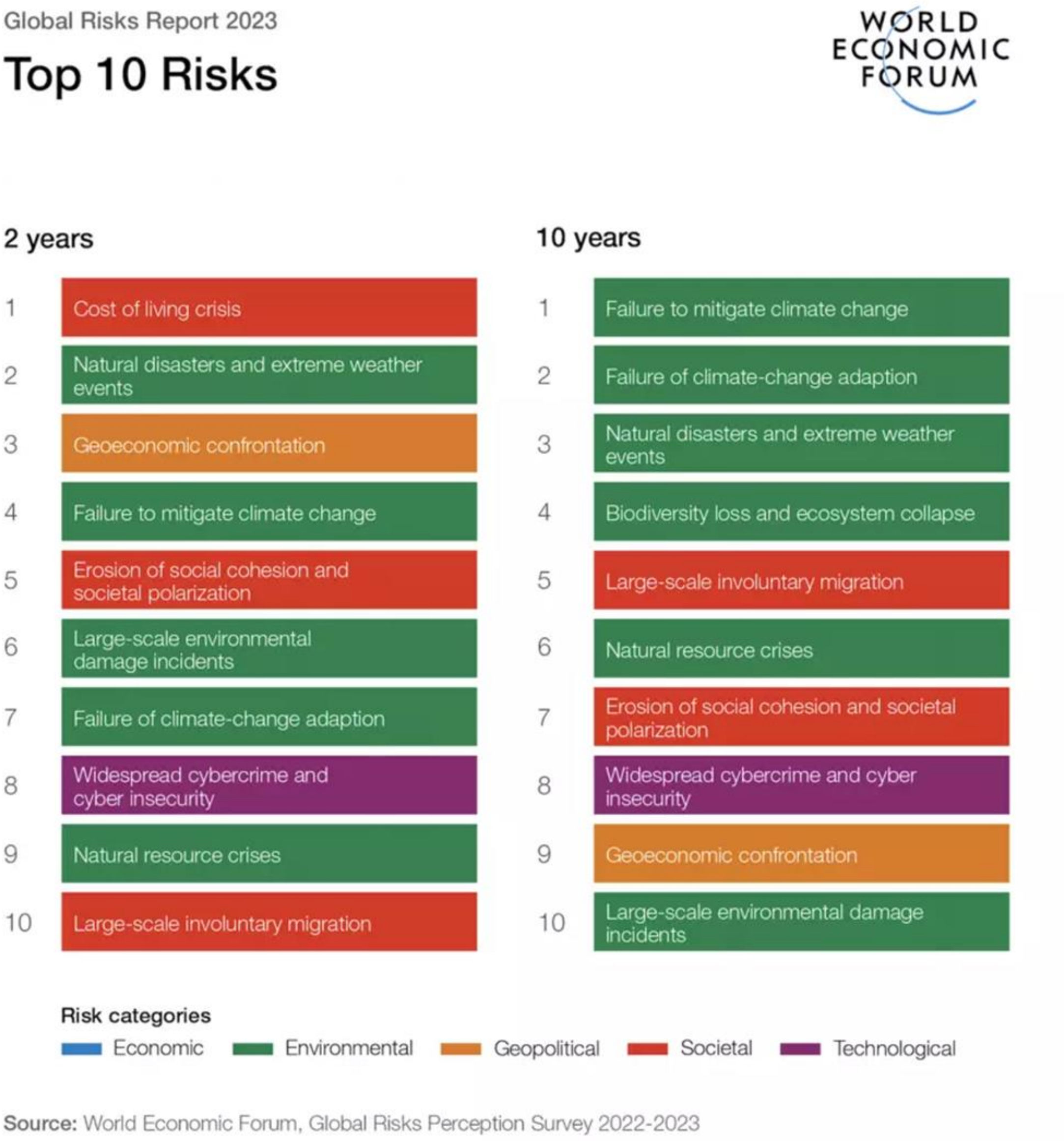

Figure 1 Global risks in terms of likelihood and impact for next 2 and 10 years [4]

The integration of heat pumps and TES uses low-carbon electricity to drive heat pumps that can transfer heat from a low-temperature source, such as ambient air, water, or ground, to a high-temperature sink, such as a building or a district heating network, and store it in TES systems for later use [5]. Heat pumps can also operate in reverse mode, by providing cooling to a building or a district cooling network and storing the excess heat in TES systems. The integration of heat pumps and TES can increase the energy efficiency, reduce the energy costs, and provide grid services, by exploiting the flexibility of both technologies to adjust their electricity consumption according to the availability of RES and the demand of energy [6].

Thermal energy storage (TES) is one of the key enabling technologies for sector coupling, which is the integration of different energy carriers, such as electricity, heat, and gas, to optimize the operation of the whole energy system [4]. TES can store excess energy from RES, either in the form of heat or cold, and use it when needed, for heating or cooling purposes, in buildings or districts. TES can improve the energy efficiency, reduce the energy costs, and provide grid services, such as peak shaving, load shifting, or frequency regulation [9]. TES can also facilitate the electrification of the heating and cooling sector, which is the use of low-carbon electricity to provide thermal comfort and process heat, instead of fossil fuels [10].

In summary, this thesis delves into the development of thermal energy storage technologies as a critical component for enhancing renewables penetration at building and district levels. By addressing the challenges posed by intermittent RES, TES plays a pivotal role in realizing the goals set by the UNDP and advancing towards a sustainable and low-carbon future.

1.1.2. Thermal energy storage

Thermal energy storage (TES) is the technology by means of which it is possible to store thermal energy, which can be used later to cover the mismatch between energy generation and its use. Implementing TES in an energy system results in better economics and more efficient use of energy, while lowering CO_2 emissions and make a system's performance reliable [7], [8].

TES can be classified into three main types, according to the physical principle involved: sensible heat storage, latent heat storage, and thermochemical heat storage [5]. A detailed classification of TES is given in Figure 2. Sensible heat storage involves storing energy by changing the temperature of a storage medium, such as water, rocks, or metals. One of the main advantages of sensible TES is its low cost, for instance 50-100 times cheaper than electrical storage [9]. Latent heat storage involves storing energy by changing the phase of a storage material, such as ice, wax, or salt hydrates. For latent storage, phase change materials (PCM) are used which can store and release heat during phase transition. Generally, solid-liquid phase change is used, in which heat is absorbed by material upon melting and released during solidification [10]. Latent heat storage has several benefits including high energy density and capability to store heat at a constant or near constant temperature.

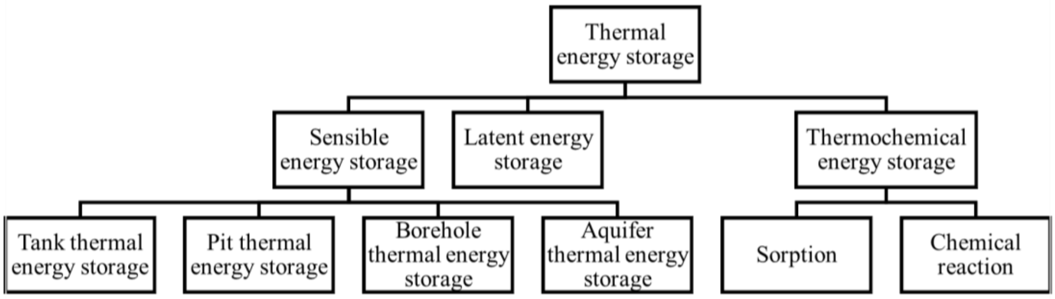

Figure 2 Classification of thermal energy storage [5]

Thermochemical heat storage involves storing energy by breaking or forming chemical bonds in a storage material, such as zeolites, metal hydrides, or carbonates. Generally, chemical energy conversion has greater efficiency than sensible and latent storage [11]. The main advantage of this kind of storage is that, as long as the products and reactants are kept separated, there are no losses and therefore it is possible to realise long-term storage.

Each type of TES has different advantages and disadvantages, depending on the application, such as the required temperature, capacity, and duration of storage. Some examples of TES systems in operation or under development are water tanks, ice storage, molten salts, phase change materials, or reversible chemical reactions [11].

As stated by IRENA [12], TES technologies provide distinctive advantages, including the ability to decouple heating and cooling demands from immediate power generation and supply availability. This enhanced flexibility enables a more substantial reliance on variable RES like solar and wind power. TES diminishes the necessity for expensive grid reinforcements, aids in balancing seasonal demand, and facilitates the transition toward a predominantly renewable-based energy system. Some of the TES benefits as per IRENA report are shown in Figure 3.

TES also finds its application in district heating and cooling (DHC) systems. DHC systems are entering 5th generation, and their main features are ultra-low temperature distribution and a high penetration of renewables. The erratic nature of low temperature heat production from solar collectors, heat pumps and industrial excess heat demands a storage mechanism in low temperature district heating systems which can be managed through TES systems.

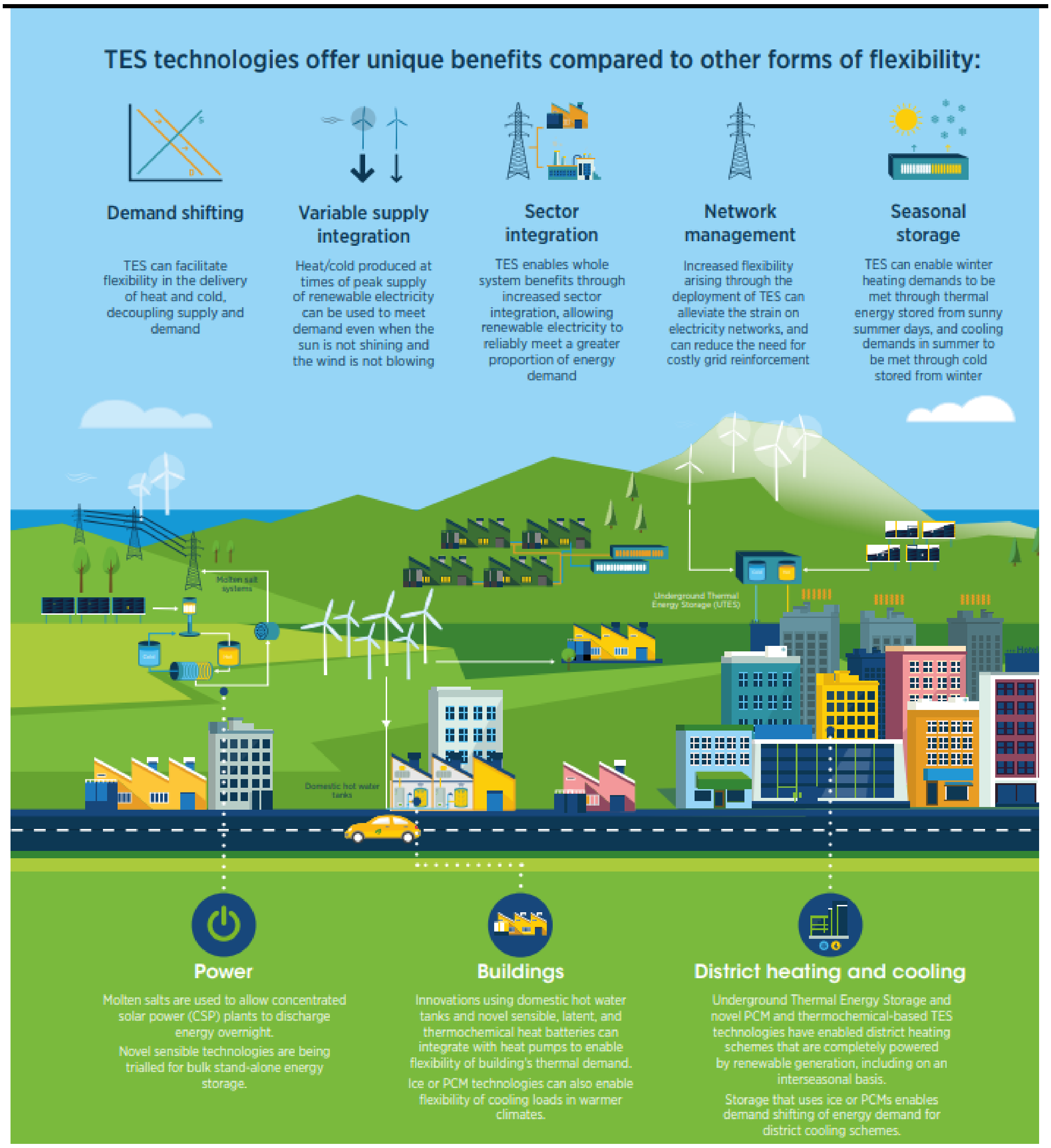

Figure 3 Benefits of TES technologies from IRENA report 2020 [13]

Recent studies emphasize the importance of shifting our focus towards residential and commercial buildings to mitigate our carbon footprint. These structures contribute significantly, constituting 40% of the overall primary energy consumption in the European Union (EU) [14]. Within this context, heating, ventilation, and air conditioning (HVAC) systems alone contribute to 76% of the mentioned primary energy consumption [15]. Figure 4 shows the technology status and innovation outlook of TES technology in the buildings sector. UTES stands for underground TES and TTES stands for tank TES (with water as storage medium). TTES is in commercial phase while for latent energy storage, ice storage is in commercial phase. Absorption systems are in demonstration phase. The glass scanner in the figure means that values are not available yet. It is aimed that efficiencies of sensible and latent TES will be increased to 90% and above 92% respectively.

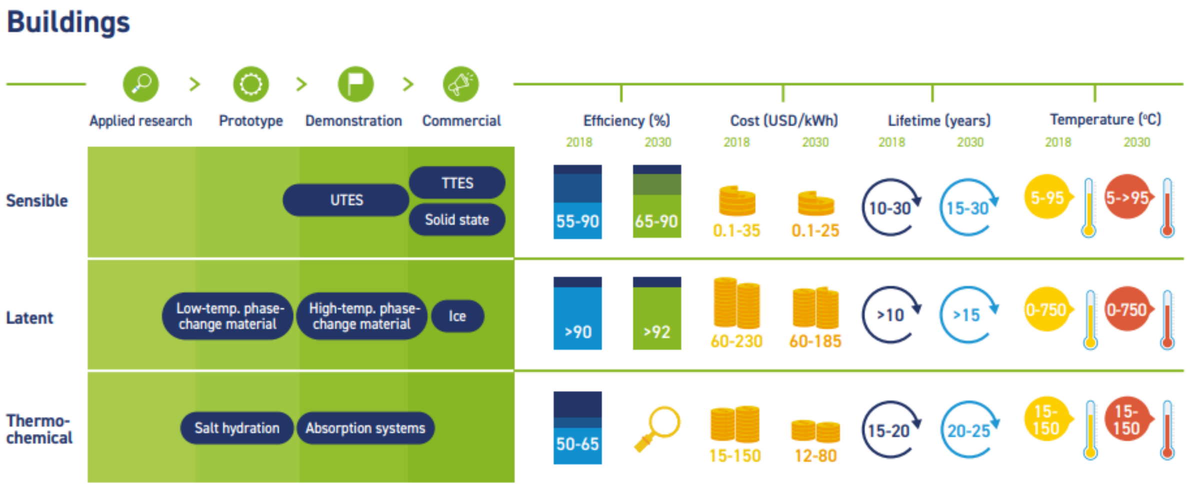

Figure 4 TES technology status and innovation outlook in the buildings sector by IRENA [13]

In conclusion, TES is a promising technology which can help to increase the penetration of RES in the energy system, especially in the heating and cooling sector, and to achieve the global climate and sustainability goals. However, there are still technical, economic, and social barriers that hinder the widespread adoption of TES, such as the high capital costs, the low energy density, the thermal losses, the lack of standards and regulations, and the low awareness and acceptance of the technology. Therefore, there is a need for further research and development to overcome these barriers and to optimize the design and operation of TES systems. The main objective of this thesis is to develop novel TES systems for increasing the renewables penetration at building and district levels, by integrating heat pumps and TES with different types and materials, and by applying advanced control and optimization methods.

1.1.3. Heat pumps

TES systems are used alongside heat pumps, at residential and district level, to enhance their efficiency and effectiveness. TES can store excess thermal energy generated by heat pumps during off-peak hours and release it when needed, optimizing energy usage, and reducing overall costs. Heat pump technology represents a pivotal innovation in the realm of energy efficiency and sustainable heating and cooling solutions. Unlike traditional heating systems, which generate heat through combustion or electrical resistance, heat pumps leverage the principles of thermodynamics to transfer heat from one location to another. This transformative approach not only offers a more environmentally friendly alternative but also enhances energy conservation. At its core, a heat pump acts as a versatile system capable of both heating and cooling spaces, making it a versatile and year-round solution. By harnessing ambient heat from the air, ground, or water sources, and utilizing refrigerant cycles, heat pumps can provide warmth in winter and coolness in summer, all while significantly reducing energy consumption.

Heat pumps, when used in a controlled and appropriate way, can help easing the transition towards decentralized energy systems. Heat pumps are considered as being a low CO_2 emission technology in the residential heating sector. Generally, electricity is used to drive low exergy heat through a vapor compression cycle towards high temperature and high level of exergy [16].

An electrical driven heat pump consists of two heat exchangers; one called condenser and other evaporator, a compressor, and an expansion device. The heat is derived from low temperature renewable source which can be air, water, or ground. Working fluid, which is a refrigerant, is used for delivering heat via a vapor compression cycle. It is compressed to a higher temperature and pressure. It is then condensed to lower temperature in condenser rejecting heat to the sink. Expansion device helps in reducing pressure and refrigerant is evaporated at low temperature and thus the cycle goes on. A salient feature of heat pumps is their ability to work in reversible operation. Heat pump works between a heat sink and source at two different temperature levels. Depending on operation, useful effect can be extracted in the form of heat on condenser side and cooling on evaporator side.

Heat pumps are used mainly because of three reasons. Firstly, due to ever evolving and progressing heat pump technology, the coefficient of performance (COP) are increasing [17]. Increment in COP leads towards lower CO_2 emissions. Secondly, according to Paris climate agreement, EU along with other countries aim to reduce carbon footprint by increasing energy production from RES. This encouraged the installation of solar PV and wind farms in various parts of the world. Heat pumps can be powered by electricity produced from RES and can use renewable heat as a source which brings reduction in carbon footprint. In a simulation based optimization study, it was found out that heat pumps at residential level can significantly decrease the CO_2 emissions level in context of residential heating[18].

Thirdly, in recent years, many model based predictive controls have come in use and the concept of internet of things have allowed the appliances to operate in a much more controlled and efficient way. Such predictive controls have also been applied in heating sector to meet the demand and maintaining the thermal comfort by taking in to account the thermal load, pricing indexes and future predicted heating demands. The vision of internet of things [19] have also given rise to the concept of smart grid which focuses on minimum costs for operating an electric grid, bringing stability in the operation of grid for voltage, transmission capacity and frequency; and using the generation resources optimally within boundaries set for limiting the CO_2 emissions.

Heat pumps are part of demand side in the context of smart electric grid [16]–[18] and help increasing thermal comfort for humans. Installing heat pumps for coupling with TES or with buildings to use their thermal inertia helps in reducing the electricity consumption for heating demand. Decoupled electricity from heating demand can be used in other operations of smart grid resulting in increased flexibility.

This thesis deals with developing TES for increasing share of renewables at building and district level. It also takes in to account the integration of TES with HP to electrify heating and cooling sector. For this purpose, a bibliometric analysis was carried out to find literature gaps which highlighted sector coupling, low GWP refrigerants, experimental studies on water source HP, encapsulation techniques for phase change materials, and control strategies for energy systems with RES integration. Further steps for this PhD were developed based on these findings and model of an energy system consisting of both TES and electrical storage with solar assisted HP employing low GWP refrigerant was developed. A control strategy was also developed to operate this system. Moreover, an experimental study on macro-encapsulation techniques of PCM was also conducted to cover research gap highlighted by bibliometric study.

1.2. PhD objectives

Main objectives of this PhD are as follows:

- Performing a literature review on role of TES in increasing RES penetration in energy system.
- Performing a thorough analysis on role of heat pumps and TES for coupling of power and heating/cooling sectors.
- Finding literature gaps to understand the role of TES in increasing RES share in buildings.
- Performing a policy analysis to understand the current and future policy trends of deployment of heat pumps and TES.
- To identify the main challenges associated with the deployment of heat pump and TES.
- To develop an energy system at residential level involving heat pumps and TES integrated with electrical grid.
- Lab-scale activities to assess the thermal performance of a TES unit with different macro-encapsulation / innovative component with higher energy storage density.

Chapter 2
PhD thesis structure and methodology

This chapter describes the structure of thesis as well as the methodology adopted to carry out the simulation and experimental work of the PhD.

2.1. PhD thesis structure

This thesis is divided in to five chapters. First chapter states the need of actions to be taken for preserving the climate, presents the importance of building sector and highlights how to increase the penetration of RES at building and district levels. It also explains the importance of technologies which can play an important role in reducing carbon footprint. The potential of TES to increase the share of RES and benefits of its integration with heat pumps is discussed in detail. Chapter 2 contains the details about materials and methodology adopted for this PhD. It contains details of simulation and experimental work along with information on bibliometric analysis and literature review. Chapter three comprises of four published papers . It also contains an overview of the publications along with their contribution to state-of-art. Moreover, author’s role is also described. Fourth chapter contains global discussion of results obtained through all publications. These results cover technical and social aspects of HP and TES technologies. Lastly, fifth chapter sheds lights on conclusions drawn from this PhD and recommendations for future work. Figure 5 shows the structure followed for writing this PhD thesis.

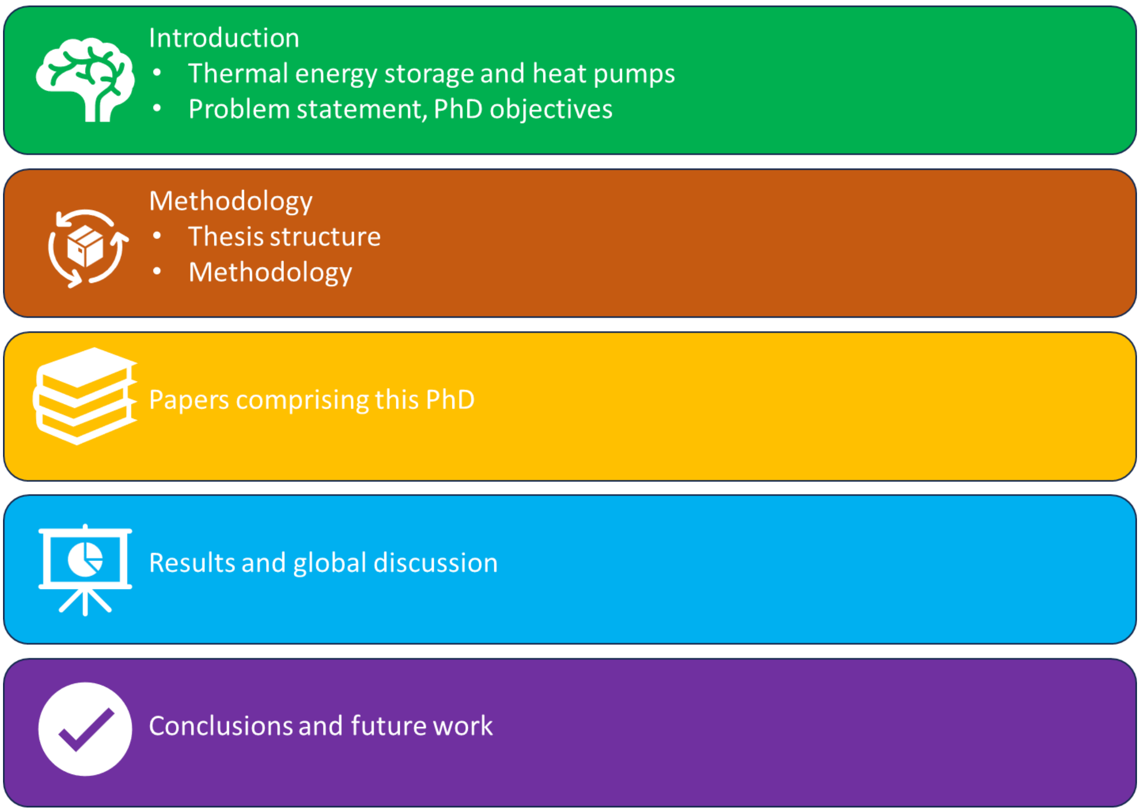

Figure 5 PhD thesis structure.

2.2. Methodology

This section presents the methodology adopted to achieve the PhD objectives. As first step, a bibliometric analysis was carried out to identify the trends and patterns of research and to find the research gaps to fit in the PhD objectives. A bibliometric analysis helps to find out the current research trends, leading authors of the field, papers with highest citations and points out the possible research gaps existing in the literature. Furthermore, details on collaboration networks of countries and researchers are also provided. So, a bibliometric analysis was performed as a stepping stone. The search query used for this analysis was (“thermal storag*” OR “phase change material*" OR "pcm" OR "latent storag*" OR "sensible storage" OR "thermal energy storag*" OR "heat storag*") AND ("heat pump$" OR "heat pump systems") AND NOT ("pumped" OR "compressed air"). The query was made in “article title, abstract and keywords”. As a result, 3086 publications were obtained between the period of 1969 and 2022 from Scopus database. For bibliometric analysis, VOSviewer software was used for visualizing the data. VOSviewer requires a thesaurus file to provide results for visualization. This thesaurus file is screened by merging some similar terms so that results can be improved. Moreover, it also helps in reducing the dispersion of data. The methodology used is given in Figure 6 below.

With the help of bibliographic data, seven countries with highest research output were selected and their HP and TES deployment policies were analysed in detail. Furthermore, the challenges in the wide deployment of policies related to HP and TES were also discussed along with the recommendations to overcome those challenges. With the help of bibliographic results and policy analysis, an understanding was tried to reach if policymaking had an impact on research activity and vice versa. For policy analysis, information was collected from governmental websites of chosen countries which were UK, USA, Japan, Italy, Germany, China, and Canada. Some pieces of information also came from IEA and IRENA websites. Moreover, a short analysis was also made on number of HP and TES patents filed each year globally and what are the trends of renewable energy investments worldwide. Figure 6 shows the methodology used for carrying out bibliometric analysis.

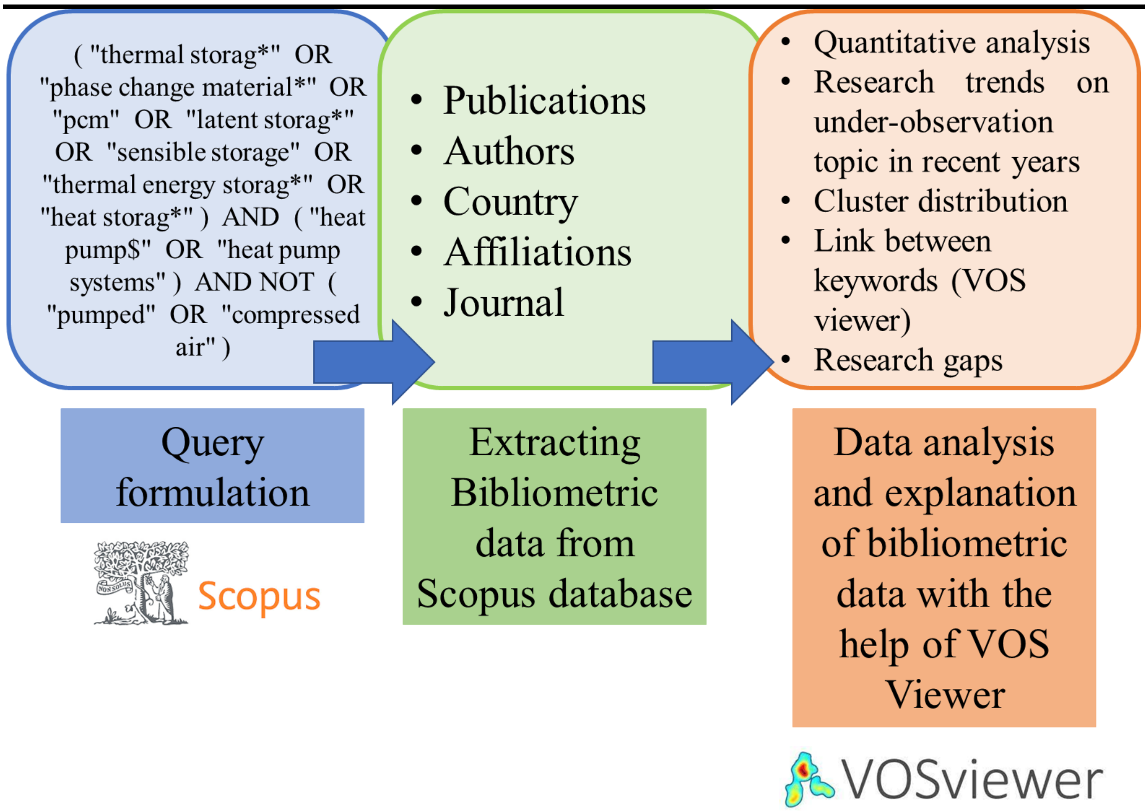

Figure 6 Methodology used for bibliometric analysis.

Bibliometric analysis helped in finding the existing research gaps and it was identified that both HP and TES technologies will be monumental for increasing RES share at building and district level. Some of the highlighted research gaps encompass sector coupling, low GWP refrigerants, experimental studies on water source and adsorption HP, encapsulation techniques for phase change materials, and control strategies for energy systems with RES integration.

To fill those gaps, next steps were planned. These steps included a thorough literature review of HP and TES technologies in context of sector coupling, numerical and experimental analysis of a solar-assisted HP model, employing low global warming potential (GWP), coupled with electrical and thermal storage to increase RES share across Europe and an experimental study on a novel TES unit with different macro-encapsulation designs.

The literature review was carried out to understand the status of HP and TES technologies along with their roles in the context of multi-carrier energy systems. The concept of a multi-carrier energy system (also known as sector coupling) is shown in Figure 7. Literature review gives a good understanding of where the technology stands now and what are the areas for further improvement. HP and TES technologies are being employed in district heating and cooling (DHC). HP technology will be of paramount importance in the upcoming 5th generation which will have ultra-low supply temperatures. TES can play an important role in bridging the heat supply and demand gap. In this paper, first an understanding of sector coupling is provided, and its benefits are discussed. Among different sector integration technologies, the integration of heating and power sector is considered important as it assumes a major role in decarbonisation strategies. Heating and cooling sector amounts to 50% of the global energy consumption thus electrification of this sector will result in reduction in carbon footprint [23]. Later in the first publication, role of HP and TES for power-thermal sector coupling is discussed in detail. It was discussed how HP could be helpful in providing ancillary services for grid, enabling integration of RES at building or grid level and operating in a price driven situation. Furthermore, role of HP in 5th generation DHC is discussed. Later, challenges associated with integrating HP in power-thermal grid are discussed and several studies are presented which state benefits, challenges and how to overcome these challenges.

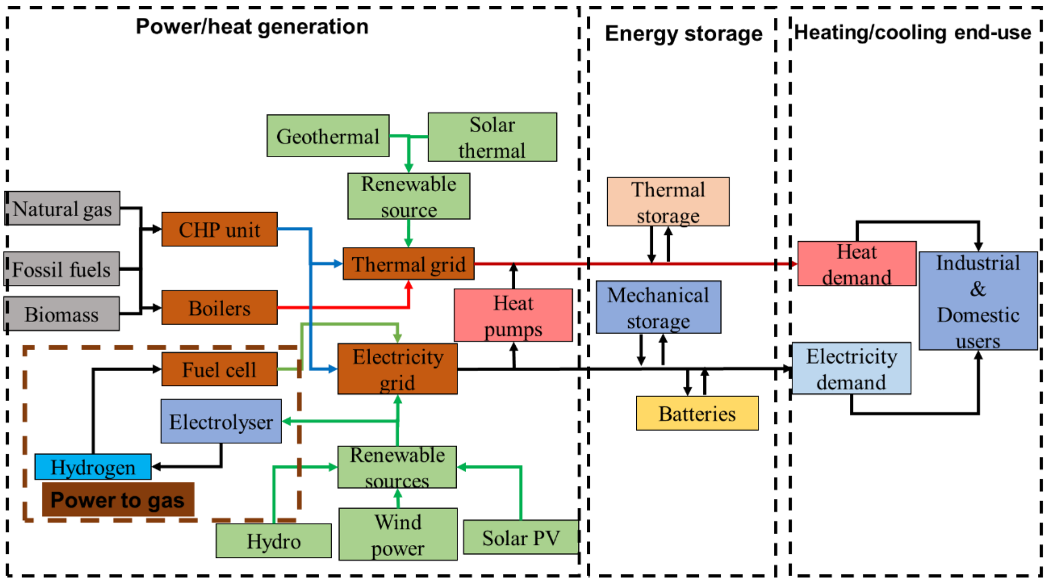

Figure 7 *Concept of a multi-carrier energy system (MCES)* [5]

The potential of every TES technology is discussed by giving examples from literature. Lastly, the benefits and challenges associated with TES technologies are discussed. A comparison of TES technology with pumped hydro energy storage and compressed air energy storage is made and it is concluded that TES is more economical and efficient.

After making a thorough study on role of HP and TES in sector coupling, further activities were planned for numerical simulation and experimental work. Methodology of HP simulation activity is given in Figure 8. Starting with the work on an HP with low GWP refrigerant, experiments were planned and carried out to develop a performance map of HP. This HP was developed by DAIKIN and NTUA and employed R1234Ze(E) as refrigerant. This was one of the initial studies on reversible HP with this refrigerant at residential level. Most of the previous studies were carried out with R134a, R407c and R410a. This study was carried out with both energy and economic points of view. The energy system includes a 10kW solar assisted reversible HP with electrical and thermal energy storage. The central part of energy system i.e. HP model is validated with experimental data. Model was developed in

Modelica/Dymola environment by using 'TIL', 'TIL media', 'TIL file reader' and 'Photovoltaics' libraries. Dymola is a commercial software for modelling of complex energy systems with a benefit of incorporating libraries from different engineering fields [24]. The cities selected for simulations are Athens, Marseille and Stuttgart which represent Mediterranean, hot semi-arid and humid continental climates according to the Köppen climate classification map [25]. The data used for batteries was also taken from the experimental activity at CNR ITAE. Lastly, a techno-economic analysis was performed to find the payback time and levelized cost of electricity.

The novelty of this study lies in using low GWP refrigerant R1234Ze(E). There is little to no data available about the performance of HP with this refrigerant. Proposed energy system contains both electrical and thermal energy storages. Main component of system i.e. HP model is validated through experimental data. Three different climates are selected to give this study a European perspective and to assess the performance of system in different climates. The study also contains an economic analysis presenting payback time periods and levelized cost of energy. Based on simulation, a suitable solar PV and electrical storage size is selected. The proposed system is compared against a conventional heating and cooling system and results proved it to be more cost effective.

The main goal of simulations was to gain an understanding about the behaviour of energy system in different climates. Moreover, simulations helped in deciding the appropriate sizes of thermal and electrical energy storages, electrical and gas heaters and solar PV. Furthermore, simulations also helped in carrying out economic analysis as energy exchange with national grid was also taken into account.

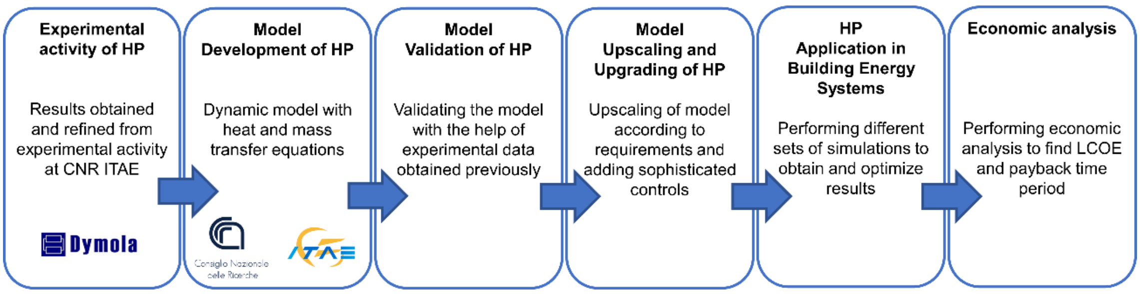

Figure 8 Methodology for HP study [6]

The experimental activity of HP was carried out using a testing rig at CNR ITAE. Experiments were performed with temperatures of 26 °C, 29 °C, 32 °C, 35 °C, and 40 °C at condenser inlet. At evaporator side, 12/7 °C condition was maintained which refers to a typical domestic application. Log mean temperature difference at condenser and evaporator sides were calculated along with UA value (product of overall heat transfer coefficient and surface area of heat exchanger), energy efficiency ratio and pressure ratio. This data was then used to validate the model.

The schematic diagram of model is given in Figure 9. The model consisted of reversible HP, thermal storage tank, PV panels, electrical batteries, and backup electric/gas heater. For Athens and Marseille, HP size is of 10kW while for Stuttgart, HP size is of 15 kW. The size of reversible HP was selected based on major thermal loads which was cooling in southern and heating in continental Europe. Moreover, the typical size of HP in residential buildings was also considered while selecting the size of HP.

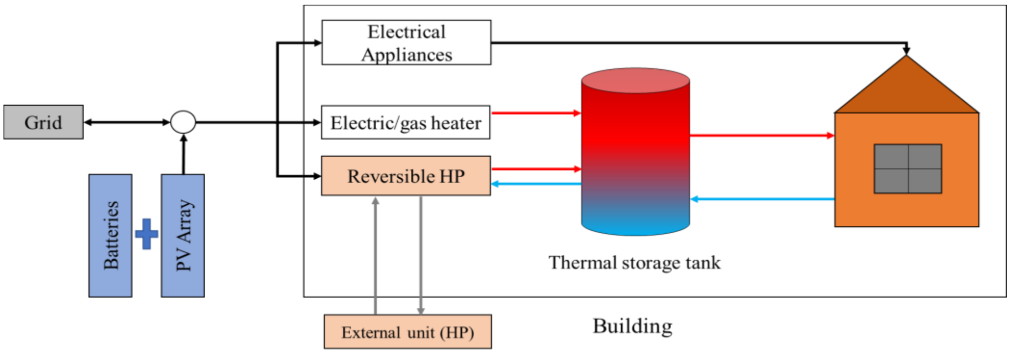

Figure 9 Schematic diagram of simulated system [6]

Backup source for Athens and Marseille was an electric heater while for Stuttgart, a gas heater is taken as a backup source. Athens and Marseille needed backup sources of 3 and 5 kW while Stuttgart needed a backup source of 15 kW. As an electric heater of 15 kW would have resulted in high consumption of electricity, so a gas heater is used for Stuttgart. The electricity profiles of household were taken from a model developed by Centre of Renewable Energy Systems Technology at Loughborough University [26]. House occupancy of four people was considered. Thermal loads were taken from a TRNSYS simulation study of an existing class-A building [27], [28]. TES tank sizes considered for Athens and Marseille were 700 litres while for Stuttgart, a TES size of 900 litres was considered. Three different PV sizes of 3, 4.5, and 6 kW and three electrical storage sizes of 5, 10 and 15 kWh were selected for simulations. The sizing of all components in the model was done while keeping in mind the typical sizes of equipment in the market. For PV sizing, not only typical household sizes were taken into account but space on the rooftops was also considered. Simulations were carried out for both winter and summer seasons. Self-sufficiency index (SSI) and self-consumption (SC) of energy system were presented as results.

Figure 10 shows the control strategy adopted for battery management and energy exchange with the grid. The process initiated from comparing the solar PV power and building load. If PV power is greater, the state of charge (SOC) of batteries is checked. If SOC is greater than 0.8, extra energy is sent to grid otherwise batteries are charged with that energy. In the same way, when building load is higher than PV power, the SOC of batteries decide if energy should be supplied by batteries or obtained from grid.

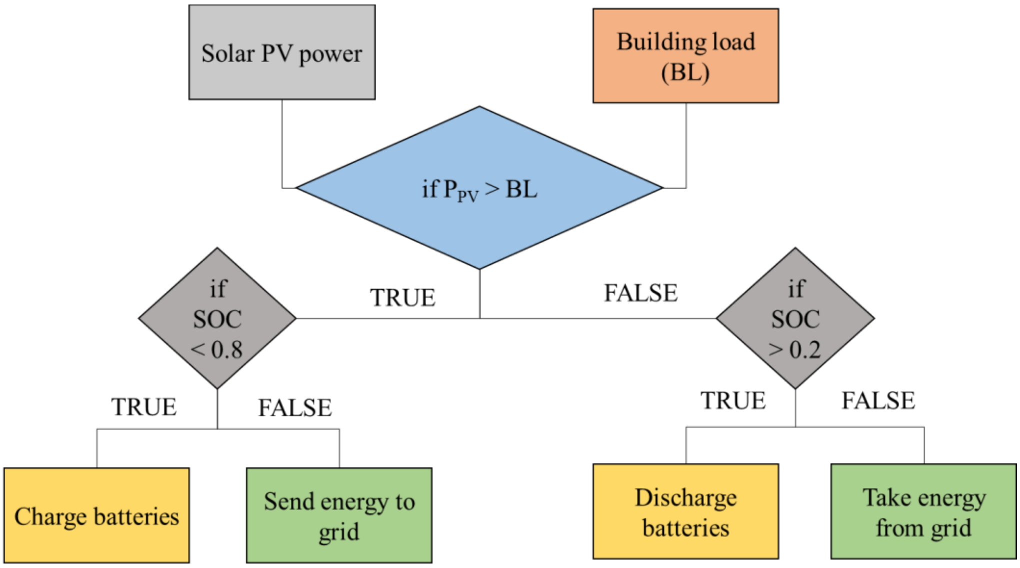

Figure 10 Control strategy for energy system [6]

Economic incentives given by Greece [29], France [30], and Germany [31] were identified and included in calculations for economic analysis. Payback time periods for all simulated cases were calculated along with levelized cost of energy. A comparison with typical heating and cooling system based on gas boiler and split air-conditioner was also made to assess the economic feasibility of both systems.

Sensible TES was used in this study. Sensible storage is mostly used in an energy system since it is most mature technology among the TES technologies. However, latent thermal energy storage (LTES) can also be beneficial when incorporated in energy system. LTES makes use of phase change materials (PCM) which are encapsulated in different shapes and sizes. Encapsulation helps in preventing leakage and helps to maintain the stability of the material. PCM encapsulation is mainly divided into two types namely micro (capsule size ~1–1000 μm) and macro (capsule size above 1000 μm). From the literature review in bibliometric analysis, it was concluded that experimental analysis of macro-encapsulation is an existing research gap. Moreover, it was also concluded that the instances of studies on cooling applications were also quite scarce. Accordingly, a study was made on experimental evaluation of three different designs of macro-encapsulation for PCM storage for cooling applications. A commercial TES tank employed these encapsulations namely ThinICE, FlatICE, and TubeICE. First two encapsulations are rectangular in shape with different thickness while TubeICE is cylindrical in shape. The dimensions of these encapsulations are given in Figure 11. The PCM used for this study is PlusICE S17, a salt hydrate, which is a commercial product of PCM Products [32].

Type of Slab	A	B	C	D	E	F
ThinICE	250	500	17	16	10	6
FlatICE	250	500	35	10	7	3
TubeICE	1200	50				

dimensions in millimetres

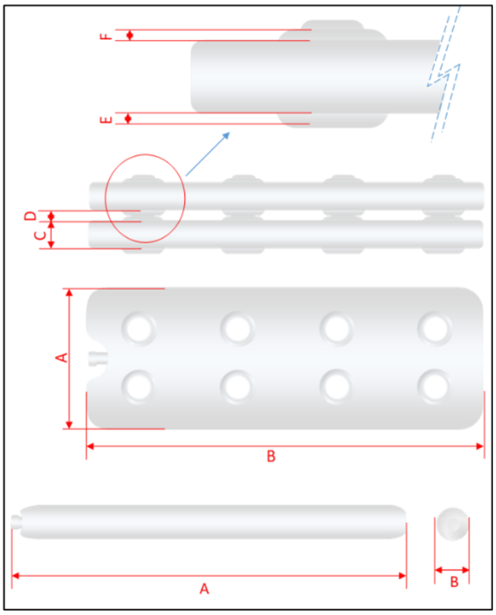

Figure 11 Dimensions of macro-encapsulations [33]

Th schematic diagram of the experimental setup is shown in Figure 12. It consisted of two variable speed pumps to regulate the mass flowrate in the circuit, the flowmeter Badger meter type ModMAG M1000, a 200 litres inertial tank, TES tank and data acquisition system. TES tank had a volume around 490 litres. The charging and discharging of TES tank are made by inertial tank. The temperature inside the inertial tank is increased by using electrical resistors and decreased through a cooling unit which consists of a Zanotti model GCU2030ED01B chiller which has a cooling capacity of 5 kW. The electrical resistors used are Astrugo model RIA-207. The components are connected with copper pipes and are insulated by polyurethane tubes. The data acquisition system consists of data logger, computer and data acquisition software SCADA developed in Indu Soft Web Studio. Time step used to record date is 1 second.

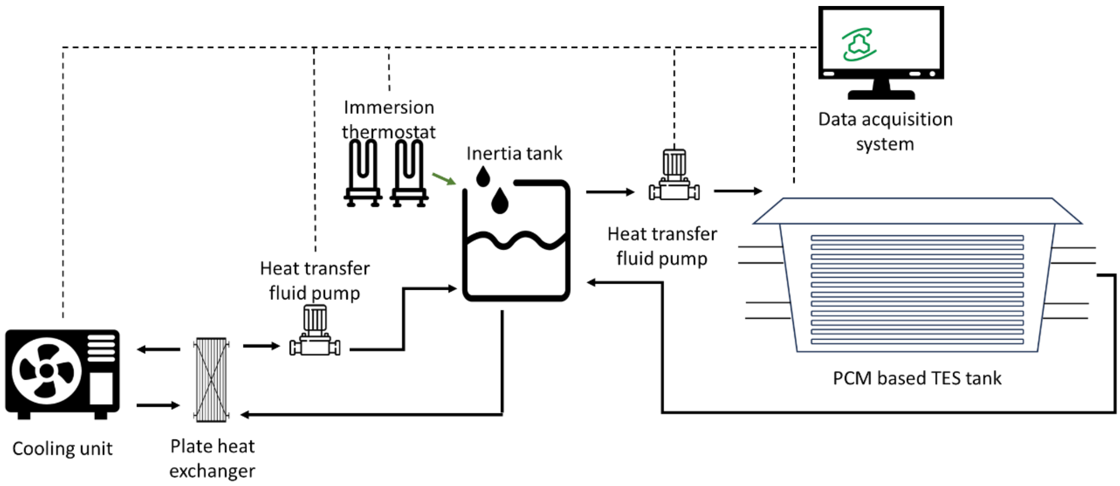

Figure 12 Schematic diagram of experimental setup [33]

Details of commercial TES tank is given in Figure 13. It contains a diffuser to distribute the water flow uniformly. Thermocouples are pasted on the top of capsules. There were 33 capsules in total, 27 of which are class B and used to measure PCM temperature while six sensors are class A and were used to measure heat transfer fluid temperature. The sensors for PCM are placed at heights of 400mm (Top), 260 mm (Mid) and 110 mm (Bottom). A heat loss test was conducted to determine heat losses attributed to the TES tank and were considered in all the subsequent calculations. The temperature for charging and discharging od tank were taken as 27 °C and 7 °C. Flowrate was maintained at 0.07 kg/s for all experiments. An experiment was repeated at least thrice for repeatability of results. For charging, temperature inside the tank was taken from 7 °C to 27 °C while for discharging, temperature inside the TES tank was taken from 27 °C to 7 °C. All experiments were considered complete when temperature sensos returned values of temperatures within ± 1 °C of final boundary condition.

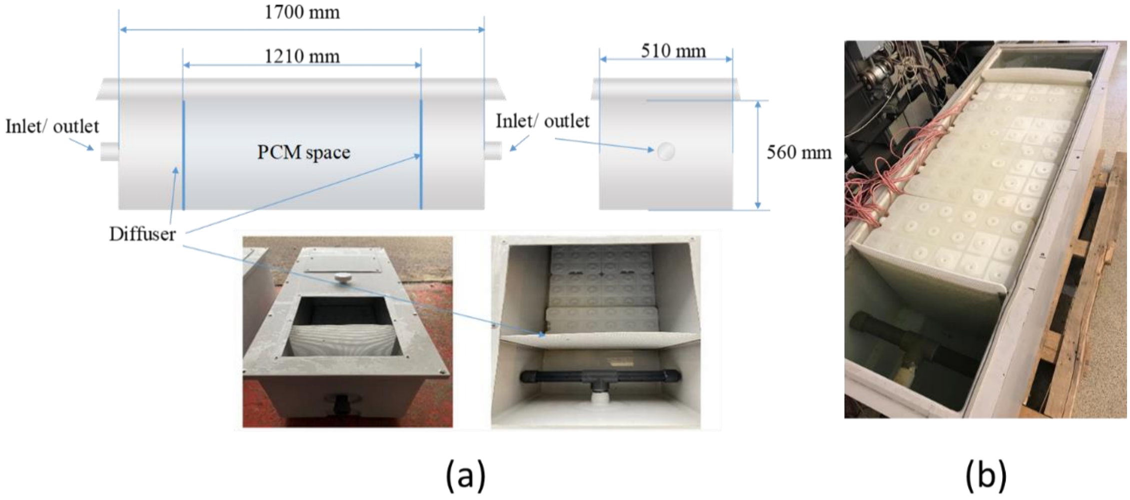

Figure 13 TES tank (a) dimensions (b) full view [33]

This study contains two different PCM configurations inside the tank to analyse the thermal behaviour of TES tank with different configurations and to assess if results for one configuration is better than the other. One configuration contains similar PCM mass inside the tank to ensure similar storage capacity (layout 1) while other configuration contains maximum PCM mass that can be put inside the tank (layout 2). Spacers were used for layout 1 for uniform distribution of PCM mass. These spacers are shown in Figure 14 below. ThinICE configuration was taken as reference and no spacers were required for it.

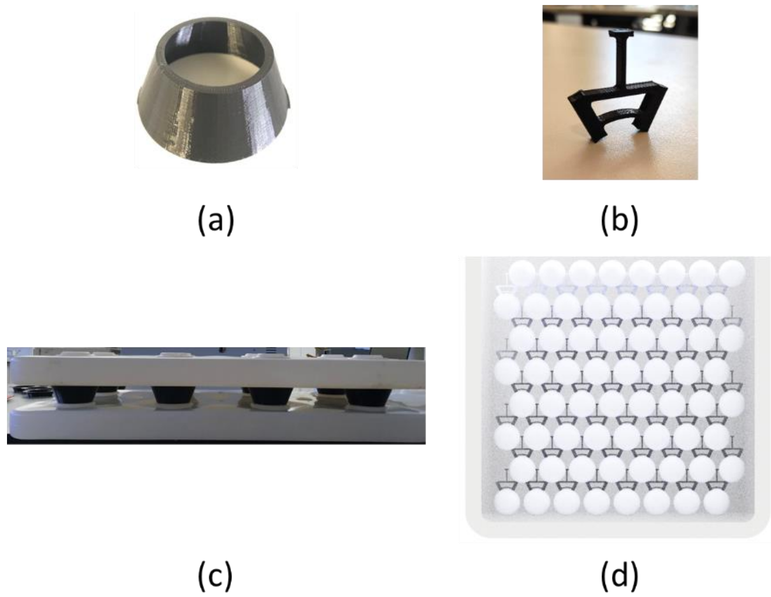

Figure 14 (a) Spacer for FlatICE, (b) spacer for TubeICE, (c) tank configuration with spacers for FlatICE, and (d) tank configuration with spacers for TubeICE [33]

Chapter 3
Results

3.1. Paper 1: Bibliometric analysis on integration of heat pumps and thermal energy storage: Insights into key countries and energy policies

3.1.1. Overview

The transition towards a low-carbon energy system has prompted increased research and development in renewable energy technologies, notably in the domains of heat pumps (HP) and thermal energy storage (TES) systems [34]. These technologies play a pivotal role in mitigating greenhouse gas emissions and enhancing energy efficiency, particularly within the heating and cooling sectors [35] [5].

In response to the growing significance of bibliometric analysis in understanding scientific literature, this paper employs this methodology to scrutinize the status of HP and TES systems in current energy scenario. By examining bibliographic data such as citation counts, publication trends, and collaboration networks, bibliometric analysis offers valuable insights into the structure and dynamics of research fields, as well as the impact of individual publications and authors [36][37]. Moreover, it helps in finding the research gaps which can be covered in future research activities.

This study conducts a comprehensive bibliometric analysis using a dataset comprising peer-reviewed articles, conference proceedings, books, and patents spanning the period from 1969 to 2022, sourced from the Scopus database. The primary objectives include identifying trends, patterns, and research gaps in the integration of HP and TES systems. Additionally, the analysis aims to provide insights into the energy policies of countries exhibiting higher research output in this field. The paper also delves into the challenges faced by HP and TES systems from technological, regulatory, and financial perspectives, offering recommendations to overcome these challenges.

3.1.2. Contribution to the state-of-the-art

The findings from the bibliometric analysis underscore the leadership of European countries in research on HP and TES systems. Particularly, the analysis reveals a notable emphasis on terms associated with heating applications, suggesting a research gap in the exploration of HP and TES operations for cooling applications. Several highlighted research gaps encompass sector coupling, low GWP refrigerants, experimental studies on water source and adsorption HP, encapsulation techniques for phase change materials, and control strategies for energy systems with RES integration.

Building upon the bibliometric analysis results, the study identifies the top seven countries with the highest scientific output and proceeds to conduct an in-depth analysis of their energy policies related to HP and TES systems. The paper delves into the primary obstacles hindering the adoption of these technologies and provides corresponding recommendations. The key aim is to investigate whether a correlation exists between policymakers and researchers' activities and how their interactions impact each other. This exploration sheds light on the dynamics between research activities and policy initiatives in the realm of HP and TES systems.

3.1.3. Contribution of the candidate

Omais Abdur Rehman along with Luisa F. Cabeza and Emiliano Borri conceived and designed the study. Omais Abdur Rehman carried out bibliometric analysis, made thesaurus files, conducted policy analysis, and prepared the original draft.

3.1.4. Journal paper

Dades de l'article

Clau	Article d'investigació
Any	2024
Caràcter	Internacional
Autors	Rehman OA, Borri E, Palomba V, Frazzica A, Brancato V, Botargues T, Cabeza LF
Títol	Analysis on integration of heat pumps and thermal energy storage in current energy system: From research outputs to energy policies
Revista	919193 - Journal Of Energy Storage - 2352-152X
Informació addicional	
Volum	97
Número	
Pàgina inicial	112795-1
Pàgina final	112795-25

3.2. Paper 2: Enabling technologies for sector coupling: A review on the role of heat pumps and thermal energy storage

3.2.1. Overview

Globally, the predominant source of electricity generation is fossil fuels, leading to the emission of greenhouse gases (GHGs) [38]. Future energy infrastructures should extensively leverage locally available RES to facilitate a sustainable and environmentally friendly transition in the economy [39]. This approach not only aids in mitigating the environmental impact associated with fossil fuel-based energy production but is also crucial for achieving a green economy.

The heating and cooling sector, identified by the International Energy Agency (IEA) as responsible for nearly 50% of global energy consumption, underscores the necessity of incorporating RES into heating and cooling processes for a sustainable energy system [23]. Given that the primary output from RES is electricity, the coupling of electricity and heating sectors assumes top significance [40]. The evolution from current energy systems to future sustainable models necessitates an integrative approach that combines various energy components and exploits synergies through sector integration [41]. Electrifying the heating and cooling sector becomes instrumental in achieving low carbon emission objectives. Moreover, the coupling of these sectors yields mutual benefits, enhancing flexibility, reliability, and adequacy in the power sector [42].

This study primarily focuses on HP and TES as key technical solutions for sector coupling. The initial discussion centres on the status of HP and TES technologies, primarily employed in district heating and cooling (DHC) networks. Subsequently, the study delves into the detailed exploration of the concepts of sector coupling and thermal grids. The analysis then extends to examining the role of HP and TES in coupling end-use sectors, providing an in-depth assessment.

Both HP and TES are poised to play pivotal roles in the development of the upcoming 5th generation of DHC. This generation is characterized by ultra-low supply temperatures, a feature instrumental in minimizing heat losses. HP emerge as viable technologies for transitioning towards low-temperature and cooling-dominated district networks. Additionally, to address the demand and supply gap, the incorporation of TES in DHC systems is proposed. TES functions as a buffer between heat demand and supply, thereby enhancing the reliability of energy supply.

3.2.2. Contribution to the state-of-the-art

This paper presents a comprehensive review of the roles played by HP and TES technologies within the framework of sector coupling, with a primary focus on the integration of electricity and heat. To facilitate an analysis of how HP and TES contribute to sector coupling, an overview of the status of both technologies is initially provided. These technologies are actively utilized in DHC systems and are anticipated to assume prominent roles in the future generations of DHC. Notably, HP technology is identified as having a substantial impact on the decarbonization of 5th generation DHC networks.

The paper explores the role of HP in smart electric grids, emphasizing its significance in supplying ancillary services to the grid and enabling the integration of RES. HP technology is seen as a key player in interconnected energy systems, promoting efficiency and renewable practices. Various studies in the literature highlight the ability of HP to provide supplementary services to the grid, including voltage control, congestion management, and balancing generation demand, as well as frequency regulation. Integration with variable speed HP is also explored to enhance on-site consumption of solar and wind power.

Additionally, different TES technologies—sensible, latent, and thermochemical—are examined in terms of their applications in DHC and multi-carrier energy systems. Literature findings suggest that TES contributes to smoothing net load variations and reducing CO_2 emissions. Seasonal storage techniques are emphasized as crucial for sector integration of power and heat. A comparative analysis with compressed air energy storage and pumped hydro energy storage demonstrates the economic competitiveness of TES. Furthermore, the paper highlights recent studies on pumped thermal energy storage, combining HP and TES technologies, as a promising solution for large-scale electrical storage.

Addressing not only technical barriers but also economic, social, and political challenges, the paper underscores the lack of national incentives and economic support for HP and TES implementation. It emphasizes the need for well-defined business models to enhance market penetration and calls for a cohesive plan at the policy level to integrate HP and TES for sector coupling. The deployment of these technologies is seen as crucial for transitioning to energy-efficient practices and decentralizing energy generation and storage. The discussion extends to social aspects, highlighting the hindrances posed by a lack of clarity and low acceptance rates. The paper concludes with recommendations aimed at accelerating the widespread adoption of HP and TES technologies.

3.2.3. Contribution of the candidate

Omais Abdur Rehman along with Valeria Palomba conceived this study. Omais Abdur Rehman developed the methodology, carried out formal analysis, literature review and prepared original draft. Co-authors helped in editing the manuscript and answering to the reviewers' comments.

3.2.4. Journal paper

The scientific contribution from this work was published in journal 'Energies' in 2021.

energies

MDPI

Review

Enabling Technologies for Sector Coupling: A Review on the Role of Heat Pumps and Thermal Energy Storage

Omais Abdur Rehman [1,2], Valeria Palomba [1], Andrea Frazzica [1,*] and Luisa F. Cabeza [2]

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Abstract: In order to reduce greenhouse gas emissions, current and future energy systems need to be made more efficient and sustainable. This change can be accomplished by increasing the penetration of renewable energy sources and using efficient technologies in energy generation systems. One way to improve the operation of the whole energy system is through the generation and end-use sector coupling. Power-to-heat energy conversion and storage technologies, in this view, are enabling technologies that can help in balancing and improving the efficiency of both thermal and electric grids. In the present paper, a comprehensive analysis of the role of heat pumps and thermal energy storage for sector coupling is presented. The main features of the analyzed technologies are presented in the context of smart electric grid, district heating and cooling and multi-carrier energy systems, and recent findings and developments are highlighted. Finally, the technical, social, and economic challenges in the adoption of investigated technologies are discussed.

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Citation: Abdur Rehman, O.; Palomba, V.; Frazzica, A.; Cabeza, L.F. Enabling Technologies for Sector Coupling: A Review on the Role of Heat Pumps and Thermal Energy Storage. *Energies* **2021**, *14*, 8195.

Keywords: heat pumps; thermal energy storage; multi-carrier systems; energy systems; sector coupling

3.3. Paper 3: Numerical and experimental analysis of a low-GWP heat pump coupled to electrical and thermal energy storage to increase the share of renewables across Europe

3.3.1. Overview

The current environmental crisis has spurred a rapid evolution in low-carbon-footprint technologies and associated policies. Recent research underscores the imperative of directing our focus toward residential and commercial buildings, which collectively contribute to 40% of the total primary energy consumption in the European Union (EU) [9]. Notably, within this sector, heating, ventilation, and air conditioning (HVAC) systems constitute a substantial 76% of the primary energy consumption [15].

Consequently, a significant portion of recent research has concentrated on strategies to diminish energy consumption and CO_2 emissions, all while ensuring the reliability of HVAC technology to uphold thermal comfort in buildings. Additionally, the imperative to electrify the heating and cooling sector has emerged as a crucial step in the quest to curtail carbon emissions. Heat-pump technology stands out as a viable solution to tackle this challenge, given its high efficiency and lower carbon footprint when compared with other contemporary heating and cooling technologies [5].

This study undertakes an evaluation of a hybrid system designed for residential applications, examining both the energy and economic aspects. The system comprises a solar-assisted 10 kW reversible water-to-water HP along with thermal and electric storage components. The core element of the system, the HP model, is based on a prototype tailored for single-family houses. Notably, this prototype employs the low global-warming-potential (GWP) refrigerant R1234Ze(E), and its performance has been experimentally assessed through dedicated activities. It is noteworthy that this study represents one of the initial instances of utilizing the low-GWP refrigerant R1234Ze(E) in a reversible HP at the residential level.

Simulations are conducted for the cities of Athens, Marseille, and Stuttgart, each characterized by distinct climate types (Mediterranean, hot semi-arid, and humid continental) to provide a comprehensive European perspective and facilitate a systematic analysis.

Beyond the energy analysis, an economic evaluation is carried out, comparing the hybrid system with contemporary technologies. This analysis involves assessing the energy exchange between the house and the grid, alongside a systematic examination of subsidies, tax regulations, and incentives related to the installation of HP or RES technologies. Special attention is given to Greece, Germany, and France—countries considered for the simulations. The study calculates the discounted payback time and the levelized cost of energy (LCoE) for all considered cases.

3.3.2. Contribution to the state-of-the-art

This study centres on analysing the potential widespread adoption of low-GWP HP for heating and cooling, complemented by onsite installed renewables and appropriately chosen electric and thermal storage solutions. An HP was developed, tested, and the validated model was implemented alongside other components in Modelica/Dymola to simulate the proposed energy system.

The investigation aimed to understand the interaction between the HP and thermal/electric storage to maximize the self-sufficiency and self-consumption of the system. The findings revealed that, for photovoltaic (PV) sizes typical of residential buildings, a battery size exceeding 5 kWh does not yield benefits in terms of the self-sufficiency index (SSI). The SSI is notably influenced by the PV system size and climatic conditions. For instance, a 6-kW PV system can achieve high SSI values in summer in Athens (above 0.9), while it is limited to around 0.5 in Marseille and Stuttgart. Moreover, the proposed system outperformed a reference heating and cooling system based on gas boiler and split air conditioner.

The techno-economic analysis considered the discounted payback time and the levelized cost of electricity (LCoE), factoring in energy policies and subsidies in various EU countries. Results indicated a reasonable payback period of around 3.8 years in Athens, contrasting with a more extended period of up to around 8 years in Stuttgart. Similarly, the LCoE was substantially lower in Athens (e.g., EUR 0.18/kWh) compared to Stuttgart (e.g., EUR 0.32/kWh), attributed to the system's capability to operate year-round with greater electricity production from onsite PV, which is more limited in northern EU countries.

3.3.3. Contribution of the candidate

Omais Abdur Rehman along with Valeria Palomba and Andrea Frazzica conceived this study. Simulation work, calculations for techno-economic analysis, policy analysis, discussion of results and preparation of original draft was done by Omais Abdur Rehman. Co-authors helped in revising the manuscript and answering to the reviewers' comments.

3.3.4. Journal paper

The scientific contribution from this work was published in journal 'Sustainability' in 2023.

sustainability

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Article

Numerical and Experimental Analysis of a Low-GWP Heat Pump Coupled to Electrical and Thermal Energy Storage to Increase the Share of Renewables across Europe

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Abstract: In order to reduce the dependence on fossil fuels in the residential sector, low-carbon-footprint technologies such as heat pumps should be used. To fully exploit solar-assisted heat pumps, an effective control strategy is required. This study employs a low-global-warming-potential (GWP) refrigerant for a water-to-water reversible heat pump, which is assisted by a thermal energy storage tank, photovoltaic (PV) installation, and battery storage system using a dedicated control strategy. The heat pump's operation is validated against the experimental data. Simulations are carried out for three different climates to analyze the performance of reversible heat pumps across Europe. The reversible heat pump fully meets the summer cooling demand in all three climates, while the heating demand is covered with the help of a backup source. An economic analysis is carried out for three different PV sizes and the results are compared with the reference energy systems. The inclusion of a battery storage system results in high payback times but increases overall flexibility and self-sufficiency.

Keywords: reversible heat pump; low-GWP refrigerant; self-sufficiency index; Dymola modeling; thermal energy storage; battery storage; energy policies; economic analysis

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Citation: Rehman, O.A.; Palomba, V.; Frazzica, A.; Charalampidis, A.; Karellas, S.; Cabeza, L.F. Numerical and Experimental Analysis of a Low-GWP Heat Pump Coupled to Electrical and Thermal Energy

3.4. Paper 4: Experimental evaluation of different designs for PCM storages for cooling applications

3.4.1. Overview

TES stands out as a highly promising technology with the potential to drive decarbonization in the heating and cooling sector, while concurrently increasing the utilization of RES [6]. TES encompasses various types, including sensible energy storage, latent heat thermal energy storage (LHTES), and thermochemical storage. LHTES, in particular, has garnered extensive research attention due to its high energy density and versatile applications. It relies on phase change materials (PCMs) capable of storing and releasing latent heat during phase transitions. The use of micro or macro-encapsulation techniques for PCMs ensures efficient thermal management and energy storage [43]. Encapsulation helps prevent leakage and maintain material stability over time, with micro (capsule size ∼1–1000 μm) and macro (capsule size above 1000 μm) distinctions [44]. While micro-encapsulation involves complex processes like spray drying and interfacial polymerization [45], macro-encapsulation, enclosing PCMs within larger containers or slabs, is more cost-effective and offers better protection against leakage [45] [46].

Macro-encapsulation, due to its practicality in manufacturing and cost-effectiveness, is widely utilized in TES systems. However, there is a dearth of experimental evidence in existing literature regarding the impact of macro-encapsulation on the performance of LHTES. This paper seeks to fill this research gap by conducting a comprehensive analysis of the thermal behaviour of three macro-encapsulation designs (ThinICE, TubeICE, and FlatICE), employing both rectangular and cylindrical shapes. The study investigates parameters such as energy storage, energy release, and charging and discharging durations to offer valuable insights into the performance of these macro-encapsulation designs for LHTES applications.

The study proposes two experimental configurations with different arrangements of PCM capsules inside the tank, enhancing the understanding of the role of encapsulation designs for future control implementations in TES tanks.

3.4.2. Contribution to the state-of-the-art

In this study, two distinct layouts were investigated, each employing three different macro-encapsulation designs to examine the thermal behaviour of a TES unit. Layout 1 had similar storage capacity while layout 2 had maximum packing factor configuration. The findings are discussed in the context of the epsilon-NTU method, commonly used for heat exchanger analysis. Among the layouts considered, TubeICE demonstrated the highest effectiveness in Layout 1, while ThinICE exhibited the highest charging effectiveness in Layout 2. A number of results are presented which explain the thermal response of TES tank when exposed to certain boundary conditions. Ratio of accumulated energy in terms of time for both layouts is also presented which will help in applying control strategies for TES systems.

The results obtained will offer valuable support to industries and manufacturers engaged in energy storage systems. These findings can be applied to evaluate the most suitable arrangement of storage media when the tank's external dimensions are predetermined. The results indicate that the thermal behaviour and performance of the energy system are directly impacted by the encapsulation design. Therefore, it is imperative to consider related design parameters when addressing specific application needs. The results from this study will help in informed decision-making and provide support in the selection of appropriate encapsulation designs, ultimately elevating the overall efficiency and effectiveness of energy storage systems.

3.4.3. Contribution of the candidate

Omais Abdur Rehman along with Luisa F. Cabeza and David Verez conceived and designed the study. Omais Abdur Rehman performed experiments for three macro-encapsulation designs, made all calculations involved, analysed and discussed results and prepared the original draft. Co-authors helped in revising the manuscript and answering to the reviewers' comments.

3.4.4. Journal paper

The scientific contribution from this work was published in the 'Journal of Energy Storage' in 2023.

Journal of Energy Storage 74 (2023) 109359

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Research papers

Experimental evaluation of different macro-encapsulation designs for PCM storages for cooling applications

Omais Abdur Rehman [a,b], Valeria Palomba [a], David Verez [b,c], Emiliano Borri [b], Andrea Frazzica [a], Vincenza Brancato [a], Teresa Botargues [d], Zafer Ure [e], Luisa F. Cabeza [b,*]

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ABSTRACT

Extensive research has been conducted on utilizing phase change materials for cooling applications, making it one of the most explored techniques in this domain. This research paper presents a comprehensive performance evaluation of a latent heat thermal energy storage unit featuring three distinct macro-encapsulation designs for phase change materials. The study aims to assess the thermal performance, efficiency, and practical applicability of these macro-encapsulation designs in a storage system. The PCM macro-encapsulation designs under investigation include cylindrical and rectangular shapes, each possessing different geometry. Two different configurations have been considered in this study. One configuration contains same PCM mass in order to have similar storage capacity while the other configuration has maximum PCM mass that can be inserted inside the tank. The used phase change material is a salt hydrate with melting temperature of 17 °C. The experimental setup consists of a controlled test rig that simulates real-world conditions and enables the comparative analysis of the three designs. Key performance parameters such as the charging and discharging time, temperature profiles, heat transfer rate, and energy storage/retrieval rates are measured and analysed. The results obtained from the experimental study provide valuable insights into the thermal behaviour, energy storage capacity, and overall effectiveness of the three macro-encapsulation designs. It is important to mention that use of an encapsulation design is highly dependent on application. The findings of this study contribute to the understanding of the impact of different macro-encapsulation designs on performance of thermal energy storage units. The results serve as a basis for optimizing macro-encapsulation designs, improving the efficiency and reliability of latent heat storage systems, and promoting their wider adoption in various energy management applications.

Chapter 4
Global discussion of results

4.1. Global discussion of results

To reduce the GHG emissions and to achieve SDGs, it is important to incorporate RES technologies in current energy systems, but their intermittent nature is a major challenge. While TES enables increased penetration of RES, heat pumps play a significant role in electrifying the heating and cooling sector. Both these technologies combined can help achieve both these purposes along with other economic and environmental benefits.

4.1.1. Bibliometric analysis

To understand the role of heat pumps and TES technologies in current energy scenario along with policies related to them, the first study made for this PhD was a bibliometric and policy analysis. This analysis helped to understand the trends and pattern of research on this topic along with identifying the research gaps for further investigation of this field. Research gaps identified through bibliometric analysis suggest that future studies should be carried out to understand role of heat pumps and TES in sector coupling, low GWP refrigerants and experimental studies on PCM macro-encapsulation designs. Results showed that European countries are at forefront of developing heat pumps and TES.

Figure 15 presents a holistic picture of publication and patents on heat pumps and TES. The data shown in blue color comes from Scopus and dates to 1969. The data on patents, shown in orange, comes from a different source i.e. IRENA report and dates to 2000. This figure shows that the research output is dominated by articles in journals.

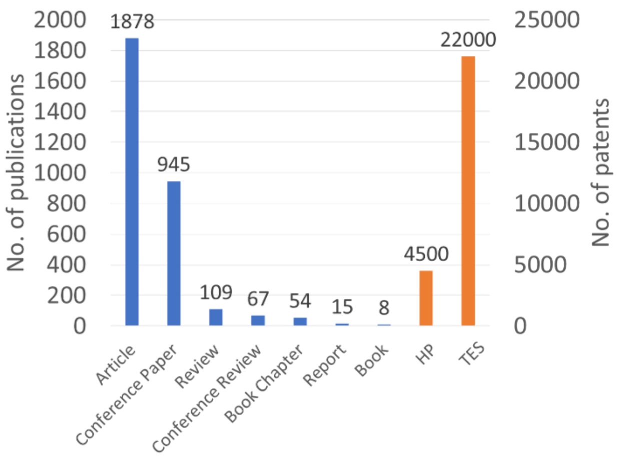

Figure 15 Holistic view of publications and patents on heat pumps and TES

Countries selected for policy analysis were based on their research output and the list consisted of China, US, UK, Italy, Germany, Japan, and Canada. So, the policy analysis provided a worldwide view of policies related to heat pumps and TES technologies. Moreover, the link between impacts of policymakers' and researchers' actions on each other were also analysed. Figure 16 shows the number of scientific outputs for top 10 countries in terms of number of publications per million inhabitants. China has highest number of publications followed by Germany and USA. Denmark and Sweden have highest number of publications per million inhabitants.

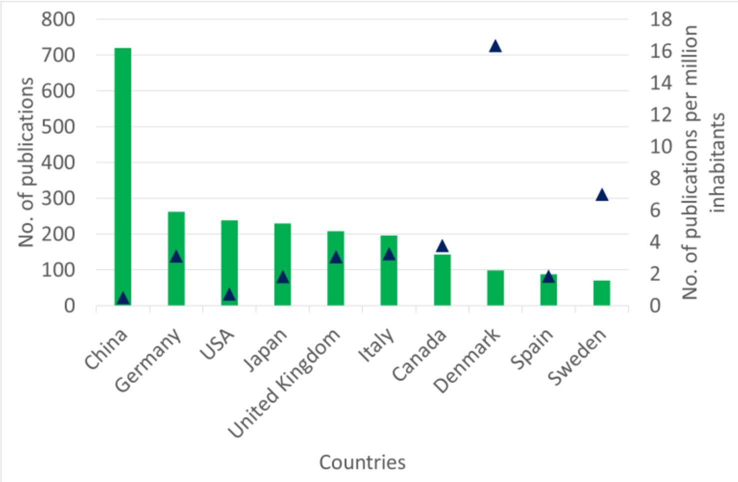

Figure 16 Scientific production for top 10 countries (in terms of number of publications) per million inhabitants.

It was seen that actions from both sides affect each other. On one hand, researchers provide empirical data, breakthroughs in technology and recommendations which can influence policymaking in a certain field while policymakers, on the other hand, set priorities and directions for research by allocating funding. Major obstacles in the widespread adoption of heat pumps and TES technologies were seen to be high upfront cost of heat pumps, less emphasize on decarbonization of heating and cooling sector, a smaller number of incentives and subsidies related to heat pumps and TES and lack of awareness about the true potential of these technologies. Number of recommendations were provided to overcome these challenges which included but not limited to reducing operating costs of heat pumps, introducing more incentive schemes, spreading the upfront costs of heat pumps over the years to lessen burden and to promote awareness about these technologies. The results of this paper will assist in shaping policy decisions and investment strategies related to HP and TES. The results address technological, regulatory, and financial challenges in these fields and offer recommendations to overcome these challenges.

4.1.2. Literature review

After identifying research gaps, an extensive literature review on role of heat pumps and thermal energy storage in context of sector coupling of electricity and heating/cooling sector was carried out. The status of both technologies was also reviewed. First, the importance of sector coupling was considered, and several studies were mentioned which highlighted its importance. It was concluded that to successfully meet the challenges of EU strategy for energy system integration, electricity and heating/cooling sectors can play an important role.

Moreover, several studies mentioned the importance of RES integration in the current energy systems, but the biggest challenge associated with RES is their intermittent nature. Generation of energy often exceeds the demand, and this excess energy can be converted to heat, using power-to-heat approach, through heat pumps and can be stored using TES means. This power-to-heat approach can be applied at centralized and de-centralized level. Furthermore, placement of heat pumps in district heating and cooling networks is also discussed and it is concluded that heat pump technology will assume a major role in upcoming generations of district heating and cooling (DHC). Through studies found in literature, it was seen that heat pump technology can play its role in sector coupling by supplying ancillary services for the grid, by allowing greater penetration of RES at centralized and decentralized level and by providing load-shifting under fluctuating electricity prices.

The latest studies have focused on 5th generation DHC which is considered neutral from perspective of thermal losses. Water is supplied at lower temperatures and local adjusters are used to increase or decrease the temperature. Reversible heat pumps technology can play the role of these local adjustors. Several studies from literature were mentioned which indicated that use of HP in DHC will result in emissions reduction. The challenges associated with placement of HP in current DHC structures were also discussed. A possibility was discussed to place HP next to local heat source or central heat source and HP be played in either series or parallel mode.

TES on the other hand provided many side-benefits along with role in sector-coupling. Literature studies showed that presence of TES helped in coping variations in heat demand side and resulted in energy savings and greenhouse gas reductions. The contribution of different TES technologies namely aquifer, pit, borehole, and thermo-chemical in district heating networks (DHN) was discussed. Sensible and latent TES technologies were termed as promising technologies for sector-integration by IRENA [12]. Sensible technology was termed suitable because of its high maturity and commercial availability while latent TES had very low physical footprint and high energy density. Another important and interesting result that was obtained from literature review was that possibility of employing TES in sector-coupling would help replacing electrical storage partially. For electricity storage, compressed air and pumped hydro energy storage were used at large scale. TES, as compared to those technologies was termed less expensive, minimized conversion losses, higher efficiency, and lifetime.

For wider deployment of both HP and TES technologies, there are some barriers to overcome. These barriers range from technical to social challenges. There is a lack of understanding on these technologies which leads to lower acceptance rates. Furthermore, some challenges are financial and regulatory. There is also a lack of confidence in TES technology which is evident from disproportionate huge shift of research funds to battery electrical storage. The employment of heat pump technology at industrial level can be improved. Heat pumps technology is already in use in food, pulp, and paper industries but use of this technology is considered a risk for production and quality of products.

4.1.3. Experimental testing and HP simulations

The third paper of this PhD involved a numerical and experimental study of a solar-assisted reversible HP utilizing a low GWP refrigerant, i.e. R1234Ze(E). This system integrated both electrical and thermal energy storage, and its HP model underwent validation through a dedicated experimental process. A simple control strategy was devised to ensure the smooth running of the energy system. The simulations were performed for Mediterranean (Athens), hot semi-arid (Marseille), and humid continental (Stuttgart) climates, providing a comprehensive European perspective. Additionally, a techno-economic analysis was presented shedding light on the economic viability of the energy system. Subsidies, tax grants, and incentives were considered for economic analysis and calculations were made for discounted payback period times and the levelized cost of electricity (LCoE). LCoE is shown in Figure 18. The analysis primarily focused on the widespread implementation of low GWP HP at the building level across diverse European climates, aided by locally available RES.

Figure 17 below shows comparison of experimental and simulated results for evaporator power at 2800 rpm. It can be seen that simulation results are in close proximity to the experimental values.

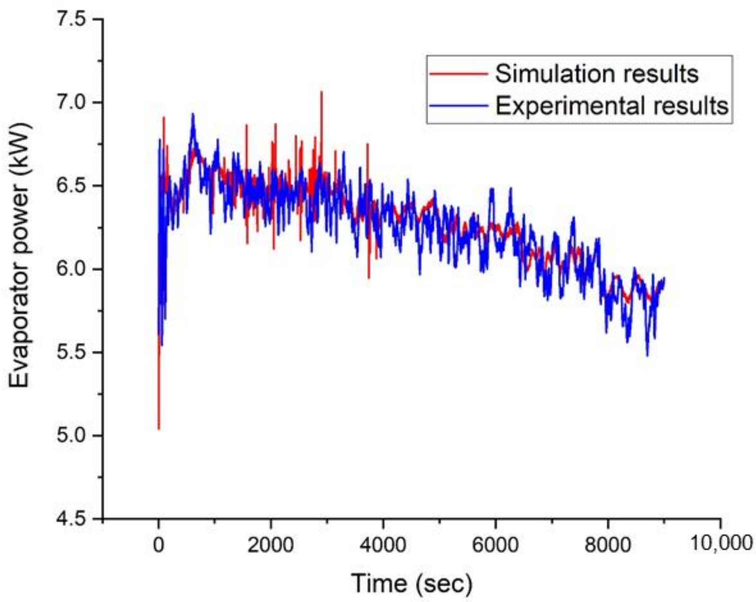

Figure 17 Experimental and simulation results for evaporator power for model validation.

Table 1 provides comprehensive information on capital costs, governmental subsidies, annual energy savings, and discounted payback periods for energy systems across the three studied cities. The economic analysis considers three different photovoltaic (PV) sizes and a uniform battery storage size of 5 kWh. In Athens, the payback periods for all three PV sizes are closely aligned. Notably, the 6 kW PV system, despite its higher initial cost, achieves breakeven in 3.9 years, comparable to the other PV sizes in Athens. It is because of the favourable scenario of selling energy to the grid at a higher price resulting in cost savings for consumers. European policies advocating for high self-consumption and self-sufficiency at the household level are reflected in these findings.

For Marseille, a 3 kW PV system breaks even in 5.8 years, followed by 6.1 and 6.6 years for the 4.5 kW and 6 kW PV sizes, respectively. Annual energy savings rise with increasing PV size, a trend reversed in Stuttgart. In Stuttgart, the system incorporates a backup gas heater during winter months when the heat pump is inactive due to extremely low temperatures. Consequently, energy bills in Stuttgart encompass both electricity and gas costs, unlike Athens and Marseille. The extended payback period in Stuttgart results from high capital costs, limited subsidies, and elevated energy prices.

The discounted payback period grows with larger PV sizes due to higher capital and maintenance costs. An estimate of the impact of government subsidies reveals an increase in payback periods by 1–2 years across all three cities. The configuration with the shortest payback period is a 3 kW PV size in Athens, while Stuttgart with a 6 kW PV configuration exhibits the longest payback period.

Table 1 Details related to all associated costs, subsidies, and break-even time [6]

Cities	**PV Power (kW)**			
		3	**4.5**	**6**
Athens	Capital cost (EUR)	21,605	23,079	24,553
	Subsidy (EUR)	6112		
	Discounted payback time (y)	3.8	3.8	3.9
Marseille	Capital cost (EUR)	21,608	23,082	24,556
	Subsidy (EUR)	4000		
	Discounted payback time (y)	5.8	6.1	6.6
Stuttgart	Capital cost (EUR)	24,166	25,640	27,114
	Subsidy (EUR)	2800		
	Discounted payback time (y)	8.1	8.9	9.9

The LCoE serves as a crucial metric for assessing and comparing various energy production methods. It represents the average total cost of the energy-generating asset and its operating cost per unit of total electricity generated throughout its operational lifespan. LCoE gains significance when comparing different energy-production techniques with varying lifespans, project sizes and capacities.

In Figure 18, the LCoE values for three cities, considering different PV sizes and a 5-kWh battery size, are presented. Athens exhibits the lowest LCoE at EUR 0.18/kWh for a 6 kW PV size, while Stuttgart records the highest LCoE value of EUR 0.32/kWh for a 3 kW PV size. Notably, there is a decreasing trend in LCoE as the PV size increases. This trend is attributed to the reduction in operational expenditures with larger PV sizes, leading to increased annual energy savings and consequently lowering the LCoE, despite a rise in capital cost. Athens reports comparatively lower LCoE values, primarily due to higher amounts of subsidies. Conversely, as associated costs increase in Marseille and Stuttgart, the LCoE also experiences an increment.

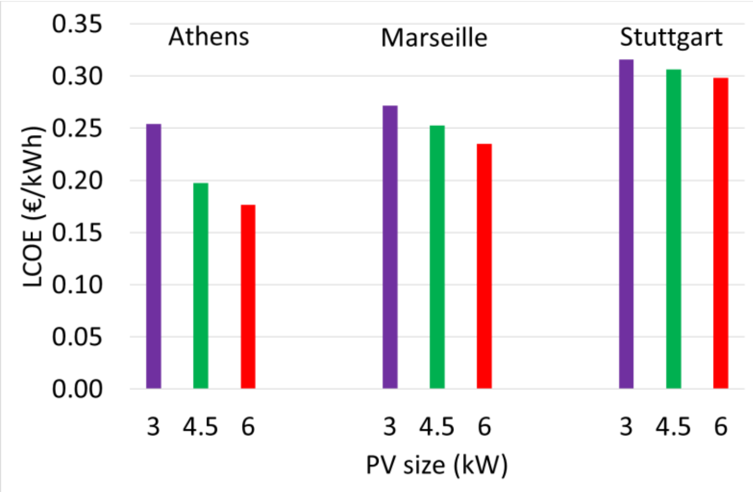

Figure 18 LCoE for the three cities, with different PV sizes and a 5 kWh battery capacity [6]

4.1.4. Experimental testing of PCM encapsulation designs

The fourth paper examines various macro-encapsulation designs for latent TES used in cooling applications temperature around 17 °C. This TES unit is intended for diverse applications, including but not limited to wine cellars, museums housing artifacts, data centres, scientific laboratories, high-temperature cooling, and low-temperature heating. The study analyses the performance of the TES unit, featuring TubeICE, ThinICE, and FlatICE macro-encapsulation, with a focus on storage capacity, temperature distribution, and heat transfer rate profiles. Valuable insights are provided for state of charge of TES with respect to energy and time for control implementation. The results obtained have implications for industries involved in TES, storage tanks, and encapsulation manufacturing. Two distinct PCM configurations were studied which helped in understanding the thermal behaviour of the TES unit, aiding in identifying the superior configuration and suitable encapsulation. The findings, presented in terms of storage efficiencies, storage densities, and the effectiveness of configurations, emphasize the significant impact of encapsulation design on the heat transfer rate and thermal performance of the storage unit. However, the choice of encapsulation design remains primarily dependent on specific application requirements.

Figure 19 (a) and (b) show the energy stored and released by all three encapsulations for layouts 1 and 2 respectively. First layout refers to similar storage mass while second refers to maximum packing factor. For layout 1, FlatICE managed to recover 84% of the stored energy while other two encapsulations released 80% energy. TubeICE released energy in 12 hours while other encapsulations took around 15 hours. It can be concluded from these results that for applications requiring shorter energy release period, TubeICE is a suitable option. ThinICE and FlatICE are preferable for applications requiring a stable release of energy over an extended period. For second layout, FlatICE stored the highest amount of energy followed by TubeICE and ThinICE. TubeICE released 82% energy followed by ThinICE (81%) and FlatICE (78%).

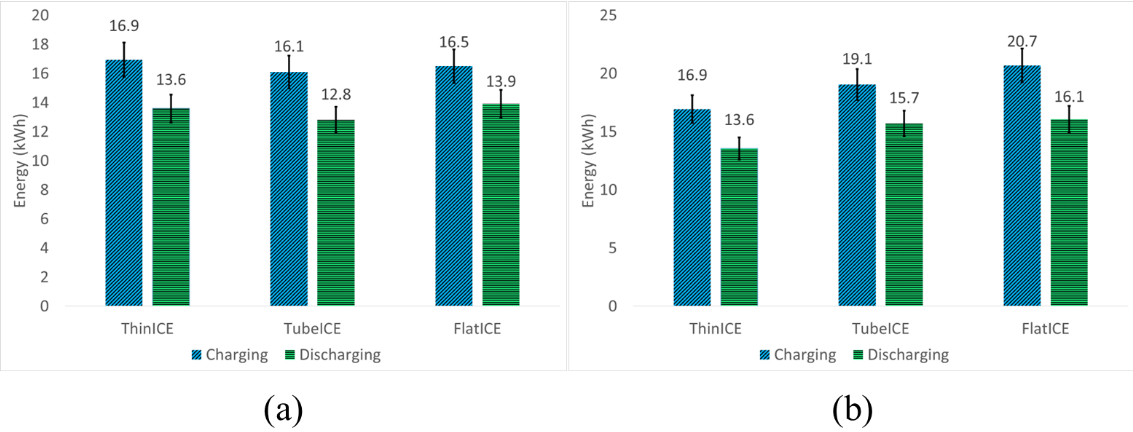

Figure 19 Total energy stored and discharged for three encapsulation systems (a) layout 1 (b) layout 2 [33]

Table 2 presents the charging effectiveness results for three encapsulations in both layouts. TubeICE exhibited the highest effectiveness value for layout 1, while ThinICE reported the highest effectiveness value for layout 2. The findings indicate a reduction in charging effectiveness for TubeICE and FlatICE in layout 2. These encapsulations demonstrated high effectiveness values for layout 1 due to wider heat transfer fluid (HTF) channels resulting from the presence of spacers. In layout 2, the narrower HTF channels altered the effectiveness, with wider channels leading to higher Reynolds numbers and consequently higher effectiveness. One contributing factor to ThinICE's high effectiveness lies in the smaller thickness of the capsule. A thinner capsule resulted in a higher heat transfer rate. To achieve higher effectiveness and faster heat exchange, the use of layout 1 was recommended.

Table 2 Effectiveness of charging process for encapsulations for both experimental layouts [33]

Encapsulation	Effectiveness (ε)	
	Layout 1	Layout 2
ThinICE	0.82	0.82
TubeICE	0.96	0.78
FlatICE	0.81	0.62

Chapter 5
Conclusions and future work

5.1. Conclusions and future work

This PhD thesis broadens knowledge about role of thermal energy storage in increasing the renewable energy resources share at building and district level. Additionally, it also sheds light on role of TES and HP technologies in context of sector coupling of power and heating/cooling sectors. The research was initiated by conducting a bibliometric study which analysed more than 3000 documents to establish bibliometric and policy analysis. Research gaps were identified through this study, and it was found out that there are limited studies on experimental results of macro-encapsulation design, heat pumps employing low GWP refrigerants and the lack of studies on heat pumps and TES coupling in context of sector coupling. A policy analysis was also carried out to understand the impact of policies on researchers' activities across the world.

The identification of research gaps led to an extensive literature review comprising of approximately 150 scientific studies to develop a thorough understanding of roles of heat pump and TES technologies in sector-integration scenario. Both these technologies were termed as monumental in shaping the future energy scenario by bringing a reduction in greenhouse gas emissions. A thorough analysis was conducted to ascertain current status of both these technologies in heating/cooling sector along with pointing out regulatory, technical and financial challenges associated with wide deployment of heat pump and TES in coming years.

The next study consisted of a solar-assisted reversible heat pump employing low GWP refrigerant i.e. R1234Ze(E) and incorporating both electrical and thermal energy storage. The model of HP was validated through a dedicated experimental activity. A simple control strategy was developed to smoothly carry out the operation of energy system. Results discuss the self-sufficiency index and self-consumption of the simulated system. The performance of this heat pump was analysed in Mediterranean (Athens), hot semi-arid (Marseille) and humid continental (Stuttgart) climates to give a European perspective. A techno-economic analysis is also presented which will help to understand the economic feasibility of energy system. Subsidies, tax grants and incentives were taken into account while carrying out the economic analysis which presented discounted payback period times and levelized cost of electricity. The analysis was mainly focused on wide deployment of low GWP heat pump at building level across different European climates assisted by locally available RES. It turned out that the proposed energy system outperformed typical heating and cooling systems consisting of gas/electrical boilers and split air conditioners. The obtained results highlight the benefits of using an innovative HP with low GWP refrigerant across different European climates under realistic operating conditions.

The last study analyses different macro-encapsulation designs for latent TES for cooling applications for temperature around 17 °C. This TES unit will find its use in wine cellars, museums having artefacts, data centres, scientific labs, high temperature cooling and low temperature heating. The performance of TES unit, which contains TubeICE, ThinICE, and FlatICE macro-encapsulation, is analysed in terms of storage capacity, temperature distribution and heat transfer rate profiles. Insights are presented on state of charge of TES respective to energy and time which will help for future control implementation. Results obtained will be beneficial for industries related to TES, storage tanks and encapsulation manufacturers. The obtained knowledge will be helpful in making informed decisions when the volume of tank is already fixed. Two different PCM configurations helped to understand the thermal behaviour of TES unit and assisted in knowing the better configuration and suitable encapsulation. Results were presented with storage efficiencies, storage densities and effectiveness of configurations. It was seen that encapsulation design greatly affects the heat transfer rate and thermal performance of storage unit. Nevertheless, selection of encapsulation design is mainly dependant on application requirements.

5.2. Future work

This PhD thesis provides knowledge about role of thermal energy storage in increasing RES share at building level. Moreover, it also sheds light on role of heat pump and TES technologies in sector-coupling approach. A thorough literature and policy analysis was presented in this thesis. There is room for further research work in the simulation and experimental studies carried out for heat pump and macro-encapsulation designs for latent thermal energy storage.

Future investigations can explore improvements to the heat pump layouts, addressing limitations such as the absence of domestic hot water production. Additionally, the consideration of incorporating defrost cycles may be explored to expand the operational capabilities of the heat pump. Moreover, modifications to the energy-selling mechanism can be an interesting point, with an evaluation of potential demand-response strategies for further optimization. Replacing sensible storage with latent TES in the system will also be an interesting aspect to cover in future studies.

Moreover, investigation of more phase change materials with varying melting temperatures can be considered which will provide insights into suitability of different PCM options for diverse applications. The study can further be expanded with by including an environmental impact assessment e.g., life cycle analysis. Moreover, the integration of the TES unit with renewable energy sources, such as solar should be considered. It will help in assessing the synergies and potential improvements in overall system efficiency when coupled with these sustainable energy inputs. Furthermore, developing mathematical or simulation model will help in future design optimization process for different macro-encapsulation designs.

Other research activities

Contribution to other publications

Conference publications

The PhD candidate contributed to following international conferences:

1. **O.A. Rehman**, V. Palomba, A. Frazzica, D. Aloisio, and L.F. Cabeza, "Evaluation of a Solar-driven Heat Pump for Power-to-Heat Applications : From Building to District Level in a Distributed Energy System," in *16th SDEWES Conference, DUBROVNIK*, 2021.
2. **O.A. Rehman**, V. Palomba, A. Frazzica, V. Brancato, D. Verez, E. Borri, L.F. Cabeza, "Development of an experimentally validated model of a PCM tank for cold storage applications in combination with heat pumps," in *Eurotherm Seminar #116 - Innovative solutions for Thermal Energy Storage deployment*, May 24-26, 2023.
3. **O.A. Rehman**, D. Verez, E. Borri, V. Palomba, A. Frazzica, V. Brancato, L.F. Cabeza, "A comparison of performance of a latent thermal energy storage unit using three PCM macro-encapsulations," in *Proceedings of the 15th International Green Energy Conference IGEC2023-000, July 10-13, 2023, Glasgow, UK*.
4. **O.A. Rehman**, V. Palomba, A. Frazzica, and L.F. Cabeza, "Analysis of a heat pump-based energy system exploiting a low GWP refrigerant in different European climates" in *SUPEHR23, SUstainable PolyEnergy generation and HaRvesting Conference and Exhibition, 6th -8th September 2023, Savona Italy.*

Scientific foreign exchange

The PhD candidate made following research stays during his PhD:

1. CNR ITAE, Messina, Italy: The candidate made stay of two years at CNR ITAE and carried out experimental and numerical study of heat pumps systems.
2. User Feedback Program SL (UFP), Lleida, Spain: The candidate made two research stays in this company for four and two months in 2022 and 2023 respectively. During these stays, candidate also benefitted from carrying out experimentation on latent thermal energy storage unit based in research laboratory of GREiA institute in UdL.

Projects participation

1. DecaTES: Ministerio de Ciencia e Innovación—Agencia Estatal de Investigación (AEI) (PID2021-123511OB-C31 - MCIN/AEI/10.13039/501100011033/FEDER, EU).
2. RedTES: Ministerio de Ciencia e Innovación—Agencia Estatal de Investigación (AEI) (RED2022-134219-T).

3. Research group GREiA (2021 SGR 01615): Generalitat de Catalunya.
4. GREiA – TECNIO: Generalitat de Catalunya.
5. CO-COOL: European Union's Horizon 2020 Research and Innovation Programme under grant agreement no. 101007976.
6. SolBio-Rev: European Union’s Horizon 2020 research and innovation program under grant agreement No 814945

Contributions to seminars and organising committee participation:

1. Researchers’ Night 2021, 16^{th} edition 2021. Lleida, Spain
2. Researchers’ Night 2022, 17^{th} edition 2022. Lleida, Spain
3. Eurotherm Seminar #116-: Innovative solutions for thermal energy storage deployment. Lleida, Spain

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