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

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Abstract

In the existing literature, the importance of control methods used to manage the operation of thermal energy storage systems increased in the last years. However, the application of smart control strategies is still far to become a significant part of the available scientific publications. Within the employed techniques, model predictive control appeared as the most promising method to control thermal energy storage systems. Therefore, in this paper, the application of this control strategy is widely studied. Regarding this analysis, significant literature gaps that have to be studied more in detail are found in the current scientific publications. The main goal of this study is to find out these gaps through a bibliometric approach, identifying the key knowledge areas using both databases Web of Science and Scopus. Results show that the main knowledge gaps in the literature are the ones related with a validation of model predictive control, its implementation in smart grids, an optimized sizing and management of the physical parts of the system, an accurate weather forecasting, and to exploit as much as possible the available renewable energy resources. Moreover, the tendency in publications during the whole period, the main authors, countries, and organisations are analysed.
**Keywords:** model predictive control; thermal energy storage; bibliometric analysis; literature evaluation; literature gaps

**Graphical abstract**
1. Introduction

In the last years, climate change has reached alarming levels and it has become a global concern that needs to be tackled. The high energy consumption speeded up the increasing of the world average temperature and its reduction become crucial to combat the climate change. Worldwide, one of the main energy consumers is the building sector, which consumes over 30% of total final energy according to the International Energy Agency (IEA) [1]. In that sense, new policies as the ones established by the European Energy Performance of Buildings Directive (EPBD) [2] encourage the users to reduce the energy consumption while increasing the energy efficiency in buildings. Moreover, the United Nations (UN) defined the 2030 agenda for the sustainable development [3] in which two goals have to be pointed out. The first one (goal number seven) underlines the necessity to achieve affordable and non-pollutant energy for everyone. The second one (goal thirteen) calls for an urgent action to prevent the climate change and its impacts.

Recently, an increasing of the use of renewable energy resources to fulfil the global energy demand helped to reduce the amount of energy produced by fossil fuels [4]. However, to accomplish the aforementioned policies and energy reduction requirements, a major growing of the renewables usage and a good energy management became key points to obtain the pursuing targets.

According to the IEA [5], energy storage plays an important role to match the peak consumption periods with both the renewable energy production and the off-grid period. Thereby, this technology became a powerful tool to tackle the climate change, while providing energy supply and security to the user. However, from the same report two common disadvantages were highlighted, the limited feedback to users regarding the systems performance and the difficulty to control the operation of such energy systems.
Consequently, Yu et al. [6] remarked that the best way to reach the full potential of thermal energy storage (TES) systems is the election of the suitable control strategy to manage its operation. Moreover, Afram and Janabi-Sharifi [7] analysed different control techniques, selecting model predictive control (MPC) as the most prominent to control heating, ventilation, and air conditioning (HVAC) systems. Thereby, the coupling between TES and MPC could be a promising technology able to reduce the peak load and to achieve both important energy and economic savings and to help in the competitiveness of the different TES technologies, as it is crucial to maximize energy and economic benefits to justify the required high initial investments. In that sense, different approaches were considered in systems that include TES and renewable energy resources controlled by an MPC strategy. To manage uncertainty and variability of renewables, the performance of cooperative [8,9] and non-cooperative [10,11] energy distribution schedules were studied in a stochastic framework of MPC, demonstrating the capacity of the control method to reduce the system operation cost.

To dimension the influence of such coupling in the literature, a comprehensive study of the available publications must be carried out. Thus, to develop this detailed literature study of the systems with TES and MPC, bibliometric analysis appeared as a useful tool to analyse a big amount of scientific data, dividing the evaluation in different scientific areas, countries in which the documents were published, the frequency of the keywords, among others [12]. According to Mukerji and Tripathi [13], a bibliometric analysis is the attempt to quantitatively assess the academic quality of journals or authors by statistical methods such as citation rates. Thereby, this technique became a useful tool to manage the knowledge in science and to analyse through an accurate study the published documents in a certain research field until now. There are some available databases within the scientific searching framework as Web of Science, Scopus, and Google Scholar.
Harzing and Alakangas [14] did a longitudinal and cross-disciplinary comparison among these three databases, to assess the scientific quality of each source. The authors concluded that all three databases provided enough stability of coverage to be used for bibliometric analysis. In that sense, Díaz-López et al. [15] studied the evolution of sustainable building assessment methods, but in this case the study was carried out with Web of Science and Scopus as databases.

There are no bibliometric studies about the importance of the smart control strategies applied to TES systems. Therefore, a detailed analysis of the research concepts in this field would help to point out the most powerful areas with less knowledge. In that sense, the aim of this study is to obtain an accurate overview of the literature gaps in the current scientific publications related to the application of MPC in TES systems, by using bibliometric methods. The promising technologies and the pending studies derived from this analysis are highlighted, to guide the future research. Besides, a detailed analysis of the statistical results achieved from Web of Science and Scopus, which identified the key points and the remarkable tendencies was done.

2. Methodology

To carry out a wide analysis of the literature in a determined research field, bibliometric is the branch of knowledge that allows to explore, in a statistical way, the existing publications [16]. In this study, a specific methodology was proposed to define all the steps to map the state-of-the-art of a scientific topic through the characterization of bibliometric parameters. This methodology is described in the flowchart shown in Figure 1. As it can be seen, the first stage of this method was the research topic definition that in this case was to assess the impact of MPC to manage TES systems. After that, the next step was the selection of the proper scientific databases to perform the literature search.
Nowadays, the most important data sources to obtain scientific publications are Web of Science, Scopus, and Google Scholar. However, Google Scholar allows publications from
predatory journals [17,18] and its lack quality control raises questions about its suitability as a bibliometric tool [19]. Therefore, Web of Science and Scopus were used in this study to perform the searching of the literature related to the selected topic over the whole history until the end of 2019.

Following the steps defined in Figure 1, as a third point, the objective and the methodology should be determined. In this case, the main objective of this research was to find out the literature gaps in the application of MPC as a control strategy in TES systems. Then, regarding the methodology, the process followed to carry out such study was defined by analysing the amount of publications in both databases, using three different query strings that are shown in Table 1. All inclusions and exclusions are detailed in both databases, since the language was not exactly the same.

<table>
<thead>
<tr>
<th>QUERY</th>
<th>Web of Science</th>
<th>Scopus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TES</strong></td>
<td>(&quot;thermal energy storage&quot; OR &quot;cold energy storage&quot; OR &quot;latent near/3 storage&quot; OR &quot;sensible near/3 storage&quot; OR &quot;thermochemical near/3 storage&quot; OR &quot;*sorption near/3 storage&quot;)</td>
<td>TITLE-ABS-KEY (&quot;thermal energy storage&quot; OR &quot;cold energy storage&quot; OR &quot;latent W/3 storage&quot; OR &quot;sensible W/3 storage&quot; OR &quot;thermochemical W/3 storage&quot; OR &quot;*sorption W/3 storage&quot;)</td>
</tr>
<tr>
<td><strong>TES + control</strong></td>
<td>(&quot;thermal energy storage&quot; OR &quot;cold energy storage&quot; OR &quot;latent near/3 storage&quot; OR &quot;sensible near/3 storage&quot; OR &quot;thermochemical near/3 storage&quot; OR &quot;*sorption near/3 storage&quot;) AND (&quot;control&quot;)</td>
<td>TITLE-ABS-KEY (&quot;thermal energy storage&quot; OR &quot;cold energy storage&quot; OR &quot;latent W/3 storage&quot; OR &quot;sensible W/3 storage&quot; OR &quot;thermochemical W/3 storage&quot; OR &quot;*sorption W/3 storage&quot;) AND (&quot;control&quot;))</td>
</tr>
<tr>
<td><strong>TES + MPC</strong></td>
<td>(&quot;thermal energy storage&quot; OR &quot;cold energy storage&quot; OR &quot;latent near/3 storage&quot; OR &quot;sensible near/3 storage&quot; OR &quot;thermochemical near/3 storage&quot; OR &quot;*sorption near/3 storage&quot;) AND (&quot;model predictive control&quot;)</td>
<td>TITLE-ABS-KEY (&quot;thermal energy storage&quot; OR &quot;cold energy storage&quot; OR &quot;latent W/3 storage&quot; OR &quot;sensible W/3 storage&quot; OR &quot;thermochemical W/3 storage&quot; OR &quot;*sorption W/3 storage&quot;) AND (&quot;model predictive control&quot;)</td>
</tr>
</tbody>
</table>

As it can be seen, the evolution of the query string made the search more restrictive each time, looking for TES in the first searching, adding control in the second one, and
specifying MPC in the last one. This searching way was used to point out the bibliometric importance of MPC in all the TES papers published until now. Once the TES + MPC query string was defined and the bibliometric data was reviewed and saved, the fourth stage was accomplished.

Considering that some scientific publications could be repeated in both databases, the next step was to import data to BibExcel tool [20] to remove the duplicities. Later, once the literature data was processed, both free software Biblioshiny [21] and VOSviewer [22] were employed to carry out the bibliometric analysis using the following data: publications, patents, countries, institutions, subject areas, journals, the reference publications in the studied field, authors, and keywords. It is worth to note that only VOSviewer was utilized to carry out the keywords analysis, since software designers unified an approach to mapping and clustering the bibliometric networks, to ensure that all techniques were based in similar assumptions. Thus, inconsistencies between results can be avoided [23]. Moreover, two different counting methods were provided by VOSviewer to analyse data: full counting or fractional counting. In this study, fractional counting was selected, since it offered a more useful perspective and helped to avoid misunderstandings in comparison with the other method [24].

Also, through this software, it was possible to plot a network mapping in which were created connections among keywords in the title, abstract, and authors keywords in a branch way. Then, the size of the node highlighted the importance of the keywords and the network showed the relation among them. Such step developed the data analysis, which is explained more in detail in the next section (Section 3). Finally, once the keywords were analysed and the literature gaps were identified, a discussion of the trend topics that should be further investigated was done and the most important conclusions were explained.
3. Results

In Section 3.1, the results regarding the influence of MPC within the TES framework are presented, together with the evolution in the number of publications while the query string changed. Then, the data of the TES + MPC query were assessed based on different criteria such as number of scientific publications (Section 3.2), a study of the patents in the field (Section 3.3), allocation of publications by country (Section 3.4), the main subject categories and the distribution by journals (Section 3.5), the most influence authors (Section 3.6), and the most recurrent keywords and their connections (Section 3.7).

3.1. Application of control systems in thermal energy storage

A further analysis about the impact of MPC in TES systems was done in the present section. As it can be seen in Figure 2, the TES research field was widely explored until now with more than 10,000 scientific publications in both databases. Then, focusing the search in the coupling of TES and control, the corresponding query string achieved a significantly reduction in number of papers, with 2,132 in Web of Science and 1,293 in Scopus. The main objective of this query was to obtain an overview of the main control strategies employed to control TES systems so far.

![Figure 2. Number of publications of the query strings obtained in Web of Science and Scopus.](image)
Moreover, a thorough search of the main keywords in the TES + control field and their influence in function of the time was performed. It should be noted that this analysis was carried out with data from both databases Web of Science and Scopus. In Figure 3 a Sankey diagram with the evolution and the emergence of the main keywords in three different periods is depicted. The impact of each keyword is provided through the volume of the rectangle and either the relation among new concepts or the evolution of the same keyword between two periods is illustrated by the flow thickness. Therefore, this diagram gives an overview of the interest transfer in the keywords during last years in research.

As it can be seen, heat storage was the predominant field in which authors focused their attention from the beginning until now. However, from 2009 to 2015 the appearance of three concepts is remarkable: phase change materials, heating, and solar energy. Finally, in the last studied period (from 2016 to 2019), authors started to analyse new storage technologies that can be linked to TES systems as electric energy storage and new smart control methods, as was the case of MPC. No more control strategies were highlighted by the keywords in this analysis, meaning that their relevance were low. Therefore, only the application of MPC techniques increased and gained interest in the scientific community to control TES systems.
Finally, coming back to Figure 2, the last search that restricted the control strategies in only MPC with the query string TES + MPC obtained 128 and 91 documents in Web of Science and Scopus, respectively. Thereby, it should be highlighted that in both databases the weight of MPC was around 6% out of the total control results obtained with TES + control query string. So far, the presented results drove to the target of studying more in detail the statistical indicators and the impact areas in which TES and MPC were used.

3.2. Trends of scientific publications per year

The trends in the number of scientific publications during the period from 2008 to 2019 with the TES + MPC query is presented in Figure 4. As it can be observed, the amount of papers raised gradually from 2008 until 2015 in Web of Science and 2016 in Scopus. Then, in 2017 the tendency changed in both databases, reducing the number of papers in comparison with the year before. However, from 2017 until 2019 the trend increased dramatically, achieving the maximum number of publications for the whole studied period. As the search was carried out at the end of the year, the documents published...
during 2019 were also included in the study. Even with three months ahead for finishing the year, the tendency was to go up and the current number of publications overcame the year before.

Moreover, it is worth to note that the coupling between TES systems and MPC recently started. This fact highlighted MPC as an important market deployment in the near future to manage TES systems in a smart way.

3.3. Overview of patents status within MPC and TES framework

To have an overview of the research status of the studied topic, other than the scientific publications, the knowledge developed through patents was also analysed. The search was carried out using the query string “thermal energy storage AND model predictive control” for the title, the abstract, and the claims in the patent databases [25]. The time frame for the study was between 2008 and 2019, the same that it was used for the scientific
publications analysis. Through such query string 159 patents were obtained and their
distribution can be seen in Figure 5, depending on their procedure status. Although there
are four different type of patents, in this study only the granted patents were considered,
since the process ended and the patent was fully accepted. Thereby, the granted patent
percentage represented a total of 36 patents distributed in the whole period study.

![patent distribution chart]

Figure 5. Patent types for the studied period with TES + MPC query string.

To clearly discern the patent distribution among the years of the studied period, in Figure
6 a column chart with the year of publication of the patents and the jurisdiction who
granted them can be seen. As it can be observed the United States Patent office was
predominant in the whole period with almost all the patent deliveries (30) except six of
them. Moreover, it should be highlighted that the tendency was to increase in the last
three years, as it happened with the scientific publications (Section 3.2). Even though,
there is no a perfect correlation between them, the behaviour of the number of both the
scientific publications and the patents per year point out to a remarkable connection from
a technological impact point of view, meaning that the scientific interest in this topic is
growing.
3.4. Geographic distribution of the publications

To have a clear view of the countries that published in the topic of study, a representative map of the publications distribution according the country of origin is shown in Figure 7. As it can be seen, the locations in Web of Science (Figure 7a) and Scopus (Figure 7b) were depicted independently. Nevertheless, there were some exceptions in Africa as Morocco, Occidental Sahara, and South Africa, Kazakhstan in Asia or Sweden in Europe, the rest of the distribution was almost the same in both databases.
It should be pointed out that United States was the country with more publications in the studied topic, followed by Italy and China. Moreover, other countries as Canada or Spain had a relevant influence in the number of publications.
3.5. Bibliometric evolution in subject categories and journals

The outputs produced from both databases can be grouped by different subject categories, depending on its area of knowledge. In Web of Science the highest percentage corresponds to the subject categories of Engineering and Energy Fuels, both with 20%. All other areas represent less than 20%, including Computer Science (13%), which is one of the main areas in the MPC framework.

Scopus has less categories, being those wider. Engineering (39%) and Energy (22%) constitute the ones with more percentage of publications, followed by Environmental Science (12%) and Computer Science (10%). Again, it should be highlighted that Computer Science represents a little part of the impact in the field of study.

The aforementioned classification in different knowledge areas is related with the journals in which the works were published. In that sense, in Figure 8 the main journals in the studied topic are detailed for both databases. As the studied topic is emerging the distribution of the papers among the journals became difficult, since all of them had close results. However, the most used journal until now is Applied Energy with 18 publications in Web of Science and 15 in Scopus. Moreover, Energy and Buildings gathered 16 and 9 papers in Web of Science and Scopus, respectively. The papers from the Proceedings of the American Control Conference appeared in the third position as a relevant source of publications in this field with 8 documents in Web of Science and 4 in Scopus. After that, other journals as Applied Thermal Engineering, Energies, and Energy have a remarkable impact in both databases.

Another important aspect to study in detail is the document type distribution among articles, conference papers, and reviews. In Figure 8 two pie-charts in a smaller subfigure depict such distribution for both databases. In that case the type divisions are practically
the same, being articles around 70% of the documents. Regarding conference papers, the distribution was 26% in Web of Science and 30% in Scopus. Finally, it is worth to note the reduced number of reviews in this field (3% and 1% of the total, respectively). This percentage is the appropriate due to the novelty of the MPC application in TES systems and the short period without a big number of publications.

Additionally, it is crucial to highlight the most relevant articles in both databases, since they have a great potential to impact on the research community. Thus, the most cited journal publications in Web of Science and Scopus are shown in Table 2 and Table 3, respectively. In both tables the most cited papers are classified in decreasing order and the ranking was based on the total number of citations accumulated from 2008 to 2019.
It is detailed the first author of each publication, the publication year, the journal, and the total citations of the articles. The annual citations are also presented over the time, detailing their historical evolution.

<table>
<thead>
<tr>
<th>Nº</th>
<th>Title</th>
<th>Authors</th>
<th>Year</th>
<th>Journal</th>
<th>Total citations</th>
<th>Evolution of citations per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Model predictive control for the operation of building cooling systems</td>
<td>Ma et al.</td>
<td>2012</td>
<td>IEEE Transactions on Control Systems Technology</td>
<td>193</td>
<td>0 0 0 0 1 9 26 31 41 33 33 19</td>
</tr>
<tr>
<td>2</td>
<td>Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices</td>
<td>Stadler et al.</td>
<td>2009</td>
<td>Environmental Modelling &amp; Software</td>
<td>79</td>
<td>0 1 1 2 9 8 12 14 12 11 2 7</td>
</tr>
<tr>
<td>3</td>
<td>Energy flexibility of residential buildings using short term heat storage in the thermal mass</td>
<td>Le Dreau and Heiselberg</td>
<td>2016</td>
<td>Energy</td>
<td>73</td>
<td>0 0 0 0 0 0 0 0 8 19 46</td>
</tr>
<tr>
<td>4</td>
<td>A review of thermal energy storage technologies and control approaches for solar cooling</td>
<td>Pintaldi et al.</td>
<td>2015</td>
<td>Renewable &amp; Sustainable Energy Reviews</td>
<td>63</td>
<td>0 0 0 0 0 0 0 4 13 20 12 14</td>
</tr>
<tr>
<td>5</td>
<td>MPC-based optimal scheduling of grid-connected low energy buildings with thermal energy storages</td>
<td>Zhao et al.</td>
<td>2015</td>
<td>Energy and Buildings</td>
<td>60</td>
<td>0 0 0 0 0 0 0 4 9 15 13 19</td>
</tr>
</tbody>
</table>

The most cited publication for the studied query string was developed for Ma et al. [26] in 2012 and it obtained a high number of citations during every year in both data sources. Regarding Web of Science (Table 2), Stadler et al. [27] was the second scientific publications with more citations. In this case, the paper was published at the beginning of the studied period and it was cited over the whole period intermittently. The other three
articles were published recently, but their annual citations were also remarkable, especially the growing trend of Le Dreau and Heiselberg [28].

Table 3. Ranking of most cited papers in Scopus.

<table>
<thead>
<tr>
<th>Nº</th>
<th>Title</th>
<th>Authors</th>
<th>Year</th>
<th>Journal</th>
<th>Total citations</th>
<th>Evolution of citations per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Model predictive control for the operation of building cooling systems</td>
<td>Ma et al.</td>
<td>2012</td>
<td>IEEE Transactions on Control Systems Technology</td>
<td>252</td>
<td>0 0 0 1 8 14 34 36 44 40 40 35</td>
</tr>
<tr>
<td>2</td>
<td>MPC-based optimal scheduling of grid-connected low energy buildings with thermal energy storages</td>
<td>Zhao et al.</td>
<td>2015</td>
<td>Energy and Buildings</td>
<td>69</td>
<td>0 0 0 0 0 0 0 0 5 11 15 16 22</td>
</tr>
<tr>
<td>3</td>
<td>Integrating scheduling and control for economic MPC of buildings with energy storage</td>
<td>Touretzky and Baldea</td>
<td>2014</td>
<td>Journal of Process Control</td>
<td>66</td>
<td>0 0 0 0 0 0 0 2 14 9 11 10 20</td>
</tr>
<tr>
<td>4</td>
<td>Gray-box modeling and validation of residential HVAC system for control system design</td>
<td>Afram and Janabi-Sharifi</td>
<td>2015</td>
<td>Applied Energy</td>
<td>62</td>
<td>0 0 0 0 0 0 0 5 11 15 18 13</td>
</tr>
<tr>
<td>5</td>
<td>Model predictive control-based operation management for a residential microgrid with considering forecast uncertainties and demand response strategies</td>
<td>Zhang et al.</td>
<td>2016</td>
<td>IET Generation, Transmission and Distribution</td>
<td>55</td>
<td>0 0 0 0 0 0 0 2 10 19 24</td>
</tr>
</tbody>
</table>

Focusing on the most cited papers obtained in Scopus (Table 3), it is worth to note that only Ma et al. [26] and Zhao et al. [29] publications were repeated in both databases, first and second in this classification, respectively. The other three publications obtained also a significant number of citations.
To have a better understanding of the contributions of the reference literature, Table 4 explains the objective, the novelty, and the main findings of all the publications presented in Table 2 and Table 3.

<table>
<thead>
<tr>
<th>Author/s</th>
<th>Title of the article</th>
<th>Objective</th>
<th>Novelty</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ma et al. [26]</td>
<td>Model predictive control for the operation of building cooling systems</td>
<td>To design a predictive controller able to minimize energy consumption while satisfying the cooling demand, using a TES system in a campus of the University of California.</td>
<td>1) The development of a simple switching nonlinear model for the storage tank which is identified and validated by historical data. 2) The systematic integration of weather prediction in the MPC design to optimize the chillers operation. 3) The design of a low-complexity MPC scheme which is guaranteed to be robust against uncertain buildings load demands.</td>
<td>The implemented MPC presented a good and a robust behaviour. Besides, it improved the plant COP efficiency by 19% as compared to the base case, for a central chiller plant.</td>
</tr>
<tr>
<td>Stadler et al. [27]</td>
<td>Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices</td>
<td>To investigate a simulation model of controllable refrigerators in regard to their ability to shift their energy demand depending on determined external signals.</td>
<td>1) The developed model simulated each device and its reaction to control signals individually, being an independent variable. 2) To study the reduction of the system complexity, aggregating subsets of devices, modelling their behaviour separately.</td>
<td>Authors found in the integration of MPC to the model, a useful tool to determine optimal signal sequences for treating timed control signals and thus, to improve the system performance.</td>
</tr>
<tr>
<td>Le Dreau and Heiselberg [28]</td>
<td>Energy flexibility of residential buildings using short term heat storage in the thermal mass</td>
<td>To assess the thermal behaviour of buildings and heating systems, to modulate their heating power and define simple control strategies to exploit the flexibility potential considering both energy and thermal comfort.</td>
<td>An accurate analysis of the storage potential in the thermal mass and its influence to compare different storage solutions and better assess the role of buildings in the future energy grids was carried out. Different scenarios of modulation: heat storage and heat conservation, as well as the effect of activation and the type of emitter were evaluated.</td>
<td>The insulation level in buildings implies differences in the control strategy, since energy flexibility, energy use, and thermal comfort must be balanced. Moreover, authors pointed out that advance control strategies are necessary to control heating systems in a well-insulated buildings.</td>
</tr>
<tr>
<td>Zhao et al. [29]</td>
<td>MPC-based optimal scheduling of grid-connected low energy buildings with thermal energy storage</td>
<td>To improve the energy efficiency of the energy systems used in low/zero energy buildings, implementing a MPC-based optimal scheduling.</td>
<td>Carbon dioxide emission, primary energy consumption, and operation cost were evaluated in a system with PV panels and TES (chilled water). Two different approaches of MPC-based strategy using non-linear programming algorithm were used: bidirectional electricity flux (buy and sell electricity) unidirectional electricity flux (only buy electricity).</td>
<td>Authors figured out that non-linear programming algorithms coupled with MPC were very effective for optimizing the scheduling of the energy systems in low/zero energy buildings. Moreover, it was demonstrated that the bidirectional electricity flux strategy was more effective in terms of cost and emissions reductions.</td>
</tr>
<tr>
<td>Touretzky and Baldea [30]</td>
<td>Integrating scheduling and control for economic MPC of buildings with energy storage</td>
<td>To develop an economic MPC for the optimal control of building HVAC systems with chilled water as a TES material. To do that, two challenges must be overcome: 1) The extended time horizon must be used to analyse the system operation. 2) Discrete operating modes must be used to design the system.</td>
<td>The study proposed a hierarchical decomposition of the economic MPC based on the following scheduling perspectives: 1) A dynamic scheduling problem in the slow time scale (optimal operation of TES system). 2) A control scheme with a shorter horizon in the fast time scale</td>
<td>Taking advantage of the known cyclical mode transitions in the TES, authors were able to eliminate the binary decision variables of the system. Then, the proposed scheme presented an excellent behaviour and fast computation in the</td>
</tr>
</tbody>
</table>
Regarding all publications presented in Table 4, general ideas can be extracted. First, MPC required simple models to be computationally feasible. Moreover, the integration of renewable energy resources and a reliable weather forecast are key concepts in which some authors paid attention to improve the performance of MPC systems with TES. Additionally, linear and nonlinear approaches were used to program MPC systems to overcome the computational issues, such as the use of larger prediction horizons. Finally, further investigations should be carried out in systems with bidirectional electricity fluxes (buy and sell electricity from the building), since smart grids and microgrids gave promising results in MPC systems with TES.

3.6. Analysis of publications by author

To sum up the most influential authors in the studied field, a timeline in which is depicted the number of publications of the main authors can be seen in Figure 9. It should be
highlighted that the author with a longer trajectory in the field was JA Candanedo from Concordia University (Canada), with 6 publications. Also, remarkable authors as MJ Vasallo and JM Bravo, both from University of Huelva (Spain), published 4 papers recently. Then, P Conti and D Testi from the University of Pisa (Italy), RD Robinett and M Shahbakhti from the Michigan Technological University in Houston, and G Aniba from Mohammed V University in Rabat were the authors that published more papers recently.

However, other authors as TF Edgar from University of Texas (United States) or WJ Cole from the National Renewable Energy Laboratory (United States) started a remarkable research line based in this field, but stopped it in 2014.

Figure 9. Authors publications over the time.
It is worth to note that the relations among them are not depicted, since the topic is very new and just the authors that work in the same institution are related one to each other. However, no strong connections were found between different countries and institutions.

3.7. Bibliometric analysis of keywords

The analysis of the keywords was done mixing both sources Web of Science and Scopus, in order to obtain a clear view of the most used keywords in the studied topic and the connection among them. Figure 10 shows a relationship network with all the keywords, where the most written ones can be seen in a higher size. Moreover, different colours were used to define the employed cluster categories, depending on the area of knowledge. It should be highlighted that MPC, TES, renewable energy sources, housing, and heat pump were located in the cluster blue, meaning that the relation among them in the publications was strong. Then, the cluster yellow shows modes to manage the delivery of the energy to the building as are smart grid and a proper storage management. Besides, in the green cluster, different type of buildings with different occupancy schedules in each one and the systems to produce energy to satisfy the users demand (heating and cooling) are shown. Finally, the red cluster gives information about different types of storage used in the literature and methods to optimize the TES systems operation as nonlinear programming, economic modelling, doing an uncertainty analysis or using weather forecasting. It is worth to note that this part is the most powerful to analyse more in detail the employed techniques to control and to optimize TES systems within the MPC framework. From Figure 10 it is also worth to note that there are no connections between some key concepts in the framework of TES + MPC. A clear example is that real time control is not connected with either weather forecasting and scheduling, meaning that a more detailed research must be done in this field, since a suitable real time control needs a wide knowledge of both. Moreover, storage management is neither linked with
uncertainty analysis nor with renewable energy resources, being necessary to achieve a
knowledge association to fully explore the three keywords.

![Figure 10. Co-occurrence keywords with both databases Web of Science and Scopus.](image)

Then, aiming to find out the most frequent words that the query brought, Figure 11 illustrates a colour map with the repetition intensity of each one. This density view of each point in the map depended both on the number of neighbouring items and on the weights of these items. The larger the number of neighbouring items and the smaller the distances between these items and the point of interest, the higher the item density, as it was carefully explained by VOSviewer designers [22].

As it can be seen in this density view map, MPC and TES appeared in the middle with a highlighted yellow region, indicating that, as expected, are the ones with more frequency
of use in the studied literature. In the rest of the map, other concepts as energy storage, optimization, and buildings have a remarkable interest in the literature. On the other hand, this colour map also allows to identify easily the literature gaps, since the lack of intensity in the colour around the keyword points out the parameters in which the researchers took less attention.

![Colour map with the frequency of occurrence of the keywords.](image)

Figure 11. Colour map with the frequency of occurrence of the keywords.

4. Discussion

According to the keywords analysis developed in Section 3.7, the publications concerning the technological options to improve the performance of the TES + MPC systems within the scientific knowledge carried out until now point out to specific literature gaps. Thus,
aiming to strengthen the selection of such literature gaps, a step forward was carried out in Table 5, where the top 10 keywords of last four years were shown (the number of repetitions of each keyword is given in brackets). Considering these concepts, an overview of the trend topics in the studied field can be obtained and the current literature gaps could be identified. It should be highlighted that thermal energy storage, model predictive control, and energy storage were excluded from the Table 5 analysis, since they were the most used in all years.

Table 5. Top 10 of most frequent keywords in the years from 2016 to 2019.

<table>
<thead>
<tr>
<th>Nº</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Energy management (7)</td>
<td>Costs (4)</td>
<td>Heat pump (10)</td>
<td>Optimization (18)</td>
</tr>
<tr>
<td>2</td>
<td>Optimization (5)</td>
<td>Electric energy storage (4)</td>
<td>Energy management (10)</td>
<td>Heat pump (16)</td>
</tr>
<tr>
<td>3</td>
<td>Integer programming (5)</td>
<td>Ice storage (4)</td>
<td>Optimization (9)</td>
<td>Energy management (11)</td>
</tr>
<tr>
<td>4</td>
<td>Electric energy storage (3)</td>
<td>Heat pump (3)</td>
<td>Buildings (8)</td>
<td>Buildings (11)</td>
</tr>
<tr>
<td>5</td>
<td>Weather forecasting (3)</td>
<td>Renewable energy resources (3)</td>
<td>Costs (6)</td>
<td>HVAC (10)</td>
</tr>
<tr>
<td>6</td>
<td>Smart grid (3)</td>
<td>Weather forecasting (3)</td>
<td>Renewable energy resources (6)</td>
<td>Costs (8)</td>
</tr>
<tr>
<td>7</td>
<td>Scheduling (3)</td>
<td>Cooling (3)</td>
<td>Electric energy storage (6)</td>
<td>Heating (8)</td>
</tr>
<tr>
<td>8</td>
<td>Solar energy (2)</td>
<td>Controllers (3)</td>
<td>HVAC (5)</td>
<td>Smart grid (8)</td>
</tr>
<tr>
<td>9</td>
<td>Concentrated solar power (2)</td>
<td>Smart grid (3)</td>
<td>Heating (5)</td>
<td>Renewable energy resources (7)</td>
</tr>
<tr>
<td>10</td>
<td>Storage management (2)</td>
<td>Storage tank (3)</td>
<td>Demand side management (5)</td>
<td>Cooling (7)</td>
</tr>
</tbody>
</table>

As it can be seen, optimization, energy management, heat pump, and costs were the most used keywords during the analysed four years, meaning that many authors focused their attention in exploring these scientific topics. However, other remarkable concepts as renewable energy resources, smart grid, buildings, HVAC, and weather forecasting appeared either in the last two years with a big impact or in an intermittent way during all the analysed years.

Therefore, taking into account the information given by the keywords in both Figure 11 and Table 5, the conclusions obtained from the most cited publications (Table 4), and also the authors expertise, Figure 12 provides a summary of the essential concepts that should
be studied more in detail in future research. These research gaps framed in the TES + MPC topic are explained more in detail in the following bullets:

- First of all, the PV surface and the TES volume optimization became crucial to optimize the performance of the system and to make the investment profitable in a short period of time.
- Moreover, in the framework of MPC another key concept is the weather forecasting, since an accurate prediction drive to important economic savings.
- Currently, the significance of smart grids increases and buildings with bidirectional energy fluxes are more common in the society. Thus, MPC systems with TES could be an interesting couple to improve the performance and the global implementation of such technology.
- As it was mentioned, the PV and also the rest of renewable energy sources must be considered as the main sources of energy in TES + MPC systems for both heating and cooling applications.
- Additionally, future research should pay attention to the scale of the system in which TES and MPC will be implemented, since the size of the building or the number of occupants can modify the system operation.
- Another important point is to analyse the suitability of the TES systems managed by an MPC strategy in different type of buildings with different occupancy schedules.
- Different HVAC systems must be tested to assess the potential of TES + MPC. The implementation of such control and energy storage technology in different types of heat pumps, its application in district heating, and a wider analysis of the performance in conventional heating and cooling systems are required.
Finally, until nowadays a real time control in a validated model was not found in the literature, being one of the most important challenges in the future to develop a robust model able to operate in occupied buildings.

Figure 12. Literature gaps in the TES + MPC topic.

5. Conclusions

The application of smart control strategies in TES systems became a key point to take advantage of full capacity of such type of storage. Because of that, this paper presents an overview of the control strategies available in the scientific publications during last years, using bibliometric techniques as the tool to manage the information obtained from Web of Science and Scopus. Considering the focus on the smart control, only MPC appeared as a powerful method in which the authors focused their attention recently.
So far, the potential of MPC applied to TES systems was not fully exploited, as it was shown in the total number of scientific papers and patents published until now. Thus, the study of the existing literature defined by the TES + MPC query string drove to find out some literature gaps through the developed bibliometric analysis. Then, these gaps were summarised in eight areas that must be studied more in detail to obtain a full knowledge of the behaviour of MPC working together with a TES system.

The application of MPC in a real time control of a validated model, as well as its suitability to be installed in a smart grid able to manage the energy fluxes of a monitored zone are the major gaps found in the existent literature. Moreover, a well-managed accurate weather forecasting, the optimization of PV and TES sizes to reduce the initial investment, and to take advantage of the full capacity of the renewable energies are three objectives that should be deeply studied to increase the potential of MPC techniques applied to TES systems. Finally, all these points are strongly linked with three physical elements in which authors must pay attention. These aspects are the type of the building that the system is implemented and its occupancy schedule, the HVAC system that must be controlled, and the scale of its system.

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