Universitat de Lleida

Use of heat pipes in latent thermal energy storage systems

José Miguel Maldonado Jiménez

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TESI DOCTORAL

Use of heat pipes in latent thermal energy storage systems

José Miguel Maldonado Jiménez

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
Programa de Doctorat en Informàtica i Enginyeria Industrial

Directors
Prof. Dr. Luisa F. Cabeza (Universitat de Lleida, Spain)
Dr. Alvaro de Gracia (Universitat de Lleida, Spain)

202

A mi abuelo.

Departament d’Informàtica i Enginyeria Industrial
Escola Politècnica Superior
Universitat de Lleida

Use of heat pipes in latent thermal energy storage systems

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida redactada segons els criteris establerts en l’Acord núm. 67/2014 de la Junta de Govern del 10 d´abril de 2014 per la presentació de la tesis doctoral en format d’articles.

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La Dra. Luisa F. Cabeza, Catedràtica de l’Escola Politècnica Superior de la Universitat de Lleida i el Dr. Alvaro de Gracia, professor lector de l’Escola Politècnica Superior de la Universitat de Lleida.

CERTIFIQUEN:

Que la memòria *Use of heat pipes in latent thermal energy storage systems* presentada per José Miguel Maldonado Jiménez per optar al grau de Doctor s’ha realitzat sota la seva supervisió.

Lleida, Octubre 2020

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Summary

In the fight against climate change, the use of renewable energies is a crucial resource. However, their dependence on climate conditions produces mismatches between energy production and demand, hampering their implementation worldwide. Therefore, energy storage systems were born aiming to complement renewable energies, tackling their supplying intermittency. Among the available energy storage technologies, thermal energy storage (TES) systems link perfectly with high temperature industries, as well as concentrated solar power plants. This PhD thesis focusses on developing a latent thermal energy system at temperature range from 210 ºC to 270 ºC, being able to work coupled with a Fresnel concentrated solar power plant. The thesis is divided in two parts. The first one is dedicated to design and manufacture the thermal energy storage system. This part included the thermophysical characterization of the available phase change materials (PCM) and also, the design and installation of the solar power plant. To ensure the latent TES power requirements, the thermal conductivity within the PCM must be enhanced. To that goal, a heat pipe array with fins attached was designed. Heat pipes are passive systems which can transport great amount of heat between two points, with minimum temperature gradient. As a results, a latent TES tank was manufactured, which works within the required temperature range, being able to supply the thermal power needed to feed an organic Rankine cycle micro-turbine. The second part of the PhD took the heat transfer enhancement in latent TES systems as objective. The different technologies were implemented in a latent TES tank at laboratory scale and low temperature (from 15 ºC to 50 ºC). Among those tested techniques, those used into the high temperature TES system were also studied.

Resumen

Las energías renovables son un recurso vital en la lucha contra el cambio climático. Sin embargo, su dependencia de las condiciones meteorológicas, generan desajustes entre la producción de energía y la demanda de la misma, dificultando su implementación en el día a día a nivel global. Los sistemas de almacenamiento energético nacen con el objetivo de complementar a las energías renovables, solucionando este inconveniente. De entre las distintas tecnologías de almacenamiento energético, almacenar energía térmica liga a la perfección con las industrias que requieren alta temperatura para sus procesos de fabricación, así como con las plantas eléctricas de concentración solar. Esta tesis doctoral centra sus esfuerzos en el desarrollo de un sistema de almacenamiento térmico latente, en un rango de temperatura comprendido entre los 210 ºC y los 270 ºC, pudiendo así dar soporte a una planta de concentración solar tipo Fresnel. La tesis se divide en dos partes: la primera es el diseño y construcción del módulo de almacenamiento térmico. Esta parte comprende desde la caracterización termoquímica de varios materiales de cambio fase susceptibles de ser empelados en el prototipo final; hasta el diseño e instalación de la planta solar. Para asegurar los requisitos de potencia del módulo de almacenamiento, la conductividad térmica a lo largo del material de cambio de fase debe ser mejorada. Con este fin se diseñó un sistema comprendido por "heat pipes" y aletas. Las "heat pipes" son una tecnología que de manera pasiva y con un gradiente mínimo de temperatura, son capaces de transportar grandes cantidades de calor entre dos puntos. Como resultado, se construyó un módulo que almacena calor latente en el rango de temperatura necesario, con capacidad para suministrar la potencia térmica que alimenta una micro turbina de ciclo Rankine orgánico. La segunda parte de la tesis toma como objetivo la mejora de la transferencia de calor en sistemas de almacenamiento latente térmico. A escala de laboratorio y a baja temperatura (entre 15 ºC y 50 ºC), se probaron diversas tecnologías, entre ellas, las implementadas en el módulo a alta temperatura.

Resum

Les energies renovables són un recurs vital en la lluita contra el canvi climàtic. No obstant, la seva dependència de les condicions meteorològiques, generen desajustos entre la producció d'energia i la seva demanda, dificultant la seva implementació en el dia a dia a nivell global. Els sistemes d'emmagatzematge energètic neixen amb l'objectiu de complementar a les energies renovables, solucionant aquest inconvenient. Entre les diferents tecnologies disponibles, l’emmagatzematge d’energia tèrmica encaixa a la perfecció amb les indústries que requereixen alta temperatura per als seus processos de fabricació, així com amb la generació elèctrica en plantes de concentració solar. Aquesta tesi doctoral centra els seus esforços en el desenvolupament d'un sistema d'emmagatzematge tèrmic latent, en un rang de temperatura comprès entre els 210 ºC i els 270 ºC, podent així donar suport a una planta de concentració solar tipus Fresnel. La tesi es divideix en dues parts: la primera és el disseny i construcció del mòdul d'emmagatzematge tèrmic. Aquesta part comprèn des de la caracterització termoquímica de diversos materials de canvi fase susceptibles de ser utilitzats en el prototip final; fins al disseny i instal·lació de la planta solar. Per assegurar els requisits de potència del mòdul d'emmagatzematge, la conductivitat tèrmica del material de canvi de fase ha de ser millorada. Amb aquesta finalitat es va dissenyar un sistema amb "heat pipes" i aletes. Les "heat pipes" són una tecnologia que de manera passiva i amb un gradient mínim de temperatura, són capaces de transportar grans quantitats de calor entre dos punts. Com a resultat, es va construir un mòdul que emmagatzema calor latent en el rang de temperatura necessari, amb capacitat per subministrar la potència tèrmica que alimenta una micro-turbina de cicle Rankine orgànic. La segona part de la tesi té com a objectiu la millora de la transferència de calor en sistemes d'emmagatzematge tèrmic latent. A escala de laboratori i a baixa temperatura (entre 15 ºC i 50 ºC), es van provar les diferents tecnologies, entre elles, les implementades en el mòdul a alta temperatura.

Table of contents

List of figures

Chapter 1

Introduction, objectives, and PhD thesis structure

1.1 Introduction

This thesis chapter stands out what have motivated this thesis, their goals, and the path followed along its development. Also, the state-of-the-art regarding the thesis topic is summarized within this chapter, since it provides the background in which the thesis is framed.

1.1.1 Motivation

Within the last years a dystopian novels writer, Ursula K le Guin, pointed out that dystopian movies, novels, comics, video games or series, have flooded our entertainment. Many of them have, as background, a global collapse because of climate change, this fact even caused that a new novel subgenre came up from science fiction, which is called climate fiction or "cli-fi" [1]. For instance, A.I. Artificial Intelligence directed from Steven Spielberg [2], based its film in a dystopian future caused by climate change; "Waterworld" produced by Kevin Costner [3], also took global warming as background, although more directly than Spielberg did. However, sea levels rising because of global warming (Waterworld), are no longer dystopian futures. There are already governments claiming for help because climate change can make the sea to swallow their land, such as Kiribati ("The Guardian: They say that in 30 years maybe Kiribati will disappear").

According to the World Economic Forum, who publish every year a Global Risks Report, climate change appeared as one of the top 5 risks in 2011; and then again from 2013 onwards. Actually, in the last ten years the global risks have moved from economic to environmental ones. Climate related issues are now on the top five in terms of likelihood and impact (Figure 1). However, everything is connected, all the global risks can be plotted as a network, which connects the risks among them (Figure 2). We can spot climate change as concentrator or origin of many other global risks, such as water shortage, leading to crop crisis and lack of food [4].

Greenhouse gasses (GHG), mainly carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), water vapour (H_2O), and chlorofluorocarbons (CFC), help the Earth atmosphere to keep the heat from the sun, what is so-called greenhouse effect. They are essential for live to grow, if not Earth mean temperature would be -18 ºC. However, those gasses have been produced in huge quantities, mainly CO_2, since the industrial revolution. This increase had caused the Earth temperature to rise more than what would be natural, causing what is known as global warming. Climate change happens because of global warming.

According to the intergovernmental panel on climate change (IPCC) fifth assessment report in 2013, it is extremely likely that more than half of the observed rise in global average temperature was due to human activity. The IPCC referred to the global warming from 1951 to 2010, and the likelihood was from 95% to 100% [5]. The global status report regarding renewables energies in 2018 stated that most of the energy consumed is for cooling and heating purposes (48%) and 39% of total annual energy-related CO_2 emissions come from heat consumption [6].

Renewable energies are key technologies to mitigate the climate change, since their carbon footprint is lower than conventional energy sources. By integrating these technologies into our society, GHG emissions can be reduced. One of the main concerns in European Union (EU) is precisely to produce decarbonized energy. Also, renewable energies already employ 10.8 million people worldwide [6]. The estimated renewable energy share from total final energy consumption in 2016 was less than 19%, even considering traditional biomass (Figure 3) [6].Those data show a long path yet to be walked if we want to move from conventional CO_2 producer towards renewable energies. However, many renewable energies depend on weather conditions, such as wind, solar or hydro power, also causing a mismatch between energy production and demand. These limitations make renewable energies less attractive to industry, slowing down their growth.

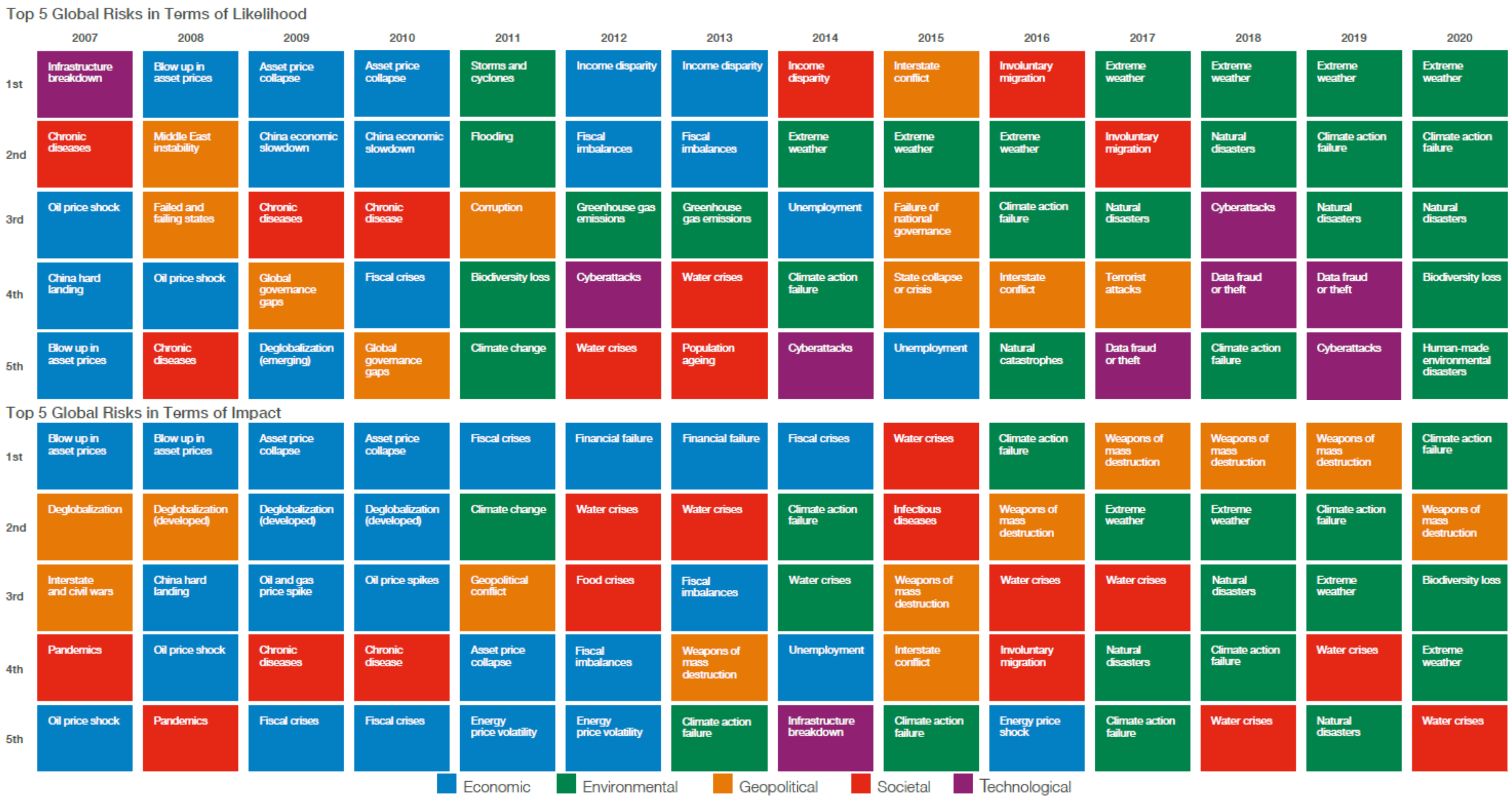


Figure 1. Top 5 Global Risks in terms of likelihood and impact along the last 13 years [4]

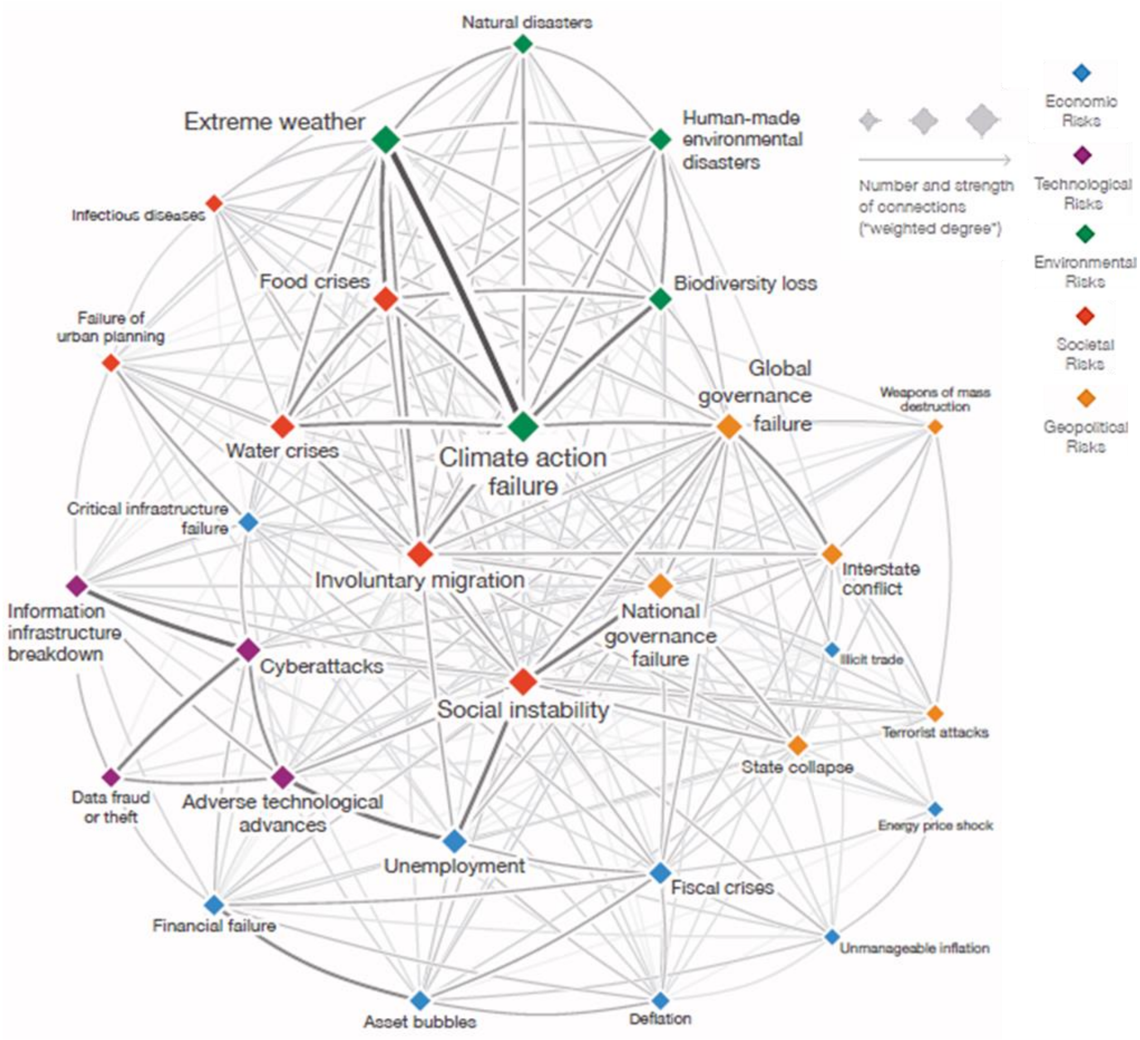


Figure 2. Connection between the different Global Risks considered in 2020 [4].

Hence, energy storage systems must be attached to any renewable technology to overcome the above mentioned drawbacks [7]. Energy storage facilities have risen their capacity, from 2008 to 2018, even if considering just those which are still operatives, with a total storing power of 68.8 GW (Figure 4a). This growth goes in parallel with the idea of becoming an environmentally friendly world. The ruling storing system is pumped hydro storage, almost 93% of the total share, followed by thermal storage (3.54%), electro-chemical (2.47%), and electro-mechanical (1.2%) storage technologies. This huge difference among storing technologies is due to the fact that hydro infrastructures, such as reservoirs or damps, are not only useful for power generation but also for water management [8]. Discarding pumped hydro storages, thermal energy storages (TES) covers almost 50% of the remaining share (Figure 4b).

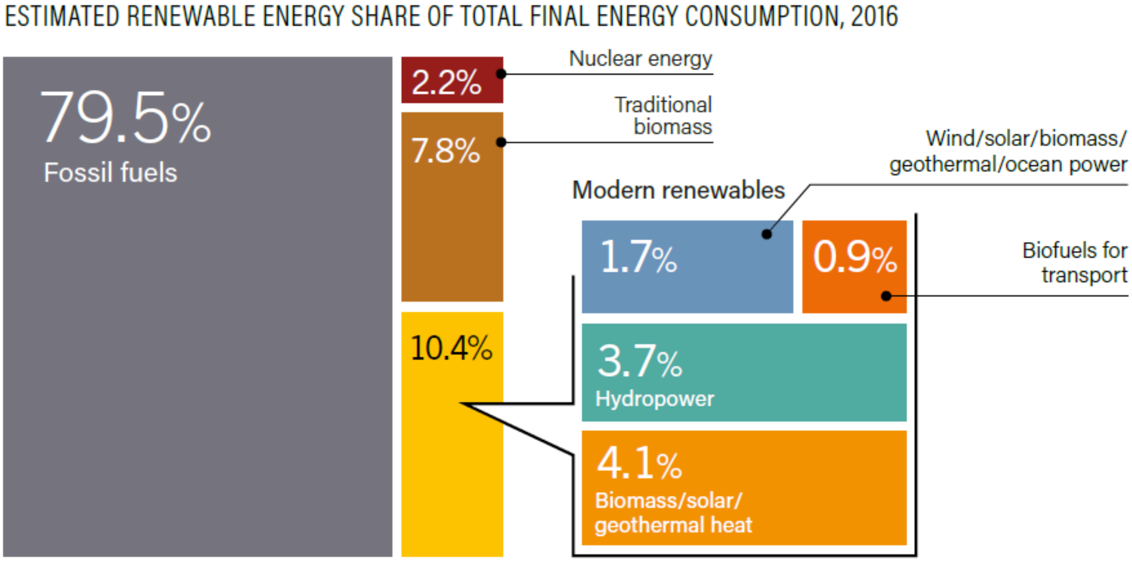
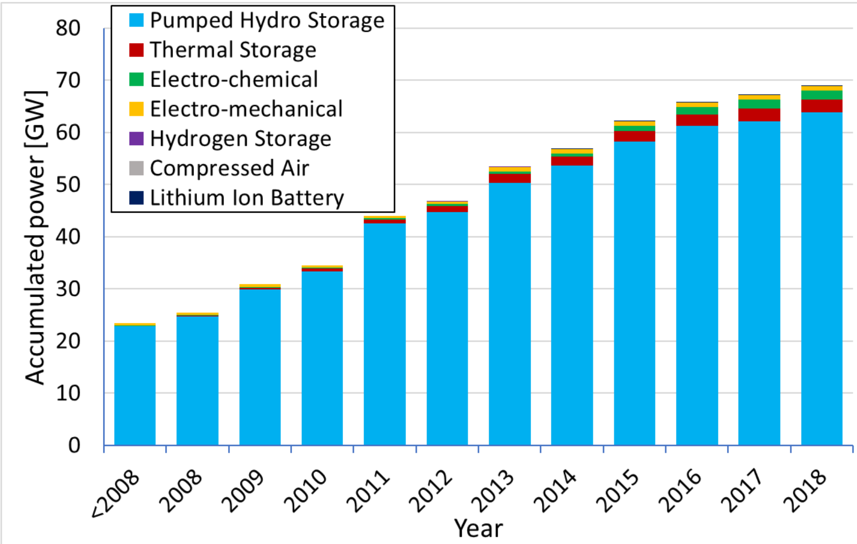
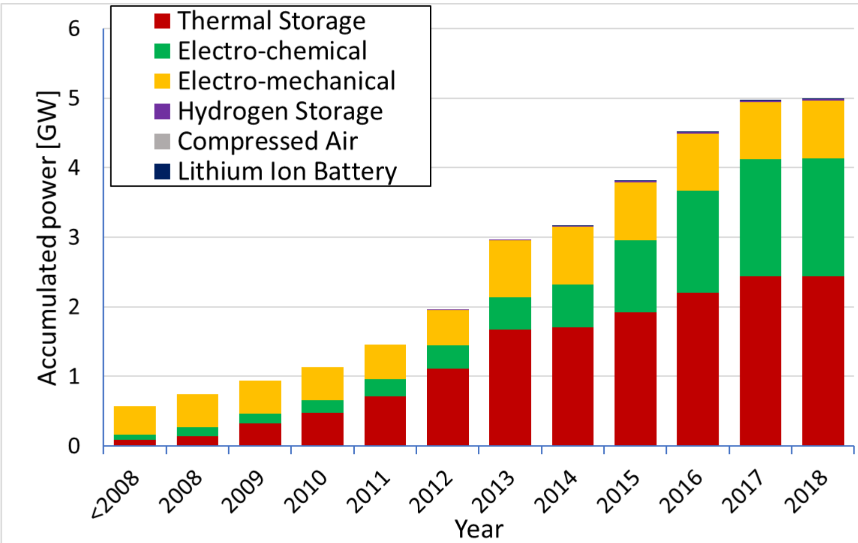


Figure 3. Estimated energy distribution by its production technology of the total final energy consumption in 2016 [6].

Among renewable energy technologies, solar energy has been called upon to tackle the greenhouse effect. Concentrated solar power (CSP) plants in particular can cover the 7% of the world energy demand by 2030, and it could supply up to 25% if they continue being developed [9]. However, yet this forecast regarding CSP plants requires to make them more competitive against conventional power plants. Their weak point is their dispacthability, as mentioned above, they must be able to supply power on grid demand, according to the market needs. From this necessity, their synergy with thermal energy storages was born. TES systems allow solar thermal plants to generate power consistently when the main energy carrier, the sun, is not available, reducing the levelized cost of electricity (LCOE) of solar thermal power plants [10]. TES systems are constantly targeted by researchers; their enhancement is key for solar thermal technology development. This thesis goal was to fight against climate change by means of boosting renewables energies. In particular, by developing a TES system to work in couple with a CSP plant, to increase its performance. For doing so, first a literature search was carried out, seeking for the state-of-the-art about this topic. Also, as the design was aimed to reach technology readiness level 6 (TRL 6) during this thesis and beyond in the future, the hypothetical consumers were pursued. Being those the building sector due to the thermal output after running the CSP plant turbine. Hence, an energy benchmarking was conducted regarding the current energy suppliers within this sector and the CO_2 emissions derived from them. The latter study helped to place the system in the market. To design the TES system itself different features were studied at lab scale, such as different storage materials to select the best option. Also, the heat transfer between the heat carrier and the storage medium is a key technological feature of TES systems. Therefore, different heat transfer techniques were analysed at the laboratory.



(a)



(b)

Figure 4. Accumulated energy storage power per year (a) by all storage technologies; (b) without considering pumped hydro storage [8].

1.1.2 Thermal energy storage and heat pipes

Thermal energy storage technology allows to store heat or cold and use it later when required. TES systems, which operate nowadays, have increased within the last ten years from 84 MW to 2433 MW (Figure 4b). This technology is not such uncommon, a solar thermal collector includes a water tank which keeps hot the water heated by the sun, for being used along the evening. What makes a perfect example of a renewable energy coupled with a TES system. However, when scaling up TES technologies for solar power plants, they are not yet in their mature stage. Three different systems are pursued: sensible heat, latent heat, or sorption and chemical reactions (also known as thermochemical energy storage). Among them, latent heat thermal energy storages provide an efficient solution since they have high energy storage density within a narrow thermal gradient. They are implemented by taking advantage of materials phase changes, usually melting (loading) and solidification (unloading), these processes happen at almost isothermal way [11].

The phase change material (PCM) selected within latent TES system has a strong influence on facilities operation and maintenance costs. Not only the material price itself, but also indirect expenses such as, its container, required operating equipment, and safety measurements. Hence, there is an exhaustive screening and characterization process before selecting a PCM for a given application. Non-flammability, low toxicity, harmlessness, a melting and solidification according to the requirements, thermal stability, high heat of fusion, and high thermal conductivity are a must when looking for a PCM. However, the latter property, high thermal conductivity, is barely achievable today by the available PCM.

Therefore, several designs, methods, materials, and devices have been tested to enhance heat transfer in latent heat TES tanks, such as adding different geometry fins, bubble agitation, embedding metal matrixes or other enhancement materials (such as graphite or nano-particles) into the PCM, and the insertion of heat pipes [12,13]. The simplest way to improve the thermal conductivity is to enlarge the heat transfer surface between the pipes, where heat transfer fluid (HTF) flows through, and the PCM. However, this implies enlarging the PCM tank piping, what can cause severe pressure drops, and higher pumping power requirement; also, it reduces the effective PCM storage volume.

Replacing the HTF piping network in the PCM by heat pipes would avoid at least, one of the above mentioned issues, since heat pipes passively transport heat at high rates even at small temperature drops [14]. More heat pipes can be added into the tank, increasing the heat transfer surface, without hampering the heat transfer fluid flow. The synergy between heat pipes and latent heat TES arose from the necessity of enhancing the heat conductivity of materials used in these TES systems [15]. Paper 1 of this thesis performed a systematic review on hybrid applications, describing in depth the state-of-the-art [16], section 1.2 Paper 1: Systematic review on the use of heat pipes in PCM thermal energy storage tanks, shares an introduction to it.

Heat pipes are passive devices which take advantage of the phase change process (from liquid to gas and vice versa) to transport great amounts of heat. A heat pipe is a sealed tube, usually made of copper or aluminium, which contains a working fluid (e.g. water or ammonia). The inner working fluid transports heat between heat pipe ends by flowing forwards and backwards into the closed pipe. They consist of three main sections: evaporator, adiabatic section, and condenser. Heat input enters through the evaporator part, where the working fluid evaporates inside the heat pipe. Vapour flows towards the condenser section along the adiabatic part, the vapour condenses and flows back to the evaporator. The liquid is pushed back by a wick structure that generates a capillary force.

1.2 Paper 1: Systematic review on the use of heat pipes in PCM thermal energy storage tanks

1.2.1 Overview

Latent heat TES systems have a large thermal energy storage capacity, also as they change their phase, loading and unloading processes are almost isothermal [11]. Nonetheless, they have low thermal conductivity, so many studies focused this issue. Among many options, we can find the use of heat pipes to increase the heat transfer in latent TES systems [11,12]. Heat pipes passively transfer heat at high rates, at almost isothermal conditions, and minimal temperature difference between the two point is needed [17,18]. Coupling heat pipes with PCM make latent heat TES systems more competitive.

This paper systematically reviewed the literature about latent heat TES and heat pipes systems, and studied their contribution to the state-of-the-art of this topic. With the retrieved documents from the query, we did a bibliometric analysis. This analysis offers an overview of this hybrid technology along time and around the world. Then, the documents were assessed and classified into two main categories, those involving experimental research, and those which develop numerical models. Also, the experimental publications were categorized accordingly to their application weather it was solar systems, heat exchangers, cooling devices in electronics, electric batteries or for cooling in buildings. However, the documents regarding numerical modelling were classified in regards to how they modelled the heat pipes; as high thermal conduction solid elements, as a simplified thermal resistance network model, or using the descriptive fluid dynamic equations.

1.2.2 Contribution to the state-of-the-art

The interest on latent heat TES with heat pipes hybrid systems has grown along the last years. Many efforts have been invested by the research community; hence this review paper aims to facilitate the access to the state-of-the-art on this topic This research provides updated guidelines for the research yet to be done on this technology. As the review categorizes the studies accordingly to their final purpose, new researchers can easily identify the gap for future investigations. The presented study pointed out the lack of experimental designs for high temperatures applications (higher than 150 ºC).

From the review it could be concluded that most of the experimental works were focused on low temperature applications (around 55ºC), so more experimental research at high temperatures is needed. Especially considering the fact that many numerical models of hybrid designs are applied for high temperature applications. The common procedure used by many publications was to develop the design model, validate it with experiments at low temperature, and apply the model for higher temperature purposes. However, the design scaling can also carry slight differences between model and prototype at low temperatures. This thesis spotted the gap in the literature, found within the review, and contributes to fill the gap in the state-of-the-art.

1.2.3 Contribution of the candidate

Jose Miguel Maldonado sought and retrieved the references related with the reviewed topic; also reviewed, synthesized and linked the research made on the studied field. Finally, Jose Miguel Maldonado proposed and conceived the way the review is structured, drawing the conclusions exposed.

1.2.4 Journal paper

The scientific contribution from this research work was published in Journal of Energy Storage in 2020.

Reference: Maldonado JM, de Gracia A, Cabeza, LF. Systematic review on the use of heat pipes in PCM thermal energy storage tanks. J Energy Storage 2020; 32: 40. doi:10.1016/j.est.2020.101733

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Systematic review on the use of heat pipes in latent heat thermal energy storage tanks

José Miguel Maldonado, Alvaro de Gracia, Luisa F. Cabeza*

GREiA Research Group, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain

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ABSTRACT

This systematic review presents and discusses the previous research about hybrid devices which combine latent thermal energy storage (TES) technology and heat pipes. A bibliometric analysis of this issue shows how hybrid systems have globally grown popularity during time, providing details about the main researchers and research centres on this particular field. Then, the identified papers are assessed and categorized in two main sections, the experimental research carried out, and the numerical modelling of hybrid systems. Experimental research is later classified regarding the operating temperature range, and their final application. Numerical studies are also further categorized, accordingly to how heat pipes were modelled in this case. This review points out the lack of experimental studies at high temperatures, especially when many simulations extended their models (validated at low temperatures) to higher temperature designs. The paper provides details about the research performed, so the gap for future investigations can be spotted.

1.3 PhD objectives

From reviewing the state-of-the-art about latent TES tanks with embedded heat pipes as heat transfer enhancement technique, we realized the lack of experimental research on high temperature applications. Many numerical studies were focussed in modelling equipment at high temperatures. Even though those models were validated with low temperatures experiments (usually around at 55ºC), when escalating up the device, slight differences between model and experimental could be also scaled up. Hence, further experimental research needs to be done to validate the models at high temperature before jumping to real scale facilities.

The above mention issue led this PhD thesis, which goal is to design, develop and run concentrated solar power plant coupled with a latent heat TES tank, which works between 210 ºC and 270 ºC. The thesis includes the latent TES tank design, from the PCM screening process up to the test at a technology readiness level 6 (TRL) scale facility. The latent TES tank required to experimentally study at lab scale the possible phase change materials thermal behaviour and corrosion compatibility. Also, the TES tank must supply enough thermal power and temperature according to the application requirements, and usually heat conductivity is the weak point of many phase change materials. for that reason, different heat transfer enhancement techniques will be tested at lab scale. A compact TES tank design with different heat transfer improvements is compared. The control tank is a common shell and tubes configuration, then fins, metal wool and heat pipes were added and thermally assessed. The experiments target to keep the same packing factor in every design.

Moreover, during this thesis the solar power plant which hosts the TES tank was designed and built. In the framework of a Horizon 2020 European project the real scale prototype is thought to enter the market in the future. Hence, the potential users (the building sector) energy consumption was studied to find the gap within the market for the developed technology. This study was also performed regarding the CO_2 emitted by the current energy carriers.

1.4 PhD thesis structure

This thesis is divided into five chapters (Figure 5). Chapter one details the research background, the PhD objectives pursued, as well as the state-of-the-art through paper 1. The second chapter describes the methodology followed along the thesis; lab protocols, and test rig description which can be found within the papers comprising the thesis. Chapter three presents and discusses from paper 2 to paper 6 of this thesis, which together with paper 1 compile the thesis. The fourth episode shows the results and a global discussion of them. Finally, within chapter five, the thesis global conclusions are stated; also some suggestions to keep on this research path can be found in this chapter.

Figure 5. PhD thesis structure by chapter.

Chapter 2

Materials and Methodology

This thesis is divided into two parts, one focussed on high temperature applications and the other in low temperature (Figure 6). Moreover, the thesis consists in three main frameworks: literature review, experiments at laboratory scale, and experimental research at TRL 6 scale.

The research developed on the existing literature allowed to find the gap to extend the state-of-the-art about the topic. As pointed out in paper 1 there is a need to further experimental research on latent heat TES coupled with heat pipes at high temperatures (above 150 ºC). As explained within the PhD objectives, the gap in the market for the developed technology along this thesis was sought. Therefore, paper 2, performed a benchmarking of the energy demand and CO_2 emissions in European residential buildings. Six different countries from EU were studied covering different climate conditions, being those: Spain, Italy, France, Germany, United Kingdom, and Sweden. The collected data was used to place the developing CSP plant in comparison with other existing technologies, full data can be found in the Deliverable 2.4 Report on the benchmark of energy and carbon saving targets [19], from the H2020 project Innova MicroSOLAR (Grant Agreement 723596).

Prior to perform experimental tests at a high temperature latent heat TES tank, a complete characterization of the selected PCM was carried out. This process included material screening, health hazard evaluation, thermophysical characterization, thermal stability assessment, thermal cycling stability, and corrosion compatibility. Those evaluations were performed at the University of Lleida laboratories, described in papers 3 and 4.

The latent TES tank required specific features in terms of thermal power and temperature. Hence, to experimentally study different heat transfer techniques between the PCM and the heat carrier another research line was carried out (Figure 6). Due to hardware and safety limitations this study was performed at low temperature. The goal sought within this these experiments was to enhance the heat transfer between PCM and heat carrier at lab-scale and then implement the results later into the real scale latent heat TES tank. The PhD experimental part at low temperature (below 100 ºC) took place at the University of Lleida laboratories in Lleida (Spain), the test rig is detailed in papers 5 and 6. This set-up hosted the comparative experiments of latent heat TES tank with and without heat pipes.

The last step of the high temperature research finishes with the experimental tests at the concentrated solar power plant. The CSP pilot plant had three main blocks: solar field, organic Rankine cycle micro turbine (ORC), and latent heat TES. The concentrated solar power plant is located at the UdL premises in Almatret (Lleida, Spain), 49 km far from the university campus (Figure 7a). Almatret city hall showed a great support to host this demo plant, since they have the desire of becoming a zero-energy town, being self-sufficient and based in green energies. The old school playground was the exact location for the solar plant (Figure 7b), which was perfect because is an open area with no sun blocking buildings around. An engine room had to be built for hosting the balance of the plant (BoP), the organic Rankine cycle, and the thermal energy storage tank (Figure 8a). Also, we built a smaller room next to the engine room where the plant smart control, and electrical cabinets are kept, the control room (Figure 8b).

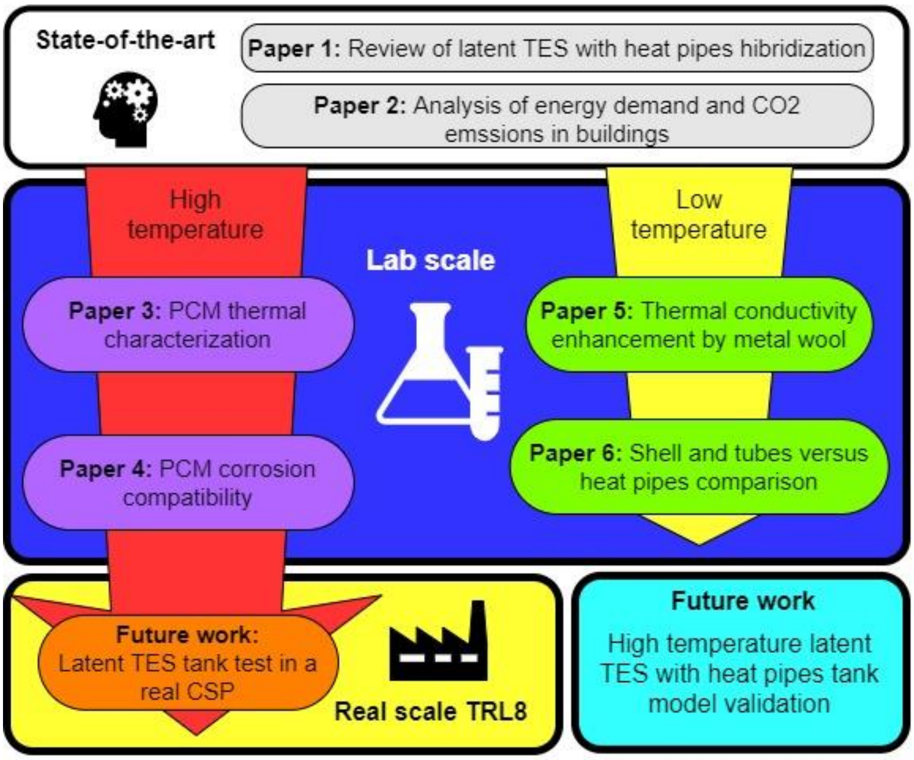


Figure 6. PhD thesis structure by papers and temperature range.

(a) (b)

Figure 7. Solar power plant location. (a) Google Earth satellite picture of Almatret; (b) zoom in of the satellite picture, showing the school.

The solar field location was analyzed in terms of solar hours before its construction started. We carried out a shadow study with a free design software, SketchUp 2017. Powered by Google, this software allows to insert the exact location for a 3D design, so the coordinates of the buildings are real. Hence, every form drawn in the design cast their shadow on the map accordingly to the sun position along the time, day, and month (**¡Error! No se encuentra el origen de la referencia.**). By combining SketchUp 2017 with a software extension, Shadow Analysis, the total shading time per day could be estimated the shading time. Two different dates were introduced in the software for doing the shading estimation time the summer solstice and the winter solstice; those are the days of the year with the most and the least sunlight, respectively. Along the summer solstice, sun rises at 5:31 hours and sunset happens at 20:29 hours, during which sunlight over the solar field was blocked from two to three hours, leaving 12 or 13 solar hours available (Figure 10a and b). Same analysis was done at winter solstice, being the sun shining from 08:26 to 17:25 hours; this time the shadow casted on the solar field lasted from two to six hours out of the total sunlight time (Figure 10c and d). Just to point out that night time is out of the study. Additionally, another software extension from SketchUp, called Solar Energy Analysis, provided an estimation of the total solar radiation on the solar field; summer and winter solstice were also analysed this time (Figure 11). Roughly speaking, on the longest day the solar field can get 4000 Wh/m^2, and around from 600 Wh/m^2 on the shortest day.

(a) (b)

Figure 8. Building process. (a) engine room; (b) control room.

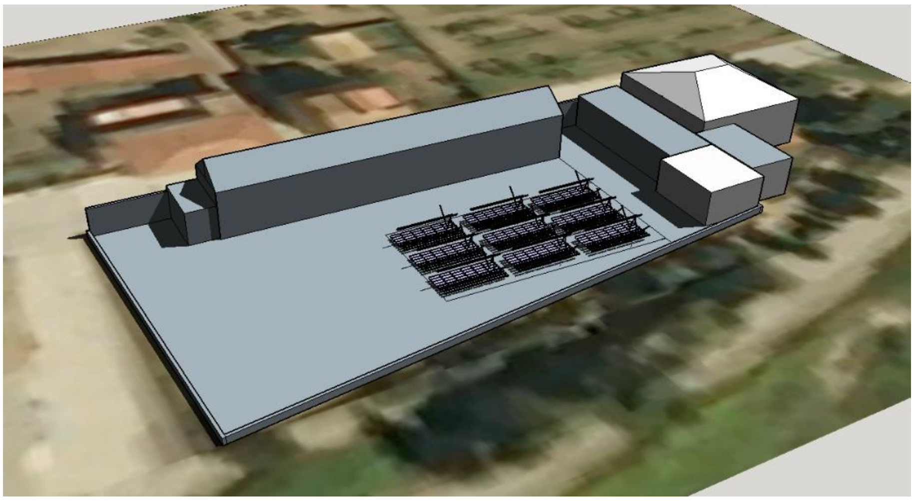


Figure 9. Almatret experimental site designed with SketchUp 2017.

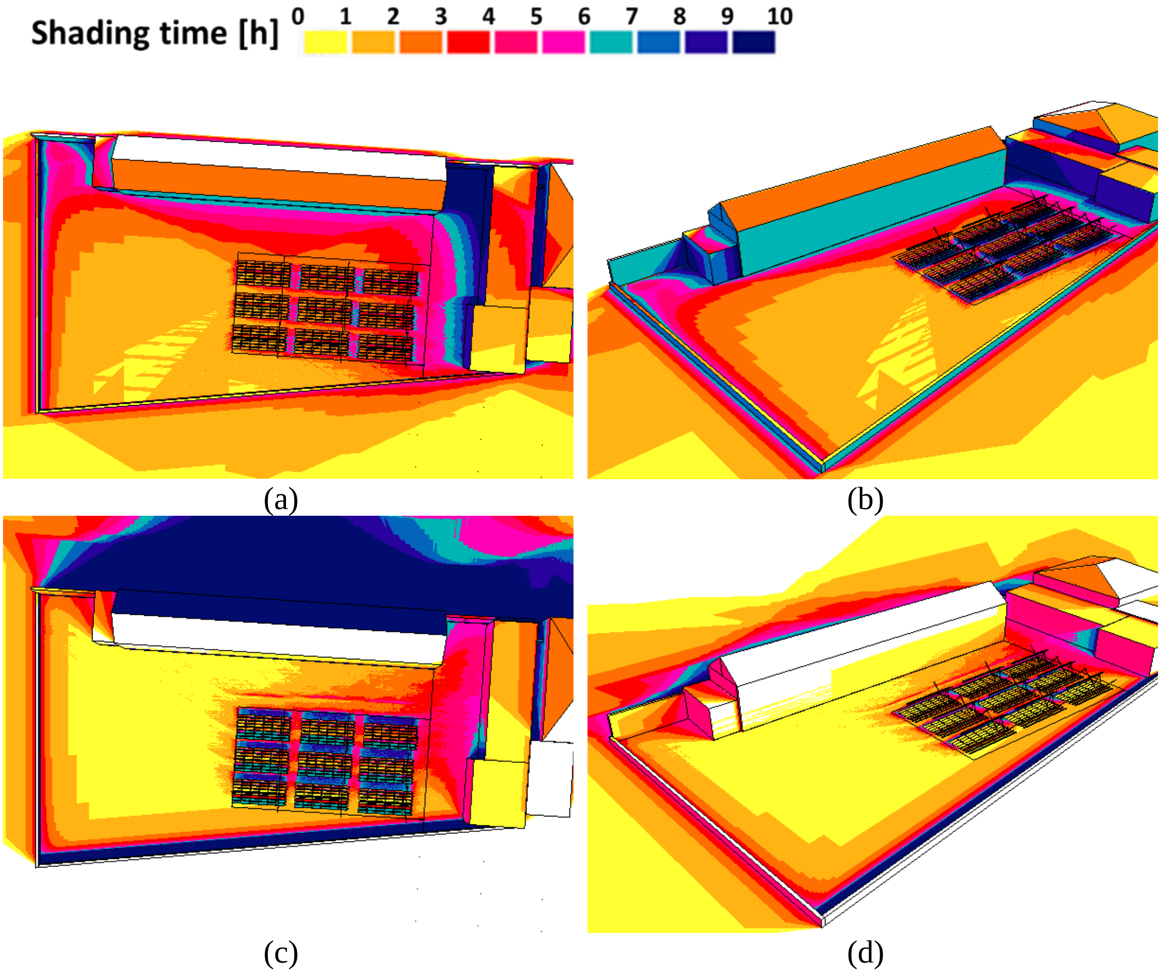
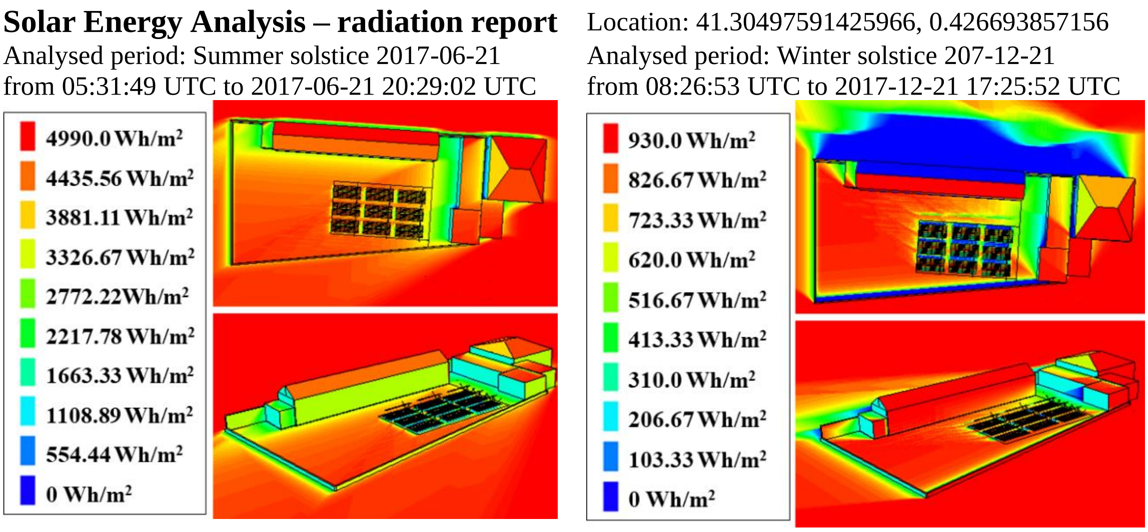


Figure 10. Shadow analysis result at summer solstice (a) top view, (b) perspective view; and at winter solstice (c) top view, (d) perspective view.

The CSP pilot plant supplies space heating (SH), domestic hot water (DHW), and electricity to the building, being the sun the energy carrier. The solar energy is collected by the solar field, heating up the heat transfer fluid; the latter flows to the ORC evaporating the ORC working fluid. The ORC vapour expands the turbine, generating electricity, and when it is condensed the heat released produces hot water for SH and DHW. If the solar radiation is too intense, part of the HTF would go to the latent TES tank, charging it. When sun goes down, the CSP would keep running but this time the latent TES tank would be the energy carrier. Figure 12 shows the prototype scheme and the way it works.



(a) (b)

Figure 11. Solar energy analysis result at (a) summer solstice and (b) winter solstice.

Linear Fresnel Solar Field

Linear Fresnel mirrors compound the concentrated solar field (Figure 13a), those mirrors are considerably easier and cheaper to manufacture than their parabolic equals. The mirrors reflect the sunlight and concentrate the light onto the absorber tube, which it is at three metres above them (Figure 13b). The solar field covered 140 m^2 surface, being able to provide from 15 to 80 thermal kW, heating up the heat transfer fluid (Therminol 62 [20]) to 300 ºC. The mirrors were mounted on a line which included a sun tracking device, ensuring that the mirrors are always focusing the absorber tube. The solar field was installed by ELIANTO S.R.L.

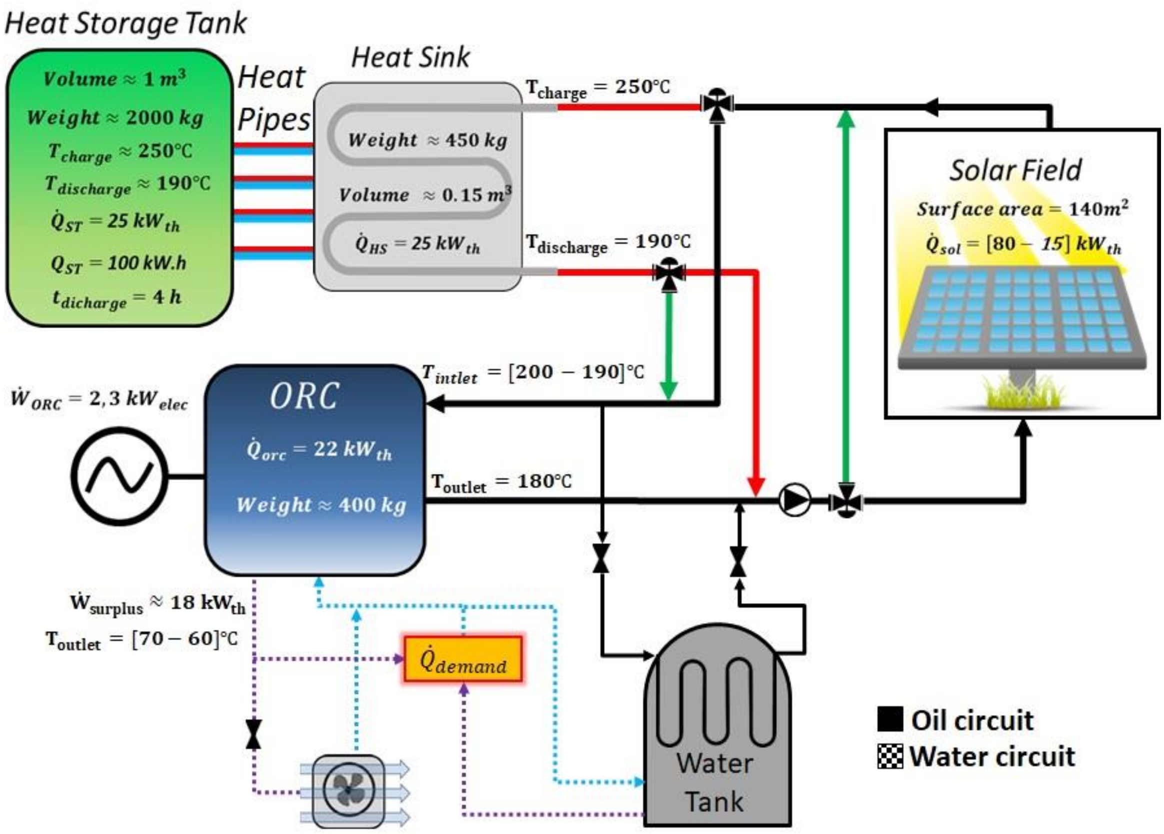


Figure 12. Pilot plant scheme.

(a) (b)

Figure 13. Linear Fresnel solar field, (a) general view, (b) absorber tube operating.

<u>Organic Rankine cycle micro turbine – ORC</u>

The power generator in this CSP plant is a micro organic Rankine cycle turbine, this equipment is also a novel system (Figure 14), designed and built by ENOGIA SAS. However, its insights are out of the scope of the PhD, although this equipment was installed and operated along the PhD development. The ORC generates 2.3 kW_{el} by means of a high speed permanent magnet AC alternator, the working fluid that expands within the micro turbine is cyclopentane [21]. The ORC thermal requirements to evaporate the working fluid are 22 kW_{th}, key parameter for the latent heat TES design. Cyclopentane condenses in a heat exchanger with water, cogenerating hot water for the final user.

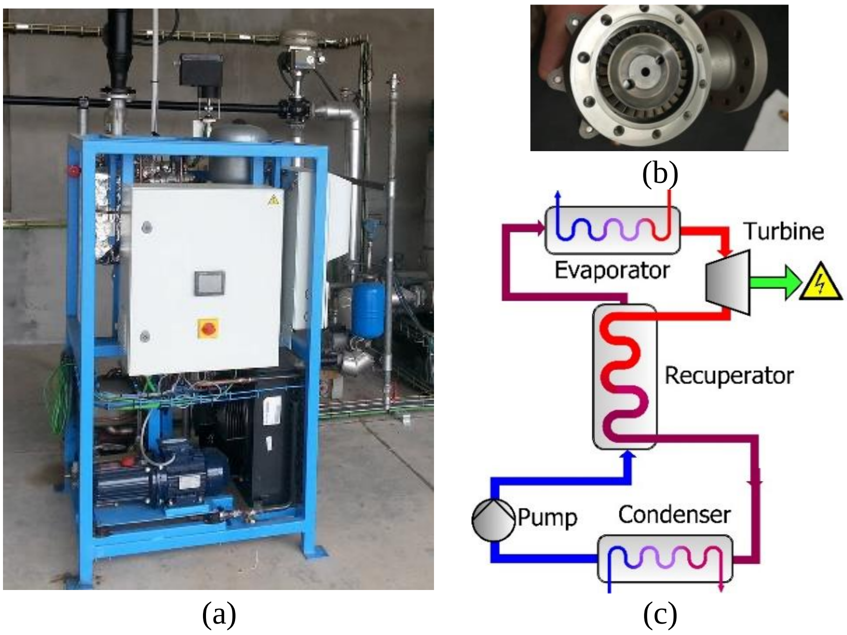
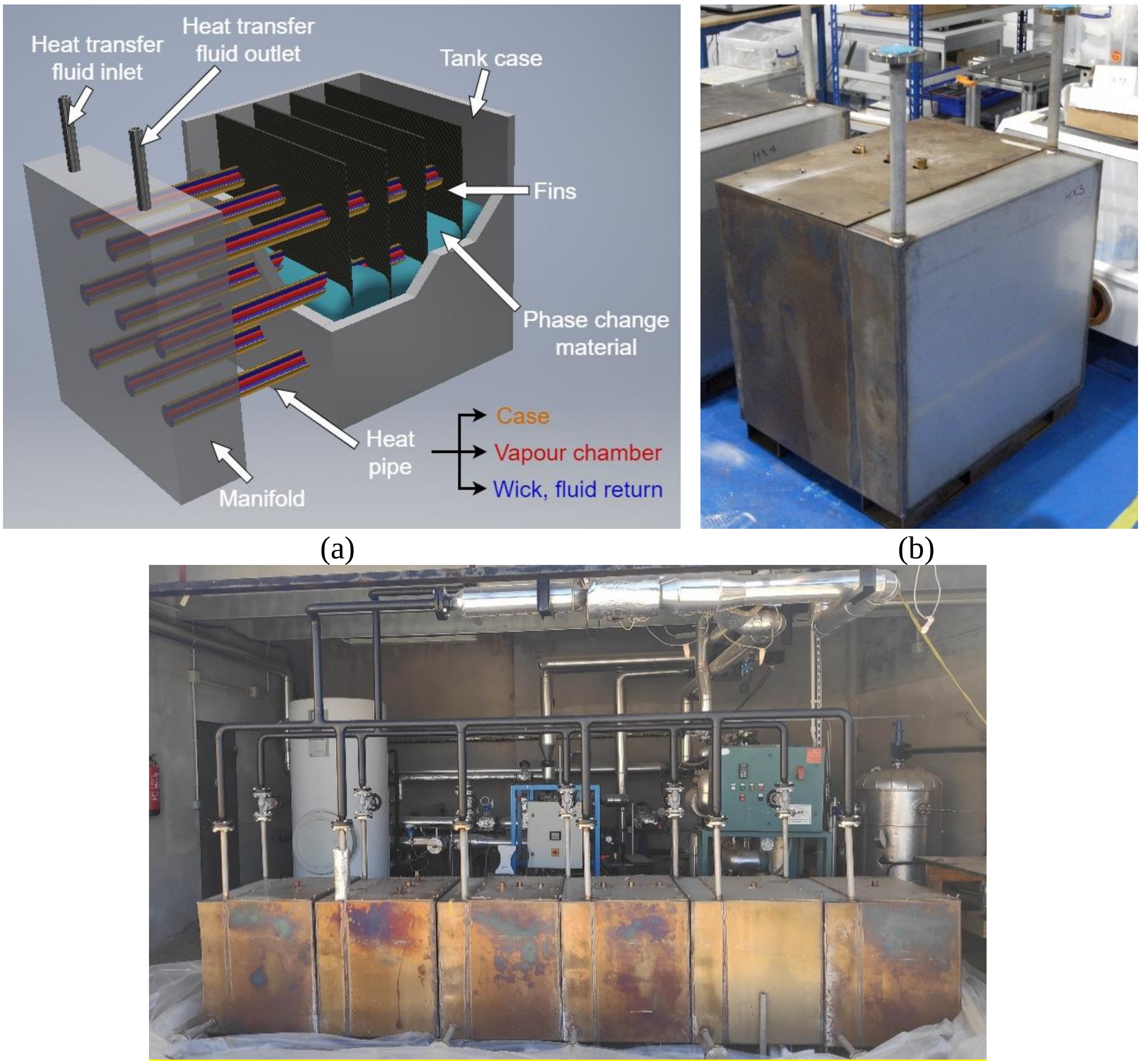


Figure 14. Organic Rankine cycle micro turbine: (a) full block, (b) micro turbine, (c) cycle scheme.

<u>Latent heat thermal energy storage tank</u>

The latent TES tank installed coupled with CSP plant was designed in collaboration with Northumbria University and AAVID Thermacore, Inc. This component consists of three main blocks: the PCM tank, the manifold, and the reversible heat pipes which connect both (Figure 15). When charging the tank, hot HTF enters in the manifold, heating the heat pipes evaporator part; which transport heat towards the PCM. Discharging process inverts the heat pipes working way, being molten PCM the heat source, and HTF is releasing the heat along the manifold. Due to ORC thermal requirements, the latent TES was designed to provide 25 kW_{th}, during four hours when fully charged.



(c)

Figure 15. Modular thermal energy storage tank: (a) concept, (b) one real module, (c) full storage tank of six modules.

Balance of Plant – Piping and instrumentation diagram

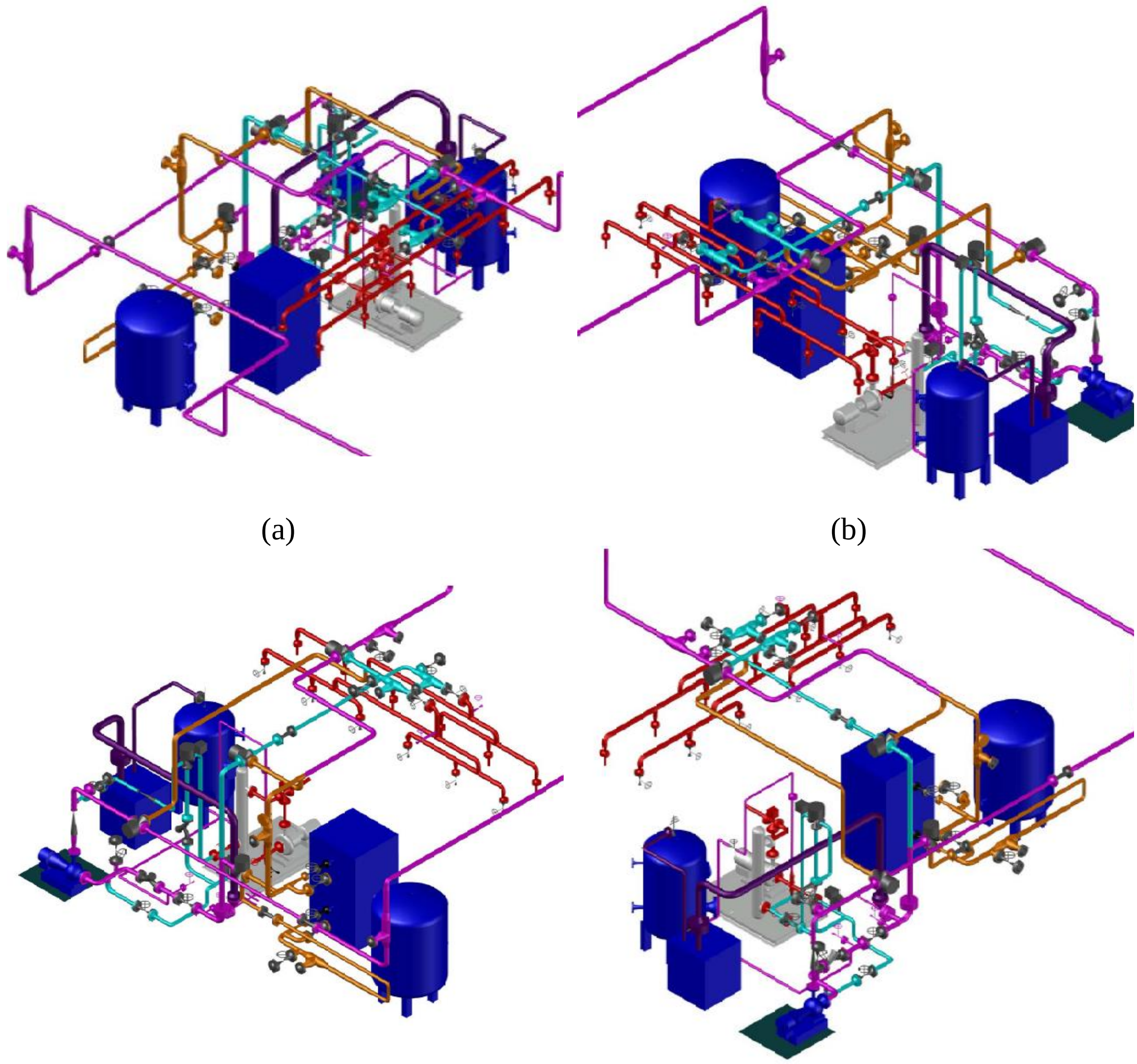
The balance of plant (BoP) includes every piping item needed to run and control the plant, such as the pipes themselves, thermal and pressure sensors, flowmeters, expansion vessel (totally equipped), manual valves, three-way electrical valves, safety valve, emergency discharge container, and the pump (Figure 16). We drew the BoP in detail by using

AutoCAD Plant 3D (Figure 17) to precisely place all the elements in the right position for our monitoring purposes and following the manufacturer recommendations.

(a)

(b)

Figure 16. Balance of plant with the ORC and before the latent heat TES tank installation: (a) general view taken from the left side, (b) and from the right side.



(a) (b)

(c) (d)

Figure 17. 3D design of the balance of plant from different points of view: (a) front left, (b) front right, (c) back left, (d) and back right.

Chapter 3

Papers comprising this PhD

3.1 Paper 2: Comparative analysis of energy demand and CO2 emissions on different typologies of residential buildings in Europe

3.1.1 Overview

One third of the global energy consumption is due to the building sector, and this number is presumed to keep growing along with the increasing living standards [22,23]. Therefore, that makes the energy consumption reduction in the building sector a main global environmental concern to be tackled in the long-term to ensure the sustainable development [22]. In Europe, 41% of the final energy consumption and 40% of the GHG emissions come from residential sector [24]. For that reason, the European Union promotes the use of active and passive energy saving systems, such as renewable technologies, and more efficient building envelopes and shapes [25–28].

The main key drivers regarding the buildings thermal energy consumption are: number of households, person per household, floor space per capita, DHW and energy consumed for heating and cooling [23,29,30]. Researchers can tackle the latter to reduce buildings energy demand. To evaluate new technology potential applicability before its implementation in real scenarios is highly useful if not mandatory. For that purpose, a comparison against conventional existing systems is required. However, the EU building stock is very diverse in regards to their design, construction method, and heating and cooling equipment [31,32]. Although massive data are available, there are no standardized methods to gather them, neither tools for assessing their energy demand [33]. Making the analysis of new technologies difficult to compare when implementing them into several building typologies and climate conditions. The paper provided a comprehensive benchmarking of the energy requirements of the residential buildings in Europe, as well as, their CO_2 emissions.

This research allowed to harvest data about the energy consumption of residential buildings in different European countries. Although out of the scope of the paper, the analyzed energy consumption data were classified regarding their producer technology, being able to discretize those coming from renewable energies. This discretization lead to a hypothetical comparison among the technology developed along the thesis and the other current renewable energy technologies. The comparison considered the energy consumed by residential and small business buildings from renewables and fossil fuels, and then compared it against the expected energy produced by the concentrated solar power plant designed within this thesis. Same comparison was done in terms of CO_2 emissions. It has to be taken into account that as the novel CSP plant is a prototype it makes no sense to compare regarding the cost, since common technologies manufactured in chain are cheaper.

3.1.2 Contribution to the state-of-the-art

This research provides a review of the most common residential building typologies in Europe, detailing their architecture, floor area, building envelope and insulation properties. The study scope covers data from Germany, France, UK, Italy, Spain, and Sweden. Also, the study benchmarks regarding the energy consumption for space and water heating, as well as, the associated CO_2 emissions. This benchmarking enclosed different building typologies and climate conditions, based in TABULA/EPISCOPE projects. Within this study, the building categorization developed within the EU project TABULA was chosen, it included: single family houses, terraced houses, multifamily houses, and apartment blocks; also categorized by construction year, and by the climate under they were built. However, this database missed energy consumption for cooling, air conditioning, lighting and electric appliances. The cross-country comparison provides a reference scenario regarding residential buildings energy demand and CO_2 emissions, allowing to assess the implementation of new energy supply technologies.

3.1.3 Contribution of the candidate

Jose Miguel Maldonado, searched, analysed, and discussed the data.

3.1.4 Journal paper

The scientific contribution from this research work was published in the journal Energies in 2019.

Reference: Coma, J.; Maldonado, J.M.; de Gracia, A.; Gimbernat, T.; Botargues, T.; Cabeza, L.F. Comparative Analysis of Energy Demand and CO_2 Emissions on Different Typologies of Residential Buildings in Europe. *Energies* 2019, *12*, 2436.

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Article

Comparative Analysis of Energy Demand and CO_2 Emissions on Different Typologies of Residential Buildings in Europe

Julià Coma [1], José Miguel Maldonado [2], Alvaro de Gracia [2,3], Toni Gimbernat [4], Teresa Botargues [5] and Luisa F. Cabeza [2,*]

1 Departament de Tecnologia de l'Arquitectura, Universitat Politècnica de Catalunya, Av. Dr. Marañón 44-50, 08028 Barcelona, Spain; julia.coma@upc.edu
2 GREiA Research Group, INSPIRES Research Centre, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain; jmmaldonado@diei.udl.cat (J.M.M.); alvaro.degracia@udl.cat (A.d.G.)
3 CIRIAF—Interuniversity Research Centre, University of Perugia, Via G. Duranti 67, 06125 Perugia, Italy
4 SINAGRO ENGINYERIA S.L.P, Av. Estudi General 7, Altell 5, 25001 Lleida, Spain; tgimbernat@e3g.es
5 USER FEEDBACK PROGRAM SL, Sant Jaume Apòstol 8, 25126 Almenar, Spain; info@ufp.cat
* Correspondence: lcabeza@diei.udl.cat

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3.2 Paper 3: Phase change material selection for thermal energy storage at high temperature range between 210 ºC and 270 ºC

3.2.1 Overview

The European Commission has promoted solar energy aiming to tackle one of their main concerns, greenhouse gasses emissions. Among the existing solar technologies, concentrated solar thermal energy could supply up to 7% of the world energy requirements by 2030, and by 2050 even 25% [9].

However, solar thermal power plants competitiveness has to be improved against fossil fuels power plants. For that purpose, solar power plants dispatchability needs to be enhanced, making them able to supply power to the grid on demand. From that necessity thermal energy storage technologies were identified, which allow solar thermal power plants to generate power invariably when sun has gone. This feature makes solar concentrated power plants more cost effective, increasing dispatchability to the grid, and allows a better use of the power-block [10].

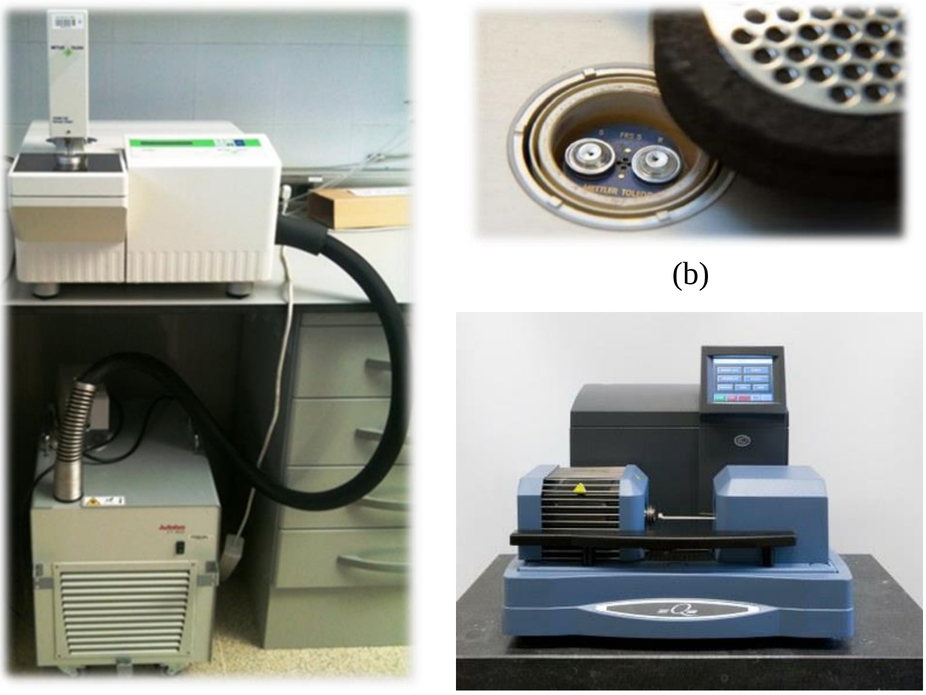
There are three different TES technologies pursued by researcher: sensible heat, latent heat, or thermochemical energy storage. Among those, latent heat TES by using phase change materials are an efficient option due to their high energy storage density [11]. The PCM selection has a direct influence on the solar plant cost; not only the material cost itself, but also its vessel, the maintenance, and safety measurements required. Therefore, a proper screening and characterization of the candidates is mandatory. Thermophysical characterization, thermal stability, cycling stability, health hazard analysis [34–38], are performed to select the best material for each system.

This paper main goal was to find suitable materials to work in a latent heat TES system, which phase change occurs between 210ºC and 270ºC. The material had to be economically viable, able to endure daily charging and discharging processes, and safe. Twenty-six materials were found as feasible candidates, but just two reached the last stages of the selection process proposed by Miró et al. [37]. These two materials were myo-inositol, and a eutectic mixture of (40 wt.%) KNO_3 and (60 wt.%) $NaNO_3$, also known as solar salts.

3.2.2 Contribution to the state-of-the-art

This study provides a suitable phase change material for latent heat TES systems at a temperature range from 210 ºC to 270 ºC. This temperature range was determined by the real application requirements, which is a concentrated solar power plant. The heat carrier is a linear mirror Fresnel solar field able to heat up the heat transfer fluid to 300ºC. The TES tank was planned to work in couple also with a micro organic Rankine cycle turbine which demands at least 210 ºC as heat input.

From the first screening process, just nine candidates passed, and consequently, they were submitted to thermophysical characterization by means of differential scanning calorimeter (DSC) (Figure 18a and b), and health hazard assessment. Three of them reached the next stage: solar salts (40 wt.% KNO_3 and 60 wt.% $NaNO_3$), myo-inositol and polybutylene terephthalate (PBT), so their thermal stability was tested. Thermal gravimetric analyses (TGA) were performed on the three materials (Figure 18c).



(a) (b) (c)

Figure 18. Equipment used for thermally characterizing the PCM candidates. (a) Differential scanning calorimetry (DSC) Mettler Toledo 822e; (b) DSC sample carrier; (c) thermogravimetric analysis (TGA) TA Instrument Simultaneous SDTQ600.

Just solar salts did not suffer a sever decomposition. However, due to myo-inositol high phase change enthalpy and low cost, we decided to performed the last experiment on it in a closed crucible. The PCM would have to endure daily loading and unloading, so cycling stability tests were carried out. Myo-inositol would require an inert working atmosphere, increasing the cost of the TES tank. Therefore, the most suitable PCM at 210 - 270ºC temperature range was solar salt.

Solar salts (40 wt.% KNO_3/60 wt.% $NaNO_3$) melting temperature was 221 ºC, they presented no subcooling, and their melting enthalpy was acceptable (94 J/g). They were successfully put through thermal stability, they started to lose mass at 500 ºC; and thermal cycling, holding 50 cycles without losing thermal properties. Also, solar salts are economically viable.

3.2.3 Contribution of the candidate

José Miguel Maldonado sought for the materials which could be used to work as PCM at 210 - 270 ºC temperature range; also analyzed and discussed the data obtained. Finally, Jose Miguel Maldonado wrote the paper.

3.2.4 Journal paper

The scientific contribution from this research work was published in the journal Energies in 2018.

<u>Reference:</u> Maldonado, J.M.; Fullana-Puig, M.; Martín, M.; Solé, A.; Fernández, Á.G.; De Gracia, A.; Cabeza, L.F. Phase Change Material Selection for Thermal Energy Storage at High Temperature Range between 210 °C and 270 °C. Energies 2018, 11, 861.

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Article

Phase Change Material Selection for Thermal Energy Storage at High Temperature Range between 210 °C and 270 °C

José Miguel Maldonado [1], Margalida Fullana-Puig [1,2], Marc Martín [1], Aran Solé [3], Ángel G. Fernández [4], Alvaro de Gracia [1,2] and Luisa F. Cabeza [1,*]

1 GREiA Research Group, INSPIRES Research Centre, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain; jmmaldonado@diei.udl.cat (J.M.M.); mfullana@diei.udl.cat (M.F.-P.); marc.martin@udl.cat (M.M.); alvaro.degracia@udl.cat (A.d.G.)

2 CIRIAF—Interuniversity Research Centre on Pollution and Environment Mauro Felli, Via G. Duranti 63, 06125 Perugia, Italy

3 Department of Mechanical Engineering and Construction, Universitat Jaume I, Av. Vicent Sos Baynat, s/n, 12071 Castellón de la Plana, Spain; sole@uji.es

4 Energy Development Center, University of Antofagasta, Av. Universidad de Antofagasta, 02800 Antofagasta, Chile; angel.fernandez@uantof.cl

* Correspondence: lcabeza@diei.udl.cat

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3.3 Paper 4: Corrosion assessment of myo-inositol sugar alcohol as a phase change material in storage systems connected to Fresnel solar plant

3.3.1 Overview

Producing decarbonized energy, which is one of the European Union main objectives, to reduce the greenhouse gas emissions. However, many renewables weak point against conventional power plants is their dispatchability. Regarding solar thermal power plants this issue is addressed by thermal energy storage systems. Enhancing concentrated solar power plants dispatchability, reduces their levelized cost of electricity and makes them more competitive within the energy market [10].

Many efforts have been invested in lowering operational and maintenance associated costs in solar power plants. Therefore, the selection of a proper storage material is an appealing task. Thermophysical characterization, thermal stability, health hazard, and cycling stability are some assays performed to assess the feasible PCM [34–39]. However, the TES tank lifespan is a key factor when design it, hence corrosion compatibility between the selected PCM and the power plant elements must be ensured. The material used for containing the PCM affects directly the plant costs and can be very relevant to reduce the plant LCOE.

Two PCMs were found as feasible options for the desire temperature range 210 - 270 ºC in a previous study [39], solar salts and myo-inositol ($C_6H_{12}O_6$), based on a thermophysical characterization. Within this research that study was completed by carrying out a corrosion assessment with copper, aluminum, stainless steel (SS304), and carbon steel (AISI 1090). The metal samples were immersed in the corrosion environments for a maximum of 2000 hours. The corrosion products on the metal specimens were analysed by X-ray diffraction (XRD) (Figure 19a), and scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) assays (Figure 19b). Also, a gravimetric study was performed to quantify the mass loss due to corrosion.

(a) (b)

Figure 19. Equipment used for analysing the corrosion compounds grown on the different metal coupons in contact with the PCM candidates. (a) X-ray diffraction (XRD) device used was the PANalytical X´Pert PRO [40]; (b) scanning electron microscopy (SEM) model used was the Quanta 250, Thermofisher [41].

3.3.2 Contribution to the state-of-the-art

This study presents a corrosion assay on two PCM candidates, solar salt (40 wt.% KNO_3/60 wt.% $NaNO_3$) and myo-inositol ($C_6H_{12}O_6$), for a concentrated solar power plant at 250 ºC. Solar salts are currently used as storage systems in CSP plants, and have been already corrosion tested on stainless steel (AISI 304, 430) and low-Cr steel (2.25% Cr) at 390 ºC and 550 ºC [42,43], since they are employed as sensible storage when molten. However, this paper shows their corrosion viability results to be used as phase change material. Two materials were used as corrosion environments: solar salts which are a eutectic mixture of 40 wt.% KNO_3 and 60 wt.% $NaNO_3$; and a sugar alcohol commonly used in food industries under the U.S.A NF12/FCCV standard, called myo-inositol ($C_6H_{12}O_6$). Corrosion rates on Aluminium, stainless steel (AISI 304), carbon steel (AISI 1090), and copper were assessed.

Myo-inositol corrosion effect on the metal coupons did not provide accurate enough results, so no conclusion could be obtained in terms of corrosion. However, this study shows the bizarre behaviour of myo-inostiol, which strongly stack to the metal coupons. That makes myo-inositol extremely hard to manage in real scale TES tank. This paper discourages myo-inositol as a PCM.

3.3.3 Contribution of the candidate

Jose Miguel Maldonado performed the experiments. Also, Jose Miguel Maldonado analyzed and discussed the data, and wrote the paper.

3.3.4 Journal paper

The scientific contribution from this research work was published in the journal Molecules in 2019.

Reference: Maldonado, J.M.; Fernández, Á.G.; Cabeza, L.F. Corrosion Assessment of Myo-Inositol Sugar Alcohol as a Phase Change Material in Storage Systems Connected to Fresnel Solar Plants. Molecules 2019, 24, 1383.

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Corrosion Assessment of Myo-Inositol Sugar Alcohol as a Phase Change Material in Storage Systems Connected to Fresnel Solar Plants

José Miguel Maldonado, Ángel G. Fernández and Luisa F. Cabeza *

GREiA Research Group, INSPIRES Research Centre, Universitat de Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain; jmmaldonado@diei.udl.cat (J.M.M.); angel.fernandez@diei.udl.cat (Á.G.F.)

* Correspondence: lcabeza@diei.udl.cat; Tel.: +34-973-003576

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3.4 Paper 5: Experimental evaluation of the use of fins and metal wool as heat transfer enhancement techniques in a latent thermal energy storage system

3.4.1 Overview

Thermal energy storage helps to solve the dispatchability issues associated with some renewables energies, reducing the mismatch between energy supply and demand. Three TES methods are available, sensible heat, thermochemical, and latent heat, among them, the latter by means of phase change materials offers a high storage density, at nearly isothermal processes (melting/solidification) [11]. However, those PCMs economically feasible, such as fatty acids, paraffin, and salts, have a weak point, their low conductivity (~0.15 W/m·K; ~0.20 W/m·K; ~0.6 W/m·K, respectively) [44]. This matter slows down loading/unloading processes, making the latent heat TES non-effective systems.

Therefore, aiming to increase the TES systems heat transfer rate within this systems, many techniques have been studied [45–47]. Fins addition in PCM storages increases the heat transfer surface, lowering the thermal resistance and providing high heat transfer rates. This method has been deeply studied by the research community, regarding fin size, space between fins, number of fins, or fin material [48–53]. However, there are some drawbacks when adding fins to latent TES systems. First and more obvious, the volume available for storing material is lower; also there is a cost associated with this enhancing method; and the fin addition has to be done within the designing stage.

The goal of this paper is to experimentally assess the performance of heat transfer enhancement technique, which can overcome the last two drawbacks. Therefore, the addition of metal wool in the PCM was found to be a potential solution, since it is cheap and easy-to-implement. Some researchers have studied similar designs, but with aluminum wool, and by using not so accessible means for the aluminum wool management [54–58]. Hence, we developed a latent heat TES system based on the shell-and-tube heat exchanger concept, employing n-octadecane ($CH_3(CH_2)_{16}CH_3$) as PCM, with metal wool embedded. This upgrade is cost accessible and easy-to-implement in an already built heat exchanger.

This paper is the first part out of two regarding this experimentation, where the TES tank with different fins configurations and metal wool distribution are added to the control tank. Then, the authors replaced the copper tubes by heat pipes, keeping the same packing factor. Within the next section 0, more details can be found.

3.4.2 Contribution to the state-of-the-art

This paper provides an experimental benchmarking of fins and metal wool addition into a latent heat TES, aiming to enhance the heat transfer rate. Fins suitability is well-known, although their installing cost is a main drawback. Hence, we assessed the potential of adding a cheap commercial metal wool instead of fins. Four different TES tank configurations were tested: (1) the reference one which had just pipes trough where heat transfer fluid flows, (2) with seventeen rectangular fins, (3) with metal wool randomly distributed, and (4) with metal wool compacted as fins. The PCM used was n-octadecane ($CH_3(CH_2)_{16}CH_3$) in all of them, and the HTF was water.

The results showed that, in terms of heat transfer effectivity, metal wool cannot achieve the heat transfer enhancement provided by the fins, no matter the metal wool distribution. However, yet metal wool randomly spread within the PCM could increase the charging process rate up to 14% when comparing against the control case.

3.4.3 Contribution of the candidate

José Miguel Maldonado designed the study, built the experimental setup, and performed the experiments. Moreover, José Miguel Maldonado collaborated on the interpretation of the results and on the preparation of the manuscript.

3.4.4 Journal paper

The scientific contribution from this research work was published in the journal Energy Conversion and Management in 2019.

<u>Reference:</u> Gasia J, Maldonado JM, Galati F, De Simone M, Cabeza LF. Experimental evaluation of the use of fins and metal wool as heat transfer enhancement techniques in a latent heat thermal energy storage system. Energy Convers Manag 2019;184:530–8. doi:10.1016/j.enconman.2019.01.085.

Energy Conversion and Management 184 (2019) 530–538

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Experimental evaluation of the use of fins and metal wool as heat transfer enhancement techniques in a latent heat thermal energy storage system

Jaume Gasia[a], José Miguel Maldonado[a], Francesco Galati[b], Marilena De Simone[b], Luisa F. Cabeza[a,*]

[a] GREiA Research Group, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain
[b] Department of Mechanical, Energy and Management Engineering, University of Calabria, P. Bucci 46/C, 87036 Rende, Italy

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Metal wool
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Heat exchanger

ABSTRACT

This paper experimentally studies and compares the addition of fins and the addition of metal wool in a latent heat thermal energy storage (TES) system as heat transfer enhancement techniques. Despite the well-known suitability of fins as enhancement technique, their implementation cost in the TES system is one of its main drawbacks. Therefore, the objective of this study is to evaluate the potential of adding a cheap and commercially available metallic wool in order to overcome the abovementioned drawback. In particular, four different latent heat TES systems based on the shell-and-tube heat exchanger concept were designed using n-octadecane as phase change material (PCM). One of them was used as a reference, while in the remaining configurations the heat transfer surface was increased by means of seventeen rectangular fins and by means of metallic wool arbitrarily distributed within the PCM and compacted in a finned shape. Charging and discharging processes with constant heat transfer fluid temperature and flow rate were evaluated from the temperature and heat transfer points of view. Results were focused on the metal wool because is a cheap and handmade solution which can be implemented in an already made heat exchanger. The addition of metal wool showed an enhancement, during the charge, higher than 10% when it was arbitrarily distributed, while compacting the metal wool in a finned shape showed practically no improvement. During the discharge, both metal wool configurations allowed minimal improvements.

3.5 Paper 6: Experimental evaluation of the use of heat pipes in latent heat thermal energy storage systems

3.5.1 Overview

Many studies focused their efforts into increasing the heat transfer rate in TES systems by using different enhancement techniques such as fins addition, bubble agitation, embedding metal matrixes or other materials (graphite or nano-particles) within the PCM, and also inserting heat pipes [12,13,45–47,59]. Heat pipes can transfer great amounts of heat with small temperature gradient as driving force [17,18]. The well-known performance of heat pipes has attracted the attention of many researchers who studied them with latent heat TES systems, experimentally [60–63] and numerically [64–68]. However, those studies compared metal rods against heat pipes, proving that they are a suitable thermal enhancement solution. Nonetheless, that comparison is not very helpful once the heat pipe competitor are conventional heat transfer systems which consist in a shell and tubes heat exchanger configuration.

Unlike previous studies, this research experimentally benchmarks heat pipe latent heat TES tanks against those conventional systems with shell and tubes. Five latent heat thermal energy storage systems were tested. One standard shell and tubes, and the other four based on heat pipes; tanks designs were developed taking into account the packing factor and system compactness. Charging processes were assessed in terms of temperature, power and process time.

3.5.2 Contribution to the state-of-the-art

This paper provides an experimental evaluation of heat pipes addition into a latent heat TES, aiming to enhance the heart transfer rate. Although heat pipes benefits over solid metal rods is well-known; unlike previous research, this study benchmarks heat pipes against a conventional shell and tubes latent TES. Five different TES tank configurations were tested: the control one which had just pipes trough where HTF flows, and the other four based on heat pipes. N-octadecane ($CH_3(CH_2)_{16}CH_3$) was PCM in all of them, and water as HTF.

The results showed that, in terms of completing process time, heat pipes with the analyzed configuration cannot match the standard shell and tubes system. Nevertheless, the heat pipes managed to melt the PCM uniformly, what avoids hot zones along the PCM vessel which could produce a thermal shock in the TES tank. In terms of heat transfer effectivity, heat pipes TES systems supplied higher rates at the beginning of the process. However, their power was muffled due to the PCM low conductivity. The inner working fluid mass flow in heat pipes requires a temperature gradient between their tips, unlike a shell and tube system where the mass flow is pumped. So, the as long as heat transfer rate in the PCM can be kept higher, heat pipes will supply high thermal power rates. Therefore, an additional heat enhancement technique, such as fins or nano-particles, must be used within the PCM.

3.5.3 Contribution of the candidate

José Miguel Maldonado conceived and designed the study, built the experimental setup, and performed the experiments. Moreover, José Miguel Maldonado analyzed the results and prepared the manuscript.

3.5.4 Journal paper

The scientific contribution from this research work was submitted to the journal Applied Thermal Engineering in October 2020.

Applied Thermal Engineering

Experimental evaluation of the use of heat pipes in latent heat thermal energy storage systems

--Manuscript Draft--

Manuscript Number:	ATE-D-20-03319
Article Type:	Original Research Papers
Keywords:	Latent heat thermal energy storage (LHTES); Phase change material (PCM); Heat pipes; Heat exchanger, Experimental analysis
Corresponding Author:	Luisa F. Cabeza University of Lleida Lleida, Spain
First Author:	José Miguel Maldonado
Order of Authors:	José Miguel Maldonado
	David Verez
	Alvaro de Gracia
	Luisa F. Cabeza
Abstract:	This paper experimentally evaluates the implementation of heat pipes in latent heat thermal energy storage systems. The well-known performance of heat pipes as a heat transfer technology makes them great candidates to be used as heat exchangers. Therefore, the objective of this study is to experimentally evaluate the advantages of using heat pipes instead of a common shell and tubes system, during charging processes. In particular, five latent heat thermal energy storage systems were tested. One based on the shell and tubes, and the remaining four based on heat pipes. The experiments were conducted at constant heat transfer fluid temperature and flow rate, and the results were analysed from the temperature, heat transfer, and visual point of view. The results show that in heat pipes systems the phase change material melts homogeneously through all the storage container. On the other hand, in the shell and tubes configuration melt from the heat transfer fluid inlet towards the outlet. Moreover, systems with more heat pipe surface inside the heat transfer fluid collector provided higher power rates, but the storing material low conductivity cushioned those high heat transfer rates.
Suggested Reviewers:	Gennady Ziskind gziskind@bgu.ac.il
	Philip Eames P.C.Eames@lboro.ac.uk
	Yukitaka Kato yukitaka@lane.iir.titech.ac.jp

Chapter 4

Results and Discussion

The results obtained from each paper can be found in the different papers that build this PhD thesis. However, this chapter discusses how those results lead us through them.

The initial literature research allowed to identify the gaps within the investigation involving latent heat thermal energy storage and heat pipes. As a consequence, a latent heat TES system with embedded heat pipes for high temperature applications was designed to work coupled with a concentrated solar power plant. The experimental test rig, in which the TES tank was installed, was designed and built along this PhD, reaching the technology readiness level 6(Figure 20). This PhD described the process to design the TES tank and the solar power plant. Additionally, it was spotted along the literature research that many experimental studies performed regarding heat pipes and latent heat TES systems, compared the heat pipes against a solid copper rod. Therefore, we considered the possibility to compare the heat pipes against a copper pipe in which heat transfer fluid flows through. Although, for this hypothesis the set up was designed to work at low temperatures (n-octadecane melting point is 27.7 ºC), so different configurations could be tested in the laboratory. As a consequence, other heat transfer enhancement techniques, such as the addition of common, commercial metal wool, were tested.

The PCM selection was a key milestone within the latent heat TES tank design at high temperature, since there were no other similar facilities which operate at the desired temperature range (210 - 270 ºC). To do so we followed a material selection procedure (Figure 21), which first step, before starting to perform any test, consists in identifying the system requirements. Some requirements are common in almost every application, such as high latent heat storage capacity, constant thermal properties during its operation, stable, safe and easy to handle, compatible with its environment, and economically viable. The main requirement dictated by

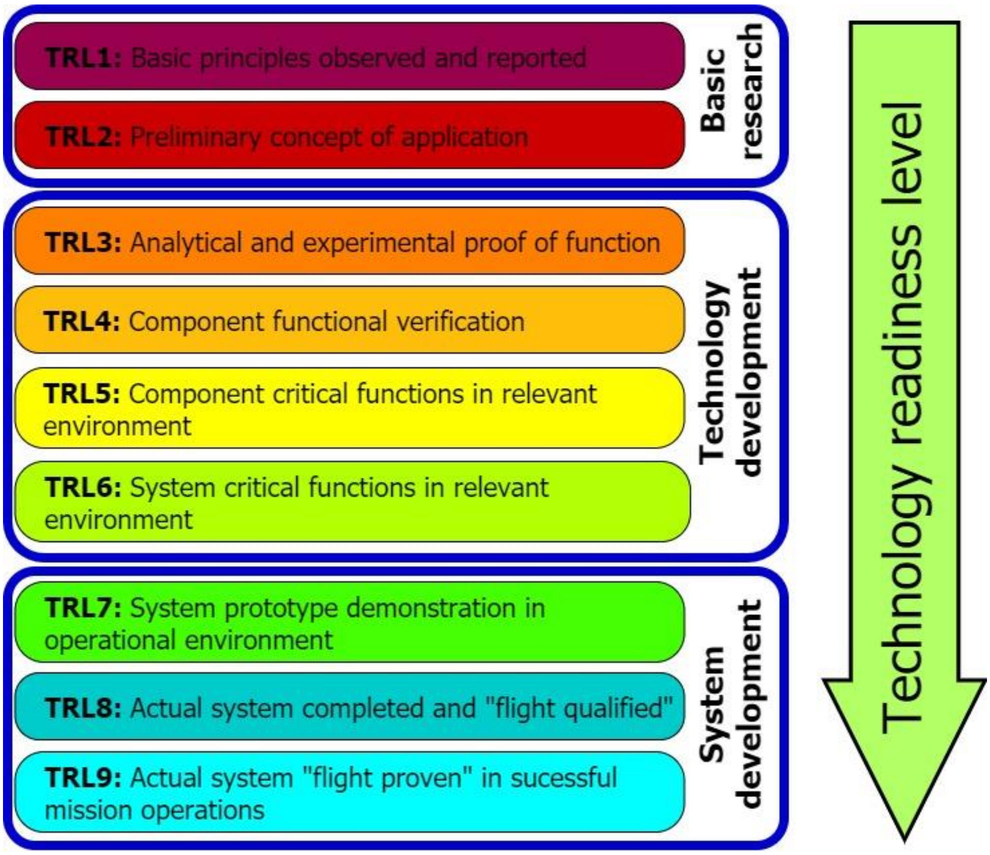

Figure 20. Technology readiness levels (TRL) [69].

the final application is the temperature range in which the PCM melts and solidifies. In our case, that range was limited by the solar field capacity and the organic Rankine cycle turbine temperature necessities, from 210 ºC to 270 ºC. Hence, within that phase change temperature range a 26 materials list was retrieved, from that list many candidates were removed even before starting the thermophysical characterization. Also, the PCM selected had to be corrosion compatible with the material tank, the material requirements for the PCM container can considerably affect their cost. In the end, just one PCM succeed on every assessment, health hazard, thermophysical characterization, thermal stability, cycling stability, and corrosion compatibility. The selection process was described in detail in papers 3 and 4. Once the PCM was selected, the tank itself was designed to comply with the solar power plant requirements. The latent heat TES system had to supply heat (at least 210 ºC) to the power plant for four hours, being able to develop 25 kW_{th}. Two tons of PCM were required and heat pipes in couple fins were installed to extract enough power from the PCM. The last step will be to run charging and discharging experiments in real conditions, due to the worldwide 2020 pandemic situation, those tests were rescheduled to be performed as soon as the global situation allows it.

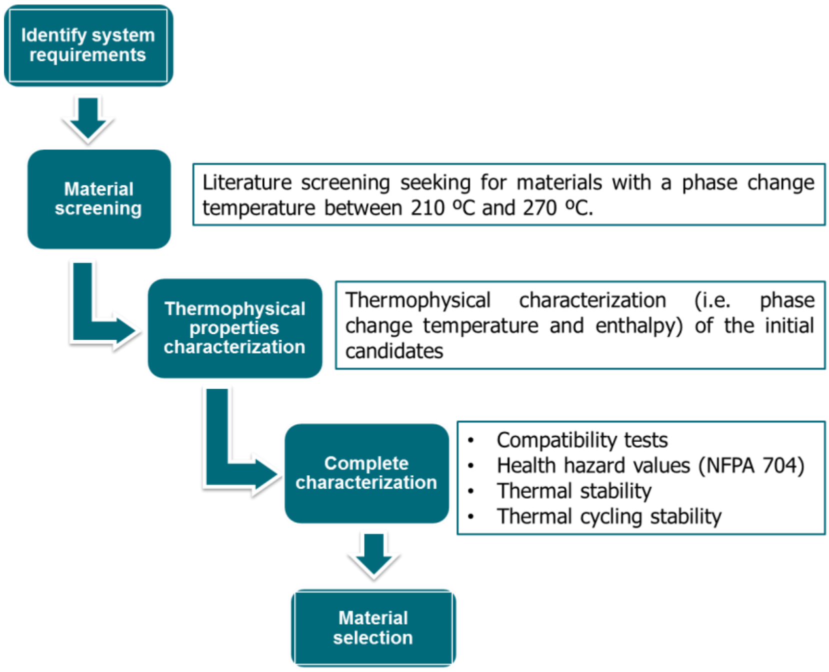

Figure 21. Material selection procedure.

Additionally, as the developed technology reached TRL 6, aiming to get TRL 9, a literature search was done regarding the energy demand and CO_2 emissions on the residential sector in Europe, which is the target market. Taking advantage of the energy consumption data collected and shown in paper 2 were also used to estimate the benefits of the designed CSP plant. By using solar data from EnergyPlus [70], the supposedly heat and electricity production of the prototype were calculated and hypothetical scenario was charted in Figure 22. Those charts show the energy consumption requirements per square meter and year for the different types of buildings while using the Innova MicroSolar power plant. The system is oversized for smaller residences such as single family or terrace houses (the production greatly exceeds the energy demand). However, when installing it in apartment blocks or multifamily dwellings the solar plant would require a backup system. This study allowed to put in place this technology within its target market.

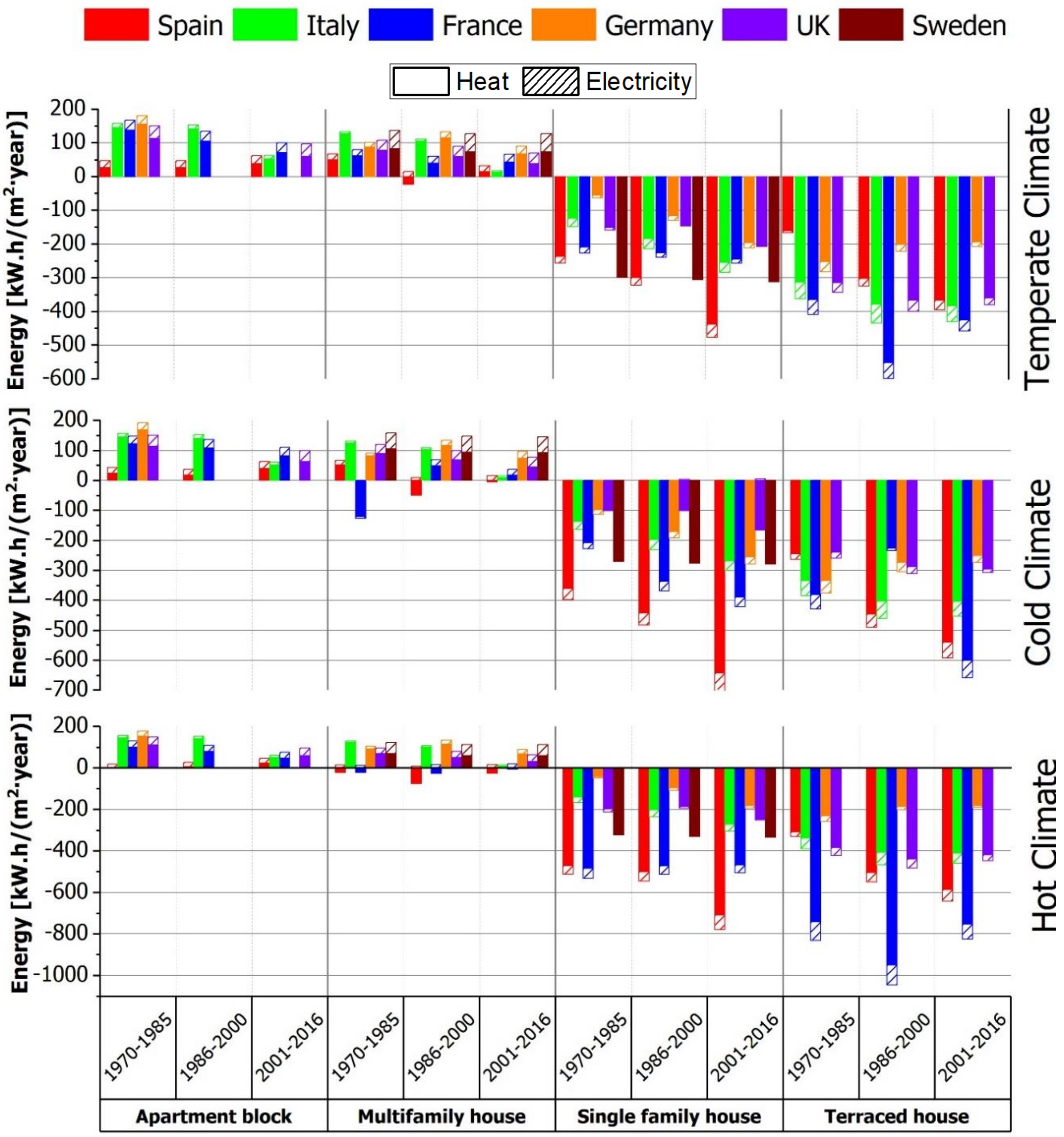

Figure 22. Estimated energy consumption requirements while using Innova MicroSolar technology at different countries and climates.

Aiming to study different heat transfer enhancement techniques, the second part of this thesis took place at lab scale and at low temperature. The goal of this part was to enhance the heat transfer in latent heat TES tanks. In doing so, the reference tank (shell and tubes configuration) was modified by adding fins, metal wool or by replacing the piping system by heat pipes. The system compactness was a must to fulfil along this study, the packing factor was taken into consideration for every configuration. The comparison was made regarding the packing factor in terms of temperature, power and process time. In the end, no matter the configuration, the PCM heat conductivity is the limiting factor which hampers this technology, so part of the materials has to be sacrificed to embed fins, or metal wool (or other technique such as nanoparticles) to enhance the TES power. The finned shell and tubes TES tank kept being the best option, metal wool turned to be a cheap solution which increased the charging rate up to 14%.

Heat pipes configurations were even more punished by the PCM low conductivity, since their high heat transfer ratios were cushioned by the PCM. When heat could not be transported within the PCM, the temperature around the heat pipe started to rise, decreasing the temperature gradient between both heat pipes tips. Lower temperature gradient can even stop the heat pipe cycle. Results also opened a new path to follow; many applications use heat pipes coupled with fins, as the high temperature latent heat TES tank designed within this thesis. Therefore, the future study yet to be done will focus on comparing the heat transfer improvement due to the fin attachment to copper pipe and heat pipes.

Chapter 5

Conclusions and future work

5.1 Conclusions

This PhD thesis broadens the knowledge about latent heat TES systems for high temperature applications, by developing a latent heat TES tank which operates from 210 ºC to 270 ºC. Additionally, it broadens the knowledge regarding the maximization of the heat transfer rate between latent the TES and the charging/discharging heat source.

More than 200 studies regarding the use of heat pipes coupled with latent heat TES systems, were reviewed. The main outcome of the review pointed out the gap within this technology, which was experimental research focused in high temperature applications (higher than 150 ºC). Many of those hybrid storage systems were thought to work in concentrated solar power applications, but tested at low temperature. Therefore, further experiments at high temperature with latent heat TES should be done.

Then a benchmark of the energy demand and CO_2 emissions on different residential buildings typologies was performed. This assessment allowed to find the hypothetical target on the market for the developed technology. The heating, DHW, and electricity consumption were assessed, as well as the CO_2 emissions derived from that consumption, taking into account the energy carrier. With those data the energy consumption requirements on the different scenarios could be estimated, while using the solar power plant designed in this PhD thesis. Confirming that the system is oversized for small residences (the production greatly exceeds the energy demand), and requiring a backup system for larger residential solutions such as apartment blocks. This study helped to target the potential users.

The material selection process stood out the lack of a cost-effective, and feasible material which offers high melting enthalpy and heat conductivity rates, fitting the application requirements. Solar salts were selected out of 26 materials, as they were affordable and the only ones to fulfil the application requirements. However, solar salts presented some drawbacks such as hysteresis, corrosion with several metals, low melting enthalpy, and low thermal conductivity. Therefore, there is a necessity to keep working in material development at the temperature range between 210 ºC to 270 ºC as it is one of the main barriers which is limiting the implementation of solar thermal power plants at these temperature levels.

The low heat conductivity of many PCMs limits its application into real energy systems, for that reason different heat transfer enhancement techniques are usually used into storage tanks. Therefore, at lab scale several heat transfer enhancement solutions were tested, fin addition, metal wool addition, and the use of heat pipes. A shell and tubes compact TES tank was designed and later modified to host heat pipes. In the end, eight different latent heat TES tank configurations were evaluated, all of them used n-octadecane as PCM. The finned shell and tubes TES tank was the best option. Also, the heat pipes margin for improvement was identified in terms of power and process uniformity. Further research is yet to be done in this way, by adding nano-particles into the PCM, or fins; to test the true potential of heat pipes. It has to be pointed out that the temperature gradient along the PCM in the shell and tubes TES tank boosted the convection mechanism, and consequently the melting process. This natural convention effect is hindered by the fins in the tank. Therefore, presumably fin implementation will mean a higher improvement in couple with heat pipes.

When going back to the high temperature application, the latent heat TES tank was designed following the lab scale research. Heat pipes were used, and to increase the heat transfer rate along the PCM part, fins were attached to the heat and embedded within the solar salts. All in all, this research pointed out that the future of latent heat thermal energy storages lies in material development. Therefore, thermal renewables energies which required a storage system to make them more competitive against conventional power plants, are in standby until a proper, cost-effective thermal storing material came forward.

5.2 Future work

The research presented in this PhD thesis provides increased the knowledge about latent heat TES systems for high temperature applications. However, further research still is needed to fully reach a commercial high temperature latent heat TES solution. The next step is to achieve the experimental testing of the high temperature latent heat TES at the solar power plant, which was stopped because of the worldwide pandemic situation that happened in 2020. In parallel, at lab scale, fins will be added into heat pipe TES design; so, the extent to which the fins improve the different systems could be experimentally tested.

Finally, during this thesis a detailed heat pipe CFD model coupled with PCM was started. Therefore, with the experimental results at low and high temperature, the model could be doubly validated, providing a useful tool to design and optimize future latent heat TES systems prior its manufacturing.

Other research activities

Other journal publications

The PhD candidate carried out other scientific research besides the one presented in this thesis during the execution of his PhD. The resulting publications are listed below:

1. **Maldonado JM**.; de Gracia A.; Zsembinszki G.; Moreno P.; Albets X.; González MA.; Cabeza LF. Frost detection method on evaporator in vapour compression systems. 904741. Int J Refrig 2020; 110:75–82. https://doi.org/10.1016/j.ijrefrig.2019.10.023.
2. **Maldonado JM**.; Zsembinszki G.; de Gracia A.; Moreno P.; Albets X.; González MA.; Cabeza LF. Control strategies for defrost and evaporator fans operation in walk-in freezers. Int J Refrig 2018; 91:101–10. https://doi.org/10.1016/j.ijrefrig.2018.05.025.
3. Arteconi A.; Del Zotto L.; Tascioni R.; Mahkamov K.; Underwood C.; Cabeza LF.; **Maldonado JM**.; Manca R.; Minsta AC.; Bartolini CM.; Gimbernat T.; Botargues T.; Halimic E.; Cioccolanti L. Multi-Country Analysis on Energy Savings in Buildings by Means of a Micro-Solar Organic Rankine Cycle System: Environments 2018;5:119. https://doi.org/10.3390/environments5110119.

Contributions to international conferences

The PhD candidate contributed to some international conferences:

1. **Maldonado JM**; de Gracia A; Mahkamov; Costa C; Kenisarin M; Pili P; Manca R; Leroux A; Mintsa AC; Bartolini CM; Pirro M; Lynn K; Mullen D; Halimic E; Cioccolanti L; Arteconi A; Gimbernat T; Botargues T; Cabeza LF. Innovative concentrated solar micro organic Rankine cycle Plant system for residential buildings. Eurotherm Seminar #112 - Advances in Thermal Energy Storage 2019, Lleida (Spain).
2. **Maldonado JM**; Zsembinszki G; de Gracia A; Moreno P; Albets X; González MA; Cabeza LF. Procedure of frost level detection and quantification in vapour compression systems. 11CNIT 2019 - XI National and II International Engineering Thermodynamics Congress, Albacete (Spain).

3. **Maldonado JM**; de Gracia A; Mahkamov; Costa C; Kenisarin M; Pili P; Manca R; Leroux A; Mintsa AC; Bartolini CM; Pirro M; Lynn K; Mullen D; Halimic E; Cabeza LF. Ensayos preliminares de una microturbina de ciclo orgánico de Rankine alimentada por un campo solar de concentración tipo Fresnel lineal. CIES 2018 - XVI Congreso Ibérico y XII Congreso Iberoamericano de Energía Solar, Madrid (Spain).
4. Coma J; **Maldonado JM**; de Gracia A; Gimbernat T; Botargues T; Cabeza LF. Benchmarking of energy demand of residential buildings. ENERSTOCK 2018 - The 14th International Conference on Energy Storage, Adana (Turkey).
5. Zsembinszki G; **Maldonado JM**; de Gracia A; Moreno P; González MA; Cabeza LF. Study on the effect of using the evaporator ice as energy storage in a walk-in freezer. ENERSTOCK 2018 - The 14th International Conference on Energy Storage, Adana (Turkey).
6. Coma J; **Maldonado JM**; de Gracia A; Gimbernat T; Botargues T; Cabeza LF. Benchmarking of energy demand of domestic and small business buildings. 10CNIT 2017 – 10^{th} Thermodynamic Engineering International Conference, Lleida (Spain).
7. Coma J; **Maldonado JM**; de Gracia A; Gimbernat T; Botargues T; Cabeza LF. Benchmarking of energy demand of domestic and small business buildings. BIRES – First International Conference on Building Integrated Renewables Energy Systems, Dublin (Ireland).
8. Coma J; **Maldonado JM**; de Gracia A; Gimbernat T; Botargues T; Cabeza LF. Comparative analysis of energy demand and CO2 emissions of residential buildings. ISES Solar World Congress 2017 and SHC2017 - Abu Dhabi (United Arab Emirates).

Scientific reports

The PhD candidate also contributed to scientific reports in the framework of Innova MicroSolar H2020 European project:

1. **Maldonado JM,** Cabeza LF. Innova MicroSolar Project of Horizon 2020 – Deliverable 2.1 - Report on the benchmark of architecture of domestic residential buildings and their seasonal and annual energy demands. 2017.

2. **Maldonado JM,** Cabeza LF. Innova MicroSolar Project of Horizon 2020 – Deliverable 2.2 - Report on the benchmark of architecture of small business buildings and their seasonal and annual energy demands. 2017.
3. **Maldonado JM,** Cabeza LF. Innova MicroSolar Project of Horizon 2020 – Deliverable 2.3 - Report on the benchmark of buildings integration requirements. 2017.
4. **Maldonado JM,** Cabeza LF. Innova MicroSolar Project of Horizon 2020 – Deliverable 2.4 - Report on the benchmark of energy and carbon saving targets. 2017.
5. **Maldonado JM,** Cabeza LF. Innova MicroSolar Project of Horizon 2020 – Deliverable 3.3 – PCM compound with expandable graphite additives to ensure the required value of the thermal conductivity. 2017.
6. **Maldonado JM,** Cabeza LF. Innova MicroSolar Project of Horizon 2020 – Deliverable 5.1 – Demonstration: System integration, evaluation and optimisation. 2019.

Scientific foreign-exchange

The PhD candidate did one stay abroad during the development of this PhD thesis.

Gannon University (Erie, PA. USA).

The research stay done by the candidate was carried out at the Gannon University. The exchange was possible thanks to the mobility scholarship funding included with the student fellowship (BES-2016-076554). In this research stay, the candidate worked on the development of detailed heat pipe coupled with PCM CFD numerical model. The model was designed in C++ to use an open source tool which could be later combined with an optimization software (GenOpt).

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Others activities

Projects participation

1. Innovative Microsolar Heat and Power Systems for Domestic and Small Business Buildings compact hybrid storage systems for low energy buildings (INNOVA MICROSOLAR). European Union's Horizon 2020 research and innovation programme under grant agreement n° 723596, 2016-2021.
2. Methodology for analysis of thermal energy storage technologies towards a circular economy (MATCE). Ministerio de Ciencia, Innovación y Universidades de España, RTI2018-093849-B-C31 - MCIU/AEI/FEDER, UE, 2019-2021.
3. Red Española en Almacenamiento de Energía Térmica (RED-TES). Ministerio de Ciencia, Innovación y Universidades de España, RED2018-102431-T, 2020-2021.
4. GREiA. Grup de Recerca en Energia i Intel·ligència Artificial (SGR). Generalitat de Catalunya, 2017 SGR 1537, 2017-2020.
5. Identificación de barreras y oportunidades sostenibles en los materiales y aplicaciones del almacenamiento de energía térmica (SOPPORTES). Ministerio de Ciencia e Innovación, ENE2015-64117-C5-1-R, 2016-2018.
6. Implementación de los algoritmos de control estándar y avanzados que permitan mirar la eficiencia (C16027). CDTI Project IDI-20160143, 2016-2017.

Organizing committee participation

1. Researchers' Night 2018, 13th edition 2018. Lleida, Spain.
2. Researchers' Night 2019, 14th edition 2019. Lleida, Spain.
3. Researchers' Night 2020, 15th edition 2020. Lleida, Spain

Patents

1. A computer implemented method, a computer program, and an apparatus for the diagnosis of anomalies in refrigeration system. European Patent Application No. 3477409B1. Registered 2017, October 31.
2. Adaptive control method for refrigeration systems. International Patent No. 2018178405A1. Issued 2017, April 5.

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