Universitat de Lleida

Smart control techniques for thermal energy storage systems

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TESI DOCTORAL

Universitat de Lleida

Smart control techniques for thermal energy storage systems

Joan Tarragona Roig

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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Departament d'Informàtica i Enginyeria Industrial
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CERTIFIQUEN:

Que la memòria *Smart control techniques for thermal energy storage systems* presentada per Joan Tarragona Roig per optar al grau de Doctor s'ha realitzat sota la seva supervisió.

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Summary

The use of energy from renewable sources is important in the fight against the climate change. However, the intermittence of their sources and the constant mismatch between energy supply and demand hamper its global integration. Therefore, thermal energy storage technologies become crucial to overcome the aforementioned disadvantages. Systems based on this technology must meet various requirements in order to be more competitive. Among the different requirements, this PhD thesis is framed in the study of a model predictive control strategy to improve the operation of a sensible thermal energy storage system. To do that, water was employed as storing material in a hybrid heating system based on a heat pump that can be supplied either by PV panels or through the electricity grid. Then, the performance of the system and the ability of model predictive control to manage the interaction among the thermal energy storage tank, PV panels, and the heat pump performance was studied at simulation level. The main goals of coupling a model predictive control strategy with a thermal energy storage tank were to minimize the operational cost of the hybrid heating system and to exploit the use of the storage to justify its initial investment. In that sense, the model predictive control strategy used a dynamic approach based on forecasting all energy inputs into the system in advance, before taking any operational decision. Through this prediction ability, the model predictive control strategy could decide to store heat surpluses in the thermal energy storage tank to consume them later, during the peak consumption hours. Moreover, the coupling between model predictive control and thermal energy storage allowed to take advantage of electricity time-of-use tariff structures, obtaining more reductions in the final energy cost. Simulation results provided guidelines to set the model predictive control operation conditions that achieve the highest economic savings. A prediction horizon of 24 hours was demonstrated to be the optimum to control the studied hybrid heating system with thermal energy storage. Moreover, simulations showed that the coupling of model predictive control, thermal energy storage, and solar PV panels was able to obtain higher energy cost reductions than the three technologies by themselves. Finally, model predictive control confirmed these capacities, overcoming the performance of other traditional control strategies when controlling the same hybrid heating system.

Resum

Augmentar l'ús d'energia provinent de fonts renovables és important en la lluita contra el canvi climàtic. No obstant, la falta de continuïtat en la seva generació i el constant desajust que existeix amb els perfils de consum obstaculitzen la seva integració. Per tant, les tecnologies d'emmagatzematge d'energia tèrmica han esdevingut crucials per sobreposar-se a aquests inconvenients. Els sistemes basats en aquesta tecnologia han de complir diversos requeriments per tal de ser més competitius. Entre ells, aquesta tesis doctoral està emmarcada en l'estudi d'una estratègia de control predictiu per millorar el funcionament d'un sistema d'emmagatzematge d'energia tèrmica. Per fer-ho, es va utilitzar aigua com a material d'emmagatzematge en un sistema de calefacció híbrid basat en una bomba de calor, la qual podia funcionar amb panells fotovoltaics o bé a través de la xarxa elèctrica. Es va estudiar el rendiment del sistema a nivell de simulació i l'habilitat de l'estratègia de control per dirigir la interacció entre el tanc d'emmagatzematge, els panells fotovoltaics i el funcionament de la bomba de calor. Els principals objectius d'emparellar l'estratègia de control predictiu amb un tanc d'emmagatzematge d'energia tèrmica eren minimitzar els costos operacionals del sistema híbrid de calefacció i explotar el potencial de l'emmagatzematge per justificar la seva inversió inicial. En aquest sentit, l'estratègia de control predictiu utilitzava un enfocament dinàmic basat en predir totes les entrades d'energia del sistema abans de prendre les decisions operacionals. A través d'aquesta habilitat de predicció, l'estratègia de control podia decidir emmagatzemar excedents de calor en el tanc d'emmagatzematge per consumir-los durant les hores amb més volum de consum energètic. A més, l'emparellament entre el control predictiu i l'emmagatzematge d'energia tèrmica va permetre aprofitar les estructures de les tarifes elèctriques amb discriminació horària i reduir així encara més els costos. Els resultats de les simulacions van donar les directrius per configurar les condicions de treball de l'estratègia de control predictiu que més estalvis aconseguia. Un horitzó de predicció de 24 hores va demostrar ser l'òptim pel control del sistema de calefacció híbrid amb emmagatzematge. Addicionalment, les simulacions van mostrar que la unió de l'estratègia de control predictiu, l'emmagatzematge d'energia i els panells fotovoltaics va ser capaç de reduir més el cost, que utilitzades de forma individual. Finalment, l'estratègia de control predictiu va confirmar aquestes capacitat, superant el rendiment d'altres estratègies de control tradicional estudiades en el mateix sistema de calefacció.

Resumen

El uso de energía procedente de fuentes renovables es importante en la lucha contra el cambio climático. Sin embargo, la intermitencia de sus fuentes y el constante desajuste entre la oferta y la demanda de energía dificultan su integración global. Por lo tanto, las tecnologías de almacenamiento de energía térmica se vuelven cruciales para superar estas desventajas. Los sistemas basados en esta tecnología deben cumplir varios requisitos para ser más competitivos. Entre ellos, esta tesis doctoral se enmarca en el estudio de una estrategia de control predictivo para mejorar el funcionamiento de un sistema de almacenaje de energía térmica sensible. Para ello, se empleó agua como material de almacenamiento en un sistema de calefacción híbrido basado en una bomba de calor que podía ser alimentada por paneles fotovoltaicos o por la red eléctrica. Se estudió a nivel de simulación el desempeño del sistema y la capacidad de la estrategia de control predictivo para gestionar la interacción entre el tanque de almacenaje, los paneles fotovoltaicos y el desempeño de la bomba de calor. Los objetivos principales de acoplar una estrategia de control predictivo con un tanque de almacenaje de energía térmica fueron minimizar el coste operacional del sistema de calefacción híbrido y aprovechar al máximo el almacenaje para justificar su inversión inicial. En ese sentido, la estrategia de control utilizó un enfoque dinámico basado en pronosticar todas las entradas de energía en el sistema por adelantado, antes de tomar cualquier decisión operativa. Mediante esta capacidad de predicción, la estrategia de control podía decidir almacenar los excedentes de calor en el tanque de almacenamiento de energía térmica para consumirlos más tarde, durante las horas de más consumo. Además, el acoplamiento entre el control predictivo y el almacenaje de energía térmica permitió aprovechar las estructuras tarifarias de electricidad con discriminación horaria, obteniendo mayores reducciones en el coste energético final. Los resultados de la simulación proporcionaron pautas para establecer las condiciones de operación del control que lograron los mayores ahorros económicos. Se demostró que un horizonte de predicción de 24 horas es el óptimo para controlar el sistema de calefacción híbrido estudiado con almacenaje. Además, las simulaciones mostraron que el acoplamiento de control, almacenaje y paneles fotovoltaicos pudo obtener mayores reducciones de costes de energía que las tres tecnologías por sí mismas. Finalmente, el control predictivo confirmó estas capacidades, superando el desempeño de otras estrategias tradicionales al controlar el mismo sistema de calefacción híbrido.

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List of symbols and abbreviations

Symbols

k	Current instant	-
δ	Time step	seconds
N_p	Prediction horizon	Time steps
N_c	Control horizon	Time steps
μ	Micro-slot	seconds

Abbreviations

TES	Thermal energy storage
MPC	Model predictive control
HVAC	Heating, ventilation, and air conditioning
ToU	Time-of-use
IEA	International Energy Agengy
PCM	Phase change material
VRE	Variable renewable energy
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
IRR	Internal rate of return
CSP	Concentrated solar plants

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Chapter 1

1. Introduction, objectives, and PhD thesis structure

1.1 Introduction

In this chapter, the motivation of the present PhD is explained from a personal and general perspectives. Additionally, the objectives pursued throughout its development are detailed. Finally, the PhD structure is showed through a flowchart.

1.1.1 Motivation/Overview/Background

Research is commonly defined as the creation of new knowledge or the use of the existing knowledge in a new way, aiming to develop new concepts, methodologies, and understandings. Therefore, from my point of view, research is one of the branches of our society that works to improve our quality of life and to transform our world in a more sustainable place. This idea was the mainstay of the present PhD and the goal that pushed me during its development.

The industrial revolution (18^{th} and 19^{th} centuries) represented a turning point from a global development perspective. Human being discovered that when burning fuel, they could obtain power and they could substitute their both hand production processes and work with animals for faster and powerful machines. However, this successful discovering evolved as an overuse of fossil fuels, especially during the last decades.

This excess of energy consumption started a global problem with no borders and hazardous for both human health and the environment, a problem called climate change. Thousands of people are affected every year by respiratory diseases induced by different air pollutants and greenhouse gases, as it was stated by the World Health Organisation [1]. Moreover, the World Economic Forum pointed out both failure of climate action and extreme weather events as two of the most important global risks during last years and the ones that can drive our society to a climate catastrophe [2]. Thus, the world is reaching the limit from both health and environmental perspective and climate change is one of the main global issues that needs to be tackle.

Considering the scenario that the world continues along its current path, energy demand will continue rising around 1.3% each year to 2040 [3]. Therefore, different actions should be implanted to reduce the impact of such increase of energy demand while the efficiencies in processes are improved. To have a better understanding, in Figure 1 the total final energy consumption of each sector during the period from 2007 to 2017 is illustrated. Moreover, the yearly CO_2 emissions can be seen (data from International Energy Agency (IEA)).

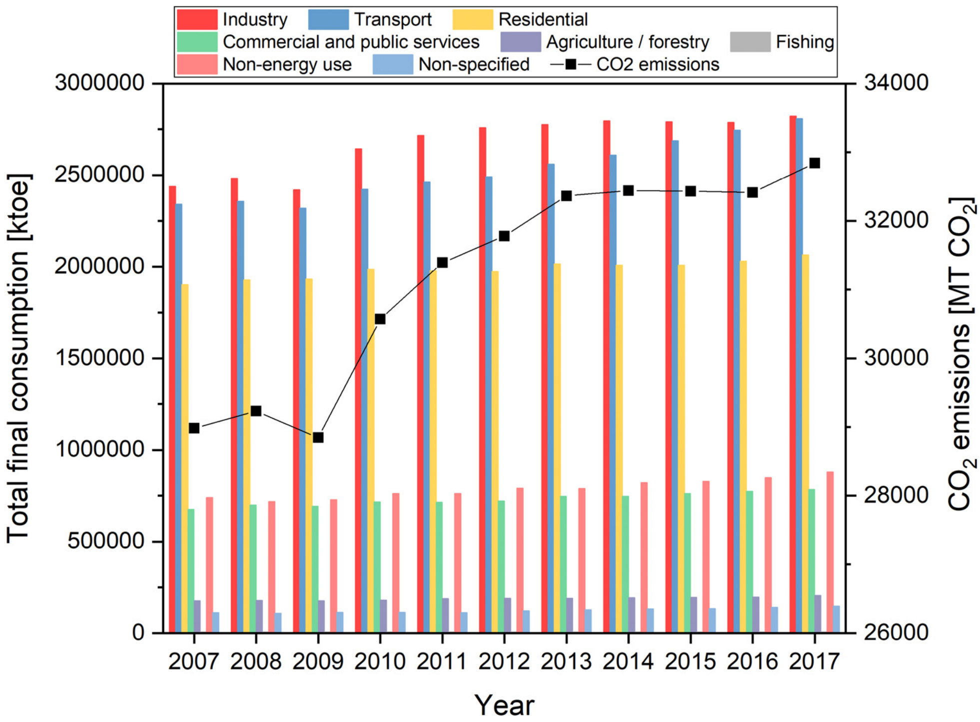

Figure 1. Total energy consumption of each sector and global CO_2 emissions.

Overall, there are two main ideas that can be extracted from this graph:

- Firstly, the total final energy consumption increased every year, highlighting industry, transport, and residential sectors as the ones with more significance in the final values.
- Secondly, CO_2 emissions had an increasing tendency during the whole studied period, which experienced a dramatically growth in 2010. Although from 2013 to

2017 shows a constant tendency, a CO_2 mitigation becomes urgent to be implemented, due to its high values.

Therefore, the current situation of climate change requires actions to reduce both energy consumption coming from fossil fuels and their related CO_2 emissions. According to the IEA [4], the integration of variable renewable energy (VRE) technologies in power systems is crucial to achieve a decarbonisation of the power sector, while the global increasing demand is supplied. In Figure 2, the six different phases in which IEA categorised the integration of VRE and their key transition challenges are explained in detail.

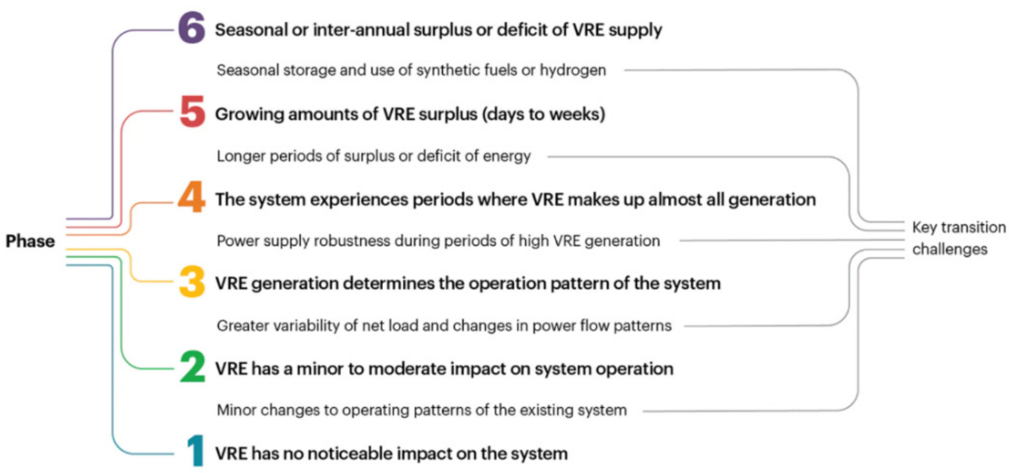

Figure 2. Key characteristics and challenges in the different phases of system integration [4].

It is worth to note that the implementation of the appropriate measures to support the integration of VRE systems can drive the share of renewables to achieve a significant growth at low, mid, and high scale. However, this remarkable impact is reached from phase 3 onwards, since phases 1 and 2 have no immediate impact and many flexibility issues emerge in these stages. Thus, the key challenges to obtain greater influence and to go ahead among the advanced phases are presented as follows:

- Additional investments such as energy storage systems are required to obtain more flexibility in the system operation.
- The necessity of surpluses of VRE generation, leading to curtailment peaks of demand.

- To couple different knowledge areas to overcome structural imbalances in energy supply at seasonal and inter-year periods.

Therefore, after presenting the main climate change challenges and the key points to overcome the main drawbacks identified by IEA, a deep analysis among the available VRE resources was carried out, finding out solar energy as one of the most powerful. Its suitability for different kind of energy system and its high potential to supply an important part of the energy demand were identified as two great advantages compared to the other renewable resources. To assess its current relevance, an increase of its market share was noticed during the last decade. The aforementioned system integration benefits, together with new policies implanted from the governments were traduced in a higher implantation of solar PV panels during the last decade, where their energy capacity went from 23 GW on 2009 to 627 GW on 2019 worldwide (an increase of 2626%) [5]. The yearly evolution of the solar PV global capacity together with the annual increase compared to the year before can be seen in Figure 3.

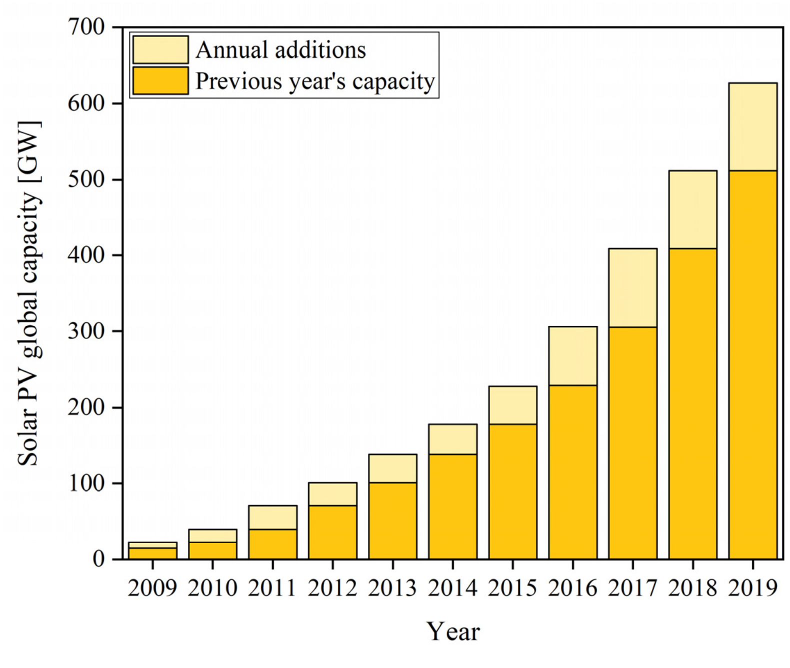

Figure 3. Solar PV global capacity and annual additions [5].

Even though the impact of solar PV looks suitable, the reality is that to achieve both short and long-term goals defined in the climate transition framework [6] requires a higher effort to have the desired global effect. In that sense, analysing the high-demanding sectors presented in Figure 1, residential sector was figured out as one of the sectors with more possibilities to increase the rate of renewables in its final energy consumption. Nowadays, only 13.6% of the total final energy consumption in buildings is produced by modern renewables (Figure 4). Within this percentage, the electricity produced by PV panels constitutes 8.3% of the total [7].

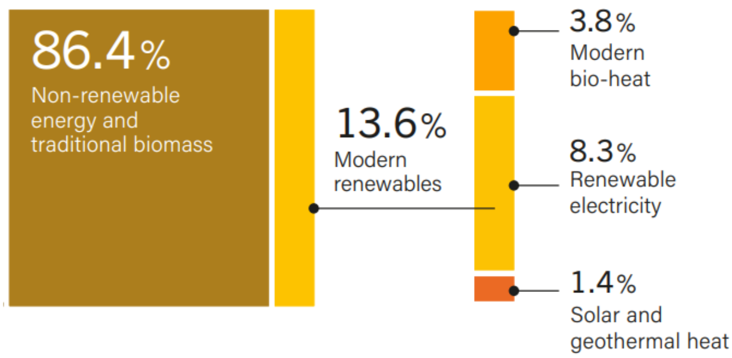

Figure 4. Renewable share of total final energy consumption in buildings [7].

As it can be seen, there is a renewable energy gap in the residential sector, since its impact is significantly low. The main reason is because of the mismatch in the time between the energy production and peak loads, which is pointed out as the main drawback to increase the incidence of this technology. Another important factor that hampers its integration is the high price of the equipment, which made difficult to justify its initial investment. Therefore, to find a system able to store energy during the hours with higher solar energy generation is essential to take advantage of the full potential of PV panels. In that sense, a first attempt to store the electricity produced by PV panels was done with electrical batteries. However, the low performance of these storage equipment together with their high price did not encourage the users to integrate them into households. Later on, thermal energy storage (TES) systems appeared in the market as a great option to substitute electrical batteries and to integrate solar PV panels in buildings. Its ability to store energy during solar hours and to consume this surplus during peak periods became crucial to improve the global performance of systems with solar PV panels [8]. Thus, an accurate and detailed analysis should be developed to evaluate the potential of TES in buildings with solar PV panels.

1.1.2 Thermal energy storage and model predictive control

The type of application where can be implanted each storage system was assessed by the IEA [9]. The aim of this study was to establish the relation between the power requirement and the discharge duration of different energy storage technologies. This evaluation is shown in Figure 5, where the main storage technologies are depicted.

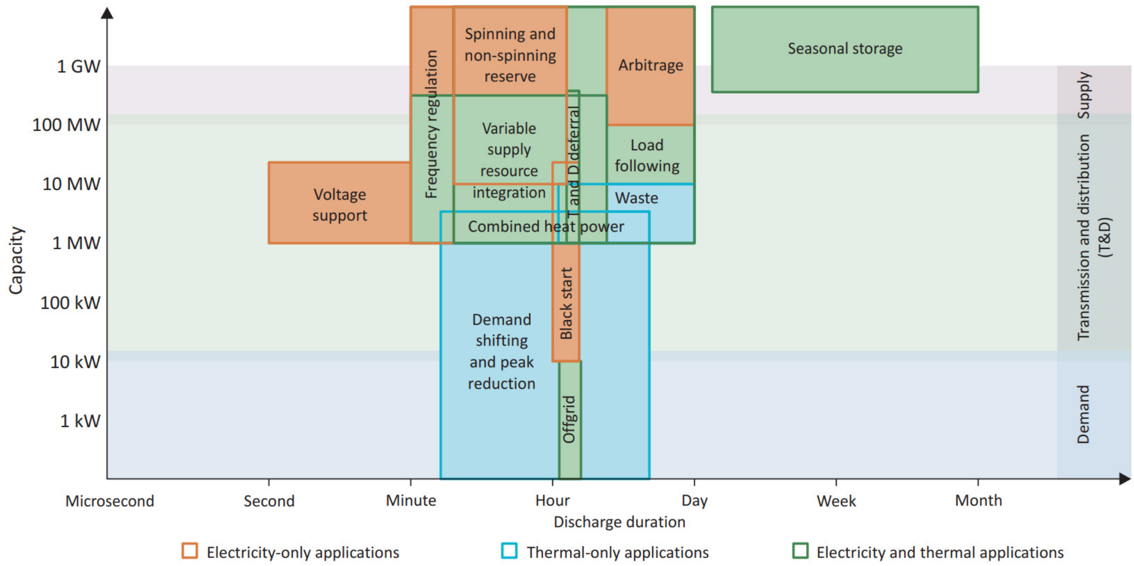

Figure 5. Power requirement versus discharge duration for some applications [9].

Focusing on demand shifting and peak reduction, and off grid technologies, the discharge duration of TES at low capacity ranges between some minutes and practically one day. Thus, these TES applications fit very well to the energy requirement of residential systems, where the energy demand is small and they can take advantage of daily solar hours. Moreover, the small response time of these TES technologies made them suitable to be applied in buildings both for space heating or domestic hot water applications.

In the market, there are two types of TES systems that are used to be implemented in buildings [10]:

- Passive systems: The main objective of these technologies is to reduce as much as possible the use of heating, ventilation, and air conditioning (HVAC) energy. Commonly, the storage in these technologies is carried out in high thermal mass materials as are rammed earth, alveolar bricks, concrete, or stone [11].

- Active systems: The main contributions of these technologies are their capacity to be implemented in HVAC systems with renewable energy resources, the performance enhancing of the current HVAC operation, and its ability to take advantage of peak load shifting applications.

Therefore, after reviewing the main characteristics of different TES technologies, active systems were pointed out as the branch of TES with more possibilities to work together with solar systems. In the market there are different storage techniques that can be employed as active systems. Overall, they are divided into two different categories, depending on the type of storage that the user wants to obtain:

- Latent storage: The energy is stored in a phase change material (PCM). Taking advantage of its latent heat, during the phase change the material stores/delivers a high quantity of energy, following an almost isothermal behavior.
- Sensible storage: There is no phase change throughout the system working range and only the temperature of the storage medium is increased or decreased.

Considering TES at low temperatures (50-100 ºC), PCMs do not offer remarkable energy storage advantages compared to sensible storage systems [12] and also they are commonly expensive. Moreover, the poor stability of the materials properties due to thermal cycling and the corrosion between the PCM and the storage vessel were identified as two important drawbacks that limit the latent storage application. Therefore, to integrate a solar system within a residential HVAC, sensible storage was pointed out as a suitable option.

Among all the materials that can act as sensible storage media, water is an interesting option, since it is non-hazardous, abundant, environmentally friendly, and it is low cost material. Also, its universal availability makes the coupling of solar energy and water TES as crucial to move current residential HVAC towards low carbon energy systems.

Nevertheless, to fully exploit the advantages given by TES systems, a control strategy that manages its operation according to the building HVAC requirements is necessary. In that sense, different approaches were tested by researches, looking for the most suitable one. Aiming to obtain a balance between a control strategy that provides a fast computation and, economic and energy savings, model predictive control (MPC) was recommended by Thieblemont et al. [13] to be implemented in HVAC systems with TES.

To have a better understanding of how MPC works, Figure 6 depicts a scheme of the timeline that describes the operational evolution of MPC along its optimization process.

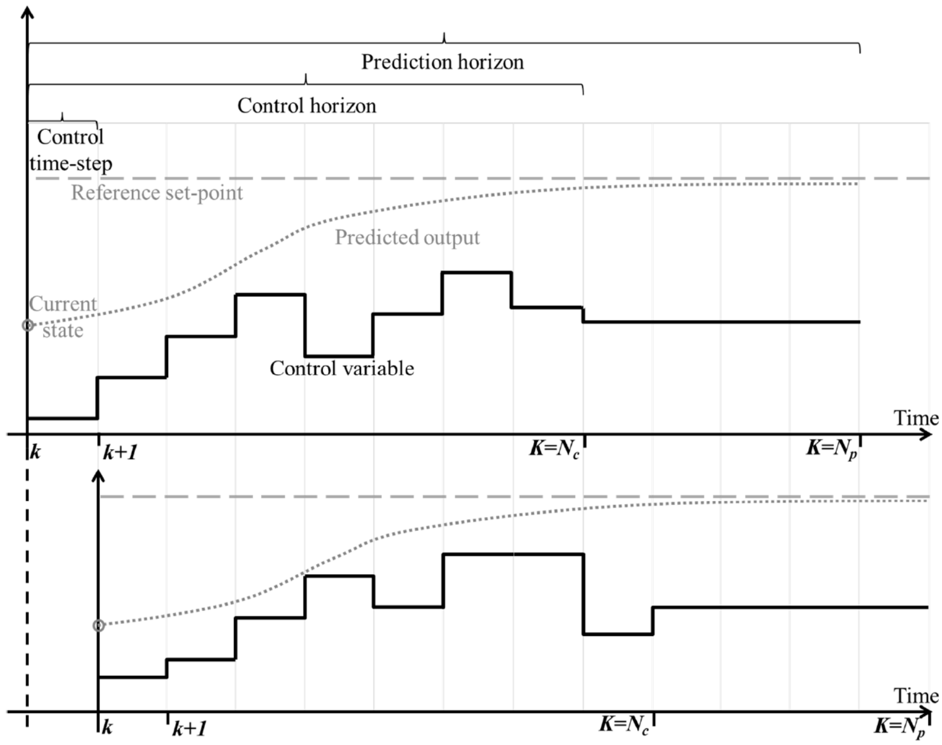

Figure 6. Operation scheme of MPC strategies [14].

The main notation elements that are shown in the figure are described as follows [14]:

- Current state (k): It is the moment where the controller starts to analyse the future conditions and select the optimum option.
- Control time step (δ): It is the slot time of the data that the control strategy employs to calculate future decisions.
- Prediction horizon (N_p): It defines the number of time steps that the system will analyse in advance before taking any decision.
- Control horizon (N_c): It is the number of variables that defines the dimension of the optimization vector.

To sum up, the features of MPC allow the global system operation to take advantage of the future conditions prediction to minimize the objective function defined by the user.

Then, concerning its application to heating systems with both PV panels and TES, MPC allows the HVAC to operate considering future conditions and, consequently, optimizing its energy consumption of the system.

1.2 PhD objectives

Considering the available literature, from both energy and economic points of view, the coupling between TES and MPC was demonstrated as a substantial improving among the techniques to enhance solar PV panels implementation in residential heating systems. The first objective is to analyse the state-of-the-art to find out the main gaps that still have to be investigated in the application of MPC to manage an HVAC system with TES.

After that, the aim of the present PhD is to develop an MPC tool able to manage a residential heating system, based on an air-to-water heat pump, with solar PV panels and sensible TES. Moreover, grid supplying following a time-of-use (ToU) tariff structure will be considered, to study the effect of MPC upon peak load shifting.

Additionally, to reinforce the potential of MPC, a comparison of its behavior in different climate zones will be done. Its capability to manage both HVAC and TES systems in different locations with multiple weather conditions becomes a key point to validate the robustness of the model. Then, the MPC performance in the aforementioned study will be compared to other non-smart control strategies.

However, to fully exploit the studied system, a proper sizing of both PV panels and TES tank will be required. Therefore, the optimal size of these elements will be studied, depending on the location, building use, and the its occupancy schedule.

1.3 PhD thesis structure

The present PhD thesis was divided into five different chapters. More details in the structure distribution can be seen in Figure 7. In the first chapter the introduction, the objectives in which this thesis was framed, and its structure are presented. The second chapter details the methodology that this PhD have followed throughout its development. Chapter three explains all papers that this PhD comprises, providing for all of them the overview of the study, its contribution to the state-of-the-art, and the contribution from the candidate. After that, chapter four explains the results obtained in the thesis and a global discussion. Finally, chapter five highlights the main conclusions extracted from this PhD and the recommendations for future work.

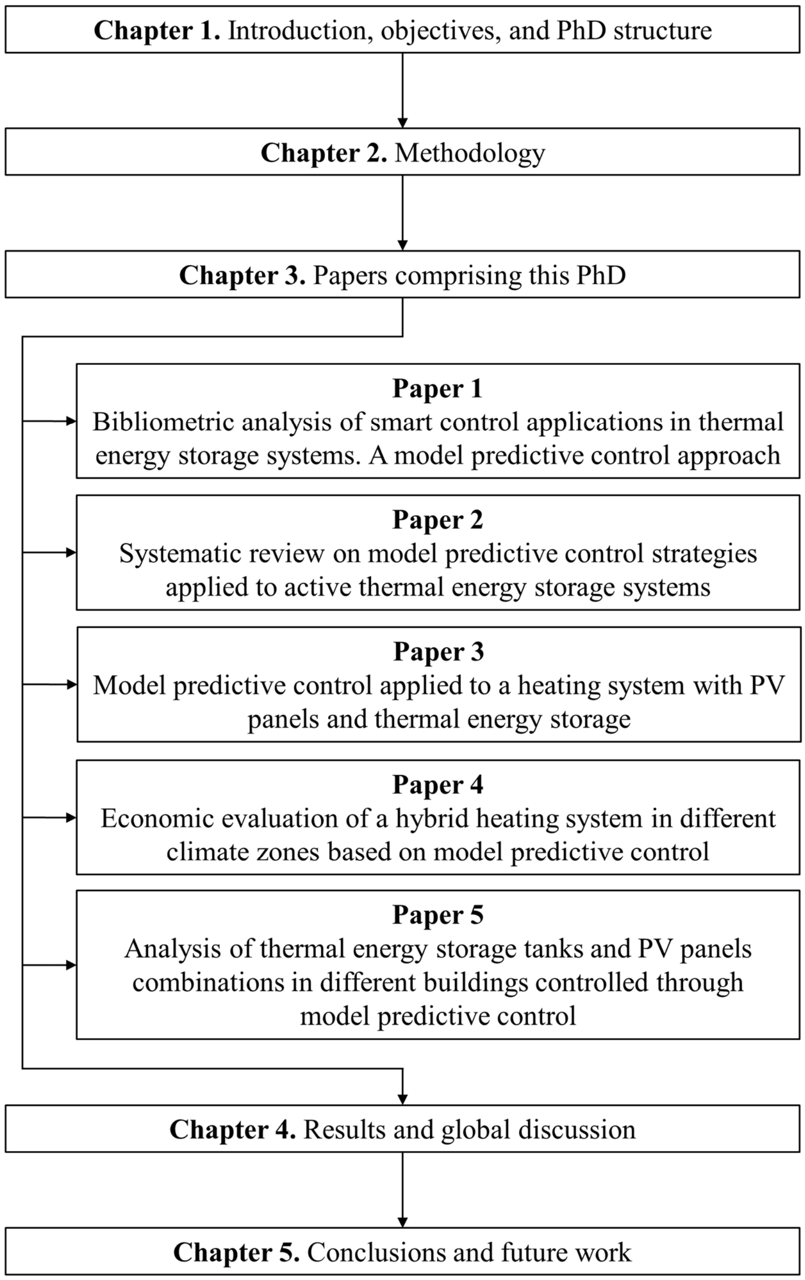

Figure 7. PhD structure.

Chapter 2

2. Methodology

This PhD aims to study the performance of an MPC strategy when managing a hybrid heating system based on an air-to-water heat pump that can be supplied by both PV panels and the electricity grid. Also, the heat pump has connection to a water TES tank, which can supply energy directly to the building. To have an overview of the path followed during its development, this study can be divided into two main groups, study and assessment of the available literature, and economic impact of the MPC strategy. A scheme of this PhD distribution can be seen in Figure 8, where a relation between the research approaches and the papers that were extracted from each of them is presented.

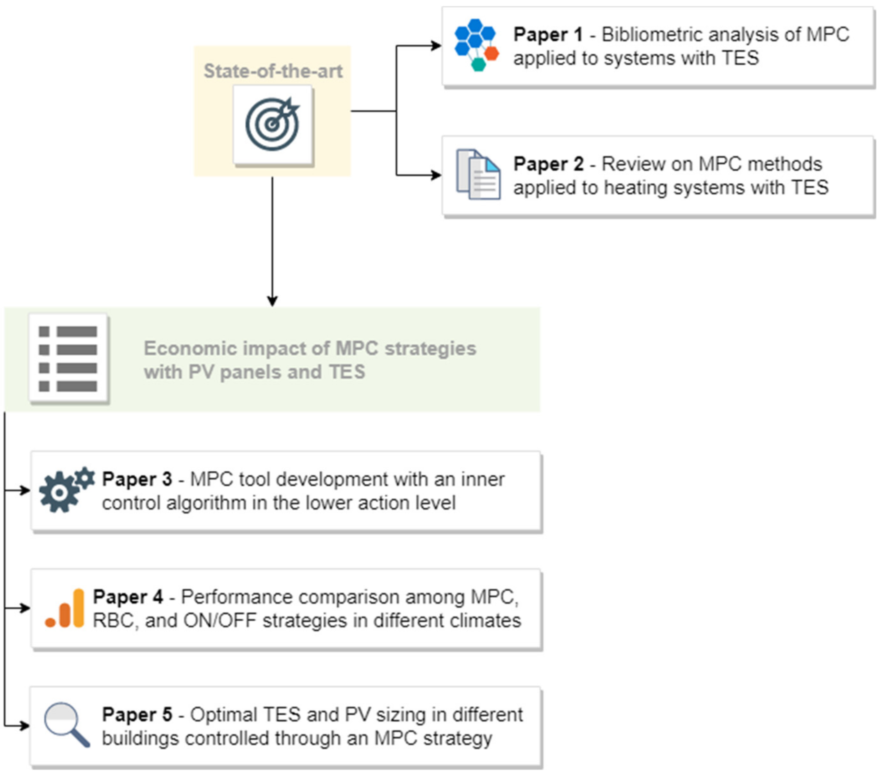

Figure 8. Studies distribution of the PhD.

The study of the state-of-the-art was divided into two different approaches: a bibliometric analysis and a review. First, in the bibliometric analysis of "paper 1", the main literature gaps of the topic were identified. A global examination of the topics and keywords explored by researchers so far was carried out using specific tools to analyse the existent literature. Second, the review in “paper 2” provided a more accurate study of the content of these research papers and it gave an overview of the state-of-the-art, identifying the most common approaches of MPC throughout last years. Moreover, the main challenges that should be explored more into detail in MPC systems with TES were described and remarked in this literature review.

After reviewing the studies published until now, an MPC tool able to operate in a system with a TES tank and supplied by PV panels and the electricity grid, following a ToU tariff structure was developed in “paper 3”. Different settings were analysed in this study, aiming to find out the best trade-off between computation time and accuracy in the final outcomes. In that sense, a double-level MPC controller was created with two levels of actuation. At the high level, the MPC strategy worked with a prediction horizon (N_p) of 24 hours and a time step (δ) of 1 hour, minimizing the final cost after considering all energy fluxes. Then, at the low level, a tool called inner control algorithm was designed to adjust the deviations between the decisions of the MPC controller at high level and the real values given by the system using a shorter time step (μ) of 5 minutes. At this low level, the concept of micro slot was created, meaning that the level of actuation of the low controller was 12 times higher than the high level one (number of micro slots). To have a clearer view of the presented MPC strategy and its inner control algorithm, a scheme of the timeline that describes such double-level operation can be seen in Figure 9. The prediction horizon N_p was defined by the number (n) of time steps (δ) that analysed the MPC strategy before taking a decision.

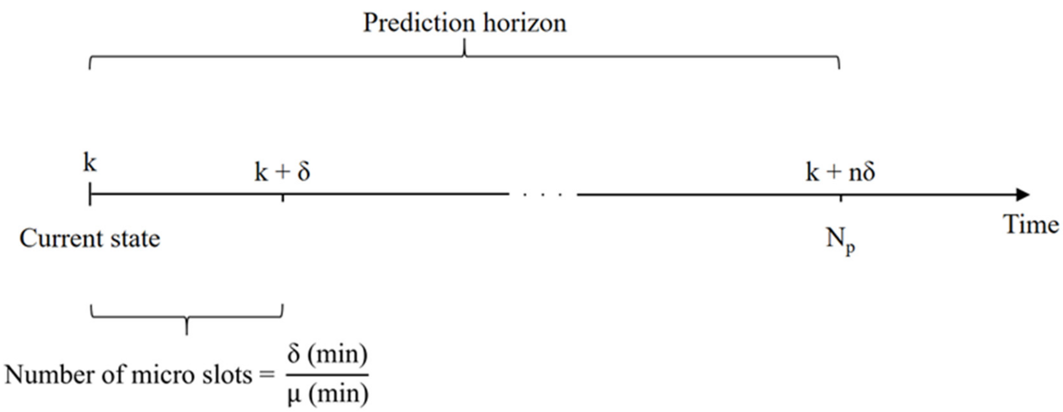

Figure 9. Scheme of the MPC double-level actuation.

Afterwards, to analyse the advantages of the MPC operation in these kind of systems against other control strategies, the performance of MPC was compared against a rule-based control strategy and an ON/OFF controller in “paper 4”. These comparisons were carried out in seventeen climate zones, to assess the ability of each strategy to deal with different weather conditions and heating demands. These climate zones were chosen because they were the ones that ASHRAE pointed out as the representative of all the different weather conditions in the world [15]. The simulations were carried out in the same heating system employed in “paper 3”, using the same surface of PV panels and TES tank volume in all the studied locations, as well as the construction characteristics of the building.

Considering the findings achieved in the presented papers, a step further was done when the MPC strategy was employed to optimize the size of both PV panels and TES tank, depending on the type of building and its occupancy schedule, and the climate region where it was located (“paper 5”). In this case, an accurate economic analysis, taking into account the price to install PV panels and a TES tank, was carried out. The study considered the annual benefits that can be obtained using this control technique when managing the same system as the one presented in “paper 3” but in the following types of buildings: an apartment, an office, and a hotel. Moreover, the energy impact of the MPC strategy was evaluated, focusing on the profit obtained by PV panels in each case and the ability of the TES tank to mitigate the peak consumption hours.

Chapter 3

3. Papers comprising this PhD

3.1. Paper 1: Bibliometric analysis of smart control applications in thermal energy storage systems. A model predictive control approach

3.1.1. Overview

Many studies in the literature contributed to identify the main findings in different research fields. Overall, reviews were focused on summarising the main findings through a deep and detailed search in the existing publications. However, recently, a new way to study the data provided by scientific literature platforms appeared in our community. This technique is commonly known as bibliometric analysis and it is based on extracting the most remarkable data from scientific databases as Web of Science and Elsevier Scopus [16].

Bibliometric is the branch of knowledge that allows to explore the existing publications from a statistical perspective [17], taking advantage of the results obtained from the scientific databases. Considering this analysis, the inherent literature gaps of a research topic can be found. Moreover, this kind of analysis gives the possibility to study the main authors of a specific topic and the relations among them, as well as the trend of publications along the years, which allows to identify easily potential researchers with whom cooperate. To carry out this wide analysis, different tools can be used to simplify the analysis work. They are the following:

- BibExcel [18]: Considering that the publications from the studied topic can be extracted from more than one database, the BibExcel tool analyse all of them and it removes the duplicities.

- Biblioshiny [19]: This statistical tool allows to process the extracted data and to plot different graphs related to the influence of different authors, institutions, and a timeline that depicts the most important years in terms of publications.
- VOSviewer [20]: It is similar to Biblioshiny, but it is focused to analyse just the keywords of the scientific publications. Once they are processed, the tool allows the user to analyse the relation among them and to plot different graphs and maps to analyse the influence of all concepts.

It is worth to note that all mentioned tools are free software available worldwide.

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

This study was focused on analysing the available scientific publications through bibliometric techniques, to find out the gaps in the literature related to TES systems controlled by MPC strategies published until now. The databases employed to look for such literature were Web of Science and Scopus.

Then, some query strings were defined to assess the influence of control techniques in the studies carried out by researchers, focusing the attention on MPC strategies. Once the searching was done, the bibliometric data was reviewed, saved, and processed.

After collecting the initial data, the main contribution of the paper to the state-of-the-art can be summarized as the definition of eight research areas that the scientific community should further investigate in the future, to fully exploit the capacity of TES systems controlled by MPC strategies. These eight areas are the following:

- Both PV panels surface and TES tank volume should be optimized, considering the system location and demand requirements.
- To improve the weather forecasting.
- To introduce both TES and MPC systems within smart grids operation.
- Renewable energy resources should be considered as the main sources of energy in this kind of systems.
- To further study the importance of the building occupancy profile.
- The size of the building and its scalability should be considered more in detail.

- To analyse the suitability of TES systems controlled by MPC strategies in either heating or cooling systems with different HVAC systems.
- To test such system in a real prototype, to demonstrate its applicability in a real time control framework.

3.1.3. Contribution of the candidate

Joan Tarragona conceived and designed the study. After that, Joan Tarragona performed the analysis of the bibliometric data and wrote the article.

3.1.4. Journal paper

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

Reference:

Tarragona J, de Gracia A, Cabeza LF. Bibliometric analysis of smart control applications in thermal energy storage systems. A model predictive control approach. Journal of Energy Storage 32 (2020) 101704.

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Bibliometric analysis of smart control applications in thermal energy storage systems. A model predictive control approach

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3.2. Paper 2: Systematic review on model predictive control strategies applied to active thermal energy storage systems

3.2.1. Overview

During last decades, the application of MPC strategies upon the engineering field has become more attractive. At the beginning of its creation, the industrial automation started to employ it to control processes, aiming to reduce their associated costs. Later on, due to its fast adaptive and its effective control operation in industry, MPC started to be applied in other research fields, such as energy sector.

The goal to implement MPC in energy systems was focused on reducing the cost derived from the energy consumption coming from fossil fuels or the electricity grid. Therefore, to reduce this impact, the contribution of renewable energy sources was pointed out as crucial. Sultana et al. [21] reviewed the level of maturity of MPC to be implemented in energy systems with renewable energy sources. Authors highlighted its capacity to adapt the control guidelines to different renewable supplies, demonstrating the flexibility of this control strategy. Later on, researchers discovered the potential of coupling MPC techniques with TES systems and they started to apply both technologies together in buildings and power generation plants.

On the one hand, regarding building energy systems, Yu et al. [22] confirmed the potential of such coupling and authors said that it was one of the most powerful options to reduce the energy cost. On the other hand, the potential of TES and MPC in concentrated solar plants (CSP) pointed out the potential of both technologies to increase the plant performance [23,24].

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

The aim of this review of the state-of-the-art was to provide a comprehensive study of the TES systems that are controlled by an MPC strategy. To do that, a systematic review methodology was employed, which helped to assess the literature available in the scientific databases.

The obtained literature pointed out two main areas that used the coupling between TES and MPC: heating/cooling systems and power generation plants. So far, authors focused their attention on applying MPC to minimize the energy cost in the case of heating/cooling systems and with the objective to increase the electricity selling benefits in the framework of the power generation plants. With the literature revision, the main technical features of MPC were identified in both energy areas and information related to both prediction horizon and computing approach were provided. Also, regarding TES systems, the paper detailed the materials employed as storage media and the occupancy schedule in which the TES tank operates.

Finally, the article highlighted the level of renewables integration in the MPC strategies applied to heating/cooling system with TES. Moreover, it showed that many studies were performed at simulation level and more effort should be done to move these systems to prototypes, aiming to assess their reliability when managing real heating/cooling systems.

3.2.3. Contribution of the candidate

Joan Tarragona conceived and designed the study. After that, Joan Tarragona reviewed the state-of-the-art and wrote the article.

3.2.4. Journal paper

The scientific contribution from this research work was submitted to the journal Renewable & Sustainable Energy Reviews in October 2020.

Reference:

Tarragona J, Pisello AL, Fernández C, de Gracia A, Cabeza LF. Systematic review on model predictive control strategies applied to active thermal energy storage systems.

Renewable and Sustainable Energy Reviews

Systematic review on model predictive control strategies applied to active thermal energy storage systems

--Manuscript Draft--

Manuscript Number:	RSER-D-20-04759
Article Type:	Review Article
Section/Category:	Energy Storage
Keywords:	Thermal Energy Storage; Model predictive control; systematic review; energy management; Renewable energy; active systems
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Abstract:	Recently, the use of smart control techniques in systems with thermal energy storage has assumed an important role as they contribute to obtain significant energy and economic savings. So far, the most relevant control technique is model predictive control. Its ability to manage different energy systems as heating, ventilation, and air conditioning equipment or power generation plants, together with its capacity to take advantage of renewable energy resources have drawn the attention of many researchers during last decade. In this regard, this paper presents the progress and results of the implementation of model predictive control in systems with active thermal energy storage. The literature was searched using a systematic methodology to establish the state-of-the-art. From the revision of the documents, it can be observed a lack of studies that analyse the model predictive control strategy design, the storage media employed for active thermal energy storage, and the influence of renewables in this kind of systems. Therefore, this article develops a comprehensive summary of the model predictive control application upon active thermal energy storage systems, paying attention to the employed technical parameters such as the prediction horizon length, the computational architecture approaches, and the employed thermal energy storage materials. Additionally, the review performs a summary of the last enhancements to overcome computational issues and an analysis of the objective functions that were employed in each study.
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3.3. Paper 3: Model predictive control applied to a heating system with PV panels and thermal energy storage

3.3.1. Overview

A step further to increase even more the performance of both renewable energy resources and TES technologies was achieved after the appearance of smart control strategies in the market. Yu et al. [22] defined the choice of an appropriate and effective control strategy as the way to reach the full potential of either active or passive integrated TES systems in buildings. Additionally, the behaviour of different smart control techniques applied to HVAC systems was analysed by Afram and Janabi-Sharifi [25] that defined MPC as the most powerful strategy to control them. In this regard, Thieblemont et al. [13] pointed out the increasing interest of researchers in analysing the behaviour of MPC techniques for single buildings with TES over the last decade. The ability of MPC to reduce the energy consumption during peak periods and its capacity to enhance the TES performance became crucial to obtain both high economic savings and an optimal building energy management.

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

This study analyses both economic and energy performance of a hybrid heating system composed by an air-to-water heat pump, PV panels, a water tank as TES, and electricity grid connection, which follows a ToU tariff structure. The whole system is controlled by an MPC control strategy that considers the weather forecasting of Puigverd de Lleida (Spain) and the heating demand obtained through EnergyPlus simulations in a building located at this place.

Bearing in mind this hybrid heating system, the main contributions to the state-of-the-art are:

- The study of different MPC settings, to analyse the impact in the control performance of the prediction horizon, the data time step, and the error that is obtained in all studied cases. This study aimed to provide an MPC configuration with a good trade-off between the accuracy in the final results and the computational effort.

- The design of an inner control algorithm that transforms the MPC strategy in a double-level control system. At the high level, the MPC predicts the future conditions using a horizon of 24 hours and a data time step of 1 hour. Then, at the low level, the inner control algorithm adapts the control decisions every 5 minutes, to the deviations of the predicted values. This double-level actuation allows the system to reduce the final error without increasing the computational effort.

Moreover, the study also analyses in detail the impact of weather variability on the system, to find out the potential of MPC to adapt its behaviour to future variations and/or instabilities.

This study demonstrated that to employ a prediction horizon longer than 24 hours did not improve economic savings for a system with PV panels, grid connection, and TES. Also, the inner control algorithm presented a good performance, reducing the final error without increasing the computational effort. Finally, all simulations highlighted that the coupling of MPC, PV panels, TES, and grid connection with a ToU tariff structures multiplied the economic benefits compared to systems in which the technologies are used individually.

3.3.3. Contribution of the candidate

Joan Tarragona conceived and designed the study. After that, Joan Tarragona performed the simulations, analysed the data, interpreted the obtained results, and wrote the paper.

3.3.4. Journal paper

The scientific contribution from this research work was published in Energy journal in 2020.

Reference:

Tarragona J, Fernández C, de Gracia A. Model predictive control applied to a heating system with PV panels and thermal energy storage. Energy 197 (2020) 117229.

DOI: 10.1016/j.energy.2020.117229

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Model predictive control applied to a heating system with PV panels and thermal energy storage

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3.4. Paper 4: Economic evaluation of a hybrid heating system in different climate zones based on model predictive control

3.4.1. Overview

The research developed upon HVAC equipment during last years pointed out that one of the most potential ways to reduce energy consumption coming from fossil fuels and to promote renewable energy resources was the coupling between TES and MPC [26]. In that sense, Bruni et al. [27] studied the behaviour of a HVAC system with energy storage controlled by an MPC strategy. Also, to assess its reliability, authors compared its performance against a rule-based control strategy.

Other than to compare the MPC performance against other control strategies in the literature, authors as Oldewurtel et al. [28] tested MPC in different climate regions, to evaluate the robustness of the system and to study its behaviour under different weather conditions.

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

In this study, two different comparisons were carried out. The first one is to assess the economic savings potential of a double-level MPC with an inner control algorithm designed to correct control deviations at the low level. The performance of this strategy was compared against an RBC strategy and an ON/OFF + PV strategy. The second one is to compare such control strategies when used in different climate zones, and to analyse the impact of both PV panels and TES through the management of all strategies in all locations.

The studied hybrid heating system was composed of PV panels and grid connection as the sources able to provide electricity to the air-to-water heat pump. Then, from the heat pump, the thermal energy could be distributed either to the TES tank or directly to the building, to satisfy the heating demand of each location. It should be highlighted that the selected electricity tariff for this study followed a ToU structure, meaning that the ability of the control strategies to take advantage of the off-peak period is crucial to contribute to the system peak load shifting.

The comparison among the energy management behaviour of the three control strategies upon the presented hybrid heating system drives to three major conclusions:

- The economic savings obtained with the MPC strategy with the inner control algorithm compared to the ON/OFF + PV one was between 17% to 46% in the coldest locations and higher than 75% in the hottest ones. Moreover, the study highlighted that although the ON/OFF + PV strategy could take advantage of free solar energy, its lack of TES reduced its potential to obtain important economic savings.
- The comparison between the self-designed RBC strategy, also against the MPC method with the low-level actuation through the inner control algorithm expanded the conclusions in another direction. Even though in this scenario the RBC strategy could take advantage of the TES system, its on-time consumption together with its lack capacity to predict future energy demand and to forecast weather conditions reduced its economic savings potential. Therefore, among the three control strategies, MPC was the one with the highest potential to decrease the energy cost in all locations.
- Finally, the study remarked that MPC could contribute to higher economic savings, if both surface of PV panels and TES volume were optimized for each location and weather conditions.

3.4.3. Contribution of the candidate

Joan Tarragona conceived and designed the study. After that, Joan Tarragona performed the simulations, interpreted the results, and wrote the article.

3.4.4. Journal paper

The scientific contribution from this research work was published in Energy Conversion and Management journal in 2020.

Reference:

Tarragona J, Fernández C, Cabeza LF, de Gracia A. Economic evaluation of a hybrid heating system in different climate zones based on model predictive control. Energy Conversion and Management 221 (2020) 113205.

DOI: 10.1016/j.enconman.2020.113205

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Economic evaluation of a hybrid heating system in different climate zones based on model predictive control

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3.5. Paper 5: Analysis of thermal energy storage tanks and PV panels combinations in different buildings controlled through model predictive control

3.5.1. Overview

To assess the impact of different building operation conditions in various scenarios, it is crucial to size renewable energy resources or TES equipment. In fact, the influence of the occupancy schedule in the HVAC operation was highlighted by Jung and Jazizadeh [29]. Moreover, Pérez-Lombard et al. [30] said that a good assessment of both building location and weather conditions defined another key factor to determine the energy use of a specific building.

The energy variations induced by both building occupancy profile and location also affect to the performance of building control strategies, such as MPC. In that sense, Oldewurtel et al. [31] assessed the influence of MPC in the energy management of different buildings, comparing three different occupancy schedules against a fixed schedule employed as a benchmark. However, authors did not add TES systems within the HVAC operation.

A wider study was performed by D'Ettorre et al [32], where authors analysed the TES optimization in a HVAC system controlled by an MPC strategy. They obtained a correlation between the storage capacity of the TES system and some technical parameters of the MPC strategy. However, it is still missing an assessment of the performance of an MPC control technique that manages a HVAC system with TES that includes different occupancy schedules, various locations, and renewable energy sources.

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

This paper studied the impact of different sizes of both PV panels and TES tanks in different buildings and locations. Its main goal was to find out which was the best combination in a heating system controlled by an MPC strategy, considering different scenarios that were defined by the following conditions:

- Occupancy schedule: Aiming to evaluate different occupancy patterns, simulations of three different type of buildings were carried out in this study: an apartment building (domestic schedule), an office building (office schedule), and a hotel building (service schedule). The number of occupants and their behaviour are distinct among these cases and, consequently, the heating demand profile varied. Therefore, the ability by the MPC strategy to manage different peak energy consumption values and amounts of total final energy use were crucial to study the reliability of MPC in different types of occupancy profiles.

- Location: The studied buildings were located in three different cities that were representative of different climate zones: Helsinki (cold), Strasbourg (temperate), and Athens (hot). Through the analysis of the location it was assessed which was the impact of the external weather conditions in both PV panels and TES tank equipment.

The study was performed taking into account both economic and energy points of view. On the one hand, the price of the equipment was considered in the economic evaluation. Then, the internal rate of return (IRR) was calculated for all cases. The higher IRR the better the investment. On the other hand, the energy analysis evaluated the impact of PV panels, considering the reduction in the grid consumption during one year of simulation. Then, regarding TES, the key parameter to size up the tank volume selection was the total heating demand that was covered by the TES tank. In case the control strategy could store a lot of energy in the tank meant that this energy came from either off-peak electricity periods or from PV panels energy surpluses.

3.5.3. Contribution of the candidate

Joan Tarragona conceived and designed the study. After that, Joan Tarragona analysed the results and wrote the article.

3.5.4. Journal paper

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

Reference:

Tarragona J, Pisello AL, Fernández C, Cabeza LF, Payá J, Marchante-Avellaneda J, de Gracia A. Analysis of thermal energy storage tanks and PV panels combinations in different buildings controlled through model predictive control.

Energy

Analysis of thermal energy storage tanks and PV panels combinations in different buildings controlled through model predictive control

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Article Type:	Full length article
Keywords:	Thermal energy storage; Model predictive control; building energy management; occupancy patterns
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Abstract:	Among different storage techniques, thermal energy storage was pointed out as a potential solution for increasing the share of renewables in the consumption of heating, ventilation, and air conditioning systems. However, to optimize the performance of both renewable energy sources and thermal energy storage, a smart control strategy to manage the energy interaction among these elements is required. In that sense, the present study analyses the performance of a heating system based on an air-to-water heat pump controlled by a model predictive control strategy, where different thermal energy storage tank volumes and installed PV power capacities are analysed. The novelty of the paper lies in studying both economic and energy impacts of each combination in different locations, buildings, and indoor occupancy schedules. The payback period, the reduction of the electricity grid consumption, and the behaviour of the coefficient of performance of the heat pump are studied in detail for all cases. Results point out that the increase of the thermal energy storage volume improves the coefficient of performance of the heat pump between 50% and 100% in cold and temperate climates, respectively.
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Chapter 4

4. Global discussion of results

Researchers pointed out to TES as one of the best techniques to reduce the mismatching between the energy produced by renewable energy sources and the energy consumption profile of the building occupants. Hence, TES contributed to integrate these renewable energy sources to the energy building operation, helping to increase its performance at the same time that the energy consumption coming from fossil fuels was reduced.

Considering this situation as a kick off framework of this PhD, the bibliometric analysis carried out at the beginning of the thesis highlighted a very important global gap related to the necessity to find out a way to optimally control the energy management in buildings, especially when the building had a TES system integrated. In that sense, focusing on the literature available about control strategies that were employed in systems with TES, it was found out MPC as the one with more influence during last years. In Figure 10 the percentage of publications that includes control strategies in systems with TES can be seen, where MPC is the predominant one. However, even being the control strategy with more relevance, the number of documents were small and the field remained to be fully explored.

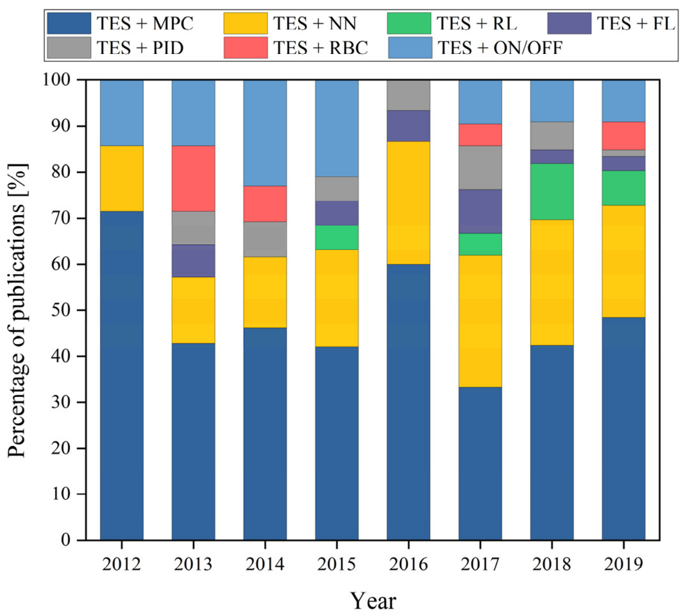

Figure 10. Influence of different control strategies in systems with TES along the years.

The first study with the self-designed MPC strategy was done considering a double-level of actuation, which was able to correct possible deviations caused during the operation of the MPC. The high-level of actuation predicted the global operation of the system with a horizon of 24 hours and a time step of 1 hour, as a standard MPC strategy does. Then, the low-level controller corrected the deviations of the system for a horizon of 1 hour and a time step of 5 minutes, using predefined rules that contributed to obtain a good trade-off between accuracy and computation time.

From this study emerged the necessity to compare the performance of the designed MPC strategy against other control strategies, to be able to validate the MPC ability. Thus, in this way, the second study was focused on comparing the behaviour of the self-designed MPC with its double-level of actuation against both RBC and ON/OFF control strategies. Additionally, to increase the reliability of the comparison, the employed building was the same of the first study, but the number of climates to run the simulations was increased until seventeen. These climates were validated from ASHRAE and they included all different weather conditions in the world, going from the hottest to the coldest one. The study showed a good performance of MPC in all climates and higher economic savings than the other two tested control strategies. However, simulations pointed out a drawback in the configuration of the global heating system. This inconvenient was the lack of optimization in the sizing of PV panels and TES tank. Even though both equipments presented a good behaviour, the enormous disparity in the weather conditions of all climates highlighted the necessity to adapt the power capacity of PV panels to the solar radiation of each place, as well as to adjust the TES tank volume to the energy requirements of each case. In that sense, after carrying out the presented two simulation studies, a summary of all the concepts that were identified as crucial to achieve a better performance of the designed MPC strategy are shown in Figure 11.

As mentioned before, two of these six variables are the PV panels capacity and the TES tank volume, which are strongly linked with the weather conditions of the climate where the building is located and the occupancy profile that it has. Moreover, another key aspect is the model of the heat pump, which should be adapted to the energy requirements of the building. In addition, the price of the electricity is the last factor to consider, to improve the system performance, from an economic point of view.

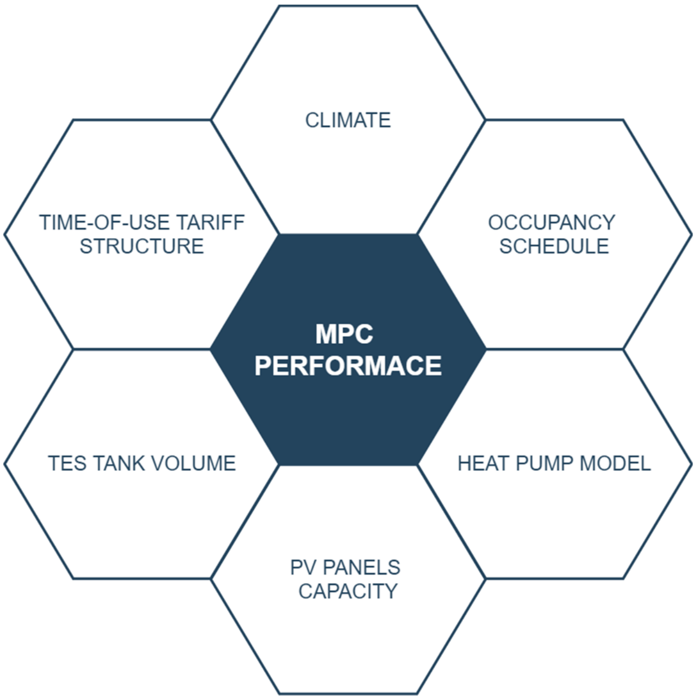

Figure 11. Key concepts to enhance the MPC performance.

Following this path, a third study with the same MPC strategy was developed, where all the points presented in Figure 11 were tackled. In this study, the influence of the occupancy schedule of three types of building (a residential apartment, an office, and a hotel) was assessed. All buildings were analysed in three locations that represented different climate profiles, Helsinki (cold), Strasbourg (temperate), and Athens (hot). The aim of this study was to find out the influence of both PV panels capacity and TES tank volume, depending on the global conditions.

Results pointed out that MPC was able to manage in an optimum way the heating system for all studied occupancies, since its predictive capacity could adapt the system operation to all future energy conditions. Regarding to the climate, to optimize the size of PV panels and especially the capacity of the TES tank contributed to achieve a very good performance of the system from a global point of view and it obtained important economic savings.

Finally, throughout the three simulation studies that were developed in this PhD, it was created a robust MPC tool able to be applied to a HVAC system with TES. The main contribution of the three studies are the following:

1. The design of the MPC tool.

2. The operation comparison of the MPC tool against other control strategies.
3. The implementation of the MPC tool in several and different possible working conditions, where all the physical elements were optimized.

Chapter 5

5. Final conclusions

5.1. Conclusions

The main objective of this PhD thesis was to contribute in improving the energy efficiency in building heating systems with TES and PV panels. To do that, it was developed an MPC strategy able to forecast weather and future demand profiles. In this framework, the main contributions of this PhD thesis are explained in this chapter.

Concerning the MPC performance, the strategy achieved the goal of reducing the final energy cost of the studied system. To do this, MPC exploited the capacity of the PV panels and the possibility to buy electricity from the grid during off-peak periods. In this sense, MPC demonstrated to be a competitive control strategy to reduce the final cost of the studied hybrid heating system.

Regarding the main accomplishments obtained from the study of the state-of-the-art (Papers 1 and 2), the following aspects should be highlighted:

- The state-of-the-art analysis was carried out considering both points of view bibliometrical and conceptual. These two perspective of the topic were studied through two different papers: a bibliometric analysis and a systematic review.
- More than 150 studies were reviewed along the development of the literature analysis.
- The main literature gaps of the topic so far were pointed out, highlighting the ones with the biggest impact upon the performance of TES systems controlled by MPC strategies.
- The application of MPC strategies in the management of heating systems that considered both PV panels and TES systems in their operation was identified as the main lack of knowledge of this field.

According to the findings obtained in the state-of-the-art analysis, an MPC strategy was designed to overcome the lack of knowledge identified from the literature. Therefore, an

MPC control tool able to manage a heating system with TES and PV panels was designed and numerically studied at simulation level (Paper 3). The main conclusions drawn from this control tool designing can be summarized as follows:

- Different settings of the MPC strategy when managing a heating system based on an air-to-water heat pump with PV panels and TES were analysed.
- A prediction horizon of 24 hours and a time step of 1 hour were identified as the MPC operational settings with the best performance in the studied system.
- It was created an inner control algorithm to actuate together with the MPC strategy, aiming to reduce the computational effort of the strategy whereas the accuracy in the final results was maintained.
- Both MPC strategy and inner control algorithm were implemented in a global control strategy based on a hierarchical structure with two levels of actuation: MPC in the high level and inner control algorithm in the low level.
- The MPC strategy with its inner control algorithm achieved a good trade-off between computational effort and accuracy in the final results, giving important economic savings.

Finally, focusing on the assessment of the MPC strategy under different working conditions, the impact of various climate conditions upon the performance of the control strategy (Paper 4), as well as different PV panels capacities and TES tank volumes were analysed (Paper 5). The main findings arisen from these studies are listed below:

- The designed MPC strategy was able to overcome different heating consumption profiles induced by different weather conditions and occupancy profiles, taking advantage of its ability to analyse future system conditions.
- The coupling between MPC and TES contributed to reduce the final energy cost while increased the global system performance. This performance increasing was noticed through the growth of the COP of the heat pump when the volume of the TES changed.

5.2. Future work

Regardless that the designed MPC strategy presented a good behaviour in distinct occupancy schedules and it showed robustness against different weather conditions, there are some aspects that should be deeper studied in the future.

Focusing on the MPC strategy application, the way to define the future heating demand should be more reliable. Considering the external conditions and the type of buildings, either a machine learning model or an artificial neural network should operate in parallel to MPC, to obtain a more accurate heating demand profile. Therefore, a hybrid control tool could contribute to reduce the final difference between real and predicted values.

Moreover, due to technical resolution restrictions, the model of TES tank employed along this PhD was modelled as fully mixed. However, to be more accurate in the storage behaviour it should be considered thermal stratification and move the model to a packed flow paradigm. Thus, improvements in this aspect should be carried out to examine the potential of more accurate TES tank design.

Finally, the most ambitious goal to achieve is to move this model towards a real prototype to validate it. The implementation of a micro-controller in an experimental test-room to assess its influence against a reference case controlled by predefined rules could introduce to the market the created MPC strategy. Already, the installation of the hybrid heating system in a container during winter to perform the assay was planned. The control decisions would be managed by a micro-controller, which would interact with the data acquired by the sensors.

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. Gholamibozanjani G, **Tarragona J**, de Gracia A, Fernández C, Cabeza LF, Farid MM. Model predictive control strategy applied to different types of building for space heating. Applied Energy 231 (2018) 959-971.
2. de Gracia A, **Tarragona J**, Crespo A, Fernández C. Smart control of dynamic phase change material wall system. Applied Energy 279 (2020) 115807.

Contributions to international conferences

The PhD candidate contributed to different international conferences:

1. **Tarragona J**, Fernández C, Cabeza LF, de Gracia A. Model predictive control strategy applied to a heating system with PV panels and thermal energy storage in different US climate zones. Eurotherm Seminar #112 - Advances in Thermal Energy Storage, Lleida (Spain). Oral presentation.
2. **Tarragona J**, Fernández C, Cabeza LF, de Gracia A. Model predictive control applied to a heating system with PV panels and thermal energy storage. Building Simulation Rome 2019, Rome (Italy). Oral presentation.
3. de Gracia A, **Tarragona J**, Pisello AL, Cotana F, Rodríguez X, Burgués JM, Cabeza LF, Fernández C. Renewable Energies in Historical Buildings (REHIB project). Building Simulation Rome 2019, Rome (Italy). Oral presentation.
4. Fernandez C, Olacia E, **Tarragona J**, Pisello AL, Rodriguez X, Cabeza LF, de Gracia A. Renewable Energies in Historical Buildings (REHIB project). 11CNIT - XI National and II International Engineering Thermodynamics Congress, Albacete (Spain). Poster presentation.

Scientific foreign-exchange

The PhD candidate did a stay of three months in Ghent (Belgium) during the development of this PhD thesis, hosted by the Ghent University.

In this research stay, the candidate worked on a thermal battery filled with PCM that was employed for refrigeration purposes. Both charging and discharging processes were studied in different operation conditions, such as distinct refrigerant temperatures and mass flow rates.

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Other activities

Book chapter participation

- de Gracia A, Crespo A, Vérez D, **Tarragona J**, Cabeza LF. Control solutions for TES applications. Encyclopedia of Energy Storage. Elsevier. Accepted in October 2020.

Projects participation

- 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.
- 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.
- Red Española en Almacenamiento de Energía Térmica (RED). Ministerio de Ciencia, Innovación y Universidades - Agencia Estatal de Investigación (AEI), RED2018-102431-T.
- Innovative Microsolar Heat and power System for Domestic and Small Business Buildings (INNOVA Microsolar). European Union's Horizon 2020 Research & Innovation Programme, Grant Agreement 723596.
- GREiA. Grup de Recerca en Energia i Intel·ligència Artificial. Generalitat de Catalunya, 2017 SGR 1537.

Organizing committee participation

- 10th Thermodynamic Engineering International Conference (CNIT) 2017. Lleida, Spain.
- Eurotherm Seminar #112 – Advances in thermal energy storage, 2019, Lleida (Spain).

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