Universitat de Lleida

Thermal energy storage solutions for building applications

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TESI DOCTORAL

Thermal energy storage solutions for building applications

David Vérez Fernández

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
Programa de Doctorat en: Enginyeria i Tecnologies de la Informació

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2022

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Dedication

To you, always with me every day of my life.

Summary

Climate change is one of the most important challenges for current and future generations. The Intergovernmental Panel on Climate Change (IPCC) estimates that human activities are responsible for approximately 1.0 °C of global warming above pre-industrial levels, resulting in major negative impacts. In this context, the IPCC has set a target of limiting global warming to 1.5 °C by 2050, above which the damage will become irreversible. Greenhouse gas (GHG) emissions are the main drivers of climate change. The period 2010-2019 showed their highest values in history. During this period, the buildings sector accounted for 21% of global GHG emissions. Such data motivated this thesis, framed in the study of the systems that comprise GHG emissions in buildings, as well as the development of technologies to mitigate them. The first section analyses, using bibliometric analysis techniques, the main systems that drive the energy demand of buildings. Therefore, building services and their impact on climate change were studied. In addition, household appliances and their trends in energy efficiency, correlated with the policies implemented at global level, were also studied. Likewise, the co-benefits of thermal energy storage (TES) extrapolated from the field of renewable energies were also studied, identifying TES as transcendental in the energy transition. The second section of the thesis focused on the experimental and simulation analysis of three thermal energy storage systems. The first system focused on decreasing the thermal losses of a heating storage tank by using vacuum insulation. It was found that vacuum insulation can reduce thermal losses by up to 10 times compared to conventional insulation. The second study performed a benchmark evaluation between two designs of phase change material (PCM) macro-encapsulation in a TES. It was concluded that the design to be used will be determined by the application and a trade-off between higher energy density or higher heat transfer. The third study identified the main challenges in using concrete to store energy at high temperature, and a new design was proposed and analysed to overcome these challenges. The results of this thesis have demonstrated that thermal energy storage represents a great potential in the energy transition in general and in buildings in particular.

Resumen

El cambio climático constituye uno de los retos más importantes para las actuales y futuras generaciones. El Panel Intergubernamental sobre Cambio Climático (IPCC) estima que las actividades humanas han sido responsables aproximadamente de 1,0 ºC de calentamiento global por encima de los niveles preindustriales, trayendo consigo grandes impactos negativos. En este contexto, el IPCC ha fijado el objetivo de limitar el calentamiento global en 1.5 ºC para el 2050; por encima de este valor los daños serían irreversibles. Las emisiones de gases de efecto invernadero (GHG) son los principales impulsores del cambio climático. El período 2010-2019 arrojó sus valores más altos de la historia. Durante este período, el sector de los edificios aportó el 21% de las emisiones mundiales de GHG. Tales datos impulsaron esta tesis, enmarcada en el estudio de los sistemas que componen las emisiones de GHG en edificios, así como el desarrollo de las tecnologías que permitan mitigarlas. La primera sección analiza, mediante técnicas de análisis bibliométricos, los principales sistemas que componen la demanda energética de los edificios. Para esto, se estudiaron los servicios de los edificios y su impacto sobre el cambio climático. Así como, los electrodomésticos y sus tendencias en eficiencia energética, correlacionadas con las políticas implementadas a nivel global. Al igual que, los co-beneficios del almacenamiento de energía térmica (TES) extrapolados desde el campo de las energías renovables, identificando al TES como trascendental en la transición energética. La segunda sección de la tesis se centró en el análisis experimental y mediante simulaciones de tres sistemas de almacenamiento térmico. El primer sistema se enfocó en disminuir las pérdidas térmicas de un depósito de almacenamiento para calefacción mediante el uso de aislamiento al vacío. Se demostró que este aislamiento puede disminuir hasta en 10 veces las pérdidas térmicas con respecto al convencional. El segundo estudio realizó una evaluación comparativa entre dos diseños de materiales de cambio de fase (PCM) macro-encapsulados en un TES. Se concluyó que el diseño a utilizar dependerá de la aplicación y de un compromiso entre mayor densidad energética o mayor entrega de calor. El tercer estudio identificó los principales retos en la utilización del hormigón para almacenar energía a alta temperatura, a la vez que se propuso y analizó un nuevo diseño para superar dichos retos. Los resultados de esta tesis han demostrado que el almacenamiento de energía térmica tiene un gran potencial en la transición energética de manera general y de los edificios de manera particular.

Resum

El canvi climàtic constitueix un dels reptes més importants per a les generacions actuals i futures. El Grup Intergovernamental d'Experts sobre el Canvi Climàtic (IPCC) estima que les activitats humanes han estat responsables aproximadament de 1.0 ºC d'escalfament global per sobre dels nivells preindustrials, portant grans impactes negatius. En aquest context, l'IPCC ha fixat l'objectiu de limitar l'escalfament global a 1.5 ºC per al 2050; per sobre d'aquest valor, els danys serien irreversibles. Les emissions de gasos amb efecte d'hivernacle (GHG) són els principals impulsors del canvi climàtic. El període 2010-2019 va donar els seus valors més alts de la història. Durant aquest període, el sector dels edificis va aportar el 21% de les emissions mundials de GHG. Aquestes dades van impulsar aquesta tesi, emmarcada en l'estudi dels sistemes que componen les emissions de GHG en edificis, així com el desenvolupament de les tecnologies que permetin mitigar-les. La primera secció analitza, mitjançant tècniques d'anàlisi bibliomètrica, els principals sistemes que componen la demanda energètica dels edificis. Per això, es van estudiar els serveis dels edificis i el seu impacte sobre el canvi climàtic. A més, es van estudiar els electrodomèstics i les seues tendències en eficiència energètica, correlacionades amb les polítiques implementades a nivell global. Així mateix, es van estudiar els co-beneficis de l'emmagatzematge d'energia tèrmica (TES) extrapolats des del camp de les energies renovables, identificant el TES com a transcendental en la transició energètica. La segona secció de la tesi es va embrancar en l'anàlisi experimental i mitjançant simulacions de tres sistemes d'emmagatzematge tèrmic. El primer sistema es va enfocar a disminuir les pèrdues tèrmiques d'un dipòsit d'emmagatzematge per a calefacció mitjançant l'ús d'aïllament al buit. Es va demostrar que aquest aïllament pot disminuir fins a 10 vegades les pèrdues tèrmiques respecte al convencional. El segon estudi va realitzar una avaluació comparativa entre dos dissenys de materials de canvi de fase (PCM) macro-encapsulats en un TES. Es va concloure que el disseny a utilitzar dependrà de l'aplicació i d'un compromís entre més densitat energètica o més entrega de calor. El tercer estudi va identificar els principals reptes en la utilització del concret per emmagatzemar energia a alta temperatura, alhora que es va proposar i analitzar un nou disseny per superar aquests reptes. Els resultats d'aquesta tesi han demostrat que l'emmagatzematge d'energia tèrmica té un gran potencial en la transició energètica de manera general i dels edificis de manera particular.

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Abbreviations

TES	Thermal energy storage
IPCC	Intergovernmental Panel on Climate Change
GHG	Greenhouse gas emissions
IEA	International Energy Agency
SDGs	Sustainable Development Goals
IRENA	International Renewable Energy Agency
PCM	Phase change material
SHTES	Sensible heat thermal energy storage
LHTES	Latent heat thermal energy storage
TCM	Thermochemical materials
CFD	Computational Fluid Dynamics
SCADA	Supervisory Control and Data Acquisition
HTF	Heat transfer fluid
HVAC	Heating, ventilation, and air conditioning
EES&L	Energy Efficiency Standards and Labelling
LNG	Liquefied natural gas
SH	Space heating
DHW	Domestic hot water
CSP	Concentrated solar power
ORC	Organic Rankine cycle

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Chapter 1

Introduction and objectives

1.1 Introduction

This chapter describes the background and motivation of the present PhD. Furthermore, it provides an overview of the state-of-the-art of the proposed technologies and finally details the objectives pursued during its development.

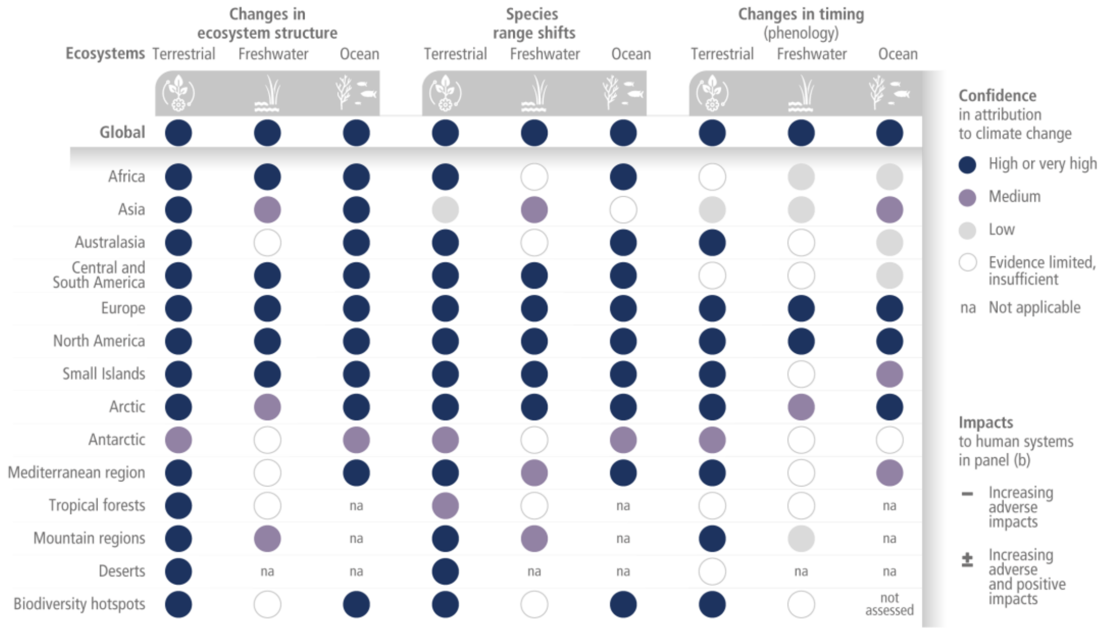
1.1.1 Statement of the problem and motivation

Climate change represents one of the most important challenge for humanity today, setting a large part of the world population at risk [1].

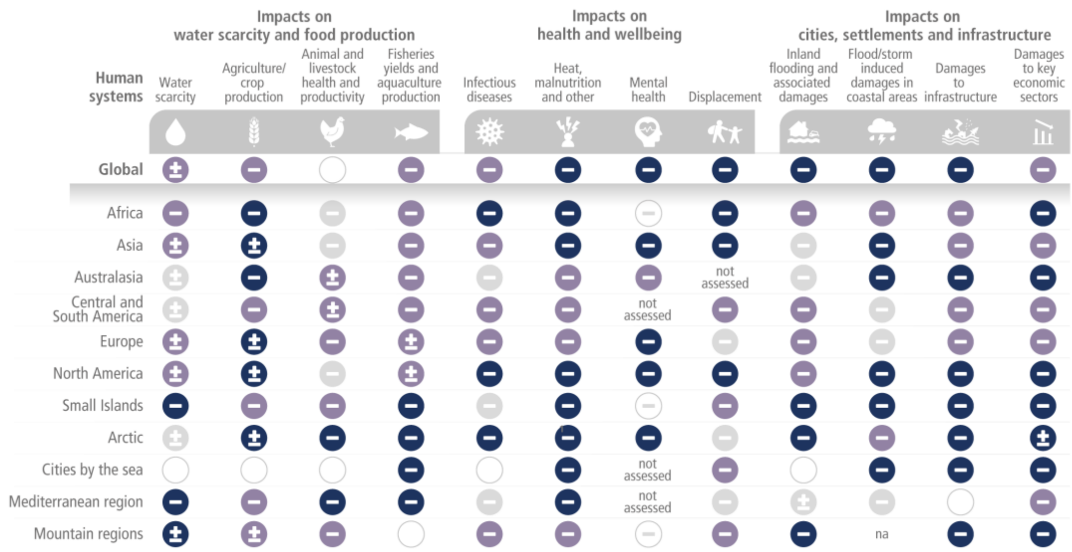
According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [2], human-induced climate change, including more frequent and intense extreme events, was the cause of widespread adverse effects and damage to nature and people, beyond natural climate variability. Human activities are estimated to be accountable for approximately 1.0 °C of global warming above pre-industrial levels. Moreover, the global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate [3].

Although development and adaptation efforts reduced vulnerability, increased extreme weather and climate events are leading to irreversible impacts, as natural and human systems are pushed beyond their adaptive capacity (Figure 1-1).

Greenhouse gas emissions (GHG) are the main drivers of climate change. Figure 1-2 shows that the total net anthropogenic GHG emissions have continued to rise during the period 2010–2019, as have cumulative net CO_2 emissions since 1850. Moreover, the average annual GHG emissions during 2010 to 2019 were higher than in any previous decade.



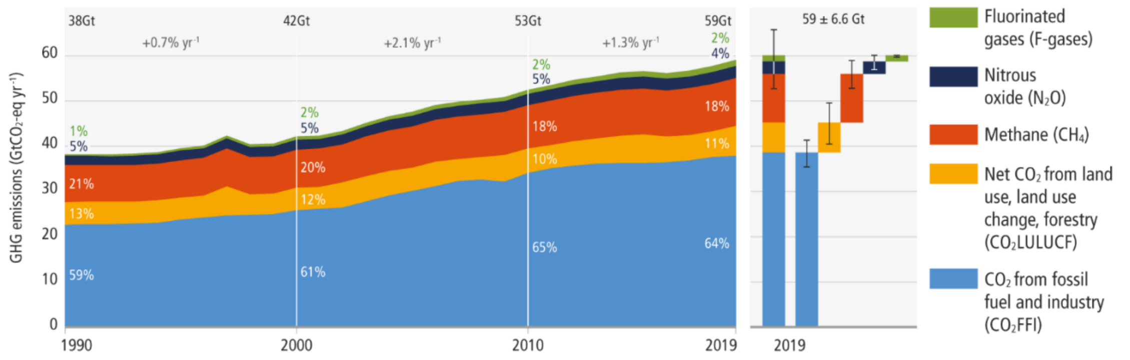
(a)



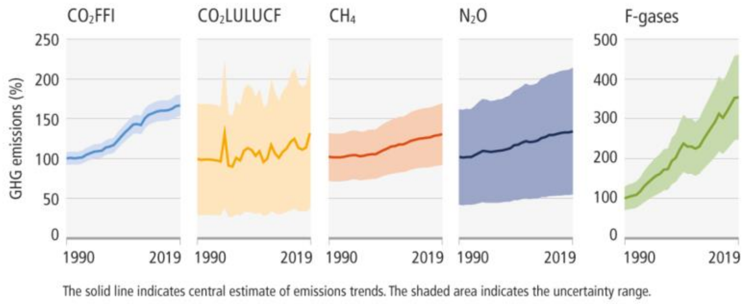
(b)

Figure 1-1. Global and regional impacts attributed to climate change, (a) on ecosystems, and (b) on human systems [2].

The above data evidence that we are approaching a decisive moment for the development of the human species, so efforts from all sectors of society are needed to tackle the climate crisis. Pivoting in the right direction, the number of countries committed to achieve net-zero emissions by mid-century or soon after continues to grow, but so do global greenhouse gas emissions [4]. This gap between rhetoric and action must be closed if we are to stand a fighting chance of limiting by 2050 the rise in global temperatures to 1.5 °C.



(a)



	2019 emissions (GtCO₂-eq)	1990–2019 increase (GtCO₂-eq)	Emissions in 2019, relative to 1990 (%)
CO_2 FFI	38±3	15	167
CO_2 LULUCF	6.6±4.6	1.6	133
CH_4	11±3.2	2.4	129
N_2O	2.7±1.6	0.65	133
F-gases	1.4±0.41	0.97	354
Total	59±6.6	21	154

(b)

Figure 1-2. Global anthropogenic GHG emissions, (a) Global net anthropogenic GHG emissions 1990–2019, and (b) Global anthropogenic GHG emissions and uncertainties by gas – relative to 1990 [2].

In this context, buildings are a source of enormous potential. The total GHG emissions in the building sector reached 12 $GtCO_2eq$ in 2019. It was, equivalent to 21% of global GHG emissions that year, of which 57% were indirect CO_2 emissions from the offsite generation of electricity and heat, followed by 24% of direct CO_2 emissions produced onsite and 18% from the production of cement and steel used for construction and/or refurbishment of buildings (Figure 1-3). If only CO_2 emissions are considered, the share of buildings CO_2 emissions increases to 31% of global CO_2 emissions. Global final energy demand from buildings reached 128.8 EJ in 2019, equivalent to 31% of global final energy demand. Residential buildings consumed 70% of global final energy demand of buildings. Electricity demand of buildings was slightly above 43 EJ in 2019, equivalent to more than 18% of global electricity demand. Over the period 1990 to2019, global CO_2 emissions from buildings increased by 50%, and global final energy demand grew by 38%, with a 54% increase in non-residential buildings and a 32% increase in residential ones [5]. Among energy carriers, the growth in global final energy demand was strongest for electricity, which increased by 161% (Figure 1-4) [6].

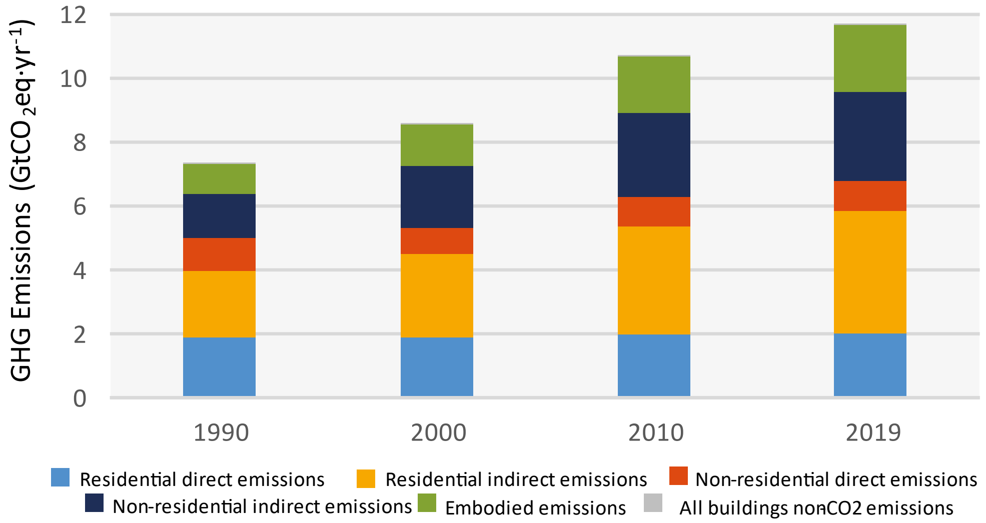


Figure 1-3. Building GHG emissions: historical data based on International Energy Agency (IEA) [6].

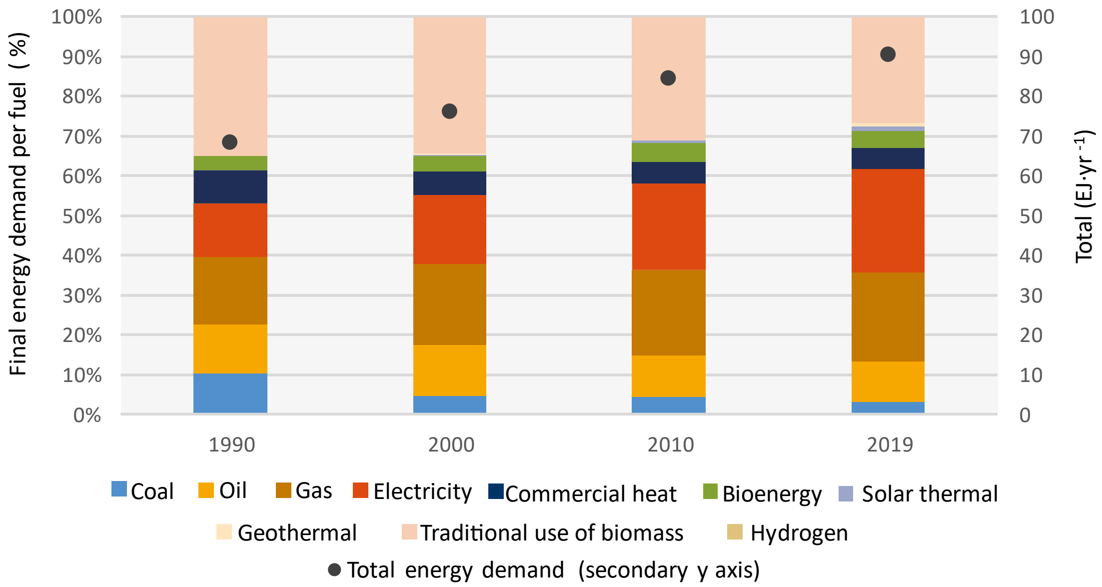


Figure 1-4. Final energy demand per fuel: historical based on IEA data. Adapted from [6].

In 2020, direct and indirect emissions from buildings operation decreased to around 9 $GtCO_2eq$, after increasing by an average of 1% per year since 2010 (Figure 1-5). Although minimum performance standards are becoming more stringent [7] and the integration of renewables is accelerating, the drop in CO_2 emissions from the buildings sector in 2020 is mainly due to lower activity in the services sector (resulting from smart working, closed schools, and empty hotels and restaurants) due to COVID-19 [5].

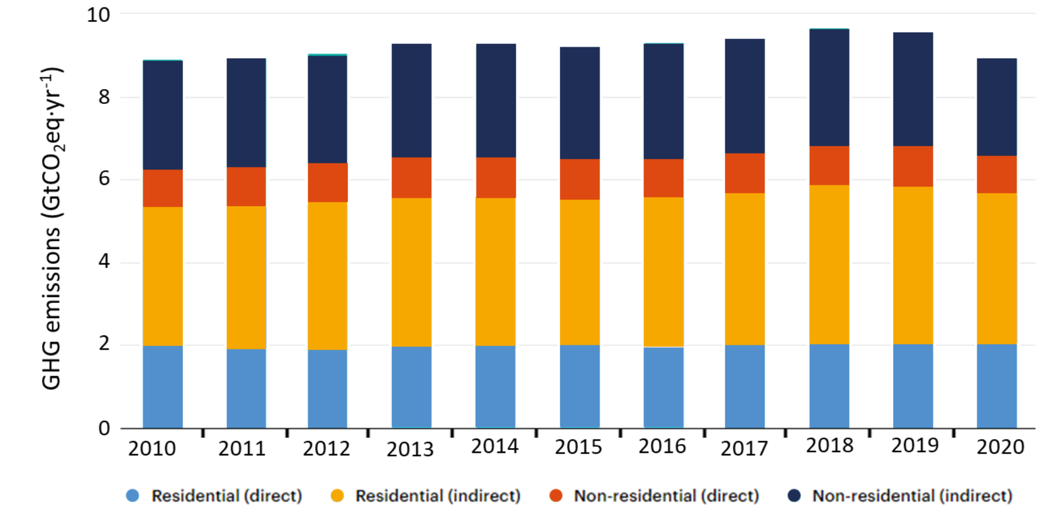


Figure 1-5. Global CO_2 emissions from building operations [5].

In 2021, global energy-related CO_2 emissions (from all sectors) are estimated to have rebounded by more than 4% as demand for coal, oil, and gas bounced back with the economy. The increase of over 1.2 $GtCO_2eq$ would be the largest single increase since the carbon-intensive economic recovery from the global financial crisis more than a decade ago [8].

IPCC AR6 Chapter 9 [6] states that the drivers of GHG emissions from buildings and their climate impact can be identified through an index decomposition analysis (Figure 1-6). Over the period 1990 to 2019, population growth accounted for 28% of the growth in global emissions in residential buildings, the growth in floor area per capita accounted for 52%, and increasing carbon intensity of the global energy mix accounted for 16%. Efficiency improvement contributed to decreasing global emissions from residential buildings by 49% [6]. Based on these results, the lack of sufficiency policies has contributed to the largest increase in CO_2 emissions. However, developing sufficiency policies is not enough, decarbonizing the power sector through the penetration of renewable energies is already a necessity to reach the Paris Agreement. According to the IEA, in order to be in line with the sustainable development goals (SDGs) by 2040, the average annual share of renewables in the energy mix should reach 45% [9]. To do so, the way in which energy is generated, stored, transmitted, distributed, and used must undergo a process of transformation. For this, the development of thermal energy storage (TES) technologies is of paramount importance.

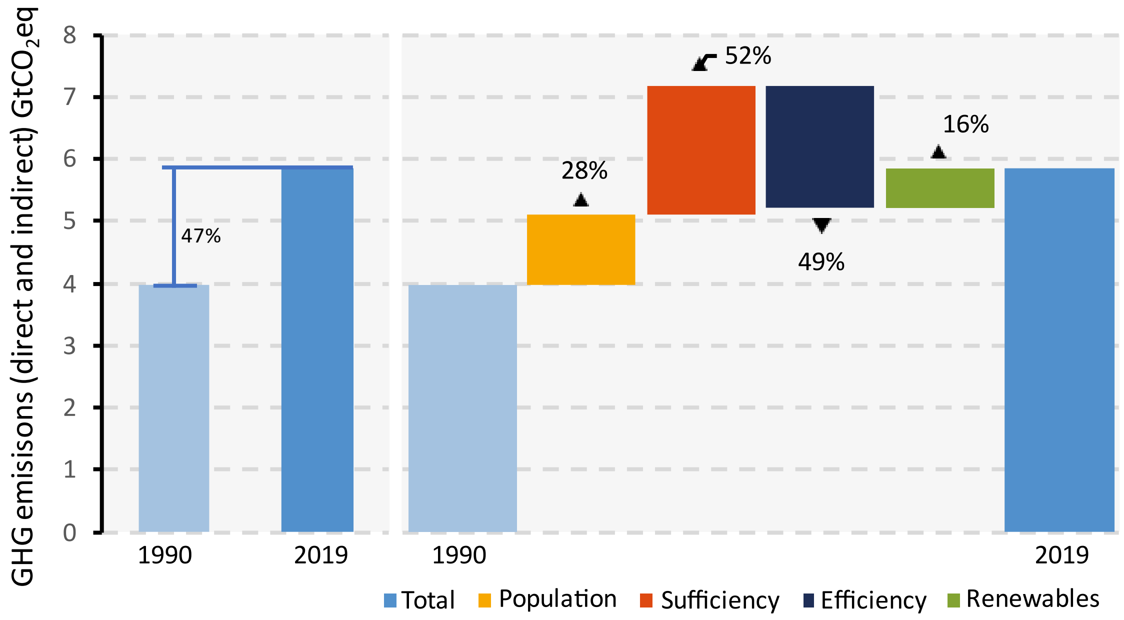


Figure 1-6. Decompositions of changes in historical residential energy emissions 1990-2019 [6].

1.1.2 Thermal energy storage

Thermal energy storage is the temporary storage of energy by heating or cooling a storage medium so that the stored energy can be used at a later time from generation. According to IRENA [10], TES technologies offer unique benefits, such as helping to decouple heating and cooling demand from immediate power generation and supply availability. The resulting flexibility allows far greater reliance on variable renewable sources, such as solar and wind power. TES reduces the need for costly grid reinforcements, helps to balance seasonal demand and supports the shift to a predominantly renewable-based energy system (Figure 1-7).

Research on TES has grown exponentially over the last decade, exemplified in various books [11–13] and journal articles [14–20]. Three main technologies have been identified for TES: sensible thermal energy, latent thermal energy, and sorption and chemical reactions, also known as thermochemical, with their respective operating temperature ranges (Figure 1-8).

Sensible thermal energy storage (SHTES) is the most deployed and commercially advanced type of TES. It stores thermal energy by heating or cooling a storage medium (liquid or solid) without changing its phase. The amount of stored energy is proportional to the temperature change on charging, within the operational temperature range, and the thermal capacity of the material. Sensible heat storage systems offer storage capacities ranging from 10 to 80 kWh/m^3 (up to 200 kWh/m^3 in the case of molten salts) and storage efficiencies between 50% and 98%, depending on the specific heat of the storage medium and thermal insulation technologies.

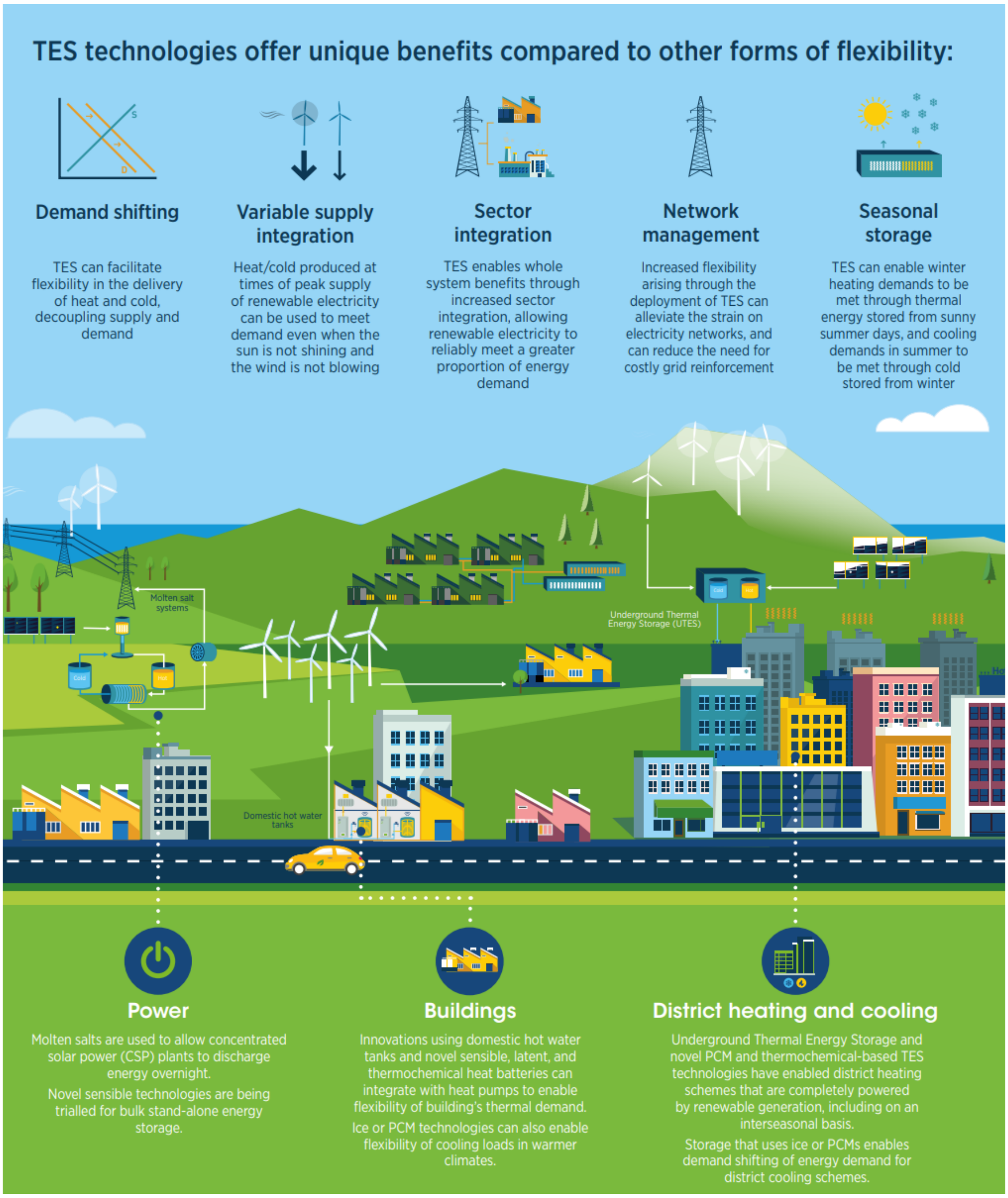


Figure 1-7. Infographic of the TES technologies benefits from IRENA (2020) [11].

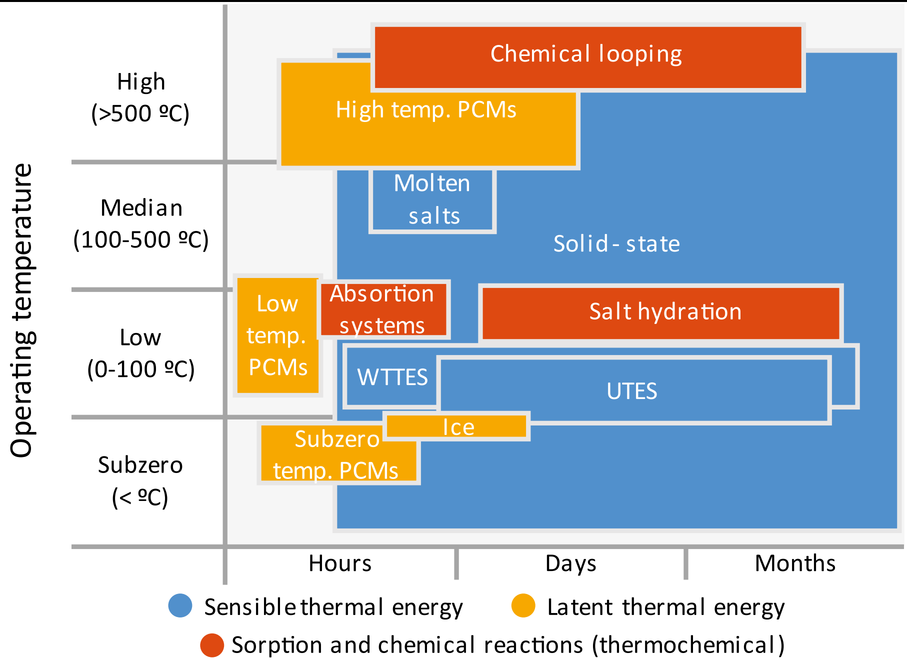


Figure 1-8. Operating temperatures and time ranges for TES technologies. Adapted from IRENA (2020) [11].

Compared to other thermal storage technologies, sensible storage offers the simplest and often cheapest form of storage. As a result, sensible technologies are the most widespread today. The most commonly used storage materials are water, concrete, rock beds, ceramic bricks, molten salts, and soil [21].

In latent heat thermal energy storage (LHTES), the energy is stored when the storage material undergoes a phase change. Unlike sensible heat storage, the process is nearly isothermal, which means that the energy is stored due to the molecular restructuration that takes place within the transition from one phase to the other. Thus, the amount of energy is proportional to the mass and phase change enthalpy of the storage medium. The most widely used and studied phase change transition is the solid-liquid transition, and the materials used are known as phase change materials (PCMs) [11]. Latent heat storage systems offer storage capacities ranging from 50 to 180 kWh/m^3 and storage efficiencies above 90%. The most commonly used PCMs can be classified into five categories (Figure 1-9): salt-water eutectics, ice, paraffin wax, salt hydrates, and salts and their eutectics mixtures [10].

Sorption and chemical reactions category, also known as thermochemical energy storage consists of reversible physical and chemical processes or reactions involving two or more substances, usually known as thermochemical materials (TCMs). This means that the heat supplied during the dissociation process can be recovered if a synthesis reaction takes place. Thermochemical heat storage systems offer storage capacities ranging from 200 to 1200 kWh/m^3 and storage efficiencies between 40% and 60%.

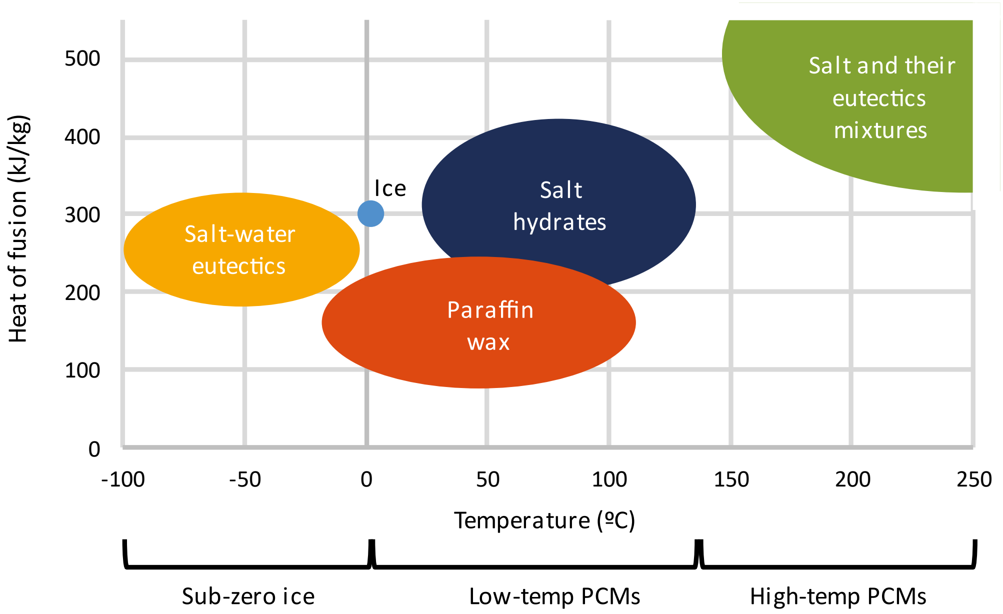


Figure 1-9. Classification of phase change materials. Adapted from IRENA (2020) [11].

1.2 PhD objectives

According to the available literature, buildings have a key role to play in reducing GHG emissions. The introduction section identified that demand shifting to maintain stable energy generation without peak carbon generation and the integration of renewable energy are two of the main measures that can influence the reduction of up to 16% of GHG emissions from buildings. TES is presented as one of the most promising technologies to meet the identified measures. Consequently, the main objective of this PhD thesis is to provide a contextualisation of the background, experimental evidence, and detailed analysis of TES for buildings integration. The research studies carried out in this thesis range from simulations, and laboratory tests, to experimental set-up analyses of full-scale TES prototypes.

The main objectives of the PhD are listed below:

- To critically assess the literature in order to identify the existing energy requirements of buildings and their future trends. Moreover, to identify the main barriers to meeting these requirements in a sustainable way.
- To identify and analyse the main co-benefits of TES integration in buildings.
- To characterise and study heat losses in TES, with special emphasis on heat loss reduction through the use of vacuum insulation.
- To experimentally evaluate different PCM macro-encapsulations for TES to optimise its distribution to match the building energy demands.
- To assess the main challenges in concrete TES and to design and evaluate new concrete TES to meet these challenges.
- Through the research results obtained in this PhD, to contribute to new approaches to commercial targets and future implementations in commercial-scale applications within R&D&I projects.

Chapter 2

PhD thesis structure and methodology

This chapter describes the structure development of the thesis and the methodology used to define the framework and experimental studies of the PhD.

2.1 PhD thesis structure

The present doctoral thesis is based on six papers, of which four are already published in SCI journals and two were submitted.

This PhD thesis is divided into five chapters, as shown in the scheme of the structure of the PhD presented in Figure 2-1. Chapter 1 introduces the urgency for climate actions, the role of the buildings sector in it, and the importance of TES in the energy transition; moreover, this chapter also presents the main objectives of this PhD thesis. Chapter two describes the structure of the PhD thesis and the methodology followed throughout the thesis. Chapter three details the six papers that make up this PhD, providing for all of them the overview of the study, their contribution to the state of the art and the contributions of the candidate. In the fourth chapter, the overall discussion of the results is presented, connecting the results obtained in the six papers, and highlighting the importance of joint efforts of all sectors of society in the fight against climate change. Finally, chapter five highlights the main conclusions drawn from this PhD and recommendations for future work.

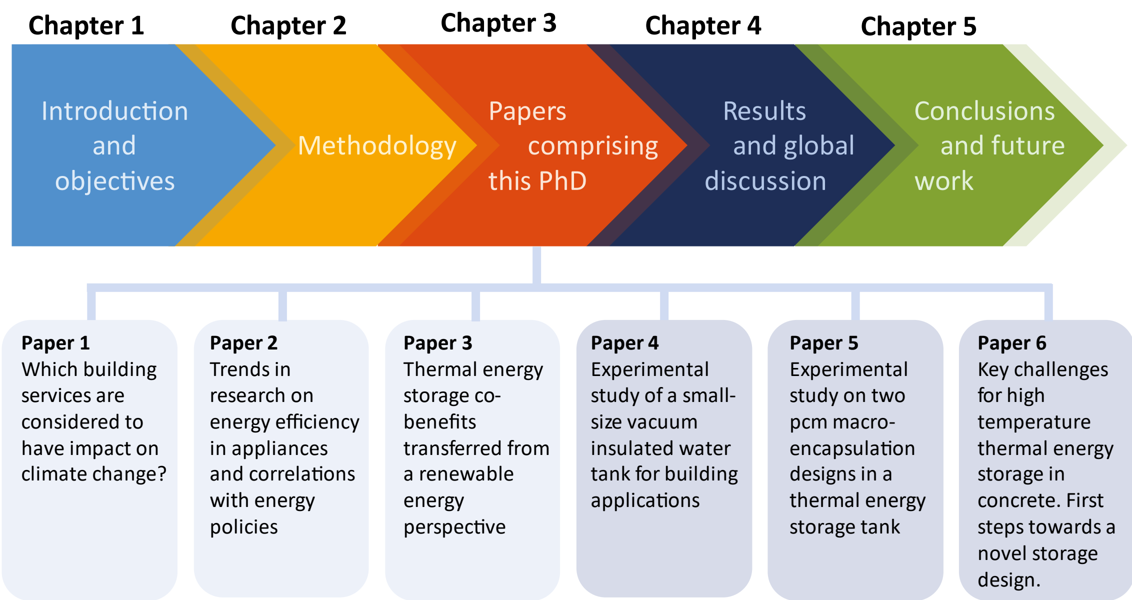


Figure 2-1. Scheme of the PhD thesis structure by chapters.

2.2 Methodology

This section presents the methodology used to achieve the objectives of the thesis and the materials used for the experimental tests. To have an overview of the path followed during its development, this thesis can be divided into two main groups: the analysis of the energy requirements of buildings through bibliometric analysis, and both experimental and simulation studies of thermal storage systems. A diagram of this PhD distribution can be seen in Figure 2-2, where the relation between the research approaches and the papers that were prepared within each of them is presented.

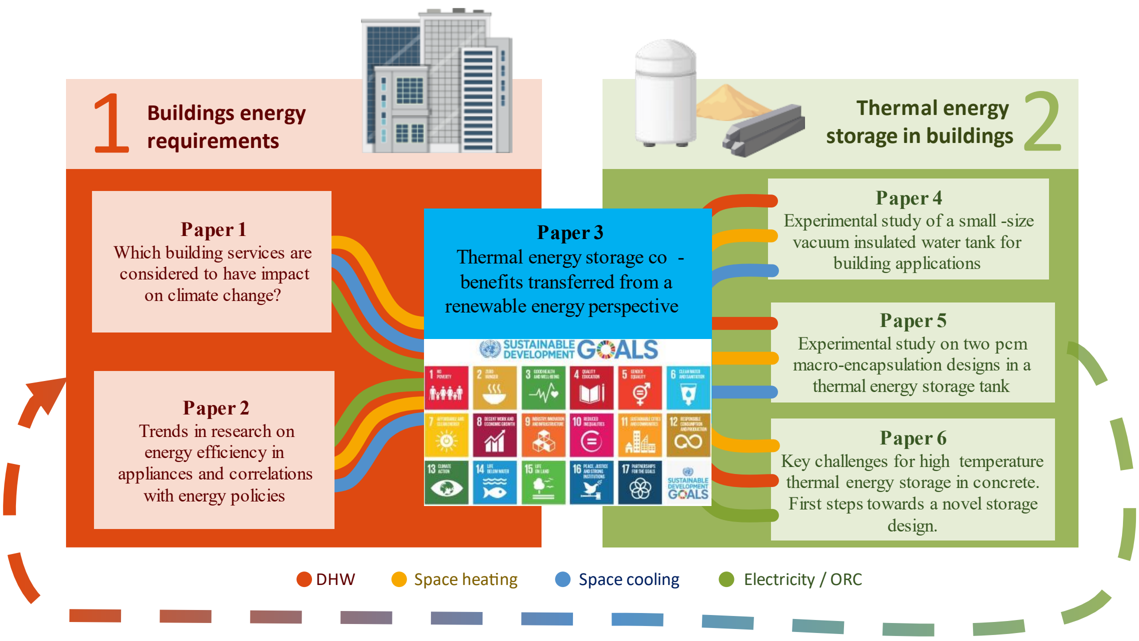


Figure 2-2. PhD thesis structure by chapter.

The first group focuses on bibliometric techniques as a source of analysis of the factors and requirements that can influence the building energy needs, and therefore the type of energy system to be used in each case.

Many studies of the literature were instrumental to identify the main findings in different research fields. In general, the reviews focused on synthesising the main findings through an in-depth and detailed search of existing publications. However, in other fields such as health and social sciences a new technique of literature review proved useful, hence it is now beginning to have a wider impact in other fields of research. This technique is commonly known as bibliometric analysis (considering only scientific literature scientometric analysis) and it is based on the extraction and quantitative analysis of the most relevant data from scientific databases such as Web of Science, Elsevier Scopus, Dimensions, and Google Scholar [22].

Through the results obtained from scientific databases, bibliometric analyses allow a more holistic perspective of the topic of study, find correlations in research and identify bibliographic gaps inherent to a research topic. Furthermore, this type of analysis enables to study the main authors of a particular topic and the relationships between them, as well as the trend of publications over the years.

The methodology followed to perform a bibliometric analysis can be summarised as in Figure 2-3. The first step is to pre-formulate the query(s). For this purpose, representative keywords are selected to ensure an adequate framing of the study. The next step is the selection of the database to be used (in the framework of the studies of this PhD, Scopus was used as the database). Next, the search criteria are established, setting both the geographical scope and the time frame (in this PhD all the studies had a worldwide and regional scope, and the entire period of available publications was analysed). A thorough review of the publications is then carried out to exclude publications that are not related to the topic. At this point the final query of the study is ready, therefore the bibliometric data is downloaded from the database, and the data analysis begins.

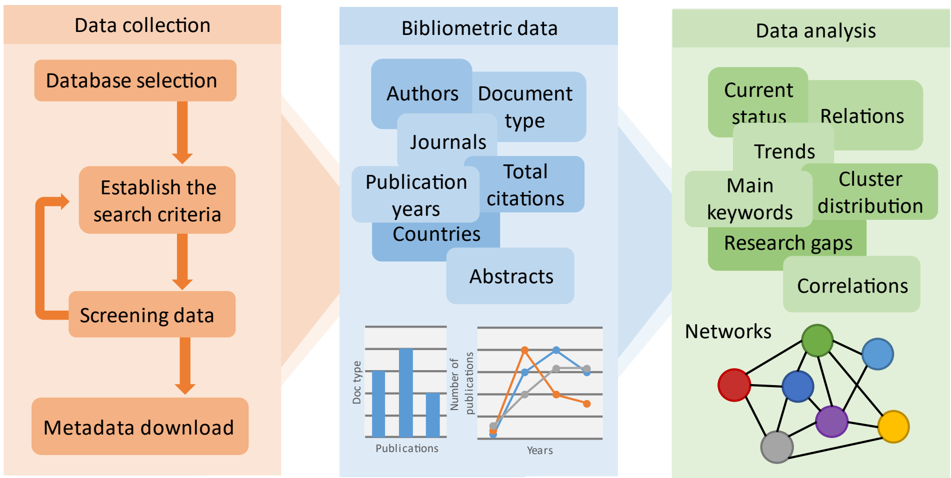


Figure 2-3. Bibliometric analysis in brief (adapted from [24]).

The analysis is divided into two sections. The first section consists of graphing and analysing the downloaded bibliometric data. This first analysis includes the trends in publications, the journals where the results are published, the authors with the most publications, among others. In the second section, a more in-depth analysis is carried out by performing a literature map of the downloaded data, which allows to group the studies into clusters, as well as to identify relationships and gaps between topics. Furthermore, by means of an overlay time-line representation of the clusters, it is possible to identify where the research is going, the lines of research that have not been successful, and to identify the most promising ones.

As a result of the first group of studies conducted for this PhD, it was identified that thermal energy storage is of vital importance for a transition to clean energy use in buildings, and required to meet the SDGs and Europe proposed 2050 targets. In addition, the great diversity of buildings that make up the global building stock and the great variety of climates worldwide mean that there is no single storage technology that can meet all building requirements. Within this context, it is essential to develop advances in all fields of thermal energy storage.

Therefore, this PhD evaluates three thermal storage systems, two of which were evaluated experimentally, and the third by means of Computational Fluid Dynamics (CFD) techniques. The systems to be evaluated were a vacuum insulated water TES tank for liquid sensible heat storage, a macro-encapsulated PCM TES tank for liquid-solid latent heat storage, and a new modular concrete storage design for solid sensible heat storage.

The experimental tests were carried out on two set-ups of the GREiA research group designed and built as part of this PhD for the testing of these TES, and for future testing of similar systems.

There are two critical variables in the performance of a water tank TES, which are stratification and heat losses. The literature reports that reducing heat losses contributes positively to the stratification of the tank [24]. Additionally, literature studies report that vacuum insulation can reduce the heat losses of a tank by at least a factor of six compared to standard insulation (only tested on TES tanks over 100 m^3) [25]. Therefore, paper four undertakes the performance analysis of a 0.535 m^3 vacuum insulated water TES tank for building applications (Figure 2-4). The performance was evaluated by analysing the heat losses of the tank. This was done by a "cooling test", preheating the tank to different temperature levels and recording the temperature inside the tank, on the external surface of the tank, and the ambient temperature for 48 hours. Mainly, two heat loss tests were performed with two different boundary conditions:

- Test A: the water tank is preheated to a uniform temperature of 65 °C.
- Test B: the water tank is preheated to 45 °C in the lower and middle layers and 65 °C in the upper layer.

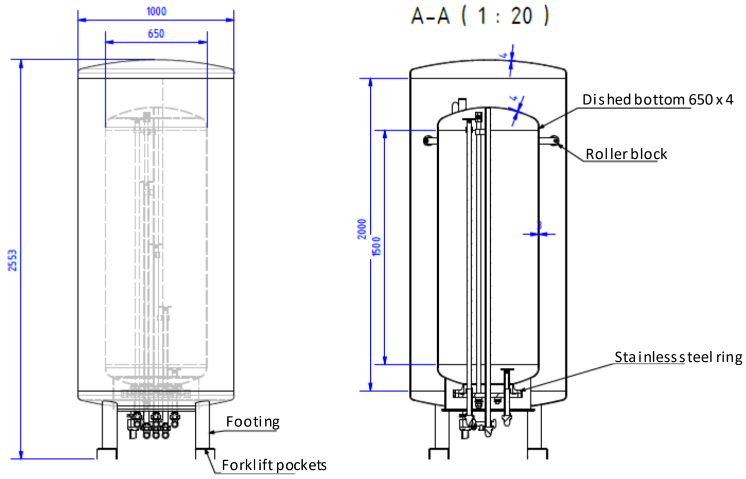


Figure 2-4. Schematic of the 0.535 m^3 water tank built by Sirch Tankbau-Tankservice Speicherbau GmbH [25]. All dimensions are presented in millimetres.

The experimental set-up developed for this test (Figure 2-5) consists of a 200-litre commercial buffer tank with a built-in 9 kW electric heater and a monobloc pump (model OE-IP22-12037) controlled by an Invertek optidrive E3 IP20 variable speed drive. To measure the ambient temperature and the external surface temperature of the tank, 3 Pt-100 class A IEC 60751 temperature sensors of standard type (accuracy 0.15 ± 0.002·t) were implemented. All control variables were recorded through a data acquisition system (STEP DL-01 data logger) connected to a computer equipped with Indusoft SCADA software [26]. The measurement interval was 1 second and the recording interval (time step) was set to 10 seconds.

According to the IEA, the use of electric air conditioners and fans to keep cool accounts for almost 20% of the total electricity used in buildings worldwide. Increased demand for space cooling is also putting enormous pressure on many countries electricity systems, as well as increasing emissions. Therefore, paper five studies two PCM macro-encapsulation designs (Figure 2-6) in a thermal energy storage tank (Figure 2-7) for low temperature applications.

The experimental tests of paper five consisted of performing four different charging and discharging processes to evaluate the effect of the PCM macro-encapsulation design and the flow rate on the temperature distribution, heat transfer rate, and energy stored/released.

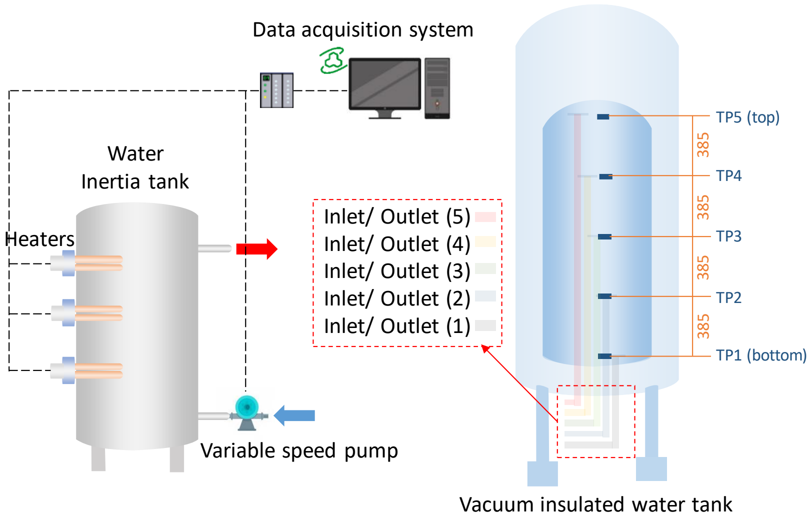
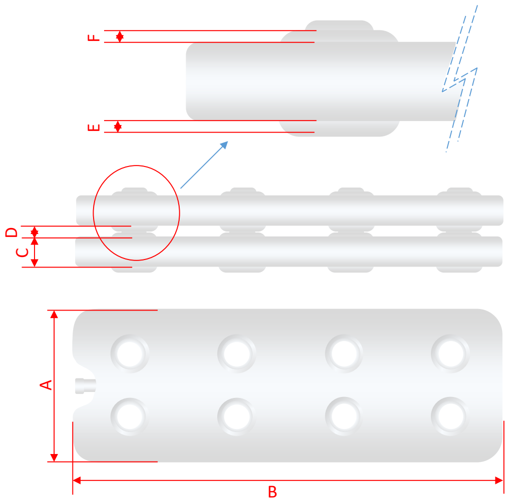


Figure 2-5. Schematic view of the experimental set-up used to perform paper four experiments.



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

Figure 2-6. ThinICE and FlatICE slabs encapsulation. Dimensions in millimetres.

Figure 2-8 shows the experimental set-up developed for the tests, which is composed of a 25-litre inertia water tank, whose temperature is controlled by a vapour compression cooling unit (Zanotti model GCU2030ED01B) of 5 kW cooling power, and two immersion thermostats (OVAN TH100E-2kW and JP SELEC-TA-1kW). The set-up also integrates: two variable speed pumps, used to control the flow and inlet temperature in the TES system; a Badger flowmeter type ModMAG M1000, with an accuracy of ±0.25 % of the actual value; and the TES latent heat storage. The data acquisition system used consisted of 3 STEP DL-01 data loggers [39] connected to a computer integrating system control and data acquisition (SCADA) software developed in InduSoft Web Studio [26]. The data logging interval was set to 10 seconds.

Figure 2-7. Latent heat TES.

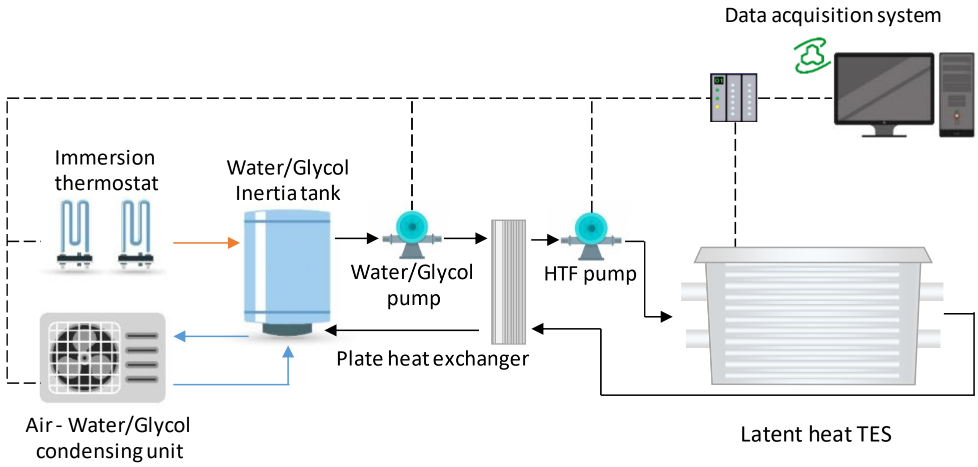


Figure 2-8. Schematic view of the experimental set-up used to perform paper five experiments.

Concerning sensible thermal storage solutions in solids, concrete has a high potential [27–29]. However, this technology still poses challenges, such as manufacturing techniques, material formulation, and design, which limit construction feasibility and thermal performance. In order to improve the current configurations, paper six proposes a new thermal energy storage design using concrete based on a modular concept, improved concrete formulation, and direct contact between the HTF and the concrete. In addition, a preliminary evaluation of the thermal performance of the new concept is carried out by means of a CFD analysis showing the temperature distribution of the modules and the feasibility of the concept.

The design of the proposed concrete module was carried out using Autodesk Inventor software [30], and the simulations were performed with Autodesk CFD software [31]. The main characteristics of the materials used in the simulation are shown in Table 2-1 and Table 2-2.

Table 2-1. Thermophysical properties of concrete implemented in CFD

Property	Value
Thermal conductivity x, y, z direction [W/m·K]	1.01
Density [kg/m^3]	2306
Specific heat [kJ/kg·K]	0.837
Emissivity [-]	0.95
Transmissivity [-]	0
Electrical resistivity [ohm·m]	0
Wall roughness [µm]	0

Table 2-2. Thermophysical properties of the HTF (air) implemented in CFD

Property	Value
Density [m^2/s^2·K]	Equation of state
Viscosity [poise]	0.0001817
Thermal conductivity [W/m·K]	0.02563
Specific heat [kJ/kg·K]	1.004
Compressibility [Cp/Cv]	1.4
Emissivity [-]	1
Wall roughness [µm]	0

Chapter 3

Results

3.1 Paper 1: Which building services are considered to have impact on climate change?

3.1.1 Overview

Buildings are large consumers of energy, with buildings and the building construction sector accounting for more than 30% of global final energy consumption and 40% of total CO_2 emissions, both direct and indirect [32]. However, heating and cooling of buildings is one of the areas with the greatest potential to reduce energy consumption and CO_2 emissions [33]. Indeed, heating and cooling are clearly identified as energy-consuming building services. However, in order to have a comprehensive view of the real climate change mitigation potential of buildings, other building energy services (e.g. lighting) should also be taken into account.

There are several definitions of building services in the literature with different scopes. One states that building services are the systems installed in buildings to make them more comfortable, functional, efficient and safe. Under this definition, building services include building control systems, energy distribution and energy supply. Another definition states that building services aim to achieve a safe and comfortable indoor environment while minimising the environmental impact of a building. Then, under this concept other scopes appear in the framework of building services, with wellbeing, circular economy, and climate change mitigation becoming increasingly important. However, a more holistic approach would also include terms such as shelter, cooking, materials, embodied energy and embodied carbon, CO_2 emissions, GHG emissions, and pollution.

3.1.2 Contribution to the state-of-the-art

This study was focused on the analysis of the available scientific literature using bibliometric techniques. Therefore, the study pursued the following research objectives: (I) to establish the main categories of building services; (II) to identify trends and geographical patterns in the building services literature; (III) to establish the most productive and influential researchers in the field of building services; (IV) to generate and analyse a keyword co-occurrence network; (V) to analyse the main gaps and emerging research themes from the keyword analysis; and (VI) to assess the impact of climate change on the building services research.

The main results of the study can be summarised as follows:

- Building services can be divided into four categories, as shown in Figure 3-1.
- The most recent research on building services can be associated with safety, comfort, and efficiency. With special emphasis on improving the building thermal efficiency and air quality by studying natural ventilation techniques coupled with HVAC systems and the development of new HVAC technologies.
- Electrical efficiency improvements focus on the use of LED lighting and the use of smart control strategies optimised through building simulations.
- When relating building services to climate change, the most recent studies focus on social aspects such as social housing, urban growth, and thermal comfort.
- The main research gaps identified is the lack of strategies that integrate the four groups of building services (identified in this study) in order to draw a more holistic and effective research in the fight against climate change.

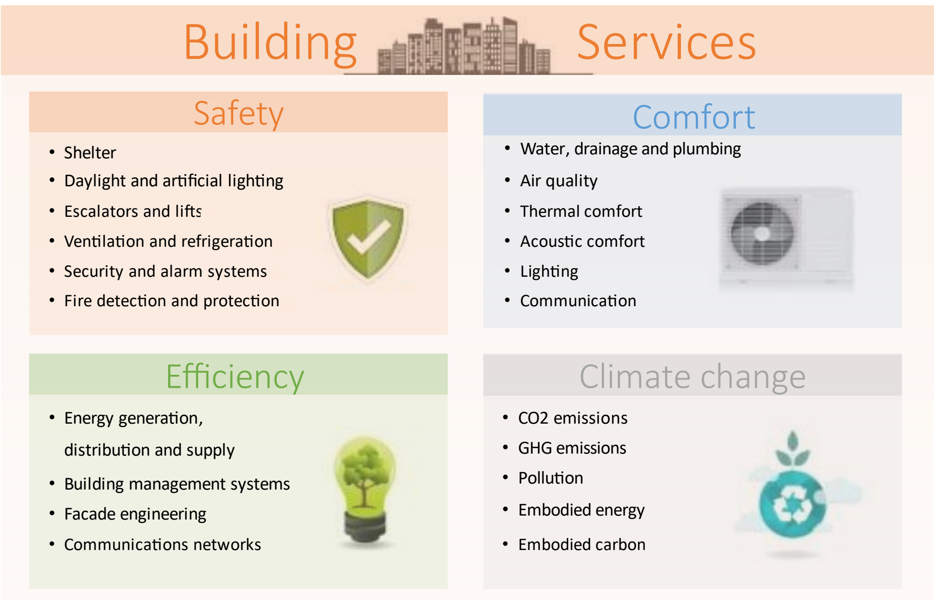


Figure 3-1. Identified building services [34].

3.1.3 Contribution of the candidate

David Vérez and Luisa F. Cabeza conceived and designed the study. After that, David Vérez performed the analysis of the bibliometric data and both co-authors wrote the paper.

3.1.4 Journal paper

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

Reference: D. Vérez, L.F. Cabeza, Which building services are considered to have impact on climate change?, Energies 14 (2021) 3917.

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Review

Which Building Services Are Considered to Have Impact on Climate Change?

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Abstract: The building sector, as a major energy consumer with high direct and indirect CO_2 emissions, plays a vital role in the fight against climate change. In order to make buildings more comfortable, functional, efficient and safe, building services are used. Therefore, building services are the key to decrease their contribution to climate change. Due to the lack of organized literature on this topic, this paper presents the first comprehensive assessment of trends in the literature on building services related to climate change, which was completed by conducting a bibliometric analysis of the existing literature on the topic. The ultimate goal is to provide a source where researchers and other interested parties can find this information in an organized manner. Results show that the most abundant and recent studies related to building services are based on improving energy efficiency by optimizing systems such as ventilation or lighting, the latter with the installation of LED lights. In addition, recent studies have focused on social factors such as housing and urban growth.

Keywords: building services; climate change; literature trends; bibliometric analysis

3.2 Paper 2: Trends in research on energy efficiency in appliances and correlations with energy policies.

3.2.1 Overview

Nowadays, the buildings sector accounts for almost a third of the total final energy consumption and 15% of the direct CO_2 emissions of the end-use sector. Moreover, its share of emissions rises to about 30% if indirect emissions from electricity and heat used in buildings are included [8].

According to the IEA (International Energy Agency), appliances are responsible for 17% of final electricity use in buildings [35]. Furthermore, the energy consumption of building appliances shows an increasing trend over the last 20 years with a small growth in highly developed regions such as North America and the European Union, and a high growth of 4 to 8 times the values reached in 2000 in regions such as China, India, and the Middle East. Nowadays, only one-third of appliance energy use is covered by mandatory performance standards. The IPCC (Intergovernmental Panel on Climate Change) 5th Assessment Report states that energy efficient appliances can reduce the expected increase in electricity consumption due to the proliferation of appliance types and their increased ownership and use. Furthermore, policy measures such as appliance standards with strong energy efficiency requirements are available to help achieve this goal [36]. United States, European Union, China, India, Brazil, Australia, Mexico, South Africa, and Malaysia, nine of the countries that have been operating the longest EES&L (Energy Efficiency Standards and Labelling) programmes, reduced annual electricity consumption in 2018 by 1580 TWh. This represents the same order of magnitude as the total electricity generated by solar and wind energy in those countries showing the high importance of energy efficiency in appliances [37].

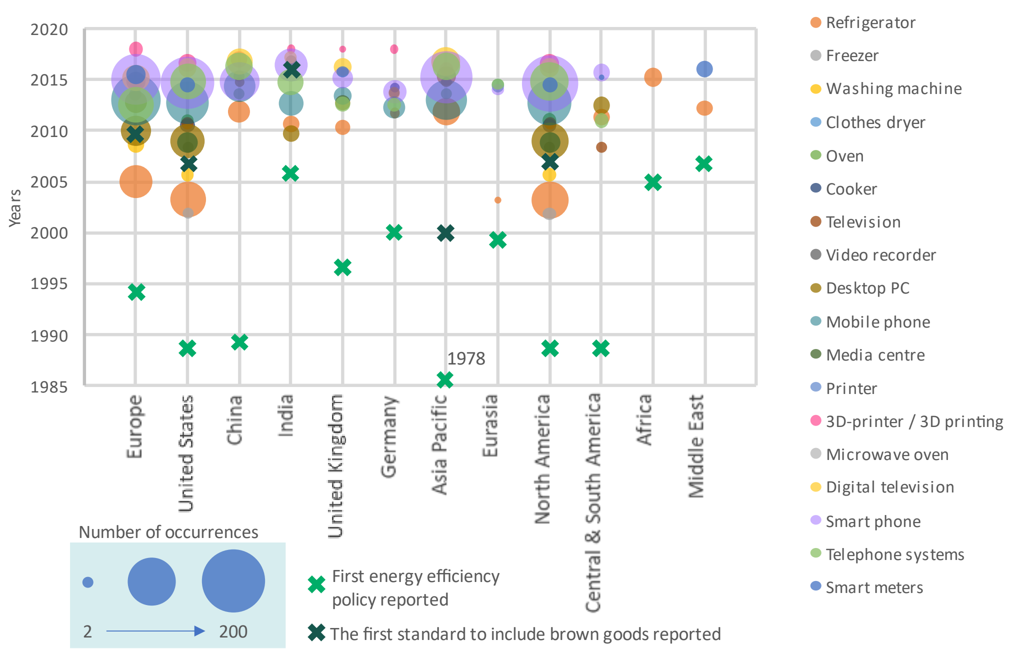
3.2.2 Contribution to the state-of-the-art

The aim of this paper is to evaluate how the energy efficiency in appliances was studied in the world and the main research question is to evaluate if there is a penetration of this concept in the research of countries all over the world and if there is a correlation with energy policies and the EES&L programmes.

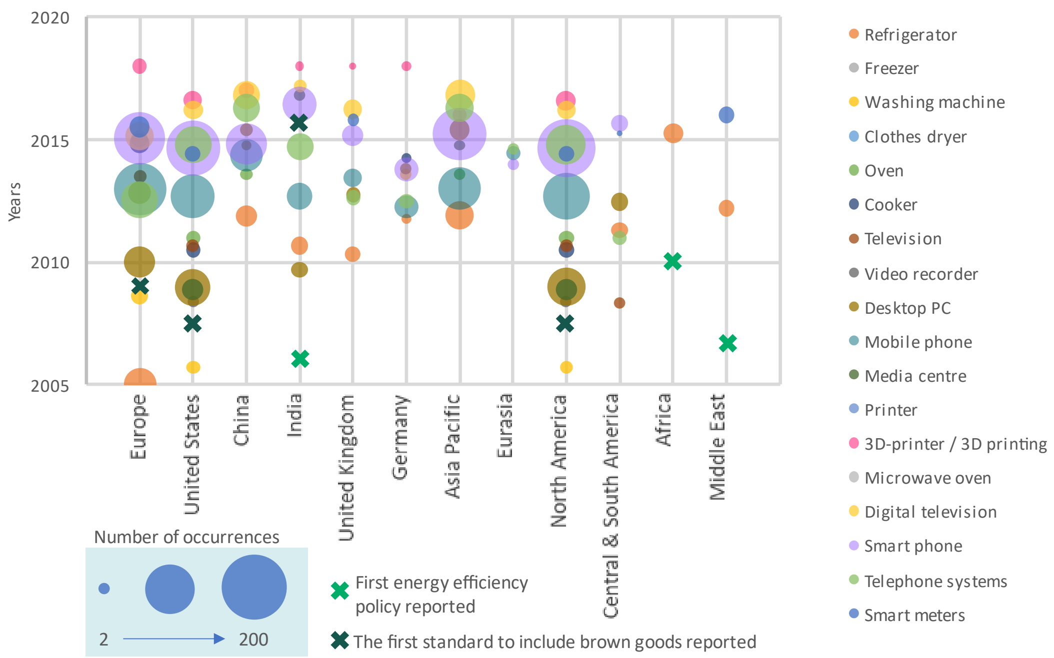
This study was focused on the analysis of the available scientific literature using bibliometric techniques.

The main results of the study can be summarised as follows:

- Energy efficiency standards and labelling (EES&L) started in the 1970s and today operate in more than 120 countries worldwide for more than 100 different types of appliances and equipment [37].
- The countries with larger EES&L programs are the United States, China, the EU, and Australia.
- In countries with strong regulations and long-standing programs that are regularly updated, the contribution was much greater, reducing the electricity consumption of many appliances by more than 50%.
- The most intensive research carried out was after 2010 (Figure 3-2).
- Refrigerators and freezers were the first appliances to be studied in the scientific literature. Moreover, 3D printers, smart meters, and smartphones are the most recent ones.
- The first regions/countries to establish policies on appliance efficiency are the ones that first started to publish on this topic and the ones with the highest overall number of publications.
- There is a 3- to 30-years gap between the establishment of the first standards or policies in the different regions and the core of publications in these regions (Figure 3-2).
- India stands out for a good relationship between publications and policies, showing a quick response of the scientific community to the policies in place.



(a)



(b)

Figure 3-2. Average publications year and number of occurrences of the different appliances in each studied country/region, (a) range of years from 1985 to 2020, (b) year range from 2005 to 2020. Data from the Scopus query. The green crosses indicate the first appliance efficiency standard or policy implemented in each country/region. The dark green crosses indicate the first appliance efficiency standard or policy that includes brown goods appliances. Data obtained from the IEA policies database [38].

3.2.3 Contribution of the candidate

David Vérez and Luisa F. Cabeza conceived and designed the study. After that, David Vérez performed the analysis of the bibliometric data. The co-authors collaborated in the preparation of the manuscript, as well as during the answer to reviewers.

3.2.4 Journal paper

The scientific contribution from this research work was published in the journal Energies in March 2022.

Reference: D. Vérez, E. Borri, L.F. Cabeza, Trends in research on energy efficiency in appliances and correlations with energy policies, Energies 15 (2022) 3047.

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Article

Trends in Research on Energy Efficiency in Appliances and Correlations with Energy Policies

David Vérez , Emiliano Borri and Luisa F. Cabeza *

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Abstract: According to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment report, energy-efficient appliances can reduce global electricity consumption even though there is an expected increase in the number and ownership of appliances. The International Energy Agency (IEA) expects a high increase in energy efficiency in traditional appliances (refrigerators, washing machines, television, etc.), and in the number of new appliances installed (also called plug loads). The bibliometric study of publications related to energy-efficient appliances carried out in this paper shows that research on this topic is growing in developed regions (North America and Europe) and even more in some developing regions (Asia Pacific) with a high emphasis on China and India. The results indicate that, in general, policies are always implemented before the core of publications on the topic, with time spans ranging from 3 to 30 years. However, the trend seems to be changing with publications related to new appliances where the core research happens shortly after or in parallel to the establishment of policies.

Keywords: energy efficiency; appliance; climate change; policies; label; bibliometric analysis

3.3 Paper 3: Thermal energy storage co-benefits in building applications transferred from a renewable energy perspective.

3.3.1 Overview

Any action in buildings may have substantial value beyond the direct impact looked for; that is, any action has multiple impacts, which can affect the economy, society, or end user []. These impacts are related to health (*better indoor conditions, energy poverty alleviation, better ambient air quality, reduction of the heat island effect*), environment (*reduced local air pollution, reduced sewage production*), resource management (*including water and energy*), social well-being (*increase productivity for women, fuel poverty alleviation, decrease in energy expenditure*), microeconomic effects (*increase productivity in non-residential buildings*), macroeconomic effects (*creation of jobs*), and *energy security*.

These positive impacts that are not related to the direct objective of study are known as co-benefits. According to the IPCC AR6 [40], *co-benefit* is "a positive effect that a policy or measure aimed at one objective has another objective, thereby increasing the total benefit to society on the environment". Another definition of co-benefit, related to climate, states that "climate co-benefits are beneficial outcomes from action that are not directly related to climate change mitigation" [41].

Highlighting co-benefits of TES technologies, such as with any other technology, contributes to social acceptance of such technologies [41]. Since literature agrees [42] that one of the main barriers for TES implementation is the lack of knowledge about these systems, dissemination of their co-benefits, especially those related to health and environment, can help in the knowledge deployment. Moreover, literature states that local climate actions would potentially occur faster and at a higher level if they generate co-benefits, such as *environmental, public health, or economic development* benefits, on top of *energy efficiency* and *cost savings*, although usually the last two are already powerful motivators [43].

3.3.2 Contribution to the state-of-the-art

The literature highlights the advantages of using TES in buildings (i.e., increasing efficiency and reliability of energy systems, better economic feasibility, reducing investment and operation costs, reducing pollution, reducing CO_2 emissions) [44–46], but these advantages have never been identified as co-benefits. Therefore, this paper aims at filling up this literature gap by evaluating the potential co-benefits of TES in buildings. To this end, this article first reviews the literature on the co-benefits of renewable energy for building applications, and then evaluates how these co-benefits can be attributed to thermal energy storage in buildings.

The main results of the study can be summarised as follows:

- By cross-sectorizing the renewable energy and thermal energy storage (TES), the co-benefits of thermal energy storage in buildings were identified.
- The TES co-benefits identified in the literature are those related to *environmental* co-benefits, *water* co-benefits, *health related* co-benefits, *economic* and *cost related* co-benefits, and benefits related to *policies.*
- TES is a fundamental technology in the *energy transition* not only to increase the efficiency of energy systems and allow a better integration of renewables but also to provide benefits to *health impact*, *economic growth*, and *energy security*.
- Economic investments in the technological development of TES together with targeted energy policy is fundamental to overcome the actual barriers and enhance the integration of this technology in the actual energy system.

3.3.3 Contribution of the candidate

David Vérez and Luisa F. Cabeza conceived and designed the study. After that, David Vérez and Emiliano Borri performed the analysis of the bibliometric data. The co-authors collaborated on the preparation of the manuscript, as well as during the answer to reviewers.

3.3.4 Journal paper

The scientific contribution from this research work was submitted to Journal of Energy Storage in May 2022.

Thermal energy storage co-benefits in building applications transferred from a renewable energy perspective.

David Vérez, Emiliano Borri, Gabriel Zsembinszki, Luisa F. Cabeza*
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Abstract

Although one of the main aims of using renewable energy sources in building applications is to reduce the environmental impact caused by the high global energy demand of buildings, it may also produce other positive effects, known as co-benefits. Thermal energy storage technologies are often used in building applications, either integrated into the renewable system or independently, for *energy savings* or *energy efficiency* reasons. This paper shows that it is possible to identify the co-benefits of the use of thermal energy storage in buildings by cross-sectorizing the renewable energy and thermal energy storage sectors. To this end, this article first reviews the literature on the co-benefits of renewable energy for building applications, and then evaluates how these co-benefits can be attributed to thermal energy storage in buildings. As a result of a keywords analysis, the main co-benefits of thermal energy storage were identified related to *environmental*, *health*, *economic*, *cost*, and *policies* aspects.

Keywords: co-benefits; renewable energy; thermal energy storage; buildings; cross-sectorisation

3.4 Paper 4: Experimental study of a small-size vacuum insulated water tank for building applications.

3.4.1 Overview

As stated in the introduction chapter, the use of renewable energy sources is one of the key actions for the reduction of GHG emissions into the atmosphere. Today, the exploitation of solar energy in building applications represents the most common alternative to the use of fossil fuels to supply thermal energy for space heating or domestic hot water. However, due to the mismatch between solar availability and energy demand, the integration of thermal energy storage (TES) is fundamental to enhance the efficiency of solar heating systems, increasing the potential use of renewable energy resources [44,47]. In solar heat applications with temperatures below 100 ºC, water represents the most common storage material due to its high specific heat, low cost, and availability. The scientific literature on water tanks as TES is mostly related to two topics: "stratification" and "heat losses". Indeed, the efficiency of water tanks can be enhanced by exploiting the stratification effect that naturally takes place due to the difference in density induced by the water at different temperatures. This allows to extract hot water at the top (that can be used for domestic hot water) and less heated water in the middle (that can be suitable for space heating). In the literature, different studies and techniques were proposed to improve the stratification by enhancing the stratification effect [48–53]. In order to reduce heat losses (which also contributes positively to stratification [54]), studies focus on improving the thermal insulation of storage tanks [55]. One of the most promising technologies is the use of vacuum insulation. Using vacuum insulation, the thermal conductivity can be reduced 6 to 10 times compared to conventional materials [56]. However, this technology has only been used for storing cryogenic materials such as liquefied nitrogen, air, or natural gas (LNG) [57,58], or for large water tanks (100 m^3 or more) [59,60].

3.4.2 Contribution to the state-of-the-art

At present, there are no studies in the literature that report the efficiency of small-size water tanks using vacuum-insulation for small building applications such as single-family house. On this basis, this paper shows the heat transfer performance of a 0.535 m^3 water tank with a vacuum insulated double wall suitable for space heating (SH) and domestic hot water (DHW) supply for domestic applications. The study shows that vacuum insulation can effectively reduce the heat losses in small-size water tanks for domestic applications. Indeed, compared to a standard water tank, the U-value can be significantly lower allowing to maintain the water at high temperature inside the tank. However, as shown in Figure 3-3, the critical part of the design of those tanks is the bottom side that is usually used to place the support parts and the piping of the tank, which act as thermal bridges to the ambient.

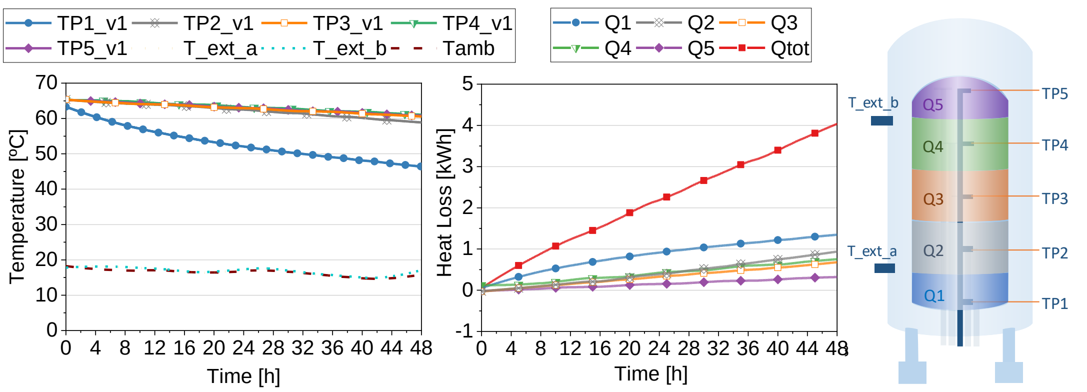

Figure 3-3. Temperature profiles (left) and calculated heat losses (right) for test A. Tamb represents the ambient temperature and Qtot is the sum of heat losses from Q1 to Q5.

The two different tests carried out in this study (Figure 3-3 and Figure 3-4) showed that the heat loss rate depends on the average water temperature inside the tank. Indeed, a tank filled with water at lower temperature due to stratification (Figure 3-4) has a considerably lower heat loss rate due to the smaller temperature difference with respect to the ambient, which is especially significant at the bottom surface, where most of heat losses occur.

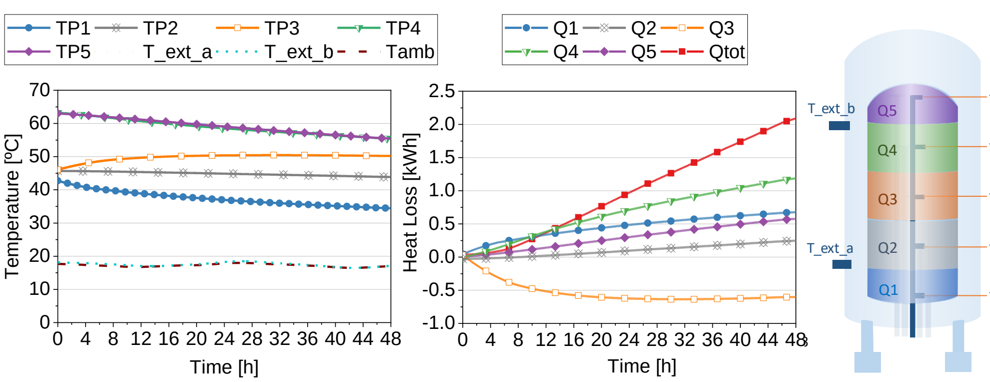

Figure 3-4. Temperature profiles (left) and calculated heat losses (right) for test B. Tamb represents the ambient temperature and Qtot is the sum of heat losses from Q1 to Q5.

3.4.3 Contribution of the candidate

David Vérez, Emiliano Borri and Gabriel Zsembinszki conceived and designed the study, David Vérez and Emiliano Borri built the experimental set-up, and performed the experiments. The co-authors collaborated on the interpretation of the results and on the preparation of the manuscript, as well as during the answer to reviewers.

3.4.4 Journal paper

The scientific contribution from this research work was published in the journal Sustainability in 2021.

Reference: D. Vérez, E. Borri, A. Crespo, G. Zsembinszki, B. Dawoud, L.F. Cabeza, Experimental study of a small-size vacuum insulated water tank for building applications, Sustainability 13 (2021) 5329.

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Article

Experimental Study of a Small-Size Vacuum Insulated Water Tank for Building Applications

David Vérez [1], Emiliano Borri [1], Alicia Crespo [1], Gabriel Zsembinszki [1], Belal Dawoud [2] and Luisa F. Cabeza [1,*]

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[2] Laboratory of Sorption Processes, Faculty of Mechanical Engineering, East Bavarian Technical University of Applied Sciences (OTH-Regensburg), 93053 Regensburg, Germany; belal.dawoud@oth-regensburg.de
* Correspondence: luisaf.cabeza@udl.cat; Tel.: +34-973-003-576

Abstract: Insulation of thermal energy storage tanks is fundamental to reduce heat losses and to achieve high energy storage efficiency. Although water tanks were extensively studied in the literature, the enhancement of the insulation quality is often overlooked. The use of vacuum insulation has the potential to significantly reduce heat losses without affecting the dimension of the storage system. This paper shows for the first time the results of the heat losses tests done for a 0.535 m^3 water tank for residential building applications built with a double wall vacuum insulation. The different tests show that the rate of heat losses strictly depends on the temperature distribution inside the tank at the beginning of the experiment. Compared to a conventional water tank insulated with conventional materials, the U-value of the lateral surface was reduced by almost three times (from 1.05 $W/K\cdot m^2$ to 0.38 $W/K\cdot m^2$) using vacuum insulation. However, the bottom part, which is usually used to place the support parts and the piping, is the critical design part of those tanks acting as a thermal bridge with the ambient and enhancing heat losses.

Keywords: thermal energy storage; water tank; thermal insulation; vacuum insulation; heat losses test; building applications

check for updates

Citation: Vérez, D.; Borri, E.; Crespo, A.; Zsembinszki, G.; Dawoud, B.; Cabeza, L.F. Experimental Study of a Small-Size Vacuum Insulated Water Tank for Building Applications. *Sustainability* 2021, 13, 5329. https://

3.5 Paper 5: Experimental study on two PCM macro-encapsulation designs in a thermal energy storage tank.

3.5.1 Overview

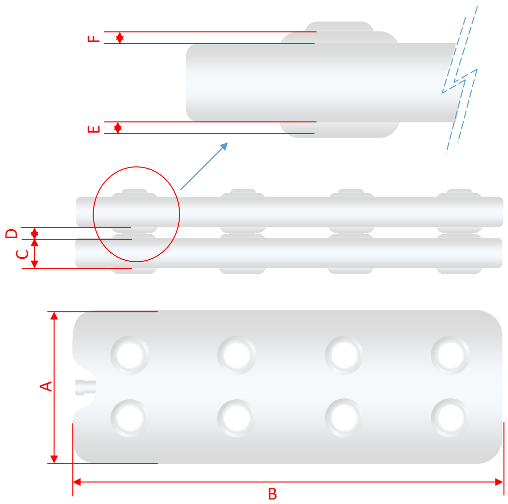
The use of thermal energy storage (TES) has proven to be an effective way to enhance the penetration of renewable energy into energy systems. Amongst all TES technologies, latent heat thermal energy storage (LHTES) received the attention of several researchers over the last decade due to its high energy density and the wide range of applications [46]. The principle behind LHTES is the use of phase change materials (PCM) as the storage medium, allowing to store thermal energy at a nearly constant temperature exploiting the latent heat during the phase transition. The most common one is the phase change from solid to liquid to minimize the impact of volume variations [11]. One of the weaknesses of PCM is its low thermal conductivity that negatively affects the thermal power involved in the charging and discharging processes of the energy storage system. Indeed, this represents one of the main challenges facing the implementation of PCM in various applications.

The main solutions that were extensively studied in the literature to overcome this drawback are the increase in the convection coefficient of heat transfer by means of dynamic systems, the addition of particles (such as carbon elements, metallic particles, and nanoparticles), the inclusion of PCM in a metallic matrix, and the increase in the heat transfer surface area by using fins, and micro and macro-encapsulation [61–63]. On the one hand, PCM micro-encapsulation allows increasing heat transfer surface area between the PCM and the heat transfer fluid. However, for PCM microencapsulation, complex and expensive processes are needed, such as spray drying (physical method) or interfacial polymerization (chemical method) [64]. On the other hand, macro-encapsulation requires a simpler making process resulting in a lower cost [65]. Macro-encapsulated PCM can be designed with different geometries mainly based on rectangular [66], cylindrical [67,68], and spherical shapes [69] that can be adapted to different applications. However, the effect of macro-encapsulation design on heat transfer performance has never been experimentally analysed in the scientific literature.

This paper shows for the first time a comparison based on experimental results of the thermal behaviour of two different designs of macro-encapsulation of rectangular PCM slabs.

3.5.2 Contribution to the state-of-the-art

This research provides an experimental benchmark evaluation of two PCM macro-encapsulation designs in a LHTES, to assess the trade-off between different macro-encapsulation design thicknesses on the heat transfer rate or energy density of the LHTES. Figure 3-5 shows the two macro-encapsulation designs employed in the research. The comparison of the two designs was done in terms of temperature profile, heat transfer rate, and energy obtained during the discharging process.



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

Figure 3-5. ThinICE and FlatICE slabs encapsulation. Dimensions in millimetres.

The effect of increasing the heat transfer surface area by using ThinICE slabs on the heat transfer rate delivered by the storage tank is noticeable at higher flow rate where the heat transferred by convection is higher. Furthermore, using thinner slabs, the higher heat transfer surface area achieves a higher discharging power but, due to the lower energy density of the LHTES with this type of slab, the power is delivered for a shorter period of time. Therefore, for longer discharging periods and for higher storage capacity given a fixed volume of storage tank, the use of FlatICE is recommended to be considered in preference.

3.5.3 Contribution of the candidate

David Vérez and Luisa F. Cabeza conceived and designed the study, David Vérez built the experimental set-up, and performed the experiments. The co-authors collaborated on the interpretation of the results and on the preparation of the manuscript, as well as during the answer to reviewers.

3.5.4 Journal paper

The scientific contribution from this research work was published in the journal Applied Sciences in 2021.

Reference: D. Vérez, E. Borri, A. Crespo, B.D. Mselle, Á. de Gracia, G. Zsembinszki, L.F. Cabeza, Experimental study on two PCM macro-encapsulation designs in a thermal energy storage tank, Applied Sciences 11 (2021) 6171.

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Article

Experimental Study on Two PCM Macro-Encapsulation Designs in a Thermal Energy Storage Tank

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Abstract: The use of latent heat thermal energy storage is an effective way to increase the efficiency of energy systems due to its high energy density compared with sensible heat storage systems. The design of the storage material encapsulation is one of the key parameters that critically affect the heat transfer in charging/discharging of the storage system. To fill the gap found in the literature, this paper experimentally investigates the effect of the macro-encapsulation design on the performance of a lab-scale thermal energy storage tank. Two rectangular slabs with the same length and width but different thickness (35 mm and 17 mm) filled with commercial phase change material were used. The results show that using thinner slabs achieved a higher power, leading to a reduction in the charging and discharging time of 14% and 30%, respectively, compared with the thicker slabs. Moreover, the variation of the heat transfer fluid flow rate has a deeper impact on the temperature distribution and the energy charged/released when thicker slabs were used. The macro-encapsulation design did not have a significant impact on the discharging efficiency of the tank, which was around 85% for the operating thresholds considered in this study.

Keywords: thermal energy storage; latent heat thermal energy storage; phase change materials (PCM); macro-encapsulation; rectangular slab; experimental study

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Citation: Vérez, D.; Borri, E.; Crespo, A.; Mselle, B.D.; de Gracia, Á.; Zsembinszki, G.; Cabeza, L.F. Experimental Study on Two PCM Macro-Encapsulation Designs in a

3.6 Paper 6: Key challenges for high temperature thermal energy storage in concrete. First steps towards a novel storage design.

3.6.1 Overview

Thermal energy storage (TES) allows overcoming the mismatch between energy supply and demand, and this mismatch can be in time, temperature, power, and location [70]. Therefore, TES has multiple applications. If high temperature is considered above 150 ºC, where water cannot be used as storage medium, high temperature TES applications include process heat and electricity production in concentrating solar power (CSP) plants.

Process heat demand in industry can be supplied by fossil fuels, as is common practice today, but could also be supplied by solar energy, or by recovery of waste heat (on-site or off-site). The integration of solar energy in the industry requires TES systems using any of the available technologies (sensible, latent, and thermochemical TES) [71]. Similarly, to efficiently use industrial waste heat as input in industry, a TES system is required [72]. The potential of waste heat recovery in the European non-metallic mineral industry in the period 2007-2012 was estimated by Miró et al. [73] using a bottom-up approach, showing an average of 0.33 PJ/year. This estimation highlights the high potential of this energy source.

Solar energy represents today the main renewable source to produce both thermal and electric power. One of the main large-scale technologies to convert solar energy into electricity is represented by CSP plants. According to REN21 [74], in 2020 the total capacity installed worldwide amounts to 6.2 GWe, and it is expected to continue growing. In order to deal with the intermittency of the sun, thermal energy storage is an essential component. Current commercial CSP technologies mainly rely on the use of molten salts as storage medium [75]. However, its main drawbacks consist of corrosion issues and its limited operating temperature range (up to 360 ºC), which limits CSP in both global performance and cost [76]. Amongst all storage medium alternatives, the use of concrete represents a viable option due to its versatility, relatively low cost, and the possibility to reach a high operating temperature above 500 ºC [77].

Although concrete has a high potential as a storage solution, there are still challenges posed by this technology that need to be addressed, including its fabrication techniques, material formulation, and design, which limit the construction feasibility and thermal performance.

3.6.2 Contribution to the state-of-the-art

This paper focused on analysing concrete as a high temperature TES. The study identified 5 key challenges for the development of this technology. They are:

- On-site construction. During this first heating up, the free water and a certain amount of chemically bonded water evaporate, which could mean excessive vapor pressure causing damage to the storage module. This pressure is higher the larger the TES module; similarly, on-site production means higher water content in the concrete than production and curing in a controlled environment [78].

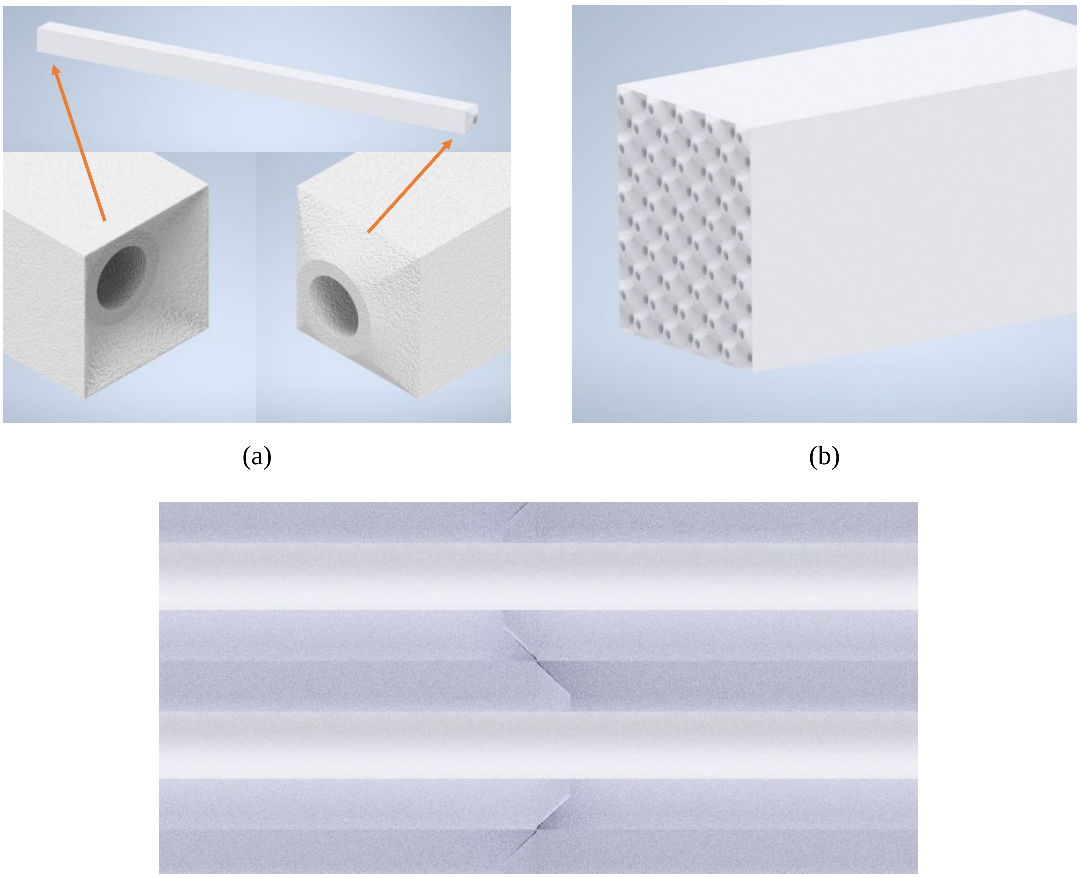
- Different thermal expansion coefficient of steel and concrete. Due to the different coefficient of thermal expansion, to maintain a correct operation of the system, the temperature difference between the metal pipes and the concrete should not be higher than 40 K, seriously penalizing the operating power of the system [79].

- Poor thermal conductivity of concrete. According to Asadi et al. [80], concrete has a thermal conductivity between 0.4 W/m·K and 1.01 W/m·K. Efforts to increase the thermal conductivity of concrete to be used in high temperature TES (Table 1) show that the use of calcium aluminate cements (CAC) brings higher thermal conductivity (up to 5 W/m·K) [81,82], and the use of metal fibres shows an increase up to 2 W/m·K [83]. Finally, the literature shows that thermal cycling can lead to a decrease in thermal conductivity, usually attributed to an increase in open porosity [84,85].

- HTF thermal oil or molten salts with limited operating temperature range. The other commercial HTF, molten salts, can theoretically withstand 600 ºC, but there is a lot of literature showing that impurities seriously compromise this temperature limit, since their decomposition starts at around 380-400 ºC [86]. Therefore, future CSP plants are considering the use of air as HTF [87].

- HTF thermal oil or molten salts in direct contact with concrete: migration of oil/salt in concrete. The use of thermal oils or molten salts as HTF when there is direct contact between the HTF and concrete would lead to migration of the HTF into the concrete, but also the contrary, contamination of the HTF by concrete components. The use of air as HTF avoids such migration and contamination, however, the low conductivity of air presents new challenges to overcome.

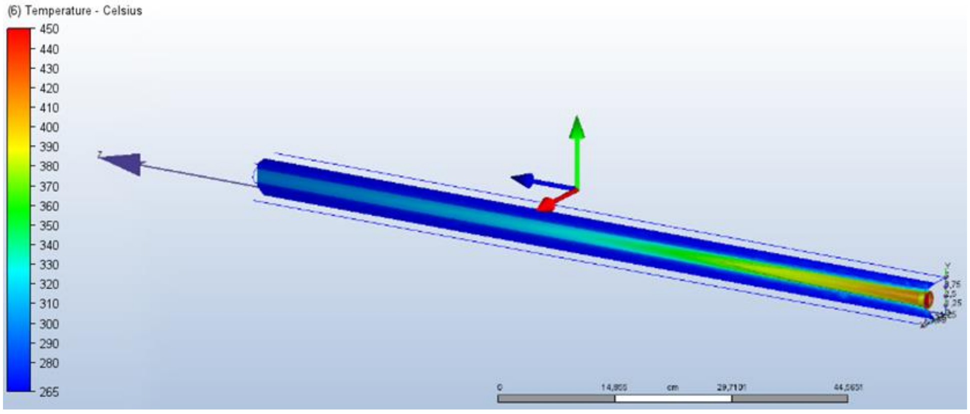
In order to improve the current configurations and to respond to the challenges posed, this study proposes a new thermal energy storage concept using concrete based on a modular concept, an improved concrete formulation, and a direct contact design (Figure 3-6). In addition, a preliminary evaluation of the thermal performance of the new concept proposed in this study was carried out by means of a CFD analysis, showing the temperature distribution of the modules (Figure 3-7).



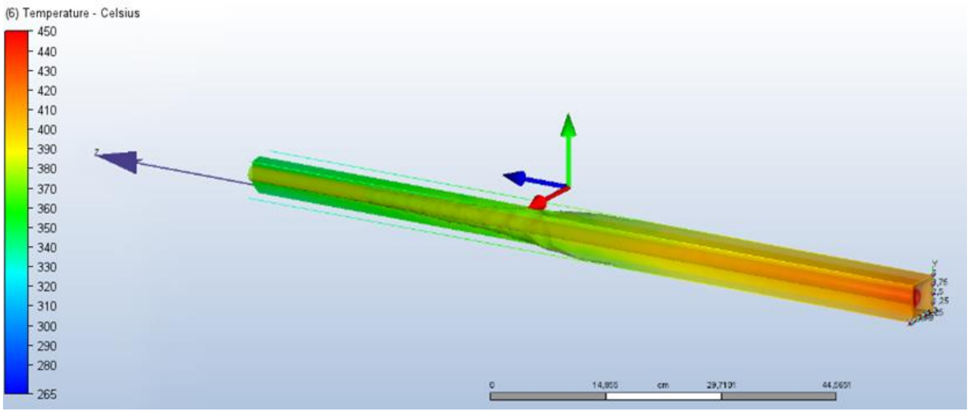
(a) (b)

(c)

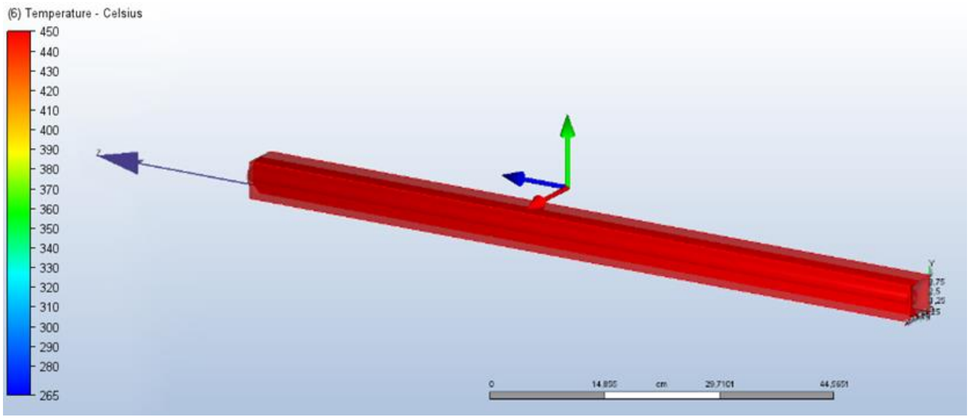
Figure 3-6. Concrete TES concept: (a) fitting connections, (b) stacked distribution example, (c) connection points.



(a)



(b)



(c)

Figure 3-7. Temperature distribution inside the proposed concrete block obtained from the CFD analysis: (a) initial charge, (b) mid-charge, (c) full charge.

3.6.3 Contribution of the candidate

David Vérez and Luisa F. Cabeza conceived and designed the study, David Vérez performed the CFD analysis. The co-authors collaborated on the interpretation of the results and on the preparation of the manuscript, as well as during the answer to reviewers.

3.6.4 Journal paper

The scientific contribution from this research work was published in the journal Energies in June 2022.

Reference: L.F. Cabeza, D. Vérez, G. Zsembinszki, E. Borri, C. Prieto, Key challenges for high temperature thermal energy storage in concrete — First steps towards a novel storage design, Energies 15 (2022) 4544.

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Key Challenges for High Temperature Thermal Energy Storage in Concrete—First Steps towards a Novel Storage Design

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Abstract: Thermal energy storage (TES) allows the existing mismatch between supply and demand in energy systems to be overcome. Considering temperatures above 150 °C, there are major potential benefits for applications, such as process heat and electricity production, where TES coupled with concentrating solar power (CSP) plants can increase the penetration of renewable energies. To this end, this paper performs a critical analysis of the literature on the current and most promising concrete energy storage technologies, identifying five challenges that must be overcome for the successful exploitation of this technology. With these five challenges in mind, this paper proposes an approach that uses a new modular design of concrete-based TES. A preliminary study of the feasibility of the proposed system was performed using computational fluid dynamics (CFD) techniques, showing promising results.

Keywords: concrete; modular system; thermal energy storage; high temperature; new concept

Citation: Cabeza, L.F.; Vérez, D.; Zsembinszki, G.; Borri, E.; Prieto, C. Key Challenges for High

Chapter 4

Global discussion of results

Today, a large share of the world population is at risk due to climate change. Without urgent action, this share will only increase dramatically. The main driver of climate change is GHG emissions. In this context, the buildings sector represents a source of enormous potential. Total GHG emissions in the buildings sector reached 12 $GtCO_2$eq. in 2019, equivalent to 21% of global GHG emissions that year. Decarbonisation of the energy sector is one of the main measures needed to reduce GHG emissions in buildings. The latter can be achieved by replacing carbon-intensive energy generation from polluting sources with renewable energy sources. To this end, the incorporation of TES in buildings plays a critical role.

Considering the aforementioned as the basis of this PhD, the first part of the research focused on using bibliometric techniques as a source to analyse the factors and requirements that can influence the type of energy system to be employed in building applications. Therefore, the first analysis focuses on building services. These are used in order to make buildings more comfortable, functional, efficient, and safe. The research showed that the most abundant and recent studies related to building services are based on improving energy efficiency by optimising systems such as ventilation or lighting. Moreover, new trends focused on social factors such as housing and urban growth. As part of the studies, building services were classified into four groups (Safety, Comfort, Efficiency, and Climate change) (Figure 3-1).

The building services study covers a wide range of energy end-uses in buildings. However, it does not capture emerging technologies that will play an important role in the building energy matrix of the coming decades, such as connected and small appliances. Therefore, the second research was focused on the study of appliances. Research on the topic began in the mid-1970s, although it was not until after the 2000s that more than 20 articles per year were published, with a linear growth trend to reach 160 publications per year by 2020. Moreover, the results showed that progress in energy efficiency in appliances is generally policy-driven, with a gap in most regions of the world because most connected and small appliances are not covered by any energy efficiency policies that regulate them.

Having identified and analysed all energy end-uses in buildings, TES presents itself as one of the most critical technologies for the decarbonisation of buildings. Therefore, the next step was to investigate the co-benefits of TES in buildings through a cross-sectorisation from renewable energies. The study showed that, in addition to higher penetration of renewable energy in buildings, the use of TES in buildings influences at least 4 groups of co-benefits (environmental, health, economics, and policy). The cross-sectorisation and identification of TES co-benefits facilitate the breaking down of social and economic barriers to the implementation of TES in buildings.

The aforementioned studies led the research to its second stage, which focused on the experimental and simulated analysis of thermal storage technologies. On the basis that no single TES technology is able to cover all the end-use needs of buildings, three thermal energy storage technologies were investigated.

Water storage tanks are the most deployed TES technology globally, therefore the first experimental study focused on decreasing heat losses by using vacuum insulation techniques. This experiment showed a good performance of the TES tank, the heat losses of the vacuum insulated tank decreased by a factor of three compared to similar sized tanks with standard insulation. However, special attention has to be devoted to the thermal bridges caused by the hydraulic connections.

Taking all the knowledge acquired in the previous experiments and with the aim of increasing the energy density of the TES to be analysed, a new study based on latent heat thermal energy storage was developed. The test consisted of an experimental benchmarking of two types of PCM macro-encapsulation design in a storage tank for low temperature applications. The encapsulation design consisted of two rectangular slabs with the same length and width but different thickness (35 mm and 17 mm). The results were compared in terms of temperature profile, heat transfer rate, and energy stored/released. The use of a thinner macro-encapsulation design (ThinICE) allowed fitting a larger number of slabs inside the tank. However, the higher amount of encapsulation material and the larger distance between the slabs (i.e., higher HTF channels height) resulted in a 30% less amount of PCM introduced inside the tank with this encapsulation design penalizing the energy storage density. Moreover, both designs reported efficiency values close to 85%.

Recent trends in the power sector include the use of distributed generation and the sector coupling, both gaining momentum as tools to incentivise the energy transition, generating gaps in existing terminal storage technologies. Therefore, it is necessary to develop thermal storage technologies for temperatures above 150 ºC that (coupled with renewable thermal power generation) will facilitate the introduction of technologies such as organic Rankine cycle (ORC) and sorption chillers in multi-family houses and localities.

Concrete, thanks to its relatively low cost, is a great alternative for high temperature thermal energy storage. However, there are still challenges with this technology that need to be addressed, including its manufacturing techniques, material formulation and design, which limit construction feasibility and thermal performance. In order to improve the currently available configurations, the last experimental study of the PhD proposed a novel concept of thermal energy storage using concrete based on a modular concept, improved concrete formulation, and a direct contact design. Moreover, a preliminary assessment of the thermal performances of the new concept proposed was analysed using CFD analysis showing the temperature distribution of the modules.

Finally, throughout the experimental and theoretical studies that were carried out in this thesis, increased knowledge is brought within the TES field, regarding building energy end-uses, liquid sensible thermal energy storage, solid-liquid latent thermal energy storage, and solid sensible thermal energy storage. The key contributions developed in this PhD are the following:

- The assessment of the building energy end-uses for energy transition toward renewable energy.
- The identification through cross-sectorisation of the TES co-benefits.
- The potential of vacuum insulation to minimise heat losses in TES tanks.
- The best distribution (depending on thermal requirements) of storage tanks with macro-encapsulated PCM for low temperature applications.
- An innovative and modular high temperature concrete storage design that addresses the current challenges identified for this technology.

Chapter 5

Conclusions and future work

5.1 Conclusions

Climate change threatens the very existence of all living creatures on our planet, including, of course, human beings. The main driver of climate change is the GHG emissions. In the period 2010-2019, they reached the highest annual average values in history. However, to ensure a liveable future, international organizations like the IPCC set the maximum allowable global warming at 1.5°C above pre-industrial levels. Beyond this margin, the damage would be irreversible and would exceed the adaptive capacity of the human species. Limiting global warming will require major transitions in all sectors. Therefore, the main objective of this PhD thesis is to provide tools to empower the building sector and consequently the energy sector to reduce their GHG emissions.

As general conclusions, in order to achieve the 1.5°C target and the SDGs, much more integrative analyses are needed, involving interdisciplinarity and multidisciplinarity between all fields of development, especially in the field of technical and social sciences. In addition, there is an urgent need to develop energy systems that are technically efficient, but also to contribute to improving energy access and security. Towards these goals, the transition of the energy sector towards renewable energies is fundamental, but their intermittent nature is a major challenge to address. Thermal energy storage therefore presents a great potential to overcome this challenge. On this basis, every advance in the field of energy storage translates into a grain of sand in the fight against climate change, and a more sustainable and equitable future.

In more detail, papers 1, 2, and 3 analysed a total of over 5400 documents to establish the current energy requirements of buildings and to identify emerging technologies that can potentially increase the energy demand of buildings. It was identified that energy storage coupled with renewable energy generation can be used to meet these requirements (both current and future) in a sustainable manner.

Among the conclusions obtained in these studies, the technologies with the greatest advances in recent years to increase energy efficiency in buildings are HVAC and lighting technologies. Moreover, although some progress is made, there are still a large number of countries without policies in place to regulate the energy efficiency of new technologies such as small and connected appliances, a critical aspect considering that these technologies are projected to become a major contributor to the energy demand matrix in buildings.

Furthermore, the co-benefits of TES identified in this PhD highlight that TES is a key technology in the energy transition not only to increase the efficiency of energy systems and enable better integration of renewables, but also to provide benefits in health, economic growth, and energy security. However, economic investments in the technological development of TES, together with a dedicated policy framework, are essential to overcome current barriers and improve the integration of this technology into the current energy system.

The above research indicated that there is no single energy storage technology that can meet the energy requirements of buildings. Therefore, this PhD focuses the experimental and simulation parts on the study of three different TES technologies. Accordingly, the main conclusions indicate that vacuum insulation is a technique that effectively reduces the heat losses in small-size storage tanks, but special attention must be paid to the thermal bridges that are generated by the hydraulic connections of the storage tank. Moreover, when designing storage tanks with macro-encapsulated PCM, the design and layout of the PCM encapsulation plays a critical role in the performance of the tank, hence the macro-encapsulation must be selected based on the application demand profile to find a balance between power output, energy density, and economic cost. Finally, thanks to its thermal and mechanical properties, relative low cost, and great abundance, concrete is an excellent candidate for storing thermal energy at high temperatures. Therefore, the proposed new design to overcome the five main challenges (identified as part of this PhD) related to the use of concrete in high temperature energy storage, has great potential for distributed energy generation in buildings.

5.2 Future work

The research presented in this PhD thesis increased the knowledge about the energy requirements of buildings and the TES systems which, coupled to buildings energy systems, can contribute to meeting these energy requirements with a high share of renewable energy. However, there are some aspects that should be further explored in the future.

Related to the energy demands of buildings, there is a low awareness of the urgency for climate action, affecting the willingness to incorporate technologies that facilitate the transition to renewable energies. Therefore, synergies between the in-depth identification and exploitation of TES co-benefits with social acceptance techniques for mainstreaming of renewable energies are needed. Moreover, related to the experimental tests, the next steps are the analysis of a latent heat storage tank with macro-encapsulated PCM with different packing factors for an optimal ratio between power output and energy storage density. The installation of the PCM tank with different packing factor in the set-up designed as part of this PhD is already planned and will be analysed in future studies.

Finally, the most ambitious goal to be achieved is to take the new high-temperature concrete storage design towards a real prototype to validate it. The implementation of a prototype in an experimental set-up to assess its strengths and drawbacks against a commercially available technology is the next step towards the future integration of the new design into the market.

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. D. Ürge-Vorsatz, R. Khosla, R. Bernhardt, Y.C. Chan, **D. Vérez**, S. Hu, L.F. Cabeza, Advances toward a net-zero global building sector, Annual Review of Environment and Resources 45 (2020) 227-269.

2. L.F. Cabeza, L. Boquera, M. Chàfer, **D. Vérez**, Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis, Energy and Buildings 231 (2021) 110612.

3. L.F. Cabeza, A. Frazzica, M. Chàfer, **D. Vérez**, V. Palomba, Research trends and perspectives of thermal management of electric batteries: Bibliometric analysis, Journal of Energy Storage 32 (2020) 101976.

4. B.D. Mselle, **D. Vérez**, G. Zsembinszki, E. Borri, L.F. Cabeza, Performance Study of Direct Integration of Phase Change Material into an Innovative Evaporator of a Simple Vapour Compression System, Applied Sciences 10 (2020) 4649.

5. B.D. Mselle, G. Zsembinszki, E. Borri, **D. Vérez**, L.F. Cabeza, Trends and future perspectives on the integration of phase change materials in heat exchangers, Journal of Energy Storage 38 (2021) 102544.

6. V. Palomba, A. Bonanno, G. Brunaccini, D. Aloisio, F. Sergi, G.E. Dino, S. Varvaggiannis, S. Karellas, B. Nitsch, A. Strehlow, A. Groβe, R. Herrmann, N. Barmparitsas, N. Koch, **D. Vérez**, L.F. Cabeza, G. Zsembinszki, A. Frazzica, Hybrid cascade heat pump and thermal-electric energy storage system for residential buildings: Experimental testing and performance analysis, Energies 14 (2021) 2580.

7. J.M. Maldonado, **D. Vérez**, A. de Gracia, L.F. Cabeza, Comparative study between heat pipe and shell-and-tube thermal energy storage, Applied Thermal Engineering 192 (2021) 116974.

8. G. Zsembinszki, C. Fernández, **D. Vérez**, L.F. Cabeza, Deep learning optimal control for a complex hybrid energy storage system, Buildings 11 (2021) 194.

9. B.D. Mselle, G. Zsembinszki, **D. Vérez**, E. Borri, L.F. Cabeza, A detailed energy analysis of a novel evaporator with latent thermal energy storage ability, Applied Thermal Engineering 201 (2022) 117844.

10. A. Crespo, G. Zsembinszki, **D. Vérez**, E. Borri, C. Fernández, L.F. Cabeza, A. de Gracia, Optimization of design variables of a phase change material storage tank and comparison of a 2D implicit vs. 2D explicit model, Energies 14 (2021) 2605.

11. B.D. Mselle, G. Zsembinszki, **D. Veréz**, E. Borri, A. Strehlow, B. Nitsch, L.F. Cabeza, Experimental assessment of the influence of the design on the performance of novel evaporators with latent energy storage ability, Applied Sciences 12 (2022) 1813.

12. G. Zsembinszki, B.D. Mselle, **D. Vérez**, E. Borri, A. Strehlow, B. Nitsch, A. Frazzica, V. Palomba, L.F. Cabeza, A new methodological approach for the evaluation of scaling up a latent storage module for integration in heat pumps, Energies 14 (2021) 7470.

Contributions to books chapters

The PhD candidate contributed to the following book chapters:

1. A. de Gracia, A. Crespo, **D. Vérez**, J. Tarragona, L.F. Cabeza, Control Solutions for TES Applications, in: L.F. Cabeza (Ed.), Encyclopedia of Energy Storage, Elsevier, Oxford, 1 (2022) 579–583.

2. C. Prieto, **D. Vérez**, L.F. Cabeza, Active Thermal Energy Storage (TES) With Phase Change Materials (PCM) for High Temperature, in: L.F. Cabeza (Ed.), Encyclopedia of Energy Storage, Elsevier, Oxford, 1 (2022) 470–478.

3. L.F. Cabeza, Q. Bai, P. Bertoldi, J.M. Kihila, A.F.P. Lucena, É. Mata, S. Mirasgedis, A. Novikova, Y. Saheb, P. Berrill, L. R. Caldas, M. Chàfer, S. Hu, R. Khosla, W. Lamb, **D. Vérez**, J. Wanemark, Buildings, in: P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (Ed.), Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel

on Climate Change, Cambridge University Press, Cambridge and New York, (2022) 1506–1673.

Contributions to international conferences

The PhD candidate contributed to several international conferences listed below:

1. **D. Vérez**, E. Borri, A. Crespo, B.D. Mselle, A. de Gracia, G. Zsembinszki, L.F. Cabeza, Methods for the determination of the state-of-charge of a thermal energy storage device, EnerSTOCK 2021 - 15th International Virtual Conference on Energy Storage, University of Ljubljana, Ljubljana, Slovenia, 2021.

2. B.D. Mselle, G. Zsembinszki, **D. Vérez**, L.F. Cabeza, Experimental study of a novel three-fluids heat exchanger embedded with phase change materials for cooling applications, EnerSTOCK 2021 - 15th International Virtual Conference on Energy Storage, University of Ljubljana, Ljubljana, Slovenia, 2021.

3. **D. Vérez**, E. Borri, A. Crespo, B.D. Mselle, A. de Gracia, G. Zsembinszki, L.F. Cabeza, Experimental study on the effect of flat and thin slab encapsulation design on a PCM tank, EnerSTOCK 2021 - 15th International Virtual Conference on Energy Storage, University of Ljubljana, Ljubljana, Slovenia, 2021.

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Contributions to seminars and workshops

1. European Researchers' Night 2020. Workshop “Batidora de colores”.

2. European Researchers' Night 2021. Poster “Optimización de sistemas de almacenamiento de energía térmica para edificaciones” in the “La nostra recerca” section.

3. European Researchers' Night 2021. Workhsop “El viatge de l’energia, des del Sol fins a la teva dutxa”.

4. RIbERA, Virtual seminar “I webinar de la red iberoamericana de investigación de las energías renovables y cuidado del medio ambiente”.

5. RedTES, Virtual seminar “Nuevos desarrollos en almacenamiento térmico para la descarbonización de la industria”.

Scientific foreign-exchange

The PhD candidate did a stay of four months in Paris (France) during the development of this PhD thesis, hosted by the OpenExp.

During his stay, the candidate worked on the assessment of global and regional greenhouse gas emissions and their drivers in the global and regional building stock, using previous data and scenarios from the International Energy Agency.

Projects participation

1. Methodology for analysis of thermal energy storage technologies towards a circular economy (MATCE). Ministerio de Ciencia, Innovación y Universidades de España, RTI2018-093849-B-C31 - MCIU/AEI/FEDER, UE, 2019-2021.
2. Red Española en Almacenamiento de Energía Térmica (RED-TES). Ministerio de Ciencia, Innovación y Universidades de España, RED2018-102431-T, 2020-2022.

3. GREiA. Grup de Recerca en Energia i Intel·ligència Artificial (SGR). Generalitat de Catalunya, 2017 SGR 1537, 2017-2021.
4. Innovative Compact Hybrid electrical/thermal storage Systems for low energy buildings (HYBUILD). European Union, 768824, 2017-2022.
5. Development and Validation of an Innovative Solar Compact Selective-Water-Sorbent-Based Heating System (SWS-Heating). European Union, 764025, 2018-2022.
6. Viabilidad técnica y comercial de PCM preparados a partir de subproductos de la industria agroalimentaria (PRODUCTE). Agencia de Gestió d'Ajuts Universitaris i de Recerca – FEDER, 2019PROD00101, 2020-2022.
7. Techno-economical evaluation of different thermal energy storage concepts for CSP plants (CSPplus). Ministerio de Ciencia e Innovación - Agencia Estatal de Investigación, PCI2020-120695-2/AEI/10.13039/501100011033, 2021-2024.

Organising committee participation

1. Researchers' Night 2019, 14th edition 2019. Lleida, Spain.
2. Researchers' Night 2020, 15th edition 2020. Lleida, Spain.
3. Researchers' Night 2021, 16th edition 2021. Lleida, Spain.

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Review

Which Building Services Are Considered to Have Impact on Climate Change?

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Abstract: The building sector, as a major energy consumer with high direct and indirect CO_2 emissions, plays a vital role in the fight against climate change. In order to make buildings more comfortable, functional, efficient and safe, building services are used. Therefore, building services are the key to decrease their contribution to climate change. Due to the lack of organized literature on this topic, this paper presents the first comprehensive assessment of trends in the literature on building services related to climate change, which was completed by conducting a bibliometric analysis of the existing literature on the topic. The ultimate goal is to provide a source where researchers and other interested parties can find this information in an organized manner. Results show that the most abundant and recent studies related to building services are based on improving energy efficiency by optimizing systems such as ventilation or lighting, the latter with the installation of LED lights. In addition, recent studies have focused on social factors such as housing and urban growth.

Keywords: building services; climate change; literature trends; bibliometric analysis

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1. Introduction

Buildings have been identified as high energy consumers, as buildings and the building construction sectors account for more than 30% of the global final energy consumption and 40% of the total CO_2 emissions, both direct and indirect [1]. However, at the same time, heating and cooling of buildings is one of the areas where there is a high potential to decrease energy consumption and CO_2 emissions [2]. Heating and cooling are indeed clearly identified as energy-consuming building services. Nevertheless, building services other than these and other building energy services (e.g., lighting) should also be considered in order to have a holistic view of the real climate change mitigation potential of buildings.

Building services are the systems installed in buildings to make them more comfortable, functional, efficient, and safe [3]. Building services might include building control systems, energy distribution, and energy supply. This traditional description includes a classification of building services such as building management systems; energy generation, distribution and supply; escalators and lifts; facade engineering; fire safety, detection and protection; heating, air conditioning and air conditioning systems (HVAC); ICT networks; lighting; lighting protection; refrigeration; security and alarm systems; and water, drainage and plumbing.

Another definition states that building services aim at achieving a safe and comfortable indoor environment whilst minimizing the environmental impact of a building [4]. Then, other concepts appear in the framework of building services, with wellbeing, circular economy, and climate change mitigation becoming increasingly important, such as air quality, thermal comfort, and acoustic comfort. However, a more holistic approach would also include terms such as shelter, cooking, materials, embodied energy and embodied carbon, CO_2 emissions, GHG emissions, and pollution. Therefore, a potential classification of such building services could be the one presented in Figure 1. As it can be seen, building services have been classified into four types; safety-related services, comfort-related, services related to efficiency, and finally, services related to climate change. Within each type, different building services are included, among them are those known as building energy services [5] (i.e., thermal comfort, lighting, energy generation, building management systems).

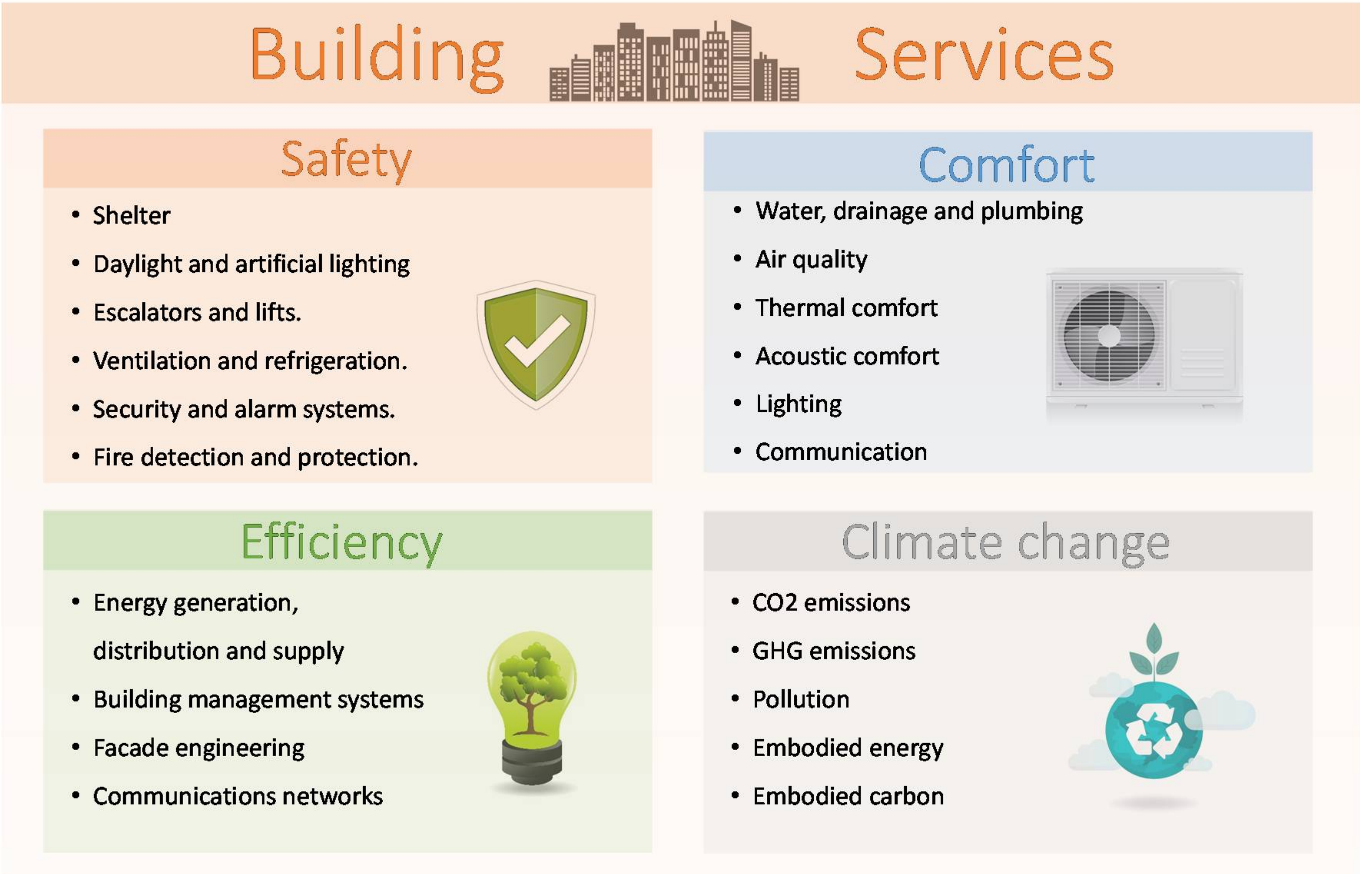


Figure 1. Identified building services.

However, when assessing the literature to evaluate building services and their relation with climate change, the literature is scarce and very dispersed. Therefore, the aim of this paper is to fill this knowledge gap by performing a bibliometric analysis of the existing literature on the topic. In more detail, this paper includes a comprehensive assessment of trends of the literature on building services related to climate change to give a source where researchers and other interested stakeholders can find this information in an organized manner.

2. Methodology

Bibliometrics allows to perform a wide statistical literature analysis of the existing publications in a determined research field [6]. Figure 2 presents the specific methodology utilized to define all the steps to map the state-of-the-art of the scientific topic researched within the scope of this paper. The first step consists of the definition of the research topic, from which two queries were developed, including the key messages of the paper. The next step was the selection of the proper database. On this matter, Wuni et al. [7] stated that the WoS and Scopus databases can be used to extract bibliometric data, but the content of both for the same research tends to differ. Moreover, Cabeza et al. [8] showed that Scopus contains more publications in the area of technology. Therefore, Scopus was selected as the database for the presented study. Then all references were downloaded, as well as the statistics for the bibliometric analysis. Finally, the software VOSviewer [8–10] was used to analyze relations between countries and keywords.

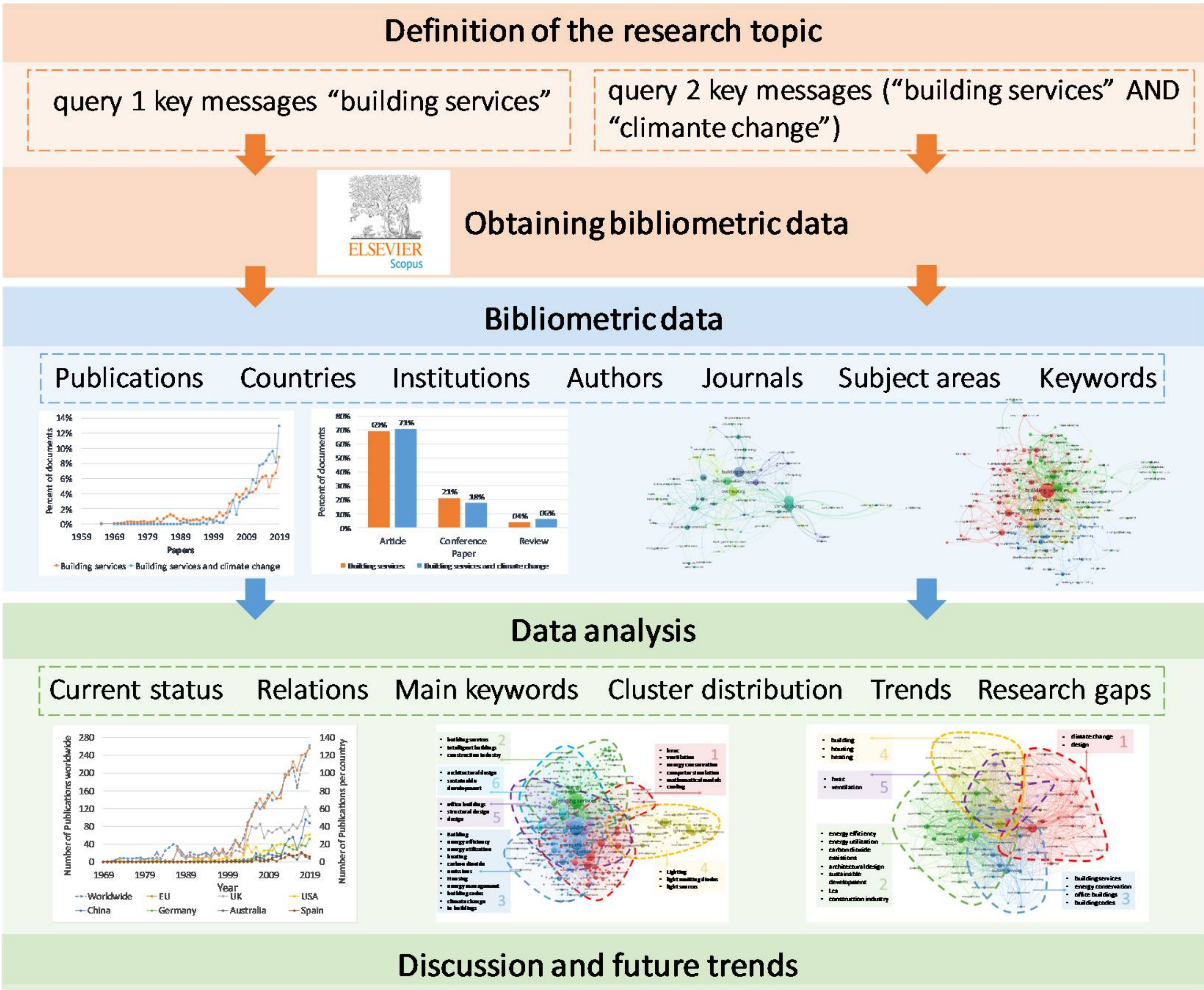


Figure 2. Methodology of the paper.

The world population was obtained from the United Nations, Department of Economic and Social Affairs [11], and the number of researchers from the United Nations Science Report [12].

3. Results

3.1. Bibliometric Analysis

The search carried out on 14 March 2020 revealed 3300 documents related to building services and 477 publications related to building services and climate change. Figure 3a shows that nearly 70% of those documents are papers/articles, and about 20% are conference papers; reviews, book chapters and other types of documents are anecdotic. Moreover, the statistics are similar for the two queries. The assessment of the trends in Figure 3b reveals that both queries have the same profile, with documents talking about the topic since 1965, but with a growth in interest in 2000–2002, and somehow a stagnation in 2014–2015. Considering the countries with more publications on the topic of study and with good representation of the different continents, Figure 3c shows that the EU publishes one-third of the literature published worldwide. The UK published a similar number of documents as the EU; although, in the last ten years, this number seemed to stagnate (in 2010, the UK had nearly the same number of publications as the EU—37 and 39, respectively, while in 2018, it had only half—62 and 122, respectively). China increased its publication rate on the topic only recently (in 2015, it published 28 documents and 48 in 2018). When the relation with climate change is considered (Figure 3d), the UK shows a higher number of publications but also more stability than the other countries/territories considered. The EU has more publications than the UK, and all other countries have much fewer documents.

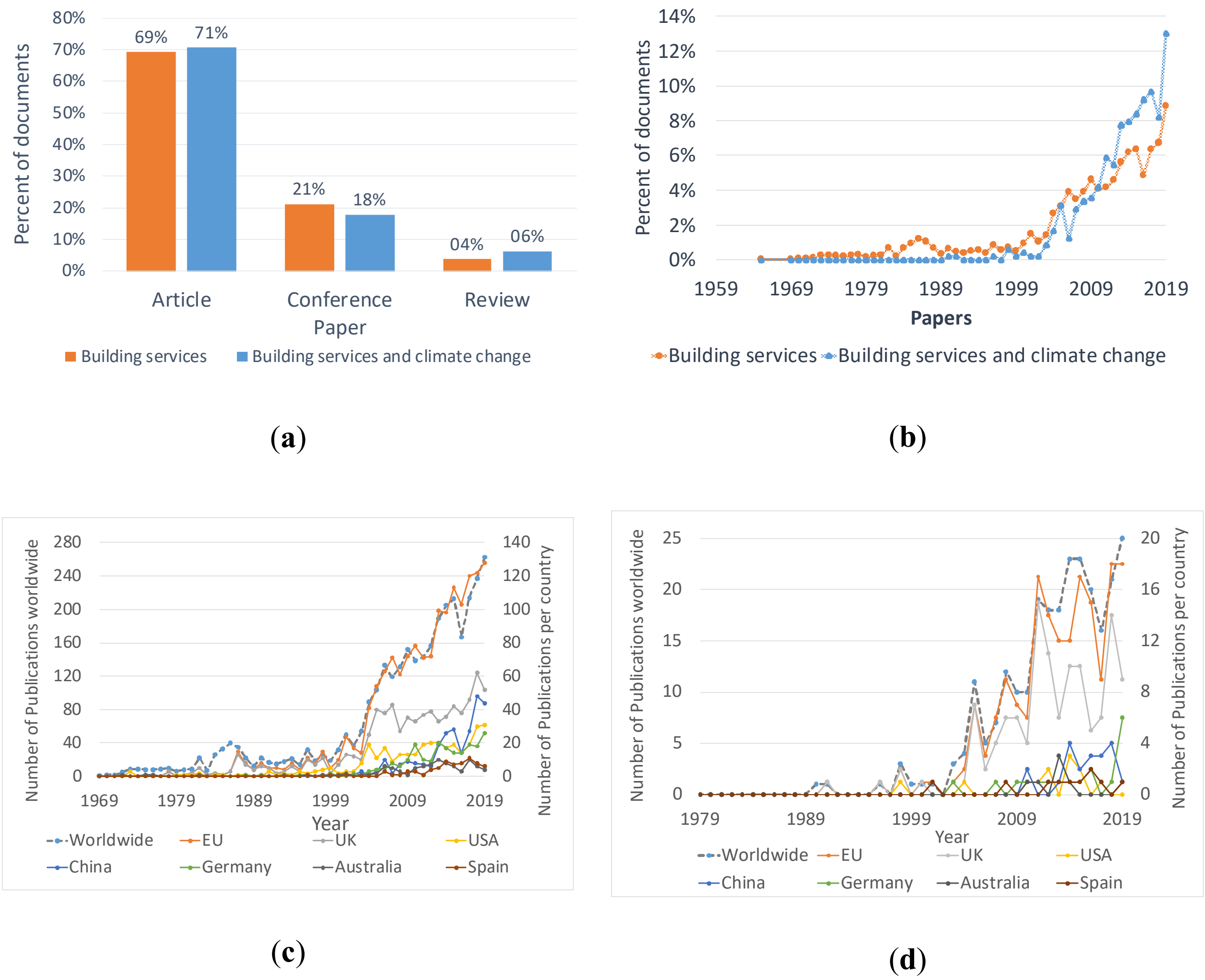


Figure 3. (**a**) Type of documents, (**b**) trends in publications, (**c**) trends in countries general query, and (**d**) trends in countries query with climate change.

Figure 4 shows the specific number of publications for the countries/territories with more documents. It is interesting to see that although the EU is the territory with more publications, its contribution only stands out when the number of documents per number of researchers with the general query is considered. The USA stands out when the number of publications per number of inhabitants is considered for both queries. China stands out when the number of publications per number of researchers in the query with climate change is considered, focusing their studies on LED light sources, as shown in Figure 4e, to improve energy efficiency [13–15], and 12 publications in the *Lighting Research and Technology* journal.

The relations between countries/territories are presented in Figure 5. In both queries, the EU centralize all collaborations, and in both queries, China and South Korea are the newest countries to appear (in the general query, Jordan also appears as new). It is interesting to see that the research on building services is older in the USA and Canada than in the EU, while its relation to climate change is older in the EU, which could be because of the fast implementation of climate change mitigation policies in the EU [16] (in general, this relation with climate change is newer).

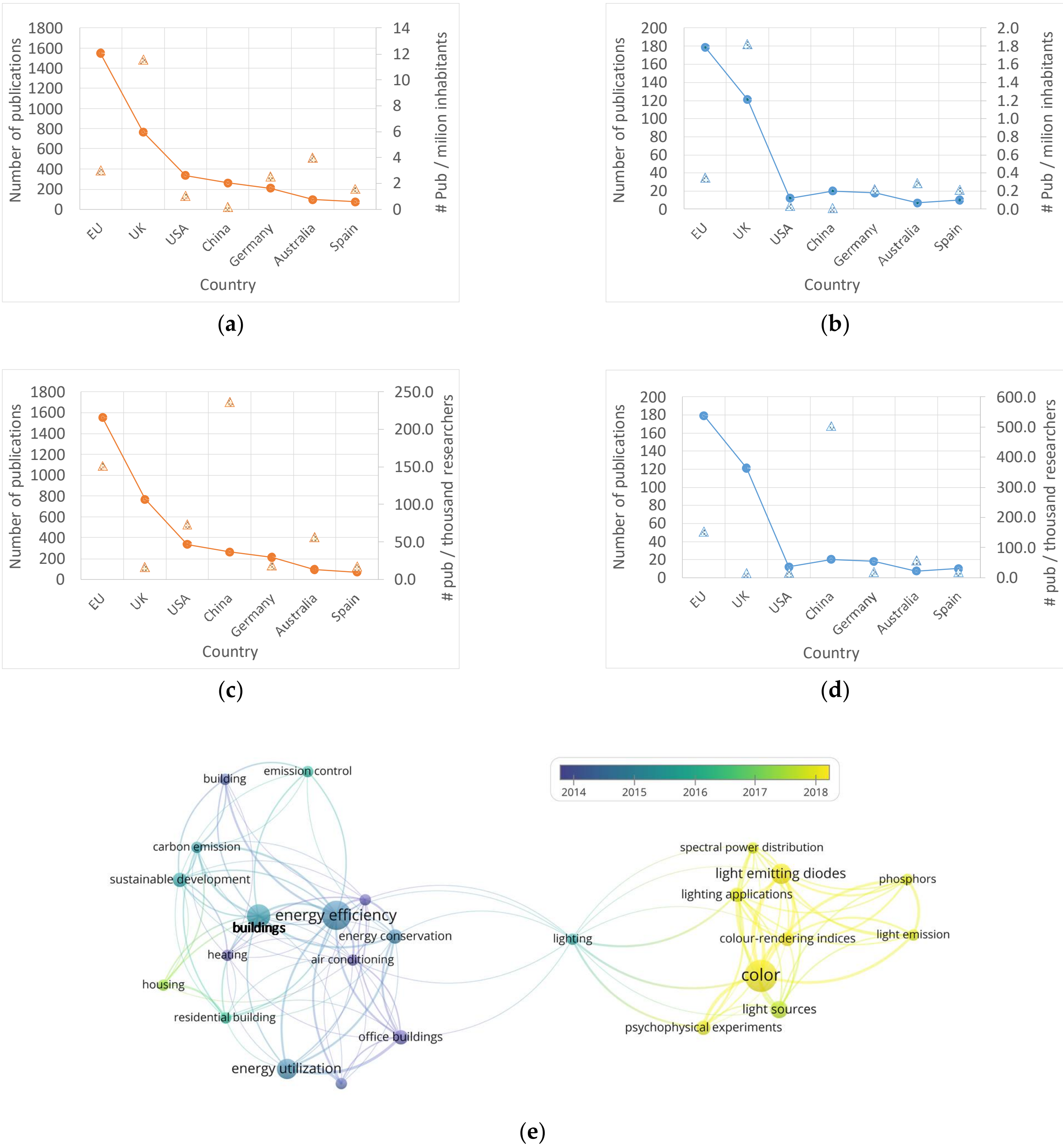


Figure 4. Scientific production per country: (**a**) per million inhabitants (general query), (**b**) per million inhabitants (query with climate change), (**c**) per thousand researchers (general query), (**d**) per thousand researchers (query with climate change), and (**e**) overlay visualization for China (query 2).

Table 1 lists the researchers with more documents on the topic of building services (Query 1). It is interesting to see that there is not a clear correlation between the authors with more publications and the countries with more publications. For example, the UK includes three authors (Steve A. Fotios, Michael J. Davis, and Chris Cheal), and only two institutions are represented (University of Sheffield with two authors and Univ. College London). Hong Kong also contributes with three researchers, but in this case, only one institution is represented (Hong Kong Polytechnic University). In both cases, we find two researchers publishing together, Steve A. Fotios and Chris Cheal for the UK, and L.T. Wong and K.W. Mui for Hong Kong.

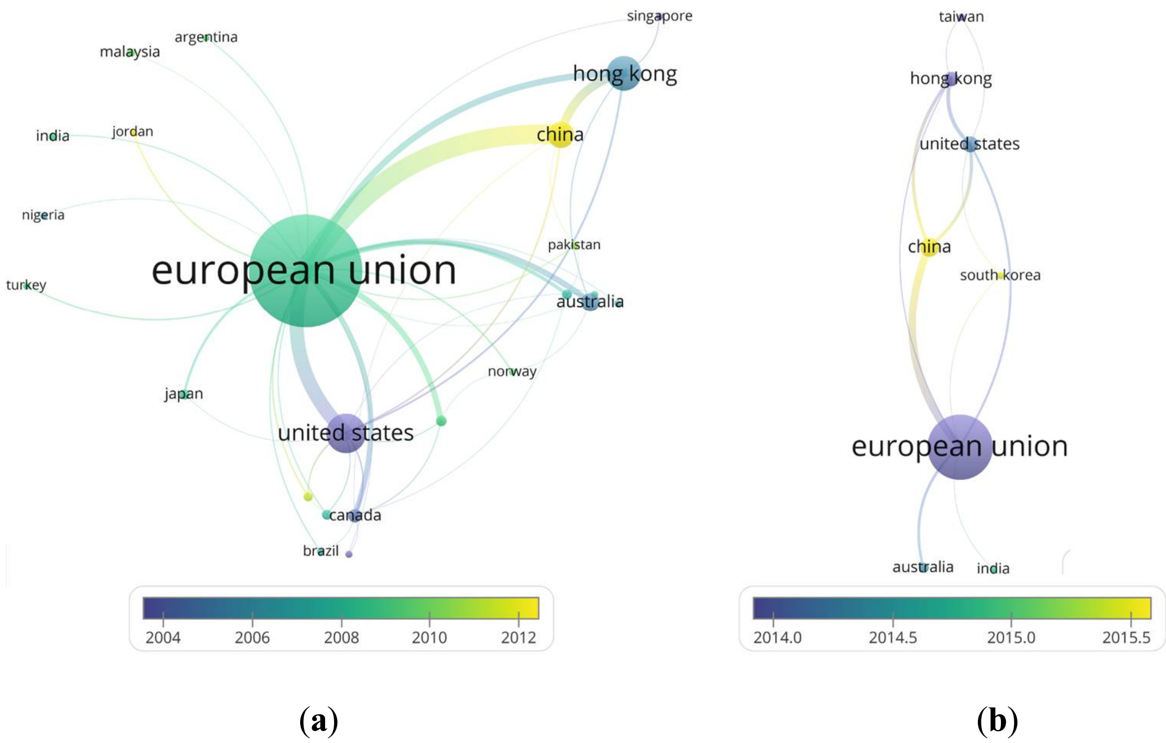


Figure 5. Relations between countries/territories: (**a**) general query, (**b**) query with climate change.

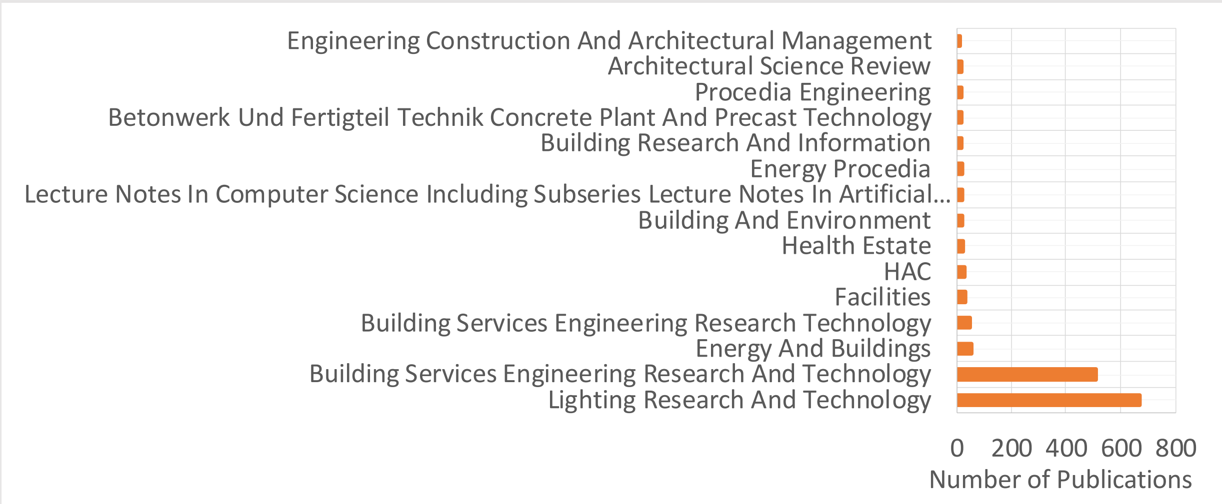
Table 1. Authors with more publications on the topic of building services and their impact.

Author	Institution	Country	#doc Search	h-Index Search	Total doc	Total h-Index
Steve A. Fotios	University of Sheffield	UK	39	13	120	20
Wim Zeiler	Technische Universiteit Eindhoven	Netherlands	32	4	171	15
Mark S. Rea	Rensselaer Polytechnic Institute	USA	29	15	220	41
L.T. Wong	Hong Kong Polytechnic University	Hong Kong	26	7	178	23
Michael J. Davis	University College London	UK	24	9	135	33
Liisa Halonen	Aalto University	Finland	24	11	75	18
Kowk Wai Mui	Hong Kong Polytechnic University	Hong Kong	24	7	142	22
Ming Ronnier Luo	State Key Laboratory of Modern Optical Instrumentation	China	23	8	129	16
Chris Cheal	University of Sheffield	UK	22	12	41	14
Cheuk Ming Mak	Hong Kong Polytechnic University	Hong Kong	21	8	203	24

Furthermore, the topics of research are different for the different authors and countries/territories. For example, the main topic of S.A. Fotios from the UK and M.S. Rea from the USA is lighting [17–22]. W. Zeiler from the Netherlands studied building design from the human perspective point of view [23], and energy efficiency [24]. L.T. from Hong Kong worked on indoor air quality, pollution, and ventilation [13].

Finally, Table 1 shows that all these authors study topics related to building services but without this being their unique research interest.

As expected, the journal *Building Services Engineering Research and Technology* is one of the journals with more documents (511) (Figure 6a), but surprisingly, the *journal Lighting Research and Technology* has more publications (670). All other journals used have much fewer documents on the topic, i.e., the third journal is *Energy and Buildings*, with 55 documents. On the other hand, when the relation with climate change is studied (Figure 6b), the journal *Building Services Engineering Research and Technology* includes 88 documents, more than four times the second journal listed.



(**a**)

(**b**)

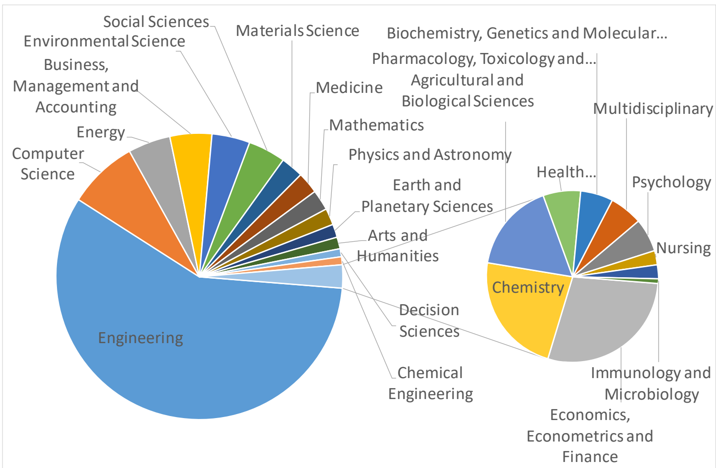
Figure 6. Journals used to publish this research topic: (**a**) general query, (**b**) query with climate change.

Table 2 shows that when the authors select the journal to publish their research on the topic, the impact factor and classification of the journal is not as important as the scope of the journal (the first and second journal are Q2 and Q3, respectively). This is interesting to highlight since this is not the same trend found in other studies on different topics [8].

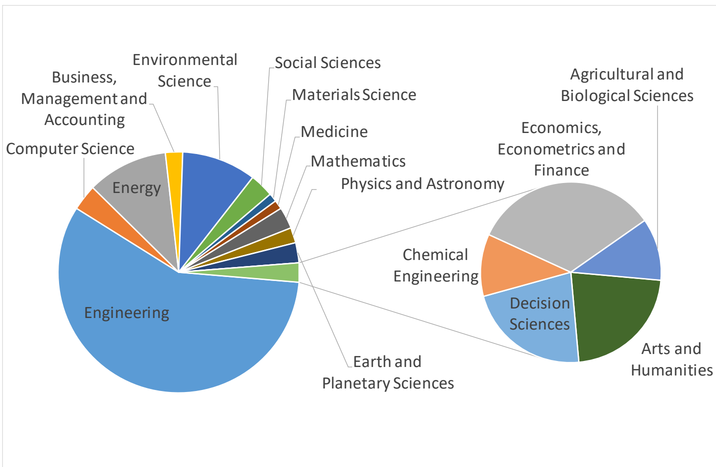
Table 2. Journals with more publications on the topic of building services and their impact.

Journal	#pub	Editorial	Impact factor (2018)	Classification (2018)	Open Access
Lighting Research and Technology	670	SAGE Journals	2.311	Q2	No
Building Services Engineering Research and Technology	558	SAGE Journals	1.170	Q3	No
Energy and Buildings	55	Elsevier	4.495	Q1	No
Facilities	33	Emerald Group Publishing Ltd.	—	—	Yes
Building and Environment	23	Elsevier	4.820	Q1	No

Finally, Figure 7 shows that most documents published on the topic of building services are within the area of engineering (77% in building services and 78% in building services and climate change). All other areas found have a much lower number of publications (i.e., computer science includes 9% of documents on building services). However, it is interesting to highlight that in building services, the next most published topics are climate change energy 15% and environmental science 13 %.



(**a**)



(**b**)

Figure 7. Subjects used to publish this research topic: (**a**) general query, (**b**) query with climate change.

3.2. Keywords Network Analysis

Table 3 and the literature map presented in Figure 8 (the one for the general query) shows that the co-occurrences keywords can be grouped into six clusters. The first one, in red, groups “hvac” and “ventilation” with the building service “thermal comfort”. Interestingly, “thermal comfort” is also linked to “air quality” and “indoor air pollution”, as is stated in [25,26]. This cluster also groups “hvac”, with “energy conservation”, “computer simulation”, “mathematical model”, “optimization”, and “control” [27–31], and “elevator”, with “Monte Carlo method” and “high rice building”. The second cluster, in green, links “building services” with “intelligent buildings” (also related to control in cluster 1), “bems”, and “control system”. It also groups “building service” with “construction industry”, and “project management”, “maintenance”, and “cost”. The third cluster, in blue, groups “building”, “energy efficiency” and “energy utilization” with “building codes”, “climate change”, “carbon dioxide emissions”, and “renewable energies”. It is important to highlight the keyword “energy efficiency” in this cluster as it has the highest number of occurrences (324) of the map (excluding the keywords present in query 1), therefore is of great interest in the research on building services [32–37]. The fourth cluster, in yellow, groups the “lighting” building service; this keyword has been of great interest globally since the introduction of light-emitting diodes (LED) and their low energy consumption as reflected in [37–41], thus the strong relationship with “energy efficiency” is expected. This cluster groups “lighting”, “engineering research” and “light emitting diodes”, with “light sources”, “color”, “luminance”, “spectral power distribution”, and “color rendering”. The fifth cluster, in purple groups “office buildings”, “structural design”, and “design”, with “lca”, “environmental impact” and “building material”. The last and sixth cluster, in light blue groups “architectural design” and “sustainable development” with “sustainable building” and “built environment.

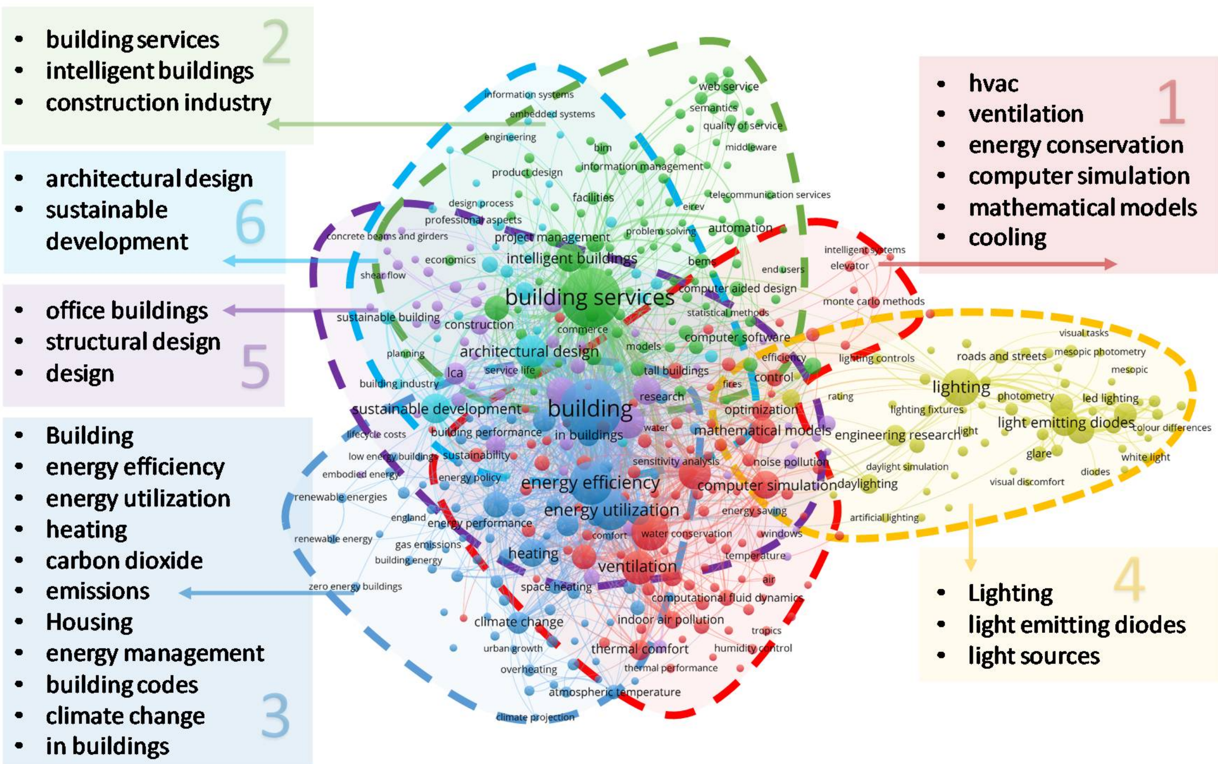


Figure 8. Co-occurrence keywords network query 1.

Table 3. Keywords with more than 80 occurrences (query 1).

Cluster	Label	Occurrences	Avg. Pub. Year	Avg. Citations
1	hvac	248	2008	10.85
	ventilation	200	2008	10.79
	energy conservation	178	2010	11.19
	computer simulation	140	2006	23.29
	mathematical models	123	2004	16.63
	cooling	108	2011	12.77
2	building services	621	2009	11.89
	intelligent buildings	135	2012	9.78
	construction industry	110	2008	8.14
3	building	666	2005	16.54
	energy efficiency	324	2013	25.08
	energy utilization	273	2012	27.60
	heating	136	2009	12.31
	carbon dioxide emissions	111	2013	15.67
	housing	108	2014	11.43
	energy management	96	2009	12.29
	building codes	87	2008	10.37
	climate change	87	2012	25.41
	in buildings	80	2011	5.33
4	lighting	256	2013	15.37
	light emitting diodes	129	2016	9.04
	light sources	127	2014	14.00
	color	94	2016	12.07
	luminance	92	2014	13.78
	engineering research	80	2014	8.95
5	office buildings	192	2012	12.52
	structural design	151	2008	8.89
	design	136	2012	8.03
	lca	89	2013	11.21
6	architectural design	185	2013	9.60
	sustainable development	152	2012	10.46

When "climate change" is added to the query, a more detailed analysis can be done, as shown in Figure 9 and Table 4. The first cluster, in red, groups "climate change" and "design" with "building simulation", "energy use", "weather data", "meteorology", and "urban heat island". This cluster shows the effort made to achieve mathematical models that represent complex phenomena such as urban heat island [42,43], which in building services is highly necessary for efficient energy retrofit of existing buildings [44] and is used to optimize the dimensioning of heating and cooling systems [45]. The second cluster, in green, groups "energy efficiency", "energy utilization", "carbon dioxide emissions" and "architectural design", with "environmental impact", "embodied energy", "lca" [46,47], "sustainable development", and "intelligent building". Interestingly, "energy efficiency" continues to have the highest number of occurrences (61) of the map (excluding the keywords present in query 2). The third cluster, in blue, links "building services", "energy conservation", and "office buildings", with "building codes", "climate control", and "lighting". The use of the Passivhaus [48] and NZEB standards [49] have proved to be effective in improving the building's energy efficiency, but it has also increased the overheating risk [50–52]. Therefore, the fourth cluster, in yellow, groups "building", "energy management", and "heating" with "thermal comfort", "building performance", and "overheating". This cluster also links "building" with "housing" and "retrofitting". The fifth and last cluster, in purple, links "hvac" with "ventilation", "air quality", and "natural ventilation".

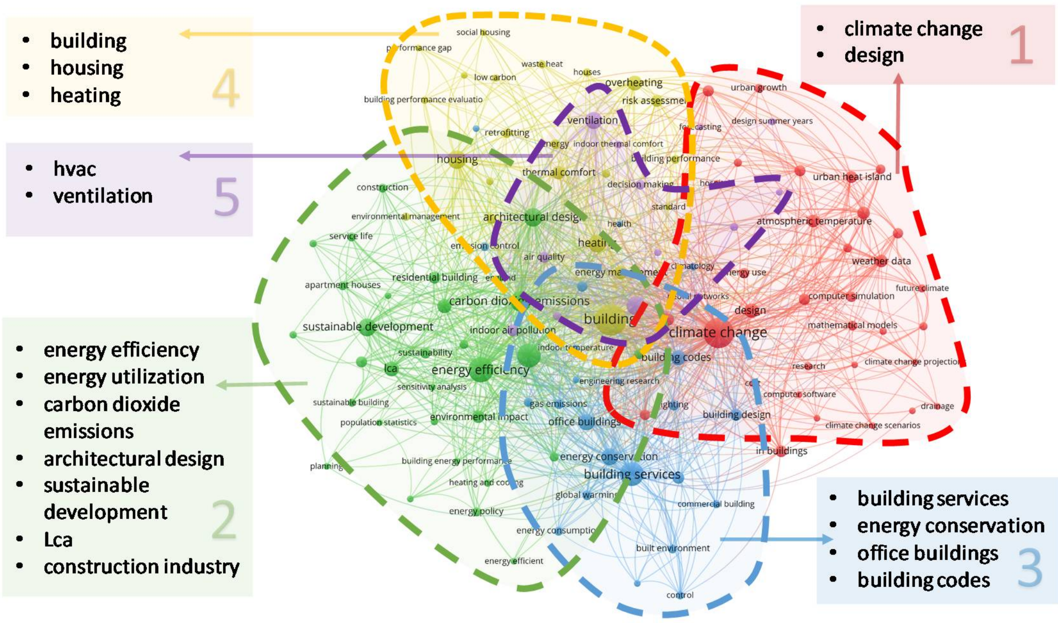


Figure 9. Keywords network (query 2).

Table 4. Keywords with more than 20 occurrences (query 2).

Cluster	Label	Occurrences	Avg. Pub. Year	Avg. Citations
1	climate change	87	2012	25.41
	design	22	2012	12.86
2	energy efficiency	61	2014	74.25
	energy utilization	55	2014	72.11
	carbon dioxide emissions	42	2015	26.00
	architectural design	34	2015	7.62
	sustainable development	31	2013	16.13
	lca	22	2015	11.23
	construction industry	20	2014	10.30
3	building services	52	2013	75.69
	energy conservation	29	2014	21.14
	office buildings	25	2013	13.84
	building codes	21	2013	22.43
4	building	97	2013	57.79
	housing	32	2016	12.00
	heating	30	2014	19.33
	overheating	22	2017	9.50
5	hvac	35	2013	14.83
	ventilation	29	2015	17.69

4. Discussion, Past Trends and Future Perspectives

To better understand which building services are analyzed in the literature with more emphasis on climate change, Figure 10 shows the keywords that have a direct link with "building services" and "climate change" keywords in query 2. It shows that "energy efficiency" is one of the most studied topics with the highest number of occurrences (440) and the highest link strength with both "building services" (16) and "climate change" (20). The next keywords are "energy utilization" and "hvac". Moreover, "ventilation", "heating" and "climate models" have a clear affinity to climate change, while "sustainable development" and "lca" have higher affinity to "building services".

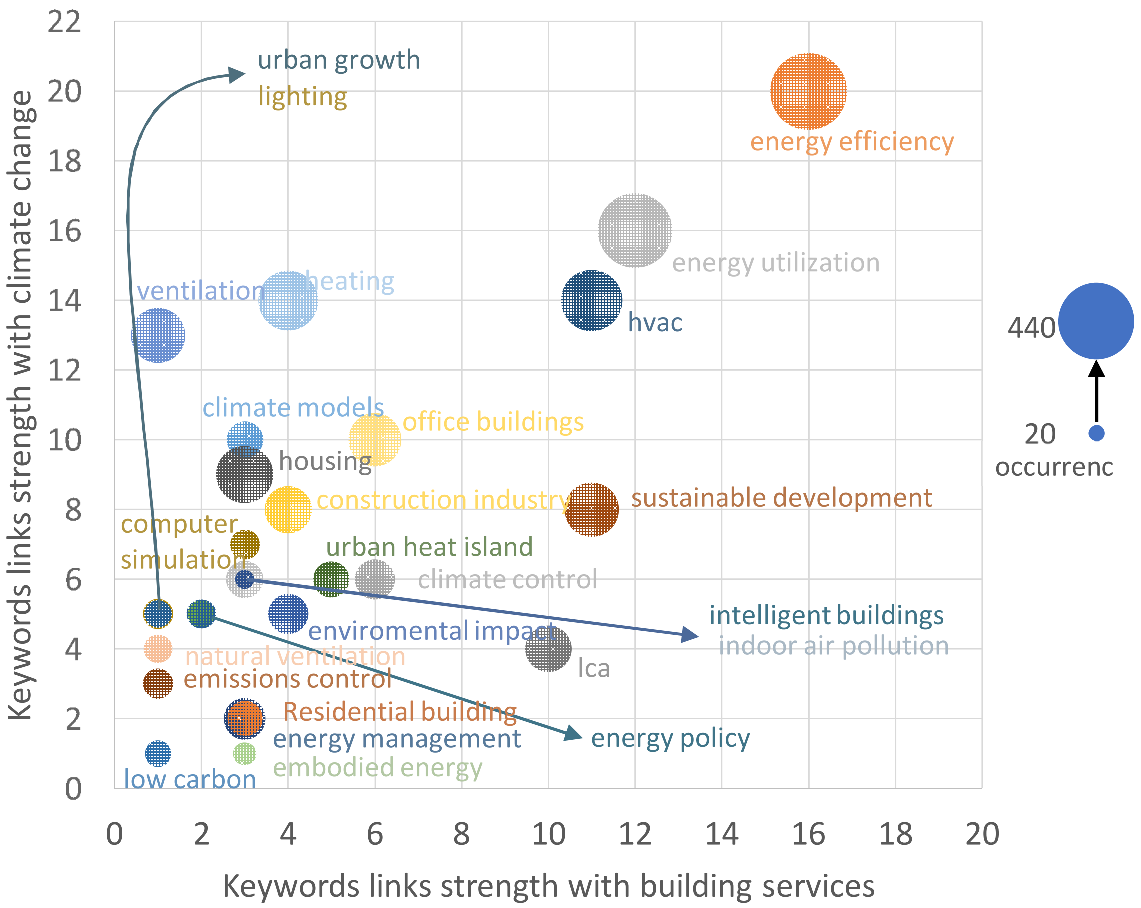
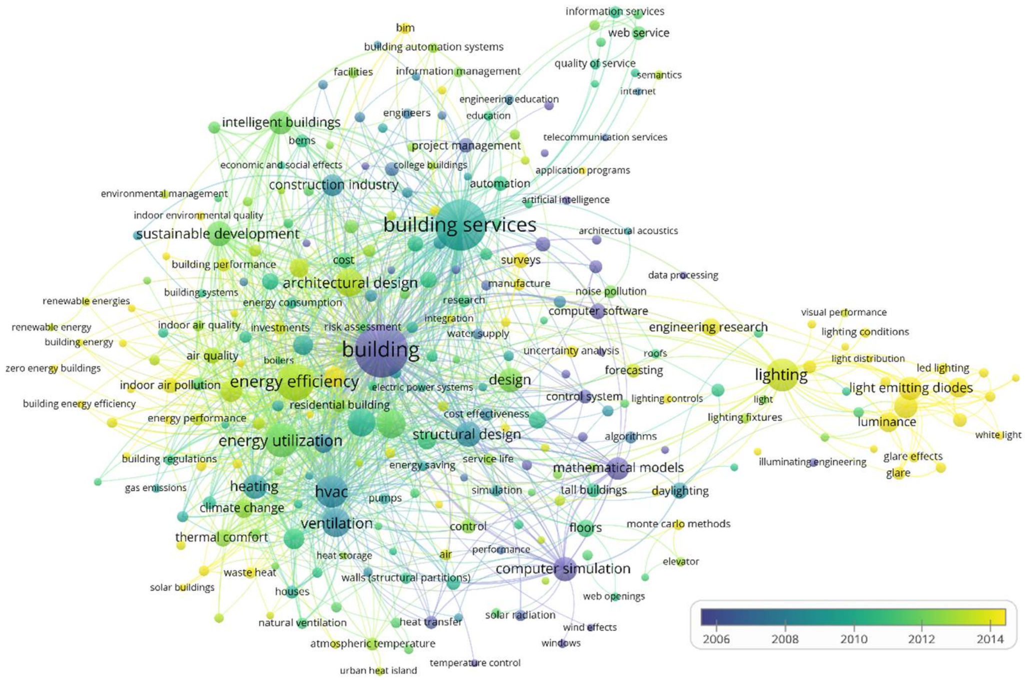


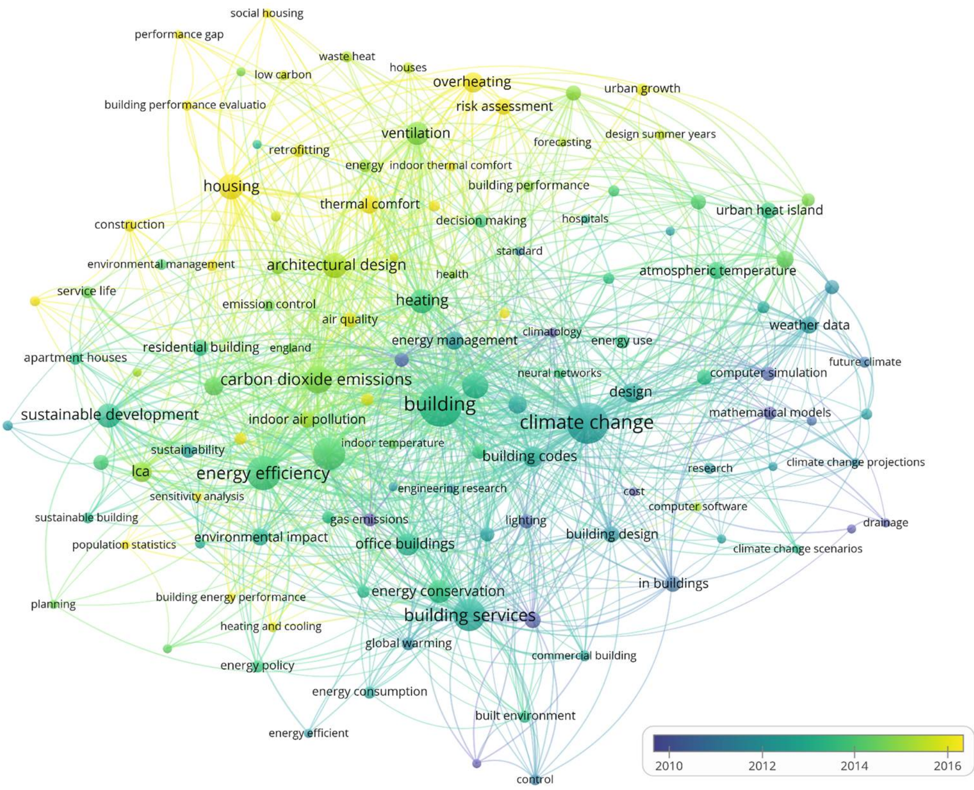
Figure 10. Keywords link strength directly related to building services and climate change in query 2 keywords network analysis.

Following the trend presented in Figure 3b, the overlay visualization by year of the keyword analyses (Figure 11) shows that most keywords appear after 2002, highlighting the progress of research towards new topics. Figure 11a shows that the keywords used in earlier documents were "maintenance", "architecture", "project management", also "computer simulation" and "mathematical models", related to "control system", "hvac", "ventilation", and "heating"; indeed, these are the building services classified within the safety and comfort types in Figure 1. However, most recent interests have changed to energy efficiency topics such as "lighting", "luminance" and "led emitting diode", the transition from building to city with "urban heat island", and more recent building subjects such as "embodied carbon", "data centre", "overheating", "performance gap", and finally "bim", which are within the efficiency and climate change types in Figure 1.

Moreover, when the relation between building service and climate change is studied Figure 11b, with all the topics newer than in query 1, the keywords used in earlier documents were "gas emissions", "climate control" and "building regulations" [53], showing that the literature related building services with climate change when HVAC systems are studied, also mentioning regulations and policies. Recent interests can be grouped, for example, social topics like "housing" close to "social housing", "urban growth" and "retrofitting" [46,54,55], highlighting that retrofitting of social housing is a topic to consider to ensure thermal comfort to low-income population and to avoid energy poverty. Other recent keywords are "overheating", "risk assessment", "thermal comfort", and "embodied energy", with the latter closely related to "carbon dioxide emissions", "energy efficiency", and "lca" [56,57], showing the growing importance of sustainable topics in recent research.



(**a**)



(**b**)

Figure 11. Trends in keywords network: (**a**) general query, (**b**) query with climate change.

5. Conclusions

This paper presents a bibliometric-driven analysis of research trends in the field of building services and their relationship to climate change. It was developed using data from the Scopus database from 1969 to March 2020. Two queries were analyzed, TITLE-ABS-KEY ("building service*") and TITLE-ABS-KEY ("building service*" AND "climate change"). The results of both queries were analyzed in terms of publications by years, countries and top journals in which the research was published and through a keyword network analysis. This made it possible to identify the most recent research trends. The most recent research on building services can be associated with safety, comfort and efficiency. The studies show that improvements in thermal efficiency in buildings and improvements in air quality are made by studying natural ventilation techniques coupled with HVAC systems and the development of new HVAC technologies. On the other hand, improvements in electrical efficiency focus on the use of LED lighting and the use of intelligent control strategies, optimized through building simulations. When relating building services to climate change, the most recent studies focus on social aspects such as social housing, urban growth, and thermal comfort. The main research gaps identified are the lack of integration of the four groups of building services identified in this study in order to draw more effective research in the fight against climate change. Finally, the study of building services not related to energy services is also a research gap.

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Article

Trends in Research on Energy Efficiency in Appliances and Correlations with Energy Policies

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Abstract: According to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment report, energy-efficient appliances can reduce global electricity consumption even though there is an expected increase in the number and ownership of appliances. The International Energy Agency (IEA) expects a high increase in energy efficiency in traditional appliances (refrigerators, washing machines, television, etc.), and in the number of new appliances installed (also called plug loads). The bibliometric study of publications related to energy-efficient appliances carried out in this paper shows that research on this topic is growing in developed regions (North America and Europe) and even more in some developing regions (Asia Pacific) with a high emphasis on China and India. The results indicate that, in general, policies are always implemented before the core of publications on the topic, with time spans ranging from 3 to 30 years. However, the trend seems to be changing with publications related to new appliances where the core research happens shortly after or in parallel to the establishment of policies.

Keywords: energy efficiency; appliance; climate change; policies; label; bibliometric analysis

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1. Introduction

In order to achieve the objectives targeted by the sustainable development goals, immediate actions are necessary. Moreover, to reach deep decarbonization, different strategies should be adopted, including the use of clean energy sources and efficient energy conversion and management approaches [1]. However, special attention should be given to the building sector, which accounts for nearly the 40% of the global energy consumption and emission to the atmosphere [2]. According to the IEA (International Energy Agency), appliances are responsible for 17% of final electricity use in buildings [3]. Furthermore, the energy consumption of building appliances shows an increasing trend over the last 20 years with a small growth in highly developed regions such as North America and the European Union, and high growth of four to eight times the values reached in 2000 in regions such as China, India and the Middle East (Figure 1). Nowadays, only one-third of appliance energy use today is covered by mandatory performance standards. The IPCC (Intergovernmental Panel on Climate Change) 5th Assessment report stated that energy-efficient appliances can reduce the electricity use expected due to the proliferation of appliances types and their increased ownership and use [4] and policy measures such as appliance standards with strong energy efficiency requirements are available to help achieve this objective. The United States, European Union, China, India, Brazil, Australia, Mexico, South Africa, and Malaysia, nine of the countries that have been operating the longest EES&L (Energy Efficiency Standards and Labelling) programs reduced annual electricity consumption in 2018 by 1580 TWh. This represents the same order of magnitude as the total electricity generated by solar and wind energy in those countries [5].

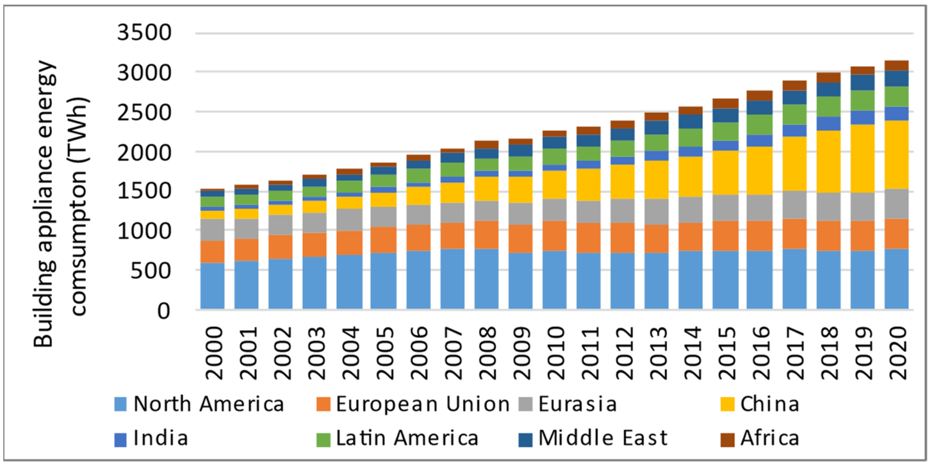


Figure 1. Energy consumption of building appliances by region. Data extracted from IEA [3].

Energy intensity improvement in appliances such as refrigerators, washing machines, TVs, and computers has counteracted the substantial increase in ownership and use since the year 2000. Moreover, digitalization is essential in buildings that support more energy-efficient systems.

Table 1 shows the worldwide final energy used by a variety of appliances and the contribution of each one of the different drivers (activity, structure, and efficiency) in the period 2000–2017. The activity driver is given by a change in the overall level of activity that drives energy consumption (i.e., population); the structure effect reflects a change in the mix of activities within a sector (i.e., appliance stocks per person); and the energy efficiency shows changes in sub-sectoral energy intensities, that is, in energy used per unit of activity (i.e., appliance energy per appliance stocks). It is clear traditional appliances (refrigerator, freezer, television, etc.), have a very low impact on the total energy intensity (understood as the quantity of energy required per unit) growth, which is due to the new appliances, also called plug loads. On the other hand, energy efficiency will have its maximum energy efficiency increase in the traditional appliances.

Table 1. Worldwide energy intensity improvements in appliances in the period 2000–2017 [6].

Appliance Type	Total (EJ)	Drivers		
		Activity (EJ)	Structure (EJ)	Efficiency (EJ)
Appliances	*+4.6*	*+3.5*	*+1.6*	*−0.5*
Refrigerator	+0.2	+0.7	+0.1	−0.6
Freezer	0.0	+0.1	0.0	−0.1
Dishwasher	+0.1	+0.1	0.0	0.0
Washing machine	+0.1	+0.2	0.0	−0.1
Clothes dryer	+0.1	0.1	0.0	−0.1
Television	−0.4	+0.6	+0.4	−1.4
Plug loads	+3.6	+1.7	+2.1	0.0

Cabeza et al. [7] studied the ownership of appliances in different countries (Figure 2). Most white goods (refrigerators, freezers, and washing machines) ownership in Europe reached saturation already in the 1970s, and other developed countries of the world (Japan and USA) show ownership higher than 100%. Developing countries show very diverse results in ownership of the different appliances, with a few already showing saturation (such as refrigerators, washing machines, and televisions (TVs) in China) and in others a slow growth (such as refrigerators and TVs in India).

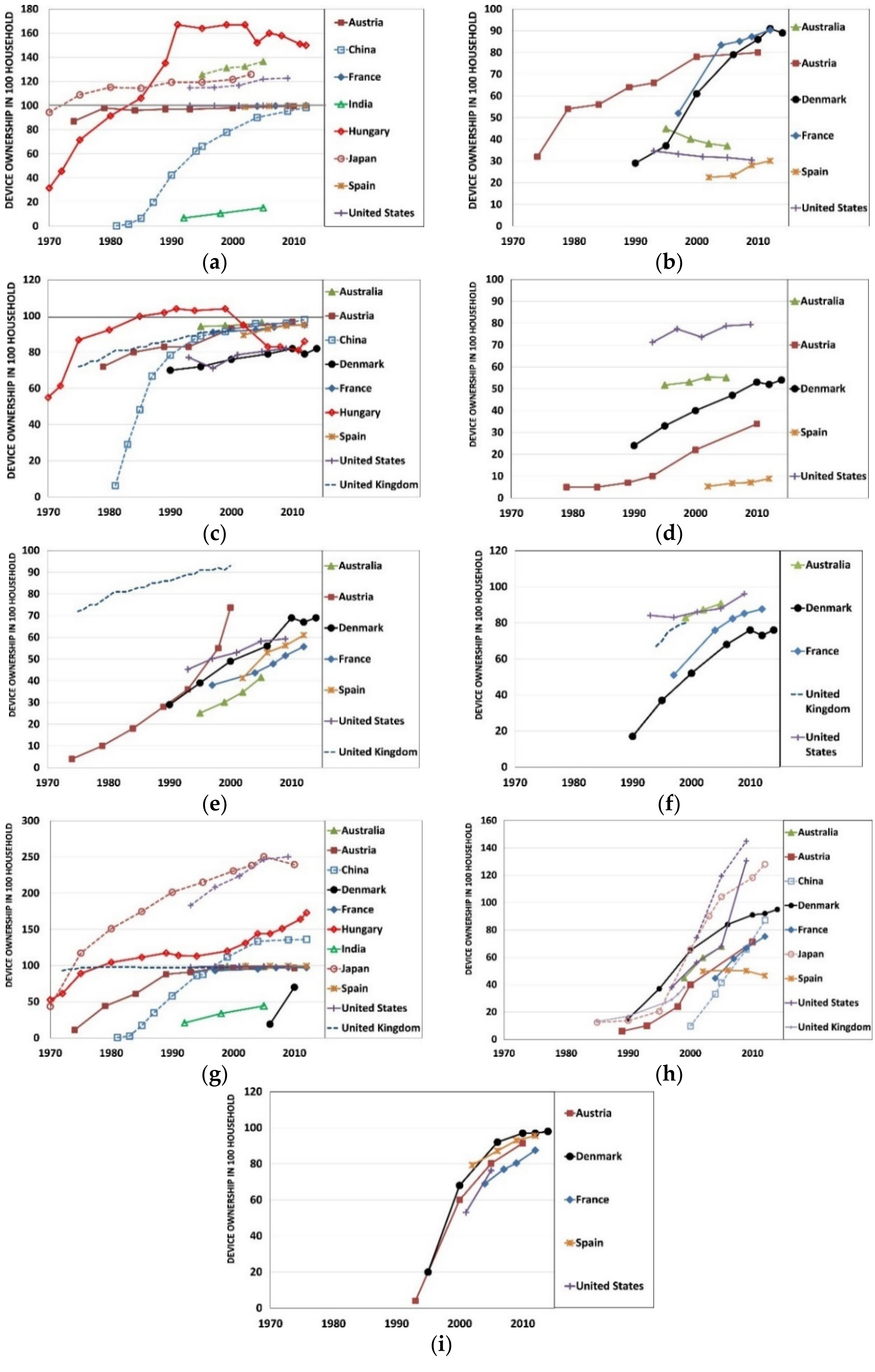


Figure 2. Appliances ownership. (**a**) Refrigerators; (**b**) freezers; (**c**) washing machines; (**d**) clothes dryers; (**e**) dishwashers; (**f**) microwave ovens; (**g**) televisions; (**h**) computers; (**i**) mobile phones. Reprinted with permission from Ref. [7]. Copyright 2018, Elsevier.

In order to identify the trends of a certain topic, bibliometric analysis techniques were recognized as an interesting approach to defining the state of the art as well as identifying research gaps using both a quantitative and qualitative approach.

The aim of this paper is to evaluate how the energy efficiency in appliances was studied in the world, and the main research question is to evaluate if there is a penetration of this concept in the research of countries all over the world and if there is a correlation with energy policies and the EES&L programs. The appliances considered in this paper are presented in Table 2. The results of this paper can be used by researchers to have a clearer picture of research trends and to understand the main pathways of the development of policies related to appliances in buildings.

Table 2. Appliances considered in this study.

White Goods		Brown Goods	Small Appliances
Refrigerator		Television	Microwave oven
Freezer		Video recorder	Coffee maker
Fridge-freezer		Laptop	Vacuum cleaner
Washing machine		Desktop	Electric mixer/Hand blender
Clothes dryer	Wet appliances	Phone	Rice cooker
Dryer machine		Record player	Kitchen robot
Dishwasher		DVD	Hairdryer
Oven		Media center	Electric toothbrush
Cooker		Media player	Towel drying rack/Towel dryer
Gas hob/Gas cooker		Printer	Toaster
Electric hob/Electric cooker		3D-printer/3D printing	Electric fan
		Console/Games machine	Ceiling fan
Kitchen smoke extractor		Tablet	Portable fan
		Consumer electronic	

2. Materials and Methods

Bibliometric analysis and bibliographic mapping were carried out following the methodology presented in Figure 3. Both studies are complementary to achieve a correlation of data based on an initial query formulation of the target topic, the energy efficiency of appliances. Four main databases are recognized for completing bibliometric analyses: Dimensions, Google Scholar, Web of Science (WoS), and Scopus. In this study, the Scopus database was selected as it provides more comprehensive content focused on science and technology disciplines [8].

This study was carried out with the following query:

KEY ((“energy efficien*”) AND (“Refrigerator” OR “Television” OR “Freezer” OR “Video recorder” OR “Fridge-freezer” OR “Laptop” OR “Washing machine” OR “Wet appliance” OR “Desktop” OR “Clothes dryer” OR “Phone” OR “Dryer machine” OR “Record player” OR “Dishwasher” OR “DVD” OR “Oven” OR “Media centre” OR “Cooker” OR “Media player” OR “Gas hob” OR “Gas cooker” OR “Printer” OR “Electric hob” OR “Electric cooker” OR “3D-printer” OR “3D print*” OR “Kitchen smoke extractor” OR “Console” OR “Games machine” OR “Tablet” OR “Consumer electronic” OR “Microwave oven” OR “Coffee maker” OR “Vacuum cleaner” OR “Electric mixer” OR “Hand blender” OR “Rice cooker” OR “Kitchen robot” OR “Hair dryer” OR “Electric toothbrush” OR “Towel drying rack” OR “Towel dryer” OR “Toaster” OR “Electric fan” OR “Ceiling fan” OR “Portable fan”) AND NOT (“combustion” OR “Computer aided engineering” OR “static mixer” OR “industrial refrigeration” OR “air duct” OR “biomass” OR “casting” OR “cryogen*” OR “drying method” OR “industry*” OR “kinetic model” OR “kiln” OR “printing technolog*” OR “polygeneration” OR “semiconduct*” OR “transportation sector” OR “corrosi*”)) AND (EXCLUDE (PUBYEAR, 2022)).

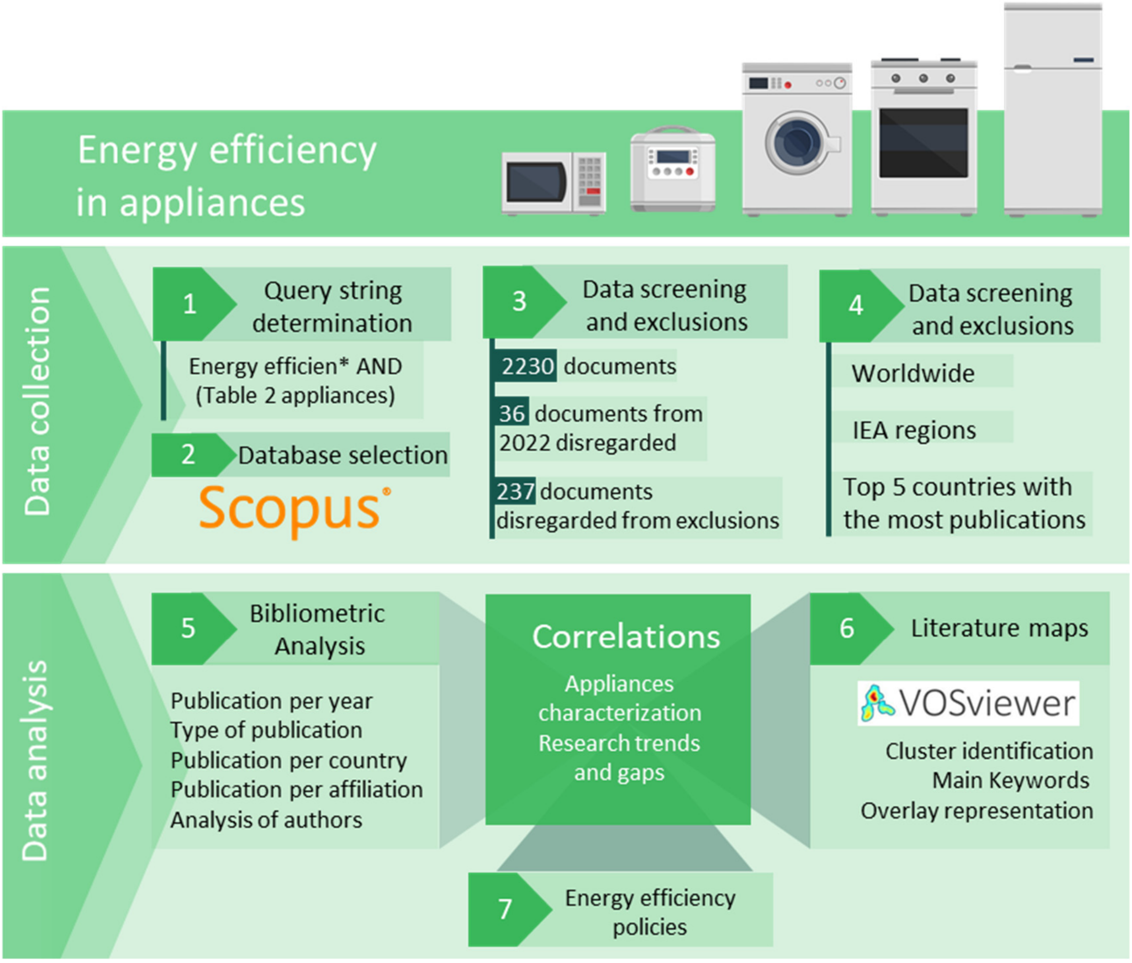


Figure 3. Methodology followed in the bibliometric analysis.

After a thorough review of the publications, a total of 273 documents were excluded from the query, 36 due to being published in 2022 and 237 for not being related to the topic. As a result, the number of publications to be analyzed was clearly identified. Figure 3 shows that the query has 1957 documents.

Once all the information and references were downloaded from the specified database, the next stage was to proceed with the data analysis. This part was divided into two sections, the results of the bibliometric analysis and the representation of the literature map. In the bibliometric analysis, the extracted data were plotted in different chart types, where there are denoted assessments, as shown in Figure 3. On the other hand, the present work encompasses a literature map analysis that was performed by taking the reference information from Scopus. These data were exported to a software tool, called VOSviewer [9]. The selected software has two visualization options, grouped clusters or an overlaid timeline representation. The latter visualization shows the analysis of the average publication date of the keywords, being able to recognize the most recent keyword in the field. The relationship between keywords, authors, and countries was studied. The last step was to analyze the correlation between the statistics of the bibliometric analysis, the literature maps, and the implementation of national standards in each region analyzed.

The study was done with different geographic coverage. First, all publications worldwide are considered. Then all countries were aggregated into IEA regions [10]. The top five countries with more publications were also considered and used to illustrate the analyses carried out (United States, China, India, United Kingdom (UK), and Germany).

The world population was obtained from the United Nations 2019 Revision of World Population Prospects [11].

3. Results

3.1. Global Bibliometric Analysis

The present search was carried out in February 2022, which is why the time frame was established in the query, considering all historical publications on the subject up to the year 2021.

Figure 4a shows that around 50% of publications on the topic are articles/papers and the other 50% are conference papers, with a small number of reviews and books. The same distribution is also followed individually by all countries included in the study. Moreover, when analyzing the number of publications by region, Figure 4b shows that the Asia Pacific and Europe show similar values, being the regions with the highest number of publications. Followed by North America with 35% fewer publications. When analyzed by country, the United States is the country with the highest number of publications, followed by China.

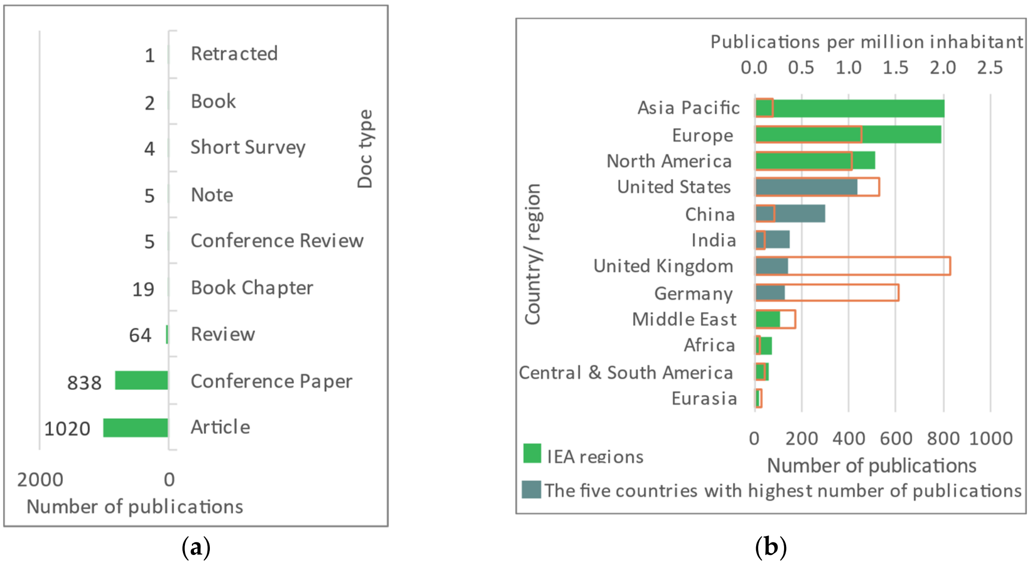


Figure 4. Distribution of documents by (**a**) type of documents (**b**) country/region of publication and in the orange bars publications per million inhabitants.

When the population of each country/region is also taken into account, the United Kingdom stands out with more than two publications per million inhabitants, followed by Germany and the United States. Regionally, Europe and North America show the highest values with one publication per million inhabitants.

The trends in the number of publications are shown in Figure 5. The figure shows that energy efficiency in appliances was already a topic of research in the 1970s, with continuous interest in the peer-reviewed literature until today. However, in 2007 the number of publications started to grow (from 51 documents in 2007 to 127 in 2011 to 166 in 2021). The same trend can be seen worldwide and for each country/region considered. Interestingly, the region that started publishing on this topic was North America, followed by the Asia Pacific and Europe. The growth in the number of publications was very high in Asia Pacific, Europe, and North America in the period 2007–2011. Then, somehow publications stagnated in North America, continuing to grow in Europe and even more so in the Asia Pacific.

Figure 6 shows the relationship between the countries' publications obtained with VOSviewer. When considering countries aggregated in the IEA regions Figure 6a, the network highlights that Europe, Asia Pacific, and North America are the regions with the oldest research publications, showing more recent interest in the remaining regions. This is evidence that this topic has spread from developed to developing regions.

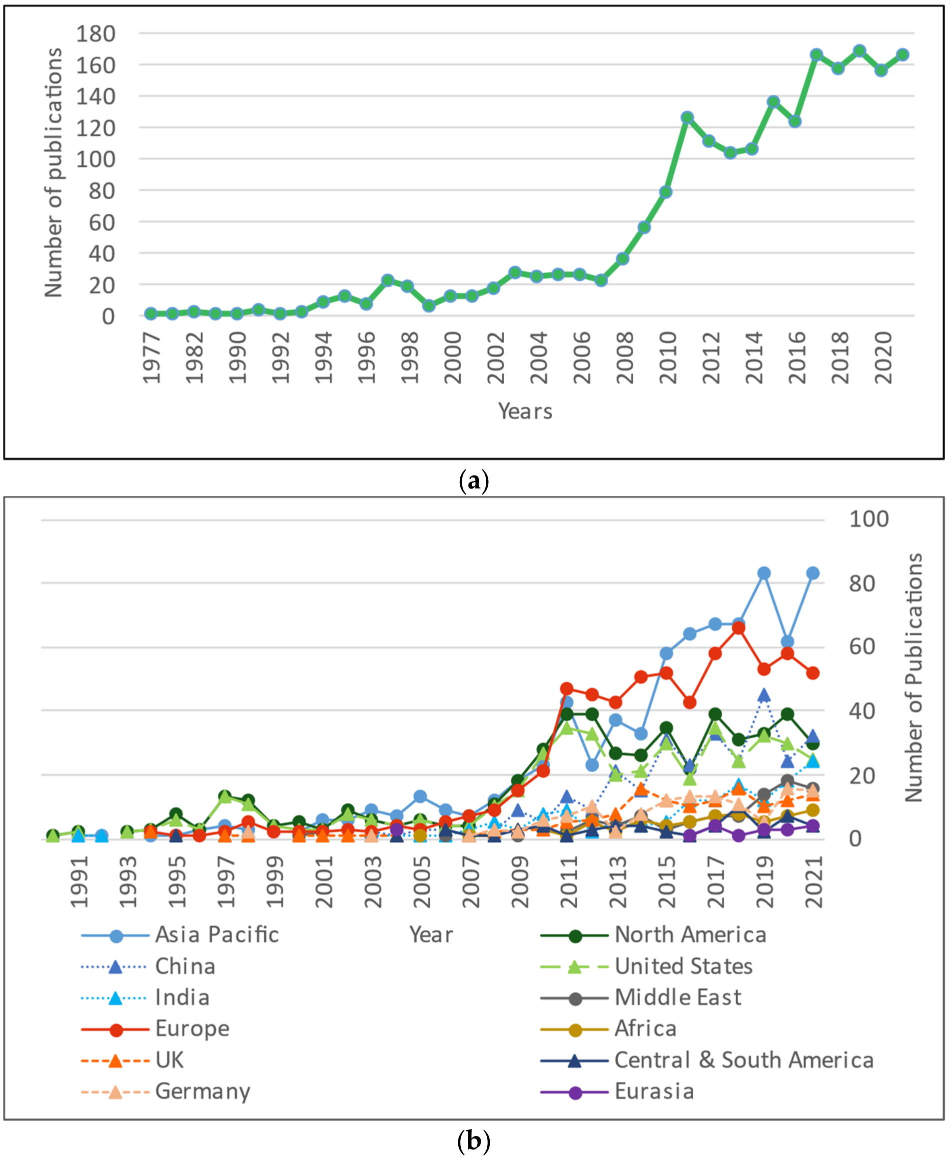
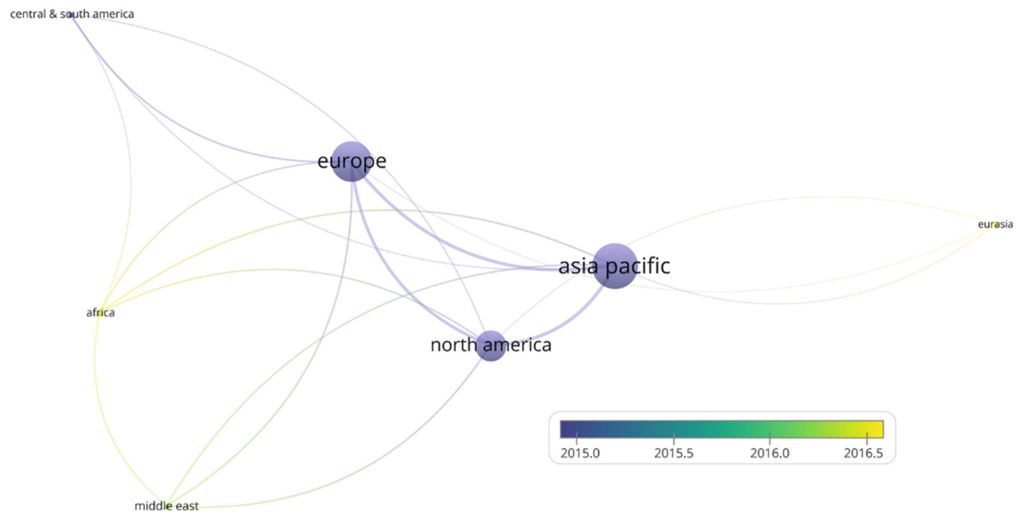


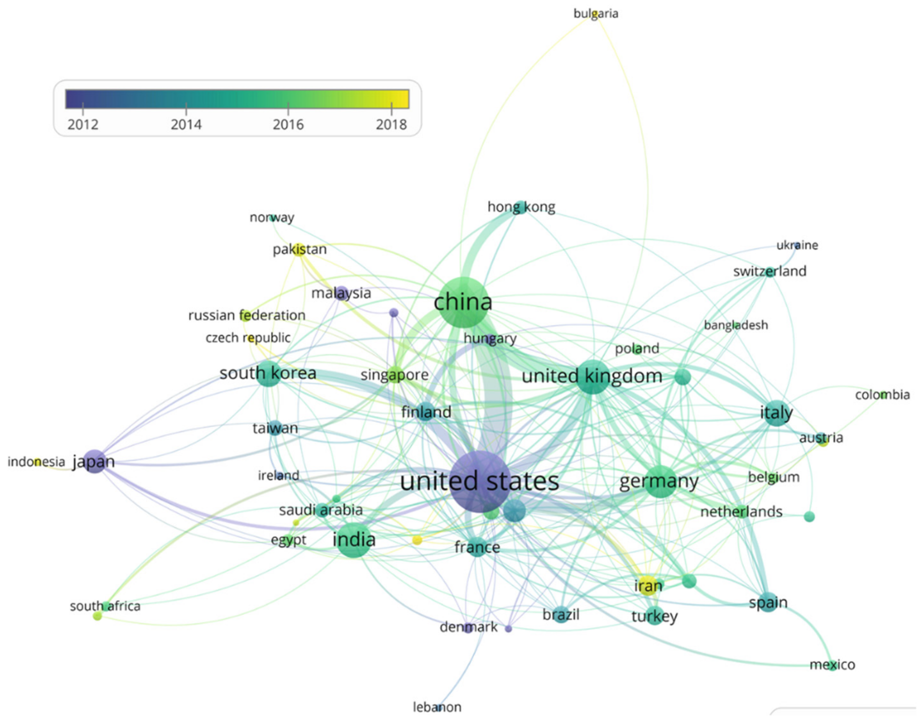
Figure 5. Trends in the number of publications in the area of study (**a**) worldwide (**b**) per country.

The analysis of country relationships in Figure 6b in accordance with Figure 6a shows that the United States, Japan, and Denmark started research on this topic at an earlier stage. The most recent countries to start research on this topic are Iran, Pakistan, United Arab Emirates, Qatar, and the Czech Republic. Moreover, it is interesting to see the strong link between the United States, China, and the United Kingdom.

The analysis of the authors with a higher number of publications (Table 3) shows that R. Saidur from Sunway University of Malaysia is the author with the most documents (12 publications). The most-cited article by R. Saidur (published in 2002) is an experimental analysis of two domestic refrigerators to investigate the effect of variables such as temperature, thermostat setting positions, and door opening on energy consumption. His research reveals that room temperature has the greatest effect on energy consumption, followed by door opening [12]. Furthermore, the most recent publication by R. Saidur (2021) reports on a thermodynamic analysis of a domestic refrigerator using the nano-refrigerant Al_2O_3. The results showed that the energy consumption of the refrigerator was reduced by approximately 2.69% when using 0.1% Al_2O_3 [13].



(**a**)



(**b**)

Figure 6. Countries' relationships (**a**) considering the IEA regions (**b**) considering all countries with publications.

The second author with the most publications is J.K. Nurminen, from the VTT Technical Research Centre in Finland. His most cited publication (published in 2009) deals with a burst content sharing mechanism for energy-constrained mobile devices. The results showed that compared to standard BitTorrent technologies the energy-limited peers can achieve 50% energy savings without significantly affecting the download speeds of regular peers [14]. The most recent publication by J.K. Nurminen (2013) deals with characterizing the energy impact of concurrent network-intensive applications on mobile platforms. Among its findings is that running multiple network-intensive applications concurrently can significantly improve energy efficiency, up to 2.2 times compared to running them separately [15].

Table 3. Authors with more publications in the field of study.

Author	Institution	Country	Number Documents Search	Number Doc Total	h-Index Total
R. Saidur	Sunway University	Malaysia	12	577	95
J.K. Nurminen	VTT Technical Research Centre of Finland	Finland	11	127	25
H.H. Masjuki	University of Malaya	Malaysia	10	510	97
R.K. Radermacher	A. James Clark School of Engineering	United States	10	359	48
U. Sharma	Indian Institute of Technology Delhi	India	9	65	10
T.M.I. Mahlia	University of Technology Sydney	Australia	8	361	67
I. Kelényi	Budapest University of Technology and Economics	Hungary	8	25	9
B. Singh	Indian Institute of Technology Delhi	India	7	2168	72
Z. Wei	Tongji University	China	7	49	11
Y. Amano			6	135	14

H.H. Masjuki is the third most published author, sharing both his most-cited publication and his most recent publication with R. Saidur.

The three authors mentioned above show a high consistency in their research line being their most-cited and most recent works on the same research topic. All of them are of high relevance for improving the efficiency of appliances. It is interesting to highlight that Table 3 does not follow the same trend of countries as shown in Figures 4 and 5. Finally, the h-index of the searched papers shows that for most of the authors the papers on the topic had a high impact.

When analyzing where the authors publish and how these documents are grouped (Figure 7), the journal with the highest number of publications is *Applied Energy*, showing that energy efficiency in appliances is very related to research in energy systems. Table 4 shows that all journals used have a high impact (being classified in the first 25% of most-cited journals–Q1) except for the journal *Energy Efficiency*, probably used because of the relation between the journal scope and the topic of study. It is interesting to see that none of the journals are open access and the documents are mostly related to Engineering, Computer Science, and Energy fields.

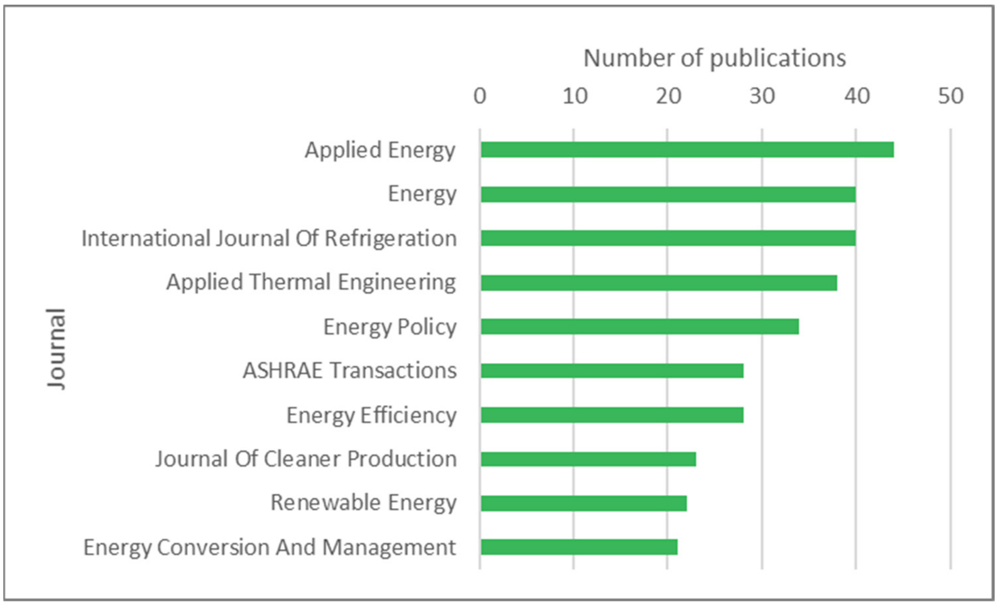


Figure 7. Journals where the documents are published.

Table 4. The journals most used and their impact.

Journal	Number Documents Search	Total h-Index (2022)	Category	Open Access
Applied Energy	51	9.746	Q1	No
Energy	39	7.147	Q1	No
International Journal of Refrigeration	21	3.629	Q1	No
Applied Thermal Engineering	38	5.295	Q1	No
Energy Policy	95	6.142	Q1	No
ASHRAE Transactions	23	—	—	No
Energy Efficiency	51	2.574	Q2	No
Journal of Cleaner Production	24	9.297	Q1	No
Renewable Energy	22	8.001	Q1	No
Energy conversion and management	21	9.709	Q1	No

3.2. Analysis of Keywords

Figure 8a shows details of the co-occurrence map of the search considering worldwide publications. The map is divided into five clusters, the first cluster in red encompasses keywords related to digital applications such as "personal computer", "digital television", "wireless communication", and "smartphone". In this cluster, we can find research studies on approaches to reduce the energy consumption of wireless networks, both at the domestic and industrial levels [10,16–18]. A special emphasis is placed on improving the energy efficiency of the new generation of devices connected to the Internet of Things (IoT), including smartphones [19–22].

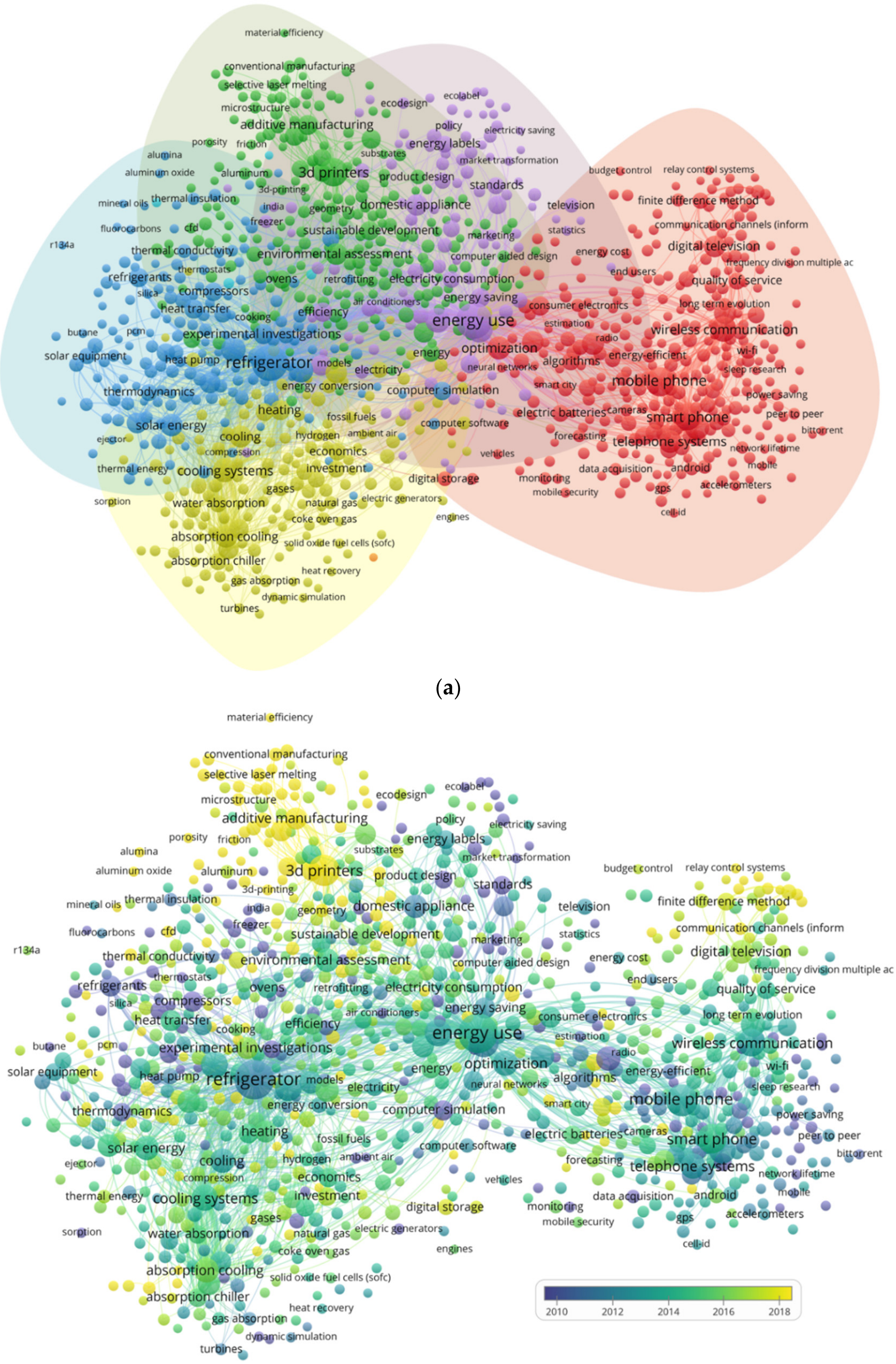
The next cluster in yellow focuses on heating and cooling appliances with keywords such as "heating", "cooling systems", and "absorption cooling". In this cluster, we can also find the keywords "carbon dioxide emissions" and "renewable energy" which demonstrate the efforts being made to transform the energy demand matrix of these highly energy-intensive appliances into renewable energy [23–26].

The third cluster in blue gathers the keywords related to refrigeration, with keywords such as "refrigeration", "refrigerants", "food preservation", "thermodynamics", and "solar energy". The latter with a strong link to "absorption cooling" from the yellow cluster. This cluster comprises a wide range of experimental studies focused on improving the efficiency [27–29] and reducing the cost [30,31] of vapor compression systems.

The fourth cluster gathers studies that pursue more efficient alternatives to the current manufacturing systems [32–34], therefore its main keywords are "3d printers", "manufacture", "additives" and "additive manufacturing". This cluster also contains the keywords "environmental assessment" and "sustainable development" closely related to the first keywords mentioned in this cluster and to "refrigerator" from the yellow cluster.

Finally, the purple cluster comprises the studies related to the use of energy in appliances and the effect of standards and policies [35–38]. Among the most relevant keywords, we can find "domestic appliances", "energy policy", "standards", "energy labels", "energy use", and "energy savings".

The overlay visualization Figure 8b shows that studies with the oldest average number of publications focus on refrigerators (average year of publications 2010), and washing machines (2008), with a strong link to refrigerants (2010), compressors (2008), standards and energy policy (2006 and 2011), respectively. Next is the keyword "domestic appliance" in (2011) related to energy label (2012), and the keyword "personal computer" (2011) related to "mobile device" in 2012 and wireless communication (2013). The figure shows that the most recent studies focus on IOT (2018), and 3D printers (2018), the latter with high attention from the scientific community representing 15% of the total publications captured by this study.



(**a**)

(**b**)

Figure 8. Efficiency in appliances co-occurrence keyword network, (**a**) grouped in clusters, where each color groups keywords in a cluster, (**b**) overlay visualization, where color indicate year of publication.

4. Discussion and Conclusions

According to the IEA TCP 4E (International Energy Agency Technology Collaboration Programme Energy Efficiency End-use Equipment), between 2004 and 2014, the average sales-weighted efficiency of new refrigerators in the EU improved by 3.4% per year, resulting in a 25% reduction in energy consumption. In Australia, the sales-weighted average energy efficiency of refrigerators increased 2.7% per year between 1993 and 2014, and 2.2% for freezers. Figure 9 shows that, in developed countries, the average sales-weighted efficiency of new refrigerators increased between 2% and 4% per year. This can be correlated with the exponential increase in publications on the topic worldwide from the late 1990s to 2011 Figure 5a. In other appliances, the range of improvement per year between the different countries is higher, but also the best energy efficiency is higher. For example, for TVs, the range varies from 1% in Switzerland to 13% in Japan. This trend cannot be directly correlated with the number of publications on the topic. Indeed, it can be correlated to the lack of standards regulating the energy efficiency of brown goods in a large number of countries (Figure 10).

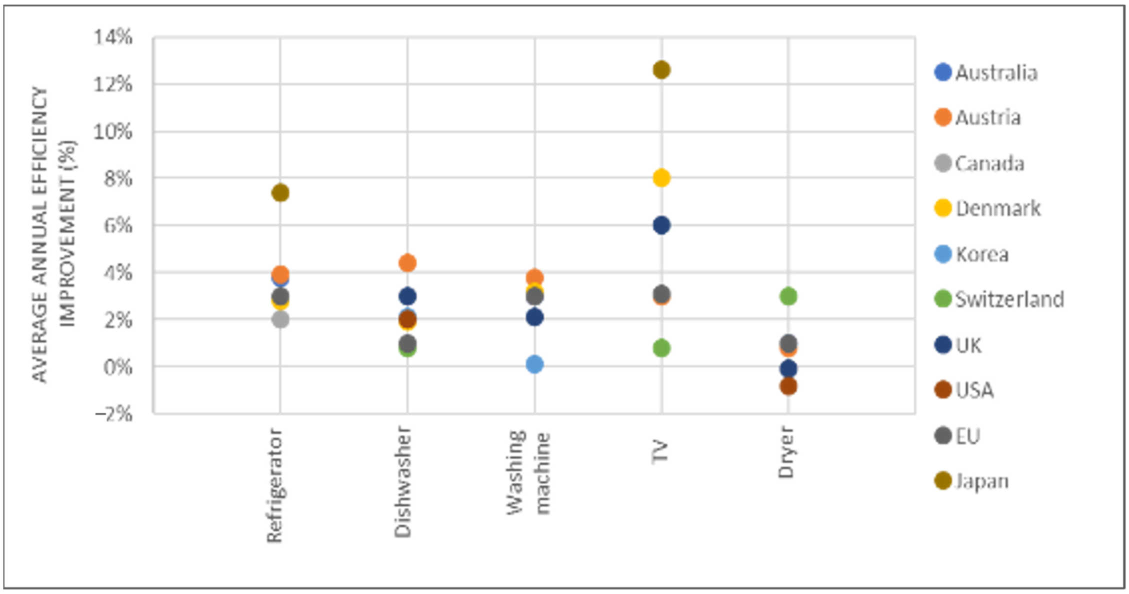


Figure 9. Annual efficiency improvement rates for different appliances in different countries, up to 2014, calculated for different time frames [39].

Energy efficiency standards and labeling (EES&L) started in the 1970s and today operate in more than 120 countries worldwide for more than 100 different types of appliances and equipment [39]. Moreover, according to the IEA, and based on global data from countries with EES&L programs, the average energy efficiency of new major appliances in these countries has increased by two to three times the underlying technology improvement rate. This has resulted in energy savings of 10 to 30% over 15 to 20 years in the stock of most regulated products in all countries. In countries with strong regulations and long-standing programs that are regularly updated, the contribution was much greater, reducing the electricity consumption of many appliances by more than 50% [3]. The countries with larger EES&L programs are the United States, China, the EU, and Australia.

The above indicates that energy efficiency policies were introduced in countries with different timeframes ranging from 1978 to the present day. This study analyses how the policies and standards in place have encouraged research in the field of appliances and vice versa. Figure 10 presents the number of occurrences of a term (the name of a studied appliance) appearing per average year of publication and per country, according to the references obtained from the Scopus search. The figure shows that the most intensive research carried out was after 2010. The results obtained are consistent with Figure 8b, with refrigerators and freezers being the first appliances to be studied in the scientific literature, and 3D printers, smart meters, and smartphones the most recent ones.

The trend in the graph indicates that the first regions/countries to establish policies on appliance efficiency are the ones that first started to publish on this topic and the ones with the highest overall number of publications (with the exception of Central and South America). Surprisingly, the first country to establish energy efficiency policies in appliances was Japan in 1978 with the Energy Efficiency Act (in force). Contrary to the trend, only 69 documents published by this country were captured in the bibliometric search of this study.

North American and European regions were next to publish on the energy efficiency of appliances. Indeed, this correlates with the legislation enforced. In the case of North America, the first appliance efficiency standard was implemented in the United States in 1987 ("National Appliance Energy Conservation Act" still in force) [40], followed by Canada in 1995 (still in force) [41]. However, these two standards do not cover the Brown goods categories in Table 2. Initiatives such as the energy star [42] created in 1992 have helped as sources of information to make well-informed purchasing appliance decisions. However, compliance with this label is not mandatory for appliance manufacturers. Therefore, the first standard in North America to include brown goods was implemented in 2006 [43]. In the case of North America, it is interesting to highlight that the policies were implemented within a time span of 5 to 15 years before the more intensive research on the appliances of the policies' scope.

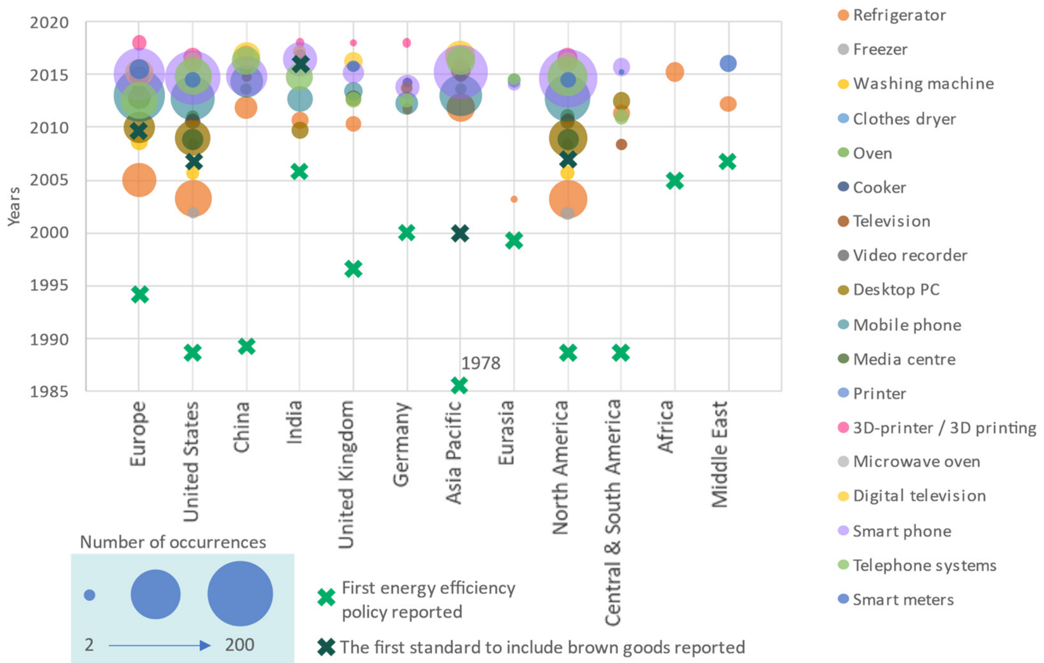
The first program developed in Europe related to the energy efficiency of appliances was in 1975 in France, with the Existing Buildings Programmes [44]. However, the first regulation established within Europe with a direct target on appliances was in Spain in 2001 [45]. This regulation was limited only to the field of household appliances, it was not until 2010 that it was amended, enlarging the scope of application to all energy-related products, and whose use may have either a significant direct or indirect impact on energy consumption. The countries with the most publications in the region (United Kingdom, Germany) show a similar trend to the results for the region. There is a difference of about 10 years between the first policies and the core of scientific publications.

The Asia Pacific region shows that the first appliance efficiency policies were applied in the region in 1978, and the first to include brown goods in 2000. The core of research in this region was from 2011 to 2016, which represents a gap of more than three decades between the first policies and the most intensive research work. On closer analysis, these leading policies were implemented in Japan, which accounts for only 9% of the region's publications. When analyzing the countries with the most publications in the region, China with 40% of the publications shows similar behavior to North America and Europe with a difference of 15 years between the first policies and the most intensive research work. On the other hand, India with 23% of the publications in the Asia Pacific region shows a great synergy between policy and research. With core research on appliances only three years after the implementation of the first policies, and even in the case of brown goods, the core research of several appliances takes place before the first policies which include it.

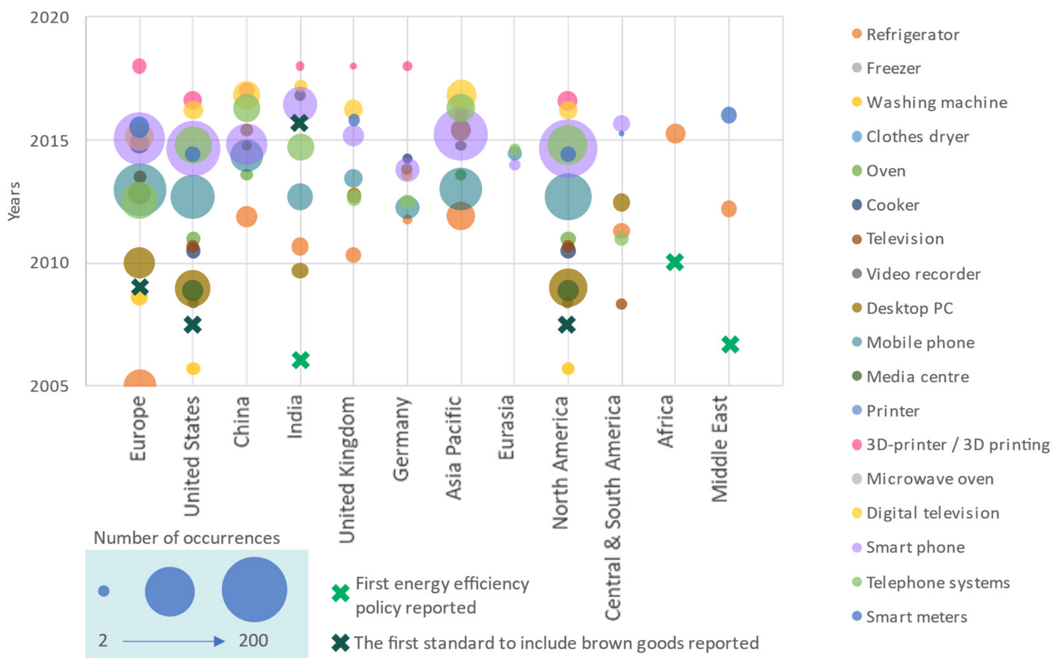
Eurasia, Central and South America, Africa, and the Middle East were the regions with the fewest publications, accounting for only 13% of the publications captured in this study. All four regions showed a similar trend with policies being implemented between 5 and 10 years earlier than the average publication. The exception to this was the Central and South America region, with the first policies implemented in Brazil in 1988, 20 years earlier than the average publications in the region.

Generally speaking, there is a 3- to 30-years gap between the establishment of the first standards or policies in the different regions and the core of publications in these regions. However, there are countries such as India that stand out for a good relationship between publications and policies, showing a quick response of the scientific community to the policies in place.

Furthermore, this trend seems to be changing as the most recent studies on improving the efficiency of appliances focus on brown goods Figure 8b, contrary to the low coverage of current policies in this category of appliances.



(**a**)



(**b**)

Figure 10. Average publications year and number of occurrences of the different appliances in each studied country/region. Data from the Scopus query. The green crosses indicate the first appliance efficiency standard or policy implemented in each country/region. The dark green crosses indicate the first appliance efficiency standard or policy that includes brown goods appliances. Data obtained from the IEA policies database [46], (**a**) range of years from 1985 to 2020, (**b**) year range from 2005 to 2020.

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Thermal energy storage co-benefits in building applications transferred from a renewable energy perspective.

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Abstract:	Although one of the main aims of using renewable energy sources in building applications is to reduce the environmental impact caused by the high global energy demand of buildings, it may also produce other positive effects, known as co-benefits. Thermal energy storage technologies are often used in building applications, either integrated into the renewable system or independently, for energy savings or energy efficiency reasons. This paper shows that it is possible to identify the co-benefits of the use of thermal energy storage in buildings by cross-sectorizing the renewable energy and thermal energy storage sectors. To this end, this article first reviews the literature on the co-benefits of renewable energy for building applications, and then evaluates how these co-benefits can be attributed to thermal energy storage in buildings. As a result of a keywords analysis, the main co-benefits of thermal energy storage were identified related to environmental, health, economic, cost, and policies aspects.
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Thermal energy storage co-benefits in building applications transferred from a renewable energy perspective.

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Abstract

Although one of the main aims of using renewable energy sources in building applications is to reduce the environmental impact caused by the high global energy demand of buildings, it may also produce other positive effects, known as co-benefits. Thermal energy storage technologies are often used in building applications, either integrated into the renewable system or independently, for *energy savings* or *energy efficiency* reasons. This paper shows that it is possible to identify the co-benefits of the use of thermal energy storage in buildings by cross-sectorizing the renewable energy and thermal energy storage sectors. To this end, this article first reviews the literature on the co-benefits of renewable energy for building applications, and then evaluates how these co-benefits can be attributed to thermal energy storage in buildings. As a result of a keywords analysis, the main co-benefits of thermal energy storage were identified related to *environmental*, *health*, *economic*, *cost*, and *policies* aspects.

Keywords: co-benefits; renewable energy; thermal energy storage; buildings; cross-sectorisation

1. Introduction

Any action in buildings may have substantial value beyond the direct impact looked for; that is, any action has multiple impacts, which can affect the economy, society, or end user [1]. These impacts are related to health (*better indoor conditions*, *energy poverty alleviation*, *better ambient air quality*, *reduction of the heat island effect*), environment (*reduced local air pollution*, *reduced sewage production*), resource management (*including water and energy*), social well-being (*increase productivity for women*, *fuel poverty alleviation*, *decrease in energy expenditure*), microeconomic effects (*increase productivity in non-residential buildings*), macroeconomic effects (*creation of jobs*), and *energy security*.

These impacts that are not related to the direct objective of study are known as co-benefits. According to the IPCC AR6 [2], *co-benefit* is “a positive effect that a policy or measure aimed at one objective has another objective, thereby increasing the total benefit to society on the environment". Another definition of co-benefit related to climate states that "climate co-benefits are beneficial outcomes from action that are not directly related to climate change mitigation" [3]. Moreover, the term co-benefits refers to simultaneously meeting several interests or objectives resulting from a political intervention, private sector investment or a mix thereof [4].

Thermal energy storage (TES) in buildings is a technology used for *energy savings*, *energy conservation*, and *energy efficiency* [5]. TES is the technology to overcome any mismatch between energy generation and energy use (in time, temperature, power, or location) [6]. TES can be used to convert an intermittent energy source, such as solar energy, in meeting the demand profile. For instance, TES can be used for free-cooling in buildings, or to increase the thermal inertia of the building (by integrating TES materials, such as phase change materials, into the building materials or into the building structure) [7].

Highlighting co-benefits of TES technologies, such as with any other technology, contributes to social acceptance of such technologies [3]. Since literature agrees [8] that one of the main barriers for TES implementation is the lack of knowledge about these systems, dissemination of their co-benefits, especially those related to health and environment, can help in the knowledge deployment. Moreover, literature states that local climate actions would potentially occur faster and at a higher level if they generate co-benefits, such as *environmental, public health, or economic development* benefits, on top of *energy efficiency* and *cost savings*, although usually the last two are already powerful motivators [9].

The literature highlights the advantages of using TES in buildings (i.e., *increasing efficiency and reliability of energy systems, better economic feasibility, reducing investment and costs, reducing pollution, reducing CO_2 emissions*) [6,10,11], but these advantages have never been identified as co-benefits. Therefore, this paper aims at filling up this literature gap by evaluating the potential co-benefits of TES in buildings. To this end, this article first reviews the literature on the co-benefits of renewable energy for building applications, and then evaluates how these co-benefits can be attributed to thermal energy storage in buildings.

2. Methodology

This section describes the methodology adopted (Figure 1) to prepare the bibliographic study and the bibliometric analysis presented in the following sections. In this study, the Scopus database was used as a reference, since it includes a large number of papers referring to technological topics compared to other databases such as Web of Science [12]. Databases such as Google Scholar or ResearchGate were excluded due to their low reliability of bibliometric results [13]. Moreover, the data on world population was obtained from the United Nations 2019 Revision of World Population Prospects [8].

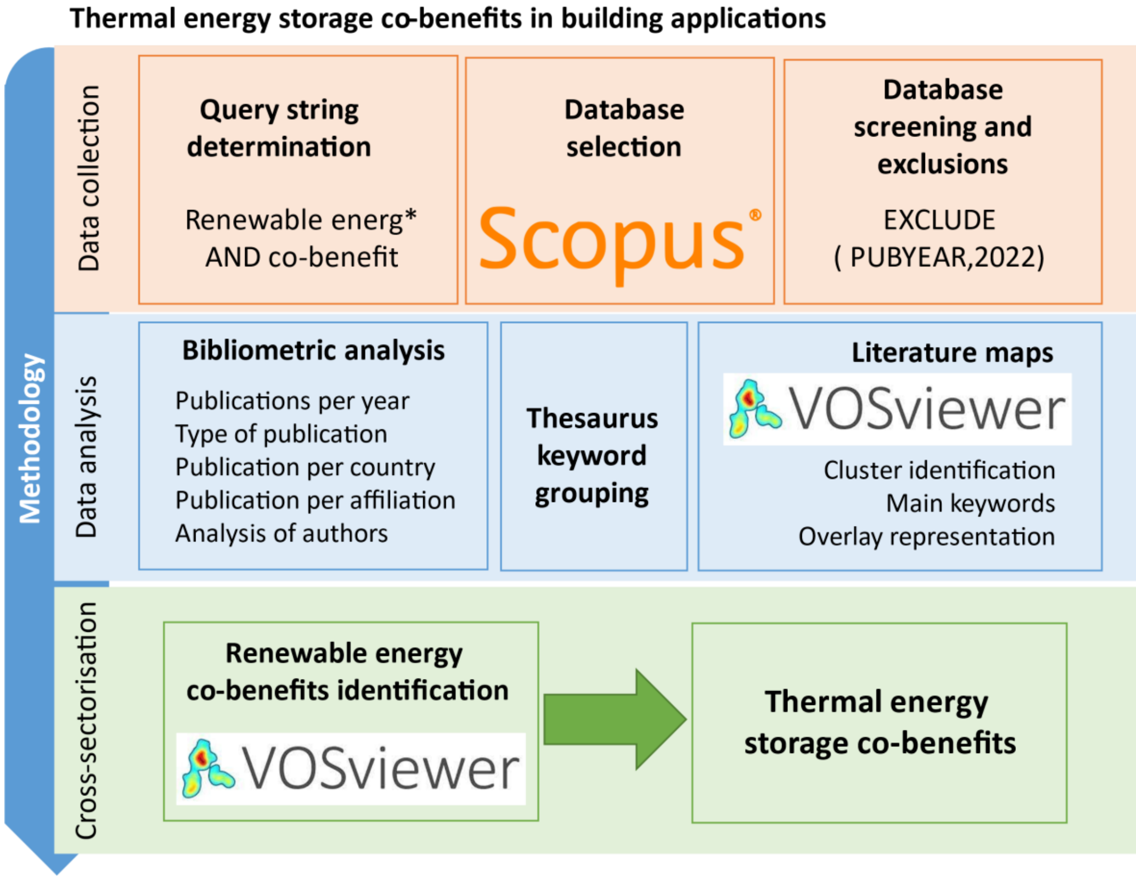


Figure 1. Methodology followed in the bibliometric analysis.

This study was carried out with the following query:

(TITLE-ABS-KEY ("renewable energ*") AND TITLE-ABS-KEY ("co-benefit*" OR "cobenefit*")) AND (EXCLUDE (PUBYEAR,2022))

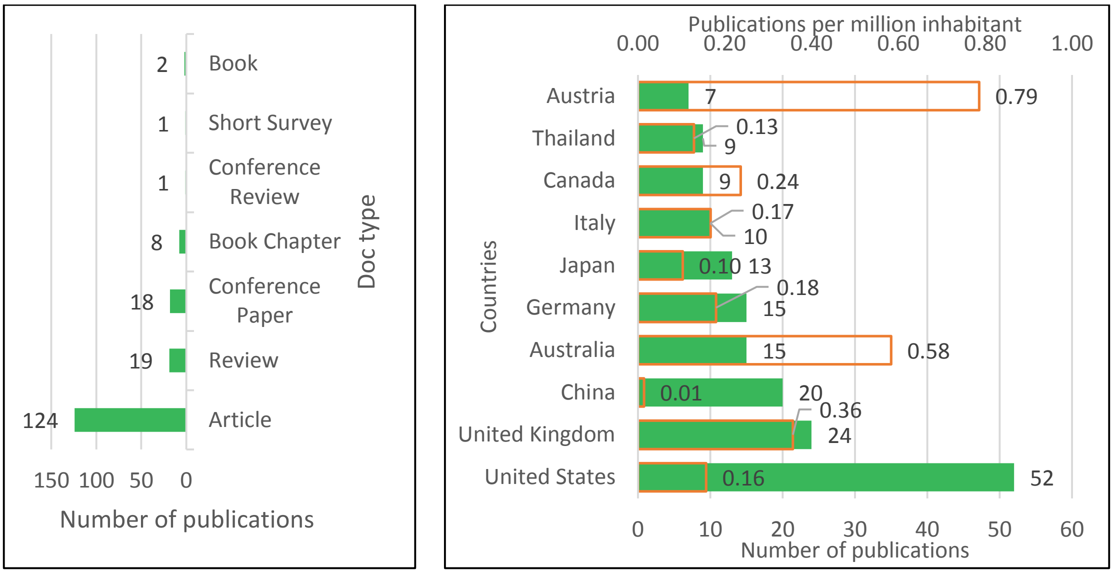
In order to obtain a clear picture of research topics, similar keywords were groups using a thesaurus file into the VOSViewer software. Moreover, this avoid having a dispersion of keywords with low relevance and highlight the macro-area of research.

3. State-of-the-art of renewable energy co-benefits

3.1. Bibliometric analysis

The present study was conducted in May 2022; therefore, the time frame was established in the query, considering all historical publications on the subject up to 2021.

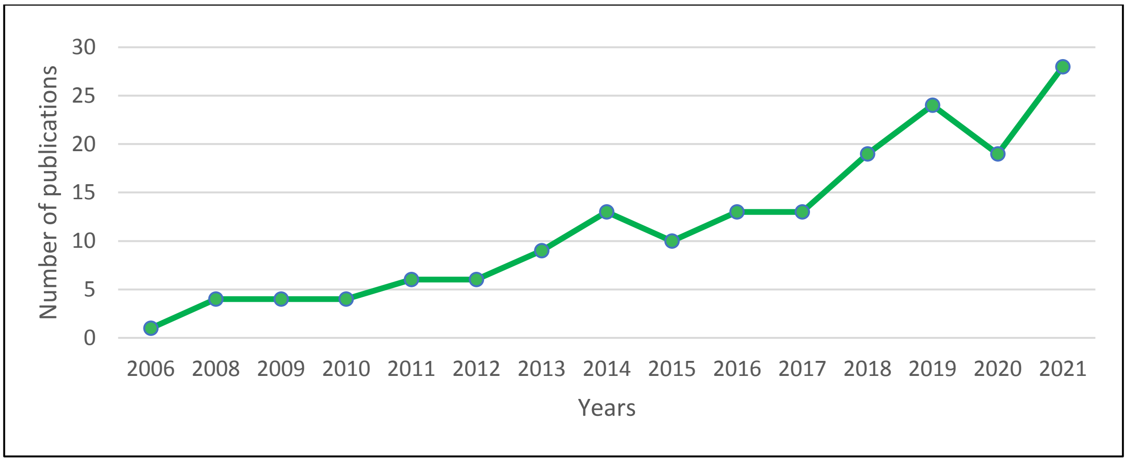
Figure 2a shows that around 70% of publications on the topic are articles/papers and the other 30% are reviews, conference papers, with a small number of books chapters. Moreover, when analyzing the number of publications by countries, Figure 2b shows that the United States is the country with more publications, having published more than twice compared to the next two countries in line United Kingdom and China.



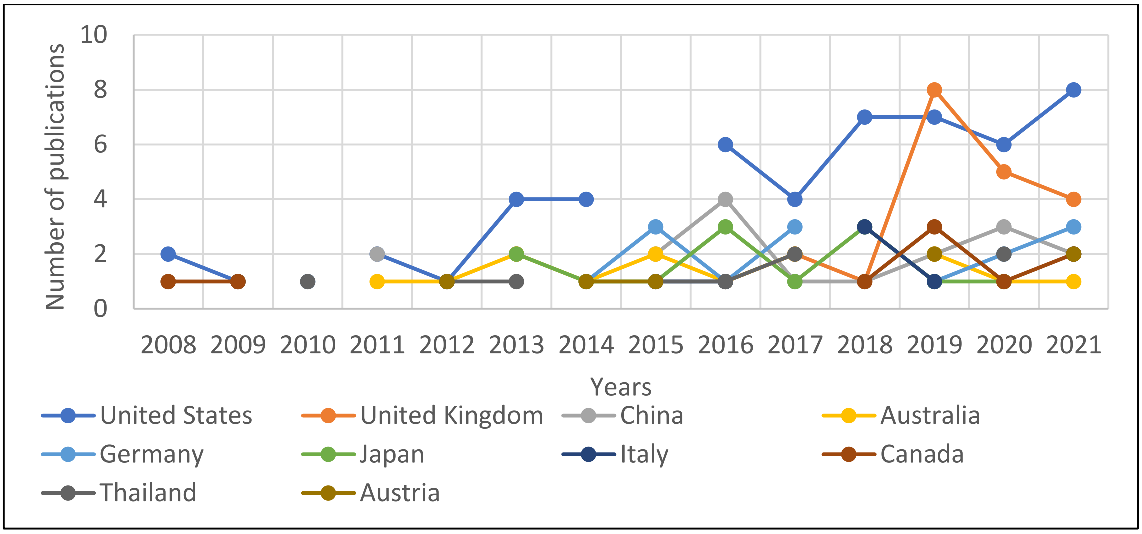
(a) (b)

Figure 2. Distribution of documents by (a) type of documents (b) country/region of publication and in the orange bars publications per million inhabitants.

The trends in the number of publications are shown in Figure *3*. The figure shows that renewable energy co-benefits started to be mentioned in research papers in 2006, with continuous interest in the peer-reviewed literature until today. The trends of paper published by the main countries that are interested in the studies of co-benefits in renewable energy is shown in Figure 3b. The figure shows that United States is one of the countries that started to publish on the topic and that today has the highest research output followed by United Kingdom.



(a)



(b)

Figure 3. Trends in the number of publications in the area of study (a) worldwide (b) per country.

The authors with more publications that are related to the co-benefits of renewable energy are listed in Table *1*. In this case it is interesting to notice that there is only one scholar from United States and that the first author publishing in the topic is B. Limmeechokchaiai, from Thammasat University located in Thailand. The first paper from this author was published in 2012 on the assessment of Thailand energy policies on renewable electricity generation and energy efficiency in industries and buildings evaluating also the CO_2 emissions from power generation expansion plans [14]. The most cited paper was then published in 2013 on the analysis of the mitigation measures in Thailand with emission trading and carbon capture and storage (CCS) using a computable general equilibrium (CGE) model (AIM/CGE) [15]. From the co-authors of this paper is worth to mention R. Shrestha, and T. Masui which is also in list of top authors. In particular R. Shrestha is author of one of the first paper published on the topic in 2010 on the co-benefits of CO_2 emissions reduction in Thailand [16]. From the authors listed in the table the most cited papers was published by Dai, H. in 2016 on the economic and environmental impact assessment of large-scale renewable energy development in China [17]. B.K. Sovacook is also author of highly cited papers including a study on energy justice of low-carbon transition in Europe [18] and a study on the o-benefits of electric vehicles and vehicle-to-grid [19]. The main journals that contain publications related to co-benefits of renewables are shown in Figure 4 and details listed in Table 2, where the most targeted journal in this case is *Energy Policy*. From the bibliometric data is possible to notice that most of journal are classified as Q1 and only few of them are full open access. Nevertheless, almost half of documents published in the topic are available in hybrid gold, bronze, or green in open access.

Table 1. Authors with more publications in the field of study.

Author	Institution	Country	Number Documents Search	Number Documents Total	h-Index Total
Limmeechokchai, B.	Thammasat University	Thailand	6	132	19
Almeida, M.	Universidade do Minho	Portugal	3	76	18
Armstrong, A.	Energy Lancaster	United Kingdom	3	41	19
Becchio, C.	Politecnico di Torino	Italy	3	53	17
Dai, H.	Peking University	China	3	86	32
Ferreira, M.	Universidade do Minho	Portugal	3	16	12
Holloway, T	University of Wisconsin-Madison	United States	3	73	31
Masui, T.	National Institute for Environmental Studies of Japan	Japan	3	176	47
Shrestha, R	Asian Institute of Technology Thailand	Thailand	3	92	25
Sovacool, B.K.	Aarhus Universitet	Denmark	3	508	74

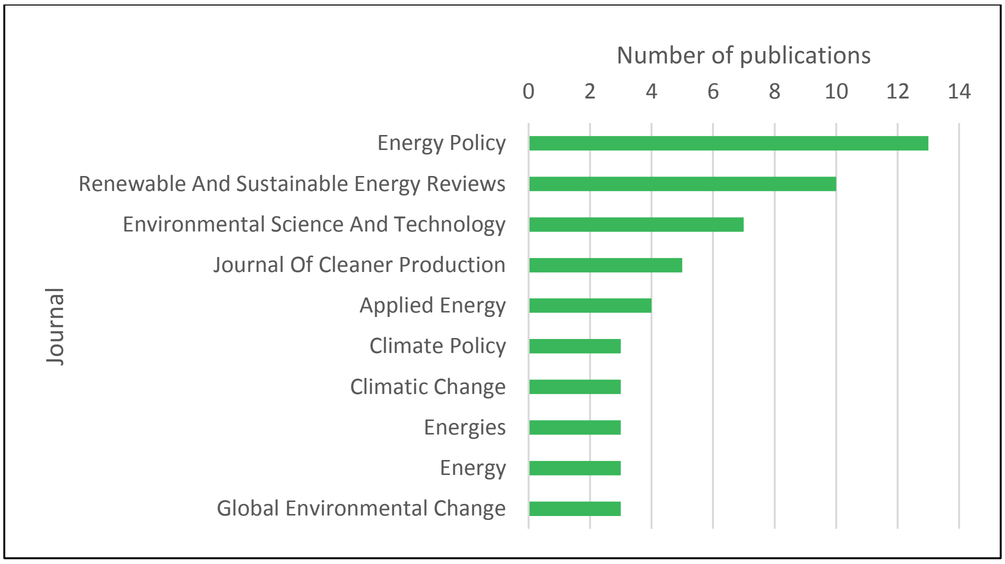


Figure 4. Journals where the documents are published.

Table 2. The journals most used and their impact.

Journal	Number Documents Search	Total h-Index (2022)	Category	Open Access
Energy Policy	13	6.142	Q1	Hybrid
Renewable and Sustainable Energy Reviews	10	14.982	Q1	Hybrid
Environmental Science and Technology	7	9.028	Q1	No
Journal of Cleaner Production	5	9.297	Q1	Hybrid
Applied Energy	4	9.746	Q1	Hybrid
Climate Policy	3	5.085	Q1	Yes
Climatic Change	3	4.743	Q2	Hybrid
Energies	3	3.004	Q2	Yes
Energy	3	7.147	Q1	Hybrid
Global Environmental Change	3	9.523	Q1	Hybrid

3.2. Keyword analysis

The data extracted from the Scopus database were implemented in a bibliographic mapping (Figure 5). This figure shows the relationships among the keywords extracted from each document. The size of the bubbles represents the occurrence of the keywords and the colours represent groupings in clusters. Given the high number of keywords found, and that the main objective of the paper is not to analyse the relationship between the keywords of renewable energy but to identify its co-benefits, the figure is not analysed in detail. To identify that relationship, all keywords related to one specific area were joined using the thesaurus technique to be able to analyse the relation between the co-benefit areas (e.g., *environment*, *health*, *policy*). 200 of the 231 keywords presented in Figure 5 were grouped into 100 main keywords groups (Figure 6). This main groups were: those related to the *energy sector*; to *health impact*; to *carbon dioxide (emissions, carbon sequestration)*; to *air pollution* and *air quality*; to t*he environmental impact management and protection*; economic aspects such as *cost* and *green economy*; biomass including bioenergy and biofuels; buildings; waste management and waste treatments; and finally, policy related keywords. The results after such grouping are shown in Figure 7.

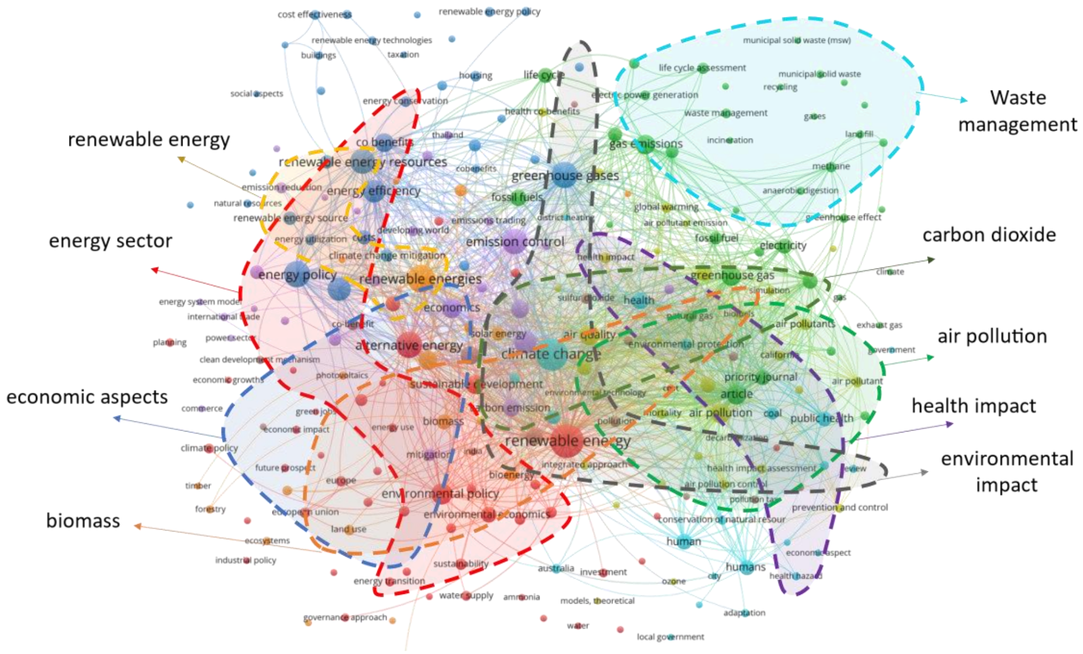
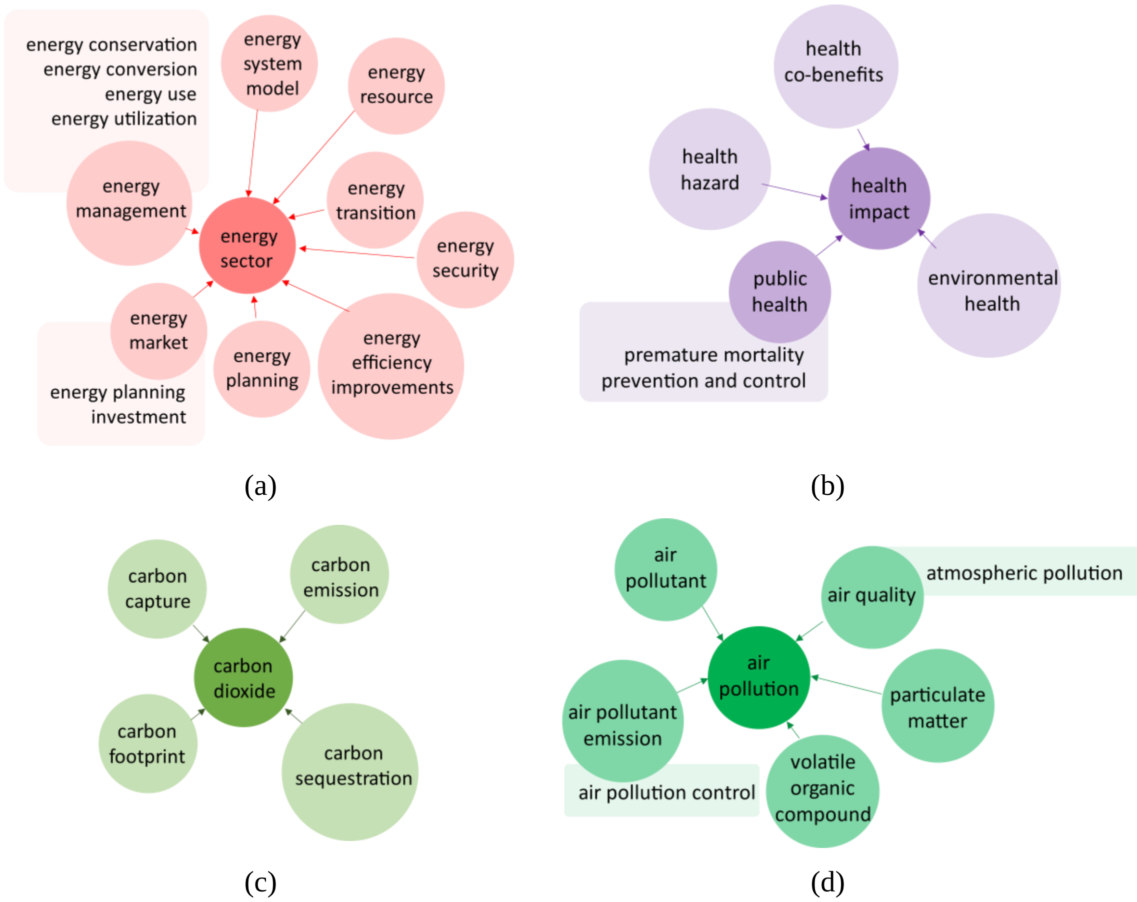
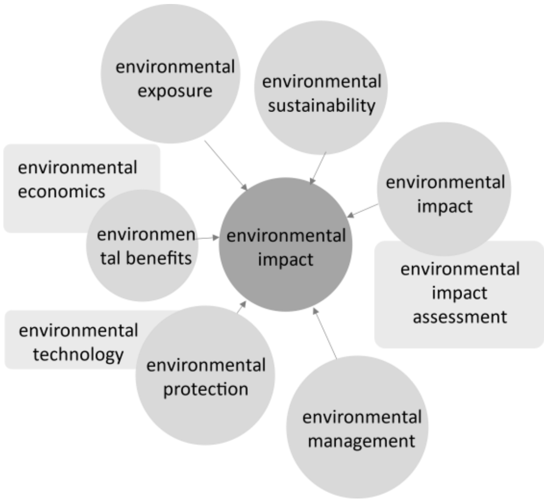


Figure 5. Keywords co-occurrences bibliographic mapping.





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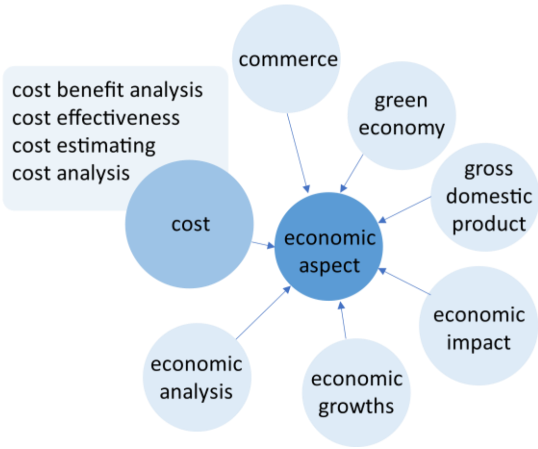

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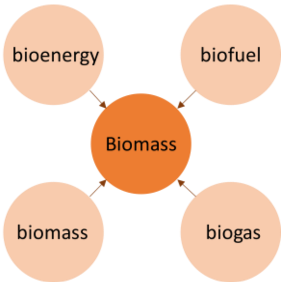

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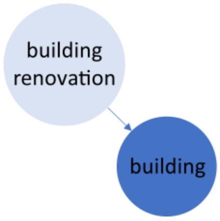
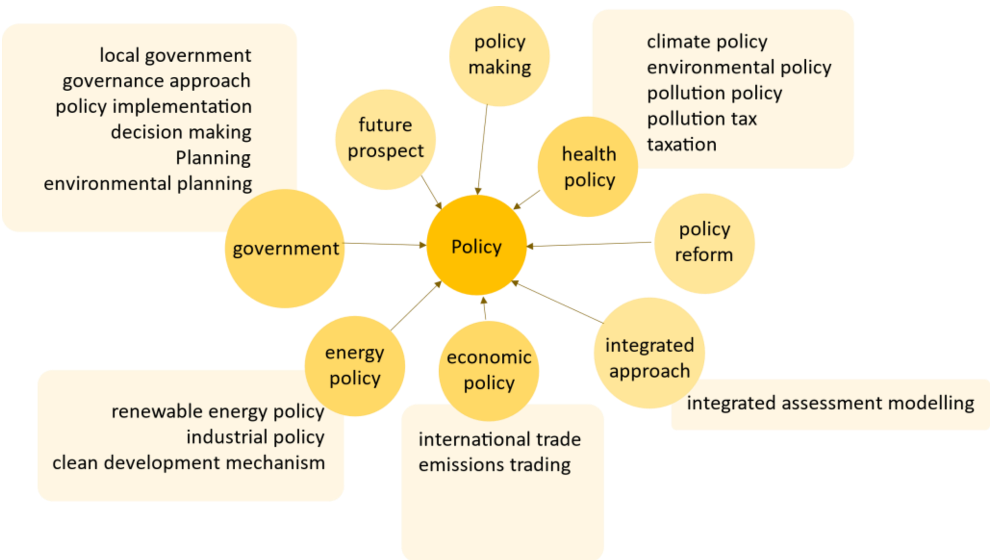


(h)

(i)



(j)

Figure 6. Keywords linked by means of thesaurus, (a) keywords related to the energy sector, (b) keywords related to the health impact, (c) keywords related to carbon dioxide, (d) keywords related to air pollution, (e) keywords related to the environmental impact, (f) keywords related to the economic aspects, (g) keywords related to the biomass, (h) keywords related to the buildings, (i) keywords related to waste management, (j) keywords related to policies.

Figure 7 shows a first cluster in green where carbon dioxide-related keywords are linked to biomass and waste management groups; other keywords also included in this cluster are climate change, landfill, nuclear energy, and electricity. Another cluster in light blue relates those keywords group in air pollution very strongly with those related to *health impact*; other keywords appearing in this cluster are fossil fuels, coal, and *employment*. The third cluster in red relates those keywords included in *policy* with other keywords such as renewable energy, *environmental impact*, *sustainability*, water, biodiversity, and conservation; and more interestingly in social aspects. Other renewable energy keywords (such as solar energy, photovoltaics) are linked in the cluster in purple with keywords co-benefits, *climate change mitigation*, and developing countries. Finally, the cluster in yellow groups keywords such as energy sector and economic aspects with renewable energy sources, *energy efficiency*, *emission reduction*, and building.

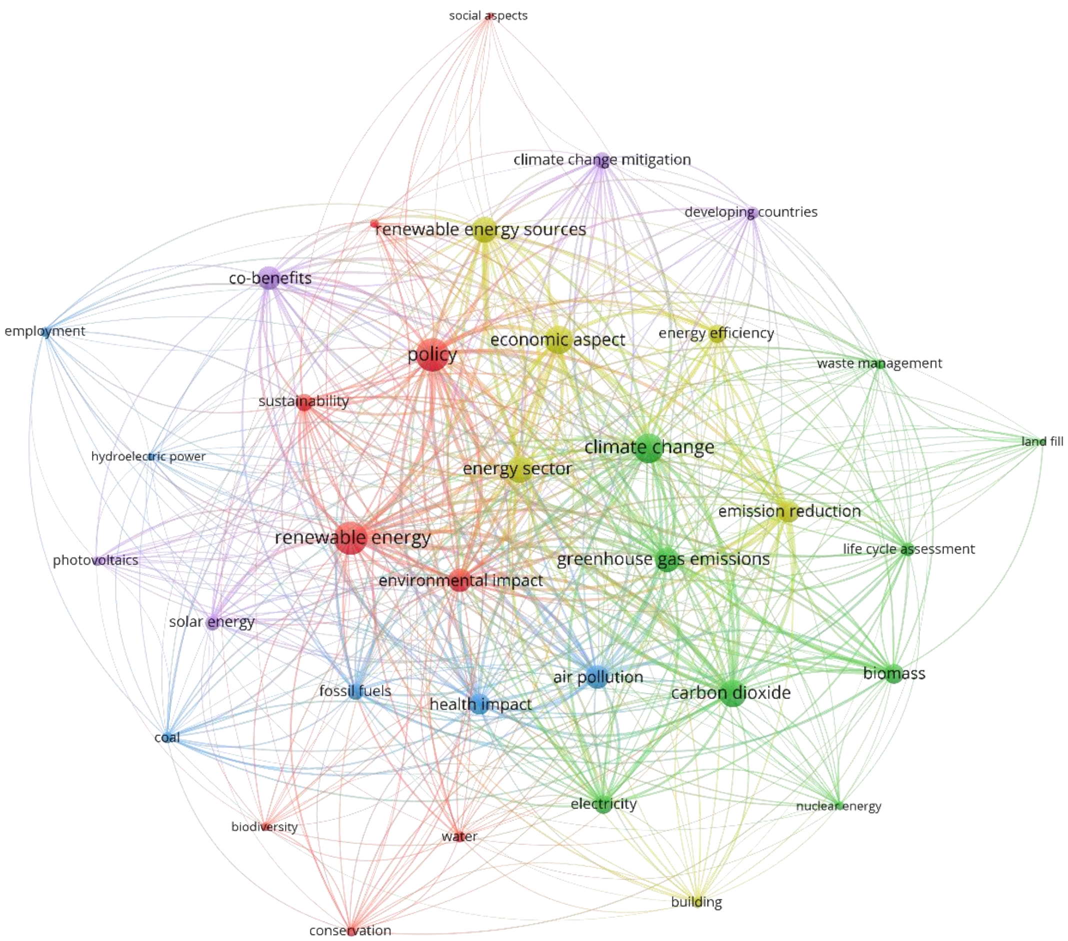


Figure 7. Keywords linked by means of thesaurus grouped by main topic

4. Cross-sectorisation to thermal energy storage

This section presents the cross-sectorisation to thermal energy storage of the renewable energy co-benefits presented in Section 3.

<u>*Environmental co-benefits*</u>

Reduction of indoors and outdoors air pollution is an identified co-benefit of local climate actions in the area of transportation (vehicle efficiency), energy efficiency (green buildings), and the use of renewable energy in cities [20–22]. This co-benefit is also related to TES as shown, for example, by Xie et al. [23] who demonstrated that TES has great potential in improving the energy efficiency of electric vehicles (i.e., cars, buses), specially low- and medium-temperature phase change materials (PCM) technology. On the other hand, electric vehicle efficiency is highly improved with a correct thermal management using TES technologies [24].

If green buildings are understood as a building that includes sustainable and energy efficient concepts and technologies, reduction of indoors and outdoors air pollution are co-benefits of TES systems demonstrated widely in the literature. For example, Palanisamy et al. [25] studied the use of a TES module in an air conditioning system to improve *indoor air quality*. Wang et al. [26] used a TES module in a biomass boiler to reduce the number of boiler cycles and, therefore, reduce indoors air pollution.

The *reduction of air pollution* due to the use of renewable energies in cities is due to the substitution of fossil fuels. The literature shows that adding TES in renewable energy systems increases its *energy efficiency*, therefore contributing again to this co-benefit. Examples of this are the increase of efficiency of photovoltaic panels when adding TES [27], the use of TES in low-temperature thermal solar systems [28], or the hybridization of a solar/geothermal system using TES [29].

Another environmental co-benefit of local climate actions is *biodiversity conservation* (habitat conservation) [20,30]; this co-benefit is classified in the area of land use and carbon offsets. An example where this co-benefit can be transferred to TES is the biodiversity conservation achieved when green roofs and green facades are used as passive TES technology [31].

<u>*Water as co-benefit*</u>

Water use efficiency, *water reduction and recycling*, *watershed health*, and *water savings* are co-benefits of local climate actions [20]. Managing the level of storage in the water damp is a potential source of hydroelectric power [32]. An example of *water management* and *water use* *efficiency* is the technology aquifer TES (ATES), where underground water is used for heating and/or cooling of buildings among other uses [33].

Health co-benefits

Public health is identified as co-benefit of local climate actions in the area of land use [20]. Offshore wind installations also contribute to the health and climate benefits of cities [34]. The 2015 Lancet Commission concluded that “tackling climate change could be the greatest global health opportunity of the 21st century” [35]. Several modelled scenarios suggest that the commitment to reduce 80% of greenhouse gas (GHG) emissions by 2050 compared to 1990 brought *health* as a co-benefit [36–38]. Therefore, transferring health co-benefits from renewable energies to TES are related to the *reduction of* CO_2 and *GHG emissions* [39,40].

Economic co-benefits

Economic growth is a co-benefit of local climate actions in the area of energy efficiency (green buildings) and the use of renewable energy in cities [20]. *New jobs opportunities* and establishment of *new economy sectors* are also co-benefits from investments in renewable energy sector [41]. Similarly and according to IRENA [42], a growing business case lies ahead for TES technologies, projections show that in the next decade investment in the range of US$ 12.8 billion to US$ 27.22 billion is foreseen for power and cooling TES applications.

Policy co-benefits

Energy security is a co-benefit of local climate actions when integrating renewable energy in cities [20]. *Employment* is another co-benefit of renewable energy integration in both the power and buildings sectors [43]. Furthermore, local municipalities besides feeling motivated to collaborate with the energy transition of the country, and the economic advantages it could bring to the municipality, also look at other co-benefits such as *enhancing the image of the town* and *strengthening community life* [10]. Moreover, TES plays a fundamental role in the implementation of renewable energies and is therefore also an important component in energy security [44].

5. Conclusions

The term *co-benefit* related to renewable energy started to be mentioned in research papers only in 2006, with a rising interest literature. The evaluation of the main keywords related to co-benefits of renewable energies assess in this paper, shows that all terms are strongly interrelated. For example, *climate change mitigation* is mostly related to renewable energy sources, economic aspects, but also to developing countries. On the other hand, all keywords related to policies has a strong relation with the energy sector and *environmental impact*. Keywords related to the *health impact* show a strong relation with air pollution. And finally, the keyword carbon dioxide has strong relationship with health impact, renewable energies, and sustainability.

This paper shows that by cross-sectorizing the renewable energy and thermal energy storage (TES) sectors it is possible to identify the co-benefits of thermal energy storage in buildings. When focusing on TES, co-benefits identified in the literature are those related to *environmental* co-benefits, *water* co-benefits, *health related* co-benefits, *economic* and *cost related* co-benefits, and benefits related to *policies.* The co-benefit of TES identified in the literature highlight that TES is a fundamental technology in the *energy transition* not only to increase the efficiency of energy systems and allow a better integration of renewables but also to provide benefits to *health impact*, *economic growth* and *energy security*. Nevertheless, economic investments in the technological development of TES together with targeted energy policy is fundamental to overcome the actual barriers and enhance the integration of this technology in the actual energy system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Highlights

- The use of renewable energy in buildings may also produce positive effects known as co-benefits
- Research on renewable energy co-benefits systems is assessed in a bibliometric analysis
- Cross-sectorizing is used to identify thermal energy storage co-benefits from renewable energy
- The main co-benefits of TES are related to *environmental*, *health*, *economic*, and *policies* aspects

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

sustainability

Article

Experimental Study of a Small-Size Vacuum Insulated Water Tank for Building Applications

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Abstract: Insulation of thermal energy storage tanks is fundamental to reduce heat losses and to achieve high energy storage efficiency. Although water tanks were extensively studied in the literature, the enhancement of the insulation quality is often overlooked. The use of vacuum insulation has the potential to significantly reduce heat losses without affecting the dimension of the storage system. This paper shows for the first time the results of the heat losses tests done for a 0.535 m^3 water tank for residential building applications built with a double wall vacuum insulation. The different tests show that the rate of heat losses strictly depends on the temperature distribution inside the tank at the beginning of the experiment. Compared to a conventional water tank insulated with conventional materials, the U-value of the lateral surface was reduced by almost three times (from 1.05 W/K· m^2 to 0.38 W/K· m^2) using vacuum insulation. However, the bottom part, which is usually used to place the support parts and the piping, is the critical design part of those tanks acting as a thermal bridge with the ambient and enhancing heat losses.

Keywords: thermal energy storage; water tank; thermal insulation; vacuum insulation; heat losses test; building applications

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1. Introduction

The use of renewable energy sources is one of the key actions towards the reduction of gas emissions into the atmosphere. Today, the exploitation of solar energy in building applications represents the most common alternative to the use of fossil fuels to supply thermal energy for space heating or domestic heat water. However, due to the mismatch between solar availability and energy demand, the integration of thermal energy storage (TES) is fundamental to enhance the efficiency of solar heating systems increasing the potential use of renewable energy resources [1,2]. TES applied to solar heating systems allows to store thermal energy when it is highly available and release it when solar radiation is low and energy demand is needed. In solar heat applications with temperatures below 100 °C, water represents the most common storage material due to the high specific heat, low cost, and availability. In this case, TES commonly refers to water tanks. This storage typology was studied in the literature for decades. In order to evaluate the topics that had the highest relevance in the scientific literature, bibliometric analysis is an effective method to evaluate research trends and gaps [3–5]. Figure 1 shows the co-occurrence of the keywords used by the authors on a total number of 2006 studies published in the literature related to water storage tanks. Documents were obtained from the Scopus database on April 2021 using the query "TITLE-ABS-KEY ("water tank" AND "storage") and analysed through the software VOSviewer [6]. The results show that studies on water tanks are mainly related to "stratification". Indeed, the efficiency of water tanks can be enhanced by exploiting the stratification effect that naturally takes place due to the difference in density induced by the water at different temperatures. This allows to extract hot water at the top (that can be used for domestic hot water) and less heated water in the middle (that can be suitable for space heating). In the literature, different studies and techniques were proposed to improve the stratification by enhancing the stratification effect [7–12]. Other studies were related to the integration of phase change materials (PCM) to increase the storing efficiency [13,14] and the use of water tanks with heat pumps using demand-side management techniques [15–17]. Furthermore, the figure shows that most of the studies were conducted through simulations, highlighting a lack of experimental studies.

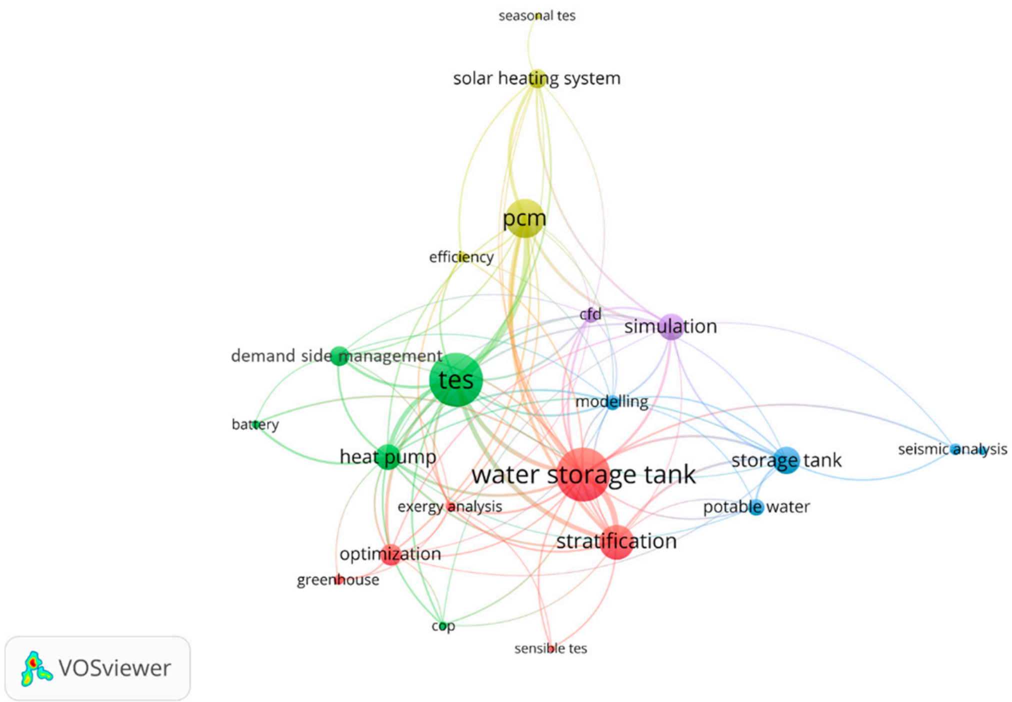

Figure 1. Co-occurrence of the authors keywords in studies related to water tanks.

In the co-occurrence of authors keywords, it is possible to notice that there are no terms related to heat losses and/or insulation. When water storage tanks are integrated into systems where the thermal energy is managed in a short-term period, the weight of heat losses on the global performance is lower compared to the quality of stratification that affects the temperature delivered by the tank.

However, today the attention is moving to thermal energy storage solutions able to manage and store thermal energy for long or seasonal periods, allowing a better use of energy coming from renewable sources. Therefore, the need for storage systems with reduced heat losses is fundamental. To achieve this, many studies in the literature focus on new emerging technologies such as thermochemical TES and only a few are based on the improvement of existing and commercially available technologies. For this reason, thermal insulation represents a significant aspect in the optimisation of commercial TES systems. Furthermore, in water tanks, the reduction of heat losses helps to maintain the stratification, thus increasing the exergy efficiency of the tank [18]. Practically, thermal insulation can be placed either inside or outside the storage system. However, placing the insulation outside is usually the simplest option. At present, most water tank storage systems are insulated using conventional materials such as mineral wool with thermal conductivity in the range of 19 to 46 mW/(m·K) [19]. Therefore, to significantly achieve low heat losses with conventional materials, thicker insulation is required to increase the living space of the storage and, indirectly, the cost.

Using vacuum insulation, the thermal conductivity can be reduced 6 to 10 times compared to conventional materials [20]. Those type of tanks are already used to store cryogenic materials such as liquefied nitrogen, air, or natural gas (LNG) [21,22].

Recently, vacuum insulation is also used in water tanks for solar heating applications to store water below 90 °C. However, only a few studies were published in the literature. The benefit of using a vacuum insulated storage tank in solar systems for a multi-family house located in Estonia was studied by Kadler et al. [23]. The results showed that using a vacuum insulated water tank to store the solar heat on a seasonal basis increases the direct renewable heating by 41%, reaching a system efficiency of 51%. Vacuum insulation can be integrated mainly into a storage tank through the use of vacuum insulation panels (VIPs) or realising a double wall vacuum envelope (done through evacuated powders) [19,24]. The testing of a 100 m^3 water storage tank using VIPs was reported in the literature by Fuchs [25]. The water tank used in [16], which was built in Sengenthal (Germany), consisted of eight precast concrete elements with VIP attached inside the storage. Heat losses tests were performed for 31 days; results gave a U-value of 0.36 $W/(m^2 \cdot K)$. This value corresponds to only 30% of the one estimated from the initial calculations due to thermal bridges and defects on the insulation. Regarding water storage with double wall, a water tank of 16.4 m^3 with a 20-cm-thick insulation of evacuated perlite was built at the Center of Applied Energy Research (ZAE) in Bavaria, Germany. Heat losses test results reported by Beikircher et al. 2014 [26] showed that the tank had a cooling rate of 0.23 K/day. Different materials to be used as vacuum insulation in a double walled water storage tank were investigated by Lang et al. [27]. The study concluded that a mixture of expanded perlite (70%) and fumed silica (30%) had the best results at vacuum pressures between 1 and 10 mbar. The mixture was tested in a real water tank of 12 m^3 built by Sirch Tankbau-Tankservice-Speicherbau GmbH. The experimental test showed an overall temperature drop of around 0.25 K/day. The heat losses were mostly attributed to the thermal bridges at the bottom of the tank due to the TES support. To the best of the authors' knowledge, the experimental studies published so far only show the performance of vacuum water tanks with a useful volume higher than 10 m^3. At present, there are no studies in the literature that report the efficiency of small-size water tanks using vacuum insulation for small building applications such as a single-family house.

To fill this literature gap, this paper shows the heat transfer performance of a water tank of a volume of 0.535 m^3 with a vacuum insulated double wall suitable for space heating (SH) and domestic hot water (DHW) supply for domestic applications. The tank was included and tested in the framework of the EU-funded project SWS-HEATING (GA 764025) to be coupled with a novel seasonal TES based on selective water sorbent materials to maximise the solar fraction. The study shows the experimental results of heat loss tests to evaluate the behaviour of the vacuum water tank, considering also the effect of stratification on the heat losses. In the literature, different methods were employed to evaluate the heat losses of solar water tanks. Cruickshank et al. [28] evaluated the heat loss coefficient through a "cool-down test". The tests were conducted in a 0.270 m^3 electric water-storage tank with fibre-glass insulation. During such experiments, the water tank was preheated to 54 °C and the temperature was recorded over a period of 48 h. Another way to estimate the heat losses in a water tank is to charge the tank over a long period with a gradual temperature increase, reaching a steady state value of heat losses, which are then evaluated from the heating power supplied to the tank and the ambient temperature, as reported by Deng et al. [29].

2. Materials and Methods

2.1. Experimental Methodology

2.1.1. Experimental Set-Up

The tests were carried out using a specific test rig built in the GREiA research group of the University of Lleida (Figure 2). The test rig consists of a 200 litres commercial buffer tank with a built-in 9 kW electric heater and a monoblock pump (model OE-IP22-

12037) controlled by an Invertek optidrive E3 IP20 variable speed drive. To measure the ambient temperature and the external surface temperature of the tank, 3 Pt-100 class A IEC 60751 standard type temperature sensors (accuracy 0.15 ± 0.002 * t) were implemented. All monitoring variables were recorded through a data acquisition system (STEP DL-01 data logger) connected to a computer equipped with Indusoft SCADA software. The measurement interval was 1 s and the recording interval (time step) was set at 10 s.

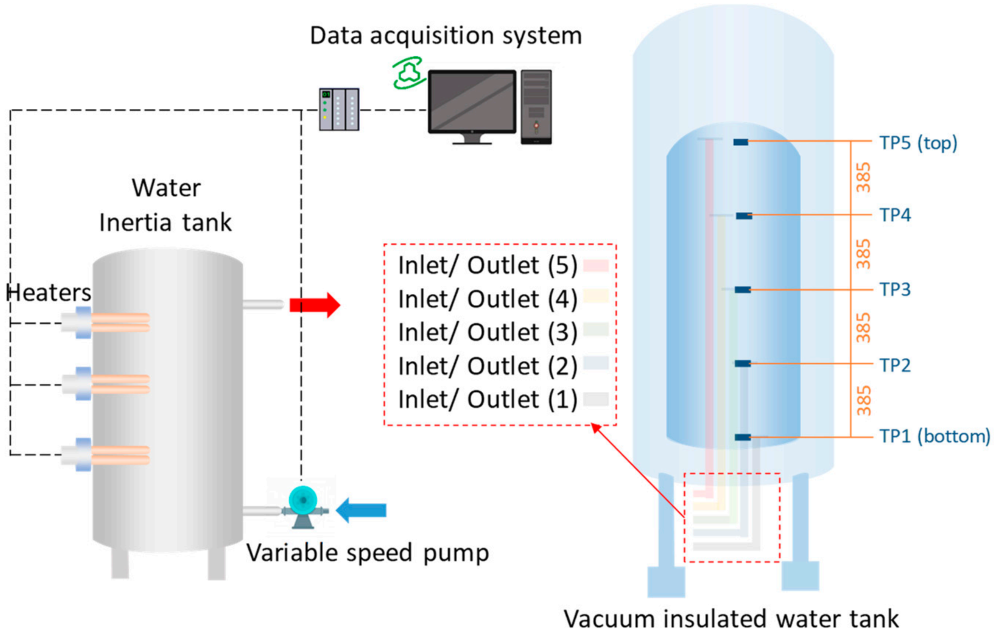

Figure 2. Schematic view of the experimental set-up used to perform the experimentation.

2.1.2. Characteristics of the Water Tank

The storage tank tested in this study is a vacuum insulated water tank built by Sirch Tankbau-Tankservice-Speicherbau GmbH [30]. A general schematic of the tank is shown in Figure 3. The tank contains 5 ports evenly distributed over the height of the tank. It is made of steel S235JRG2, has a total height of 2.5 m and an external diameter of 1 m, with a total capacity of 0.535 m^3. The water tank was built with a vacuum insulated double wall evacuated and filled with thermal radiation absorber. The vacuum insulation with a thickness of 0.17 m is not removable and, according to the manufacturer, it is characterised by an absolute pressure below 10 mbar and thermal conductivity of 0.008 W/m·K. In order to analyse the stratification and heat losses inside the tank, the manufacturer was asked to place 5 Pt-100 class A IEC 60751 standard type (accuracy 0.15 ± 0.002 * t) temperature sensors inside the tank. The sensors were placed at the central axis of the tank vertically distributed with similar spacing between them and at the same height of each tank port, as shown in Figure 4. At least three repetitions of each test were performed to ensure repeatability.

2.1.3. Heat Losses Test

In this study, heat losses were evaluated through a "cool-down test", preheating the tank at different temperature levels and recording the temperature inside the tank, in the external surface of the tank, and the ambient temperature for 48 h. Mainly, two different heat losses tests were performed with two different boundary conditions:

- Test A: water tank is preheated at a uniform temperature of 65 °C;
- Test B: water tank is preheated at 45 °C at the bottom and middle layers, and at 65 °C at the top.

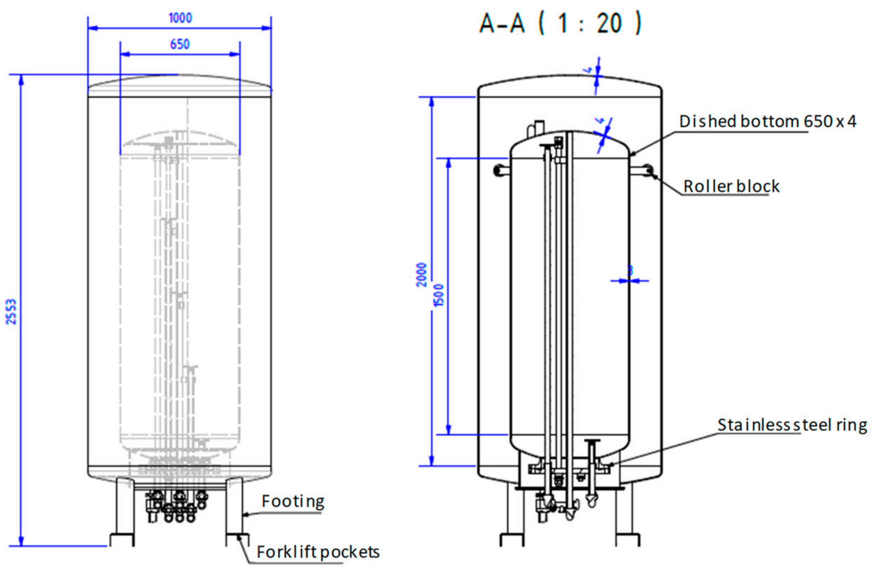

Figure 3. Schematic of the 0.535 m^3 water tank built by Sirch Tankbau-Tankservice Speicherbau GmbH [30]. All measurements are presented in millimeters.

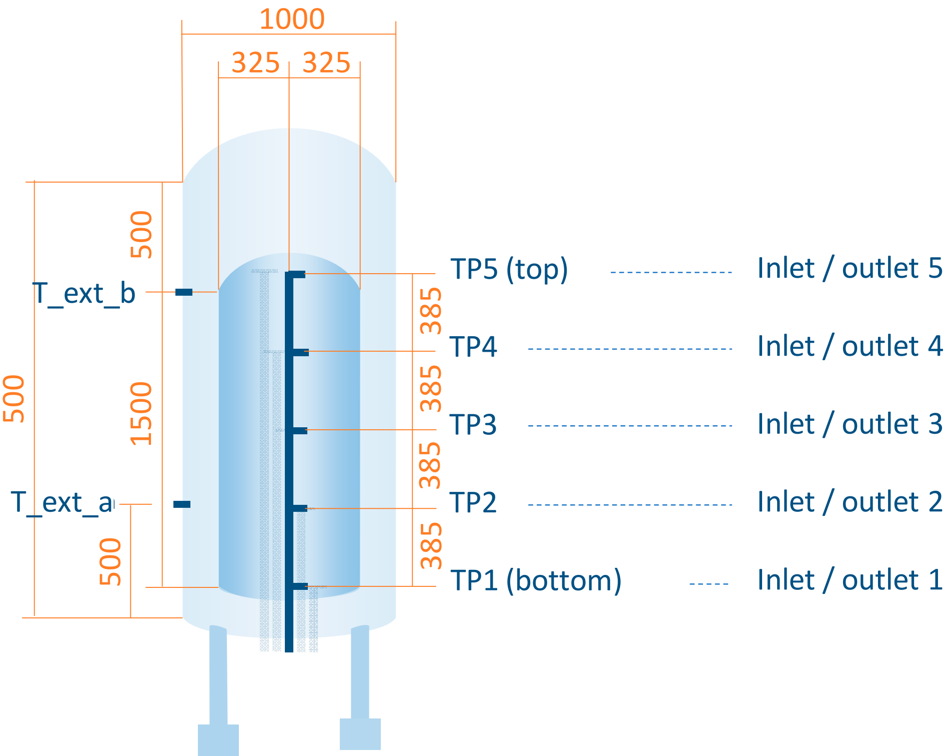

Figure 4. Schematic of the connections and sensors inserted inside the water tank (TP1, TP2, TP3, TP4, TP5), and on the outer surface (T_ext_a, and T_ext_b). All measurements are presented in millimetres.

To perform test A, water at 65 °C was circulated between the buffer tank and connections 1 and 5 of the vacuum water tank (Figure 2) until all sensors inside the tank (TP1 to TP5) were at (65 ± 2) °C. Then all connections to the vacuum water tank were closed, and temperatures inside the tank were recorded for 48 h.

To perform test B, water at 45 °C was circulated between the buffer tank and connections 1 and 5 of the vacuum water tank (Figure 2) until all sensors inside the tank (TP1 to TP5) were at (45 ± 2) °C. Next, water at 65 °C was circulated between the buffer tank and connections 4 and 5 of the vacuum water tank until the sensors TP4 and TP5 inside the tank were at (65 ± 2) °C. Then all connections to the vacuum water tank were closed, and temperatures inside the tank were recorded for 48 h.

2.1.4. Repeatability of Results

Each test was repeated three times to demonstrate the repeatability of the methodology and the experimental results. Figure 5 presents the water temperature profiles of test A at the five temperature levels presented also in Figure 5. Results from the repeatability tests show that the methodology adopted for the present experimentation produced repeatable values with a maximum standard deviation of 0.189 °C in the sensor TP1 over the first 5 min of experiments, and a mean standard deviation of 0.036 °C between all sensors throughout the experiment. Results for test B showed similar differences and are therefore not presented.

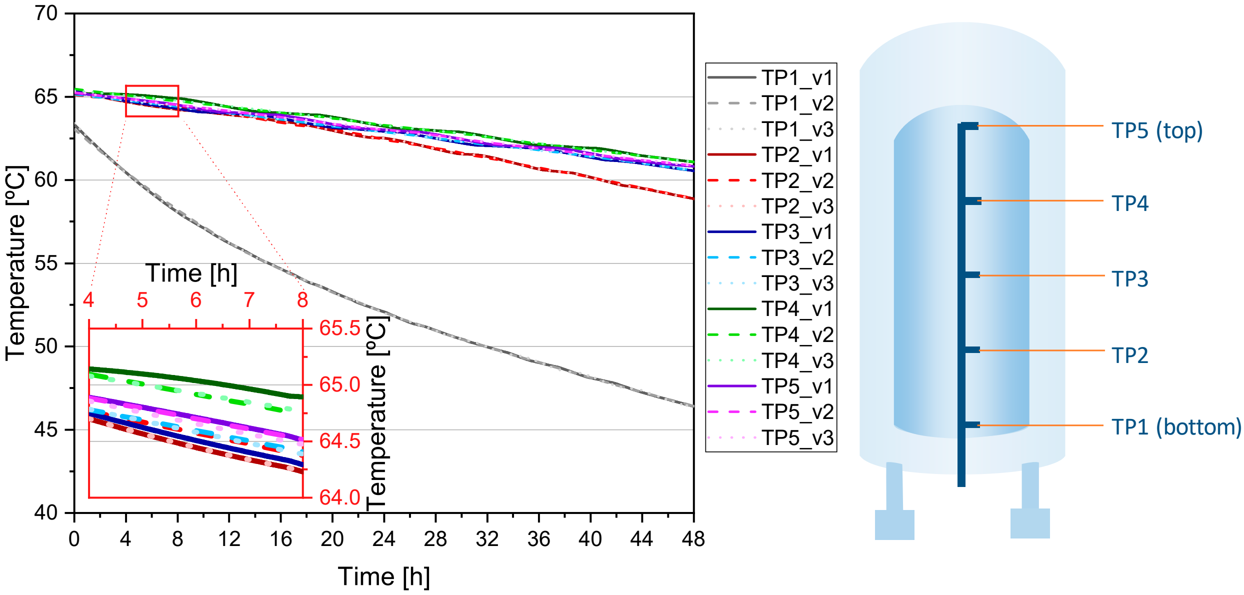

Figure 5. Repeatability tests for the case study A.

2.2. *Theoretical Methodology*

The heat losses (kWh) were calculated from the experimental data considering the variation of the temperature inside the tank at different heights. To calculate total losses, the tank was divided into five different water volumes corresponding to the position of the sensors, as shown in Figure 6. Therefore, the total heat losses were calculated as the sum of the heat loss by each element i with mass of water m_i, as shown in Equation (1):

$$Q_{loss} = \sum_{i=1}^{n} m_i \times c_p \times \Delta T \quad (1)$$

where ΔT is the temperature variation of each layer during the heat losses test.

Then, the data obtained from the heat losses test can be used to estimate the U-value and the UA-value of the vacuum water tank.

In this case, for the calculation of the U-value, heat conduction between the adjacent nodes is assumed negligible. For each volume "i", the UA-value can be calculated from the heat losses as shown in Equation (2):

$$UA_i = \frac{Q_{loss,i}}{T_{ave,i} - T_{ave,amb}} \quad (2)$$

where $Q_{loss,i}$ is the heat loss (kW) calculated from the experimental data of the volume i characterised by the average temperature value ($T_{ave,i}$), and the ambient temperature measured from the test ($T_{ave,amb}$),

The U-value can be derived from the UA-value as:

$$U = \frac{UA_i}{A_i} \quad (3)$$

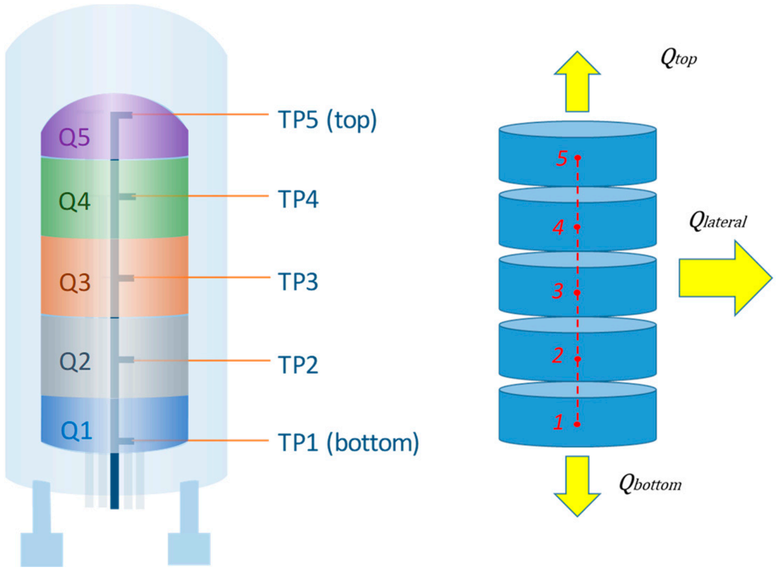

Figure 6. Volume discretisation of the tank for the U-value calculation.

According to the design of the tank, three different U-values can be calculated for three different surfaces: bottom base, lateral (side) surface, and top base.

The U-value for the lateral surface can be obtained from any of the middle layers (T2, T3, and T4) using Equation (4):

$$U_{lateral} = \frac{UA_{i,lateral}}{A_{i,lateral}} \quad (4)$$

where $UA_{i,lateral}$ is derived from Equation (3) because, for a middle layer, heat transfer only takes place through the lateral surface, and $A_{i,lateral}$ is the lateral surface area of the middle layer "i".

For the bottom layer, the total UA-value is the sum of the UA-value of the bottom base surface and the UA-value of the lateral surface, as shown in Equation (5):

$$UA_{bottom,tot} = UA_{bottom,base} + UA_{bottom,lateral} \quad (5)$$

where $UA_{bottom,tot}$ is derived from Equation (3) and $UA_{bottom,lateral}$ is obtained by multiplying the value of $U_{lateral}$ calculated in Equation (4) by the lateral surface area of the bottom layer ($A_{bottom,lateral}$).

Therefore, the U-value of the bottom base surface can be calculated as shown in Equation (6):

$$U_{bottom,base} = \frac{UA_{bottom,base}}{A_{bottom,base}} = \frac{UA_{bottom,tot} - UA_{bottom,lateral}}{A_{bottom,base}} \quad (6)$$

Equations similar to (5) and (6) can be applied to calculate the UA-value of the top base surface of the tank and derive the U-value of the top base surface, $U_{top,base}$.

3. Results

3.1. Heat Losses Test Results

3.1.1. Test A

Figure 7 shows the variation of the temperature inside the tank previously charged uniformly at 65 °C and left at ambient temperature for 48 h. The figure also reports the variation of the ambient temperature (T_{amb}) and the external temperature of the tank measured by means of two sensors placed on the surface ($T_{\_ext\_a}$, $T_{\_ext\_b}$). During the test, the ambient temperature and the external surface temperature of the tank were almost constant. From Figure 7, one can see that the temperature variation at the bottom of the tank (TP1) had the highest cooling rate, decreasing to 46 °C after 48 h. On the other hand, the temperature of the top and middle layers (TP2, TP3, TP4, TP5) experienced a small variation during the test, decreasing to 60 °C after 48 h.

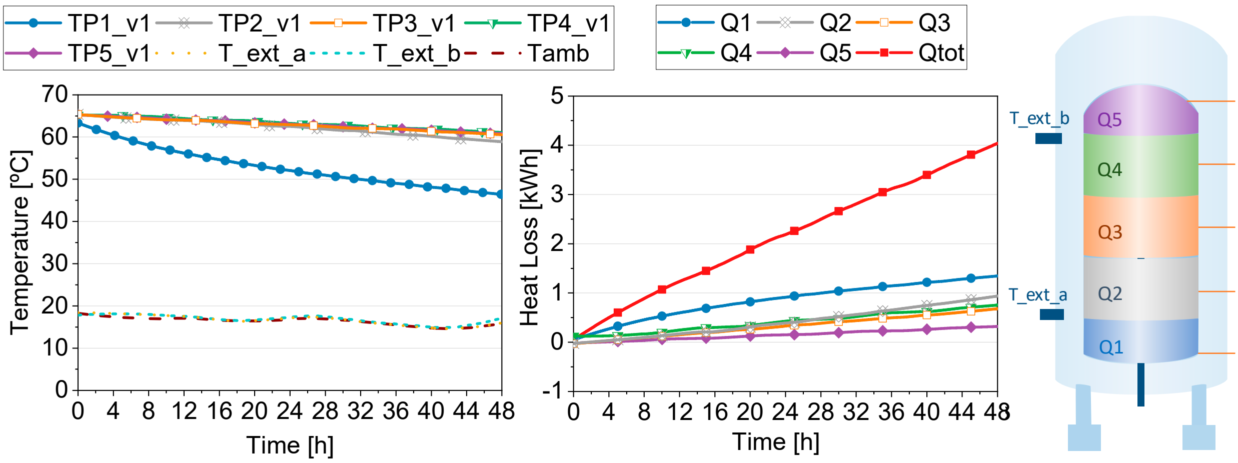

Figure 7. Temperature profiles (**left**) and calculated heat losses (**right**) for test A. Tamb represents the ambient temperature and Qtot is the sum of heat losses from Q1 to Q5.

The calculated energy losses are shown in Figure 7 right. The results show that a total energy amount of 4 kWh was lost during the test, mostly affected by the heat losses at the bottom layer of the tank (Q1).

3.1.2. Test B

The temperature profiles measured during the heat losses test of the water tank charged with a stratified profile (45 °C at the bottom and middle layers 2 and 3, and 65 °C at the top layers 4 and 5) are shown in Figure 8 left. From the results, it is possible to notice that in the middle of the tank (TP3) the temperature increases over time due to the conduction between the water volumes at different temperatures. In this case, the temperature of the top layers (TP4 and TP5) drops faster than the bottom of the tank. Indeed, due to heat transfer between layers, the temperature of the top levels drops below 60 °C after 48 h, resulting in higher energy losses compared to the previous case shown in Figure 8. The energy losses evaluated from the test are shown in Figure 8 right.

In this case, the total energy loss is almost half compared to the previous case (Test A) with the initial tank uniformly charged at 65 °C (2.1 kWh compared to 4 kWh). Furthermore, Figure 8 right shows that the part of the tank with the highest temperature drop are the top layers of the tank (TP4, TP5) and the bottom layer (TP1). The temperature drop at the top part are probably mostly due to heat transfer towards the middle part of the tank, while the temperature drop at the bottom is mainly due to heat losses to the ambient.

However, compared to the previous case with the water tank fully charged at 65 °C, the final value of heat losses at the bottom layer is lower (0.7 kWh) due to the lower temperature difference between the water inside the tank and the ambient that results in a lower heat transfer rate, thus reducing the heat losses. On the other hand, Figure 8 right shows that in the middle layer (Q3) the heat losses has a negative value (that in this case is a heat gain) due to the increase in temperature (TP3) shown in Figure 8 left.

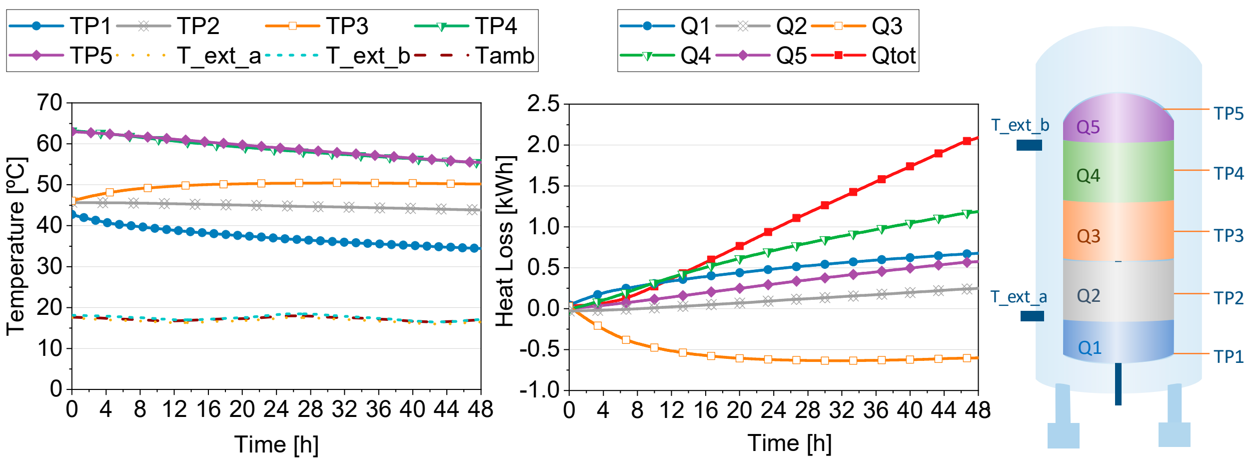

Figure 8. Temperature profiles (**left**) and calculated heat losses (**right**) for test B. Tamb represents the ambient temperature and Qtot is the sum of heat losses from Q1 to Q5.

3.2. *U-Value Calculation*

The results of the heat loss tests were used to obtain a first estimation of the U-value of the water tank tested in this study. To reduce the effect of the conduction between the layers inside the tank, the results of Test A (preheating at a uniform temperature of 65 °C) were used. The U-values calculated for the different sections of the tank are presented in Table 1. To quantitatively evaluate the values obtained from the calculation, the U-values were compared with the one obtained from the literature. In particular, Table 1 shows the comparison of the U-value with the one obtained from Cruickshank et al. [28] calculated for a commercial 0.270 m^3 standard water storage tank insulated with 0.047 m of fibre-glass (k = 0.036 W/(m·K)).

Table 1. U-values calculated for this study and comparison with the literature.

	Tank Volume (m^3)	Insulation Type	U-Value (W/(m^2·K))		
			Top	Lateral	Bottom
This study	0.535	Double wall with vacuum	0.32	0.38	2.00
Cruickshank et al. [28]	0.270	Fibre-glass	0.66	1.05	2.54

Table 1 shows that the U-value of the bottom surface of the vacuum tank is the highest compared to the one estimated for the lateral surface due to the high energy loss observed at the bottom of the tank (Figure 6). This value is similar to the one of a standard electric water tank due to the absence of vacuum insulation in the bottom part of the tank. However, the U-value of the lateral and the top surface, calculated for the vacuum water tank tested in this study, are significantly reduced compared to conventional insulation due to the minor energy losses at the top and middle layers of the tank.

4. Discussion and Conclusions

The reduction of heat losses of thermal energy storage is important to maintain high efficiency and to increase the solar fraction of solar heating systems. However, the enhancement of insulation quality is often overlooked, still representing a research gap in the literature. Reducing the heat losses using conventional materials with high thermal conductivity could lead to an increase of the dimension of the storage systems indirectly affecting the cost of the storage itself. Vacuum insulation is one technique proposed to effectively reduce heat losses in large-size water tanks. In this study, heat loss tests were carried out to evaluate the performance of a 0.535 m^3 water tank built with a vacuum insulated double wall for residential building applications. In particular, two different tests were carried out, preheating the tank at different temperature levels and recording the temperature without supplying heat to the tank for 48 h.

The results showed that the technique of vacuum insulation can effectively reduce the heat losses in small-size water tanks for domestic applications. Indeed, compared to a standard water tank, the U-value can be significantly lower, allowing to maintain the water at high temperature inside the tank. However, the critical part of the design of those tanks is the bottom side that is usually used to place the support parts and the piping of the tank, which act as thermal bridges to the ambient. Furthermore, due to the lack of insulation, the bottom surface is the most exposed to the outside temperature thus reducing the effectiveness of the insulation and enabling significant heat losses.

The two different tests carried out in this study showed that the heat loss rates depends on the average water temperature inside the tank. Indeed, a tank filled with water at lower temperature due to stratification has a considerably lower heat losses rate due to the smaller temperature difference with the ambient, which is especially significant at the bottom surface where most of heat losses occur.

Although vacuum insulation was proven to have benefits in reducing heat losses, it has to be considered that a water tank with this type of insulation has a much higher cost compared to a standard water tank. Therefore, in order to prove the real benefit of using vacuum insulation in solar heating systems, further research needs to be done in future studies, including detailed cost-benefit analysis related to the efficiency improvement in a generic heating system.

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Experimental Study on Two PCM Macro-Encapsulation Designs in a Thermal Energy Storage Tank

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Abstract: The use of latent heat thermal energy storage is an effective way to increase the efficiency of energy systems due to its high energy density compared with sensible heat storage systems. The design of the storage material encapsulation is one of the key parameters that critically affect the heat transfer in charging/discharging of the storage system. To fill the gap found in the literature, this paper experimentally investigates the effect of the macro-encapsulation design on the performance of a lab-scale thermal energy storage tank. Two rectangular slabs with the same length and width but different thickness (35 mm and 17 mm) filled with commercial phase change material were used. The results show that using thinner slabs achieved a higher power, leading to a reduction in the charging and discharging time of 14% and 30%, respectively, compared with the thicker slabs. Moreover, the variation of the heat transfer fluid flow rate has a deeper impact on the temperature distribution and the energy charged/released when thicker slabs were used. The macro-encapsulation design did not have a significant impact on the discharging efficiency of the tank, which was around 85% for the operating thresholds considered in this study.

Keywords: thermal energy storage; latent heat thermal energy storage; phase change materials (PCM); macro-encapsulation; rectangular slab; experimental study

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1. Introduction

The use of thermal energy storage (TES) has been proved as an effective way to enhance the penetration of renewable energy into energy systems. Amongst all thermal storage technologies, latent heat thermal energy storage (LHTES) received the attention of several researchers over the last decade due to its high energy density and the wide range of applications [1]. Buildings, for example, represent one of the most common applications of the integration of LTHES as an active or passive system [2–4]. For the active systems, TES can be used in HVAC components or systems to balance the supply of domestic hot water and heating/cooling demand when renewables are used [5,6], or to reduce the energy consumption through peak load shifting [7], or free cooling techniques [8]. On the other hand, passive systems are directly integrated into the building envelope to reduce the energy demand [9,10]. Other common applications where LTHES can be integrated include solar thermal power plants, such as concentrated solar power (CSP) [11], solar cooling applications [12], district heating or cooling [13], waste heat recovery [14], solar process heat [15], or cryogenic applications [16].

The principle behind LHTES is the use of phase change materials (PCM) as the storage medium, allowing to store thermal energy at a nearly constant temperature exploiting the latent heat during the phase transition, for which the most common one is from solid to liquid to minimize the impact of volume expansions [17]. One of the weaknesses of PCM is its low thermal conductivity that negatively affects the thermal power involved in the charging and discharging processes of the energy storage system. Indeed, this represents one of the main challenges facing the implementation of PCM in various applications. However, different strategies and techniques that can be used to improve thermal conductivity were investigated in the literature. The main solutions that were extensively studied are the increase in the convection coefficient of heat transfer by means of dynamic systems, the addition of particles (such as carbon elements, metallic particles, and nanoparticles), the inclusion of PCM in a metallic matrix, and the increase in the heat transfer area by using fins, and micro and macro-encapsulation [18–20].

On one hand, PCM micro-encapsulation allows increasing heat transfer surface between the PCM and the heat transfer fluid. However, for PCM microencapsulation, complex and expensive processes are needed, such as spray drying (physical method) or interfacial polymerization (chemical methods) [21]. On the other hand, macro-encapsulation requires a simpler making process resulting in a lower cost [22]. Furthermore, larger sizes of the container also allow an increase in the mechanical stability of systems [23]. Macro-encapsulated PCM can be designed with different geometries mainly based on rectangular [24], cylindrical [25,26], and spherical shapes [27] that can be adapted to different applications. The effect of the design of macro-encapsulation on the heat transfer performance is mostly analyzed by numerical analysis with only a few experimental studies available in the literature, highlighting a research gap. Amongst the experimental studies available, Erlbeck et al. [28] and Al-Yasiri and Szabó [29] experimentally investigated the thermal behavior of concrete blocks with different shapes of microencapsulated PCM. Ismair and Moraes [30] numerically and experimentally evaluated spherical containers made with different geometries and materials and filled with PCM for cold storage domestic applications. This paper experimentally analyzes the effect of two different geometries of macro-encapsulated PCM in rectangular slabs on the performance of an energy storage tank. The analyzed TES tank is part of the generic heating system designed for the EU funded project SWS-HEATING (GA 764025). In particular, the PCM tank is used in the system as a thermal buffer to store the solar energy at low-grade temperature (15 ± 5 °C) to be supplied to a novel seasonal TES based on selective water sorbent materials. To the best of the authors knowledge, very few experimental studies on PCM tanks with rectangular slabs were published in the literature. One of the first papers was published by Moreno et al. [31] in which the performance of a TES tank filled with commercial PCM encapsulated in rectangular slabs was compared with the same tank filled with water. The results showed that the energy storage capacity of the tank filled with PCM was increased by 35.5% compared with the same tank filled with water. Another study published by D'Avignon and Kummert [32] reported the results of experimental tests performed to study the behavior of a real-scale PCM storage at different operating conditions. One of the main conclusions from the study was that the PCM hysteresis and sub-cooling effects deviate the expected behavior from the experimental results. Liu et al. [33] used the experimental results obtained from the testing of a PCM tank filled with rectangular slabs containing a PCM with a sub-zero melting temperature (−26.7 °C) suitable for refrigerated transport, and glycol as heat transfer fluid. The developed model was based on a one-dimensional approach considering the temperature variations along direction of the heat transfer fluid showing a good agreement with the test. All experimental studies mentioned were carried out using a fixed design of the PCM tank without changing any boundaries related to the geometry or the configuration of the storage tank.

However, the geometrical design of the PCM encapsulation has a large influence on the thermal behavior of the PCM affecting the melting and the solidification process, and consequently the heat transfer [34]. In the case of rectangular shapes, the aspect ratio (height to width ratio) is a parameter that has to be taken into account in the design of TES tanks [21]. This paper shows for the first time a comparison based on experimental results of the thermal behavior of two different designs of macro-encapsulation of rectangular PCM slabs. The behavior of a thermal energy storage tank was analyzed using commercial PCM slabs with different thicknesses. The comparison of the two designs was done in terms of temperature profile, heat transfer rate, and energy obtained during the discharging process.

The main results obtained from the experimental tests reported in this paper can be used as a reference for institutions and manufacturers to optimize future designs of PCM tanks.

2. Materials and Methods

2.1. Materials

The PCM selected in this experimentation was PlusICE S15 (hydrated salt), supplied by PCM products, United Kingdom [35]. The main thermophysical properties of this material are shown in Table 1. Moreover, water was used as the heat transfer fluid (HTF).

Table 1. Thermophysical properties of PlusICE S15 [35].

Properties	Value
Melting temperature [°C]	15
Latent heat [J/g]	180
Specific heat capacity [kJ/kg·K]	1.90
Density [kg/m^3]	1700–1800
Thermal conductivity [W/(m·K)]	0.43
Maximum operation temperature [°C]	60

2.2. Experimental Set-Up

The experiments presented in this paper were carried out at the laboratory of the GREiA research group at the University of Lleida in Spain, in a set-up designed to test and characterize latent heat TES systems for mid-low temperature applications (−20 °C < T < 100 °C). Figure 1 shows a detailed schematic diagram of the experimental set-up composed by a 25 L inertia water tank, whose temperature is controlled by a vapor compression cooling unit (Zanotti model GCU2030ED01B [36]) of 5 kW cooling power, two immersion thermostats (OVAN TH100E-2kW [37], and JP SELECTA-1kW [38]). The set-up also integrates: two variable speed pumps, used to control the flow and inlet temperature at the TES system; and a flow meter Badger meter type ModMAG M1000 [39] with an accuracy of ±0.25 % of the actual value, and the latent heat TES storage. The connections between components were joined using 0.5″ diameter copper pipes insulated with 18 × 0.9 mm polyurethane tubes. The data acquisition system used consisted of 3 STEP DL-01 data logger [40] connected to a computer that integrates a system control and data acquisition software (SCADA) developed in InduSoft Web Studio [41]. The data recording interval was set to 10 s.

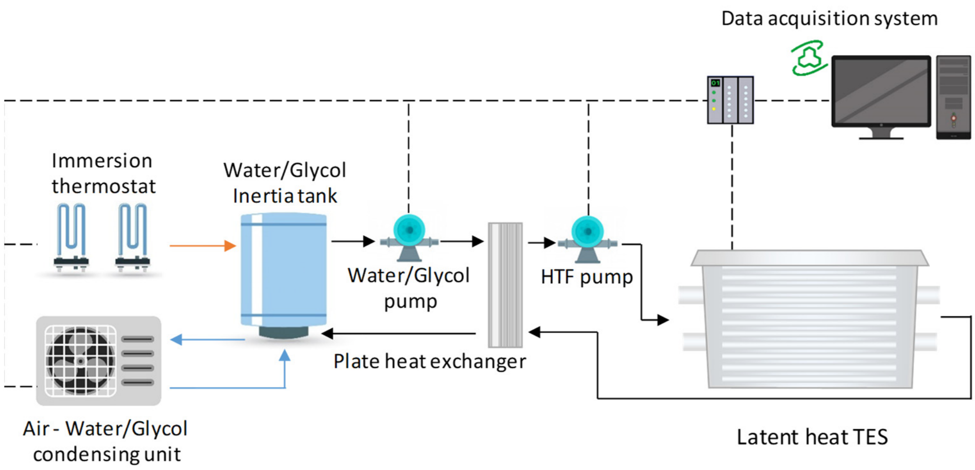

Figure 1. Schematic view of the experimental set-up used to perform the experimentation.

Figure 2 shows the PCM storage tank connected to the experimental set-up. The tests were carried out with two different PCM macro-encapsulation designs, namely, ThinICE and FlatICE (Figure 3). The containers were made in HDPE. The external dimensions of each design are reported in Figure 3, characterized by presenting similar length and width (A and B), but different thickness, with FlatICE dimensions being double that of ThinICE (C). Furthermore, the (D) dimension reveals that the use of thin macro-encapsulation enabled a larger distance between the slabs, increasing the space that allows circulating the HTF through the TES tank. Considering the aforementioned dimensions shown in Figure 3, the use of ThinICE encapsulation allowed fitting a larger number of slabs inside the tank, but less amount of latent storage material compared with the FlatICE, as shown in Table 2.

Figure 2. Latent heat TES.

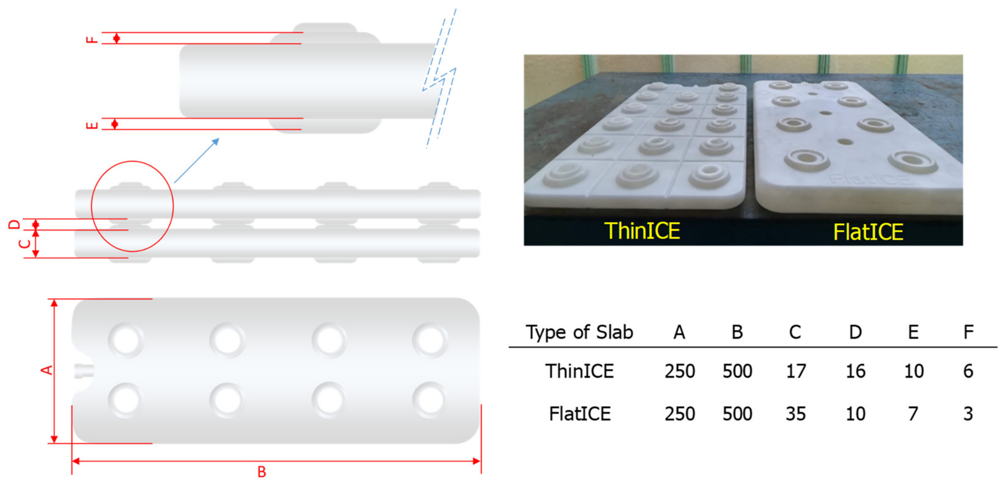

Figure 3. ThinICE and FlatICE slabs encapsulation. Dimensions in millimeters.

Table 2. Total weight of PCM inside the tank.

Properties	FlatICE	ThinICE
Capacity of the slab [liters]	3.2	1.7
Weight of the container [kg]	0.55	0.5
Total weight of a single slab [kg]	6.7	3.8
Number of slabs inside the PCM tank	10	13
Total amount of PCM inside the tank [kg]	61.5	41.9
Total weight of the slabs inside the tank [kg]	67	49.4

The temperature inside the PCM storage was measured using nine Pt-100 class B, IEC 60751 standard type, with an accuracy of (0.3 + 0.005 · T). The sensors were fixed as shown in Figure 4 to the external surface of three different PCM slabs placed at the bottom, middle, and top of the tank, respectively. Moreover, two additional Pt-100 class A IEC 60751 standard type with an accuracy of (0.15 + 0.002 · T) sensors were placed at the inlets and outlets of the storage tank.

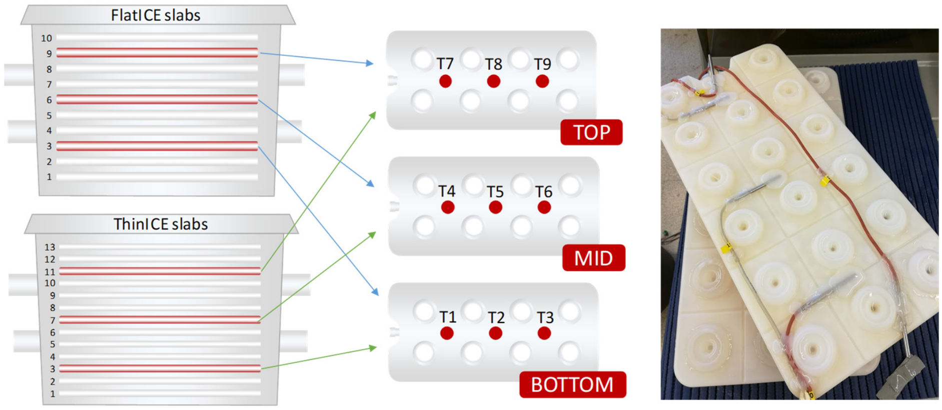

Figure 4. Temperature sensors location inside the storage tank.

2.3. Methodology

The experimental tests consisted of performing four different charging and discharging processes to evaluate the effect of the PCM macro-encapsulation design and the flow rate on the temperature distribution, heat transfer rate, and energy stored/released. At least three repetitions of each process were performed to ensure repeatability. A summary of the flow rates and temperatures used in the experimentation is shown in Table 3. Furthermore, the heat losses in the worst-case scenario analyzed represent 4% of the charging/discharging energy, therefore the analysis of heat losses was not included in the paper.

Table 3. Summary of the main parameters of the processes.

Process	Slab Type	Flow Rate [L/min]	HTF Inlet Temperature [°C]	PCM Tank Average Initial Temperature [°C]	Code
Charge	ThinICE	2	25	5 ± 1	C_ThinICE_2L
Charge	ThinICE	4	25	5 ± 1	C_ThinICE_4L
Charge	FlatICE	2	25	5 ± 1	C_FlatICE_2L
Charge	FlatICE	4	25	5 ± 1	C_FlatICE_4L
Discharge	ThinICE	2	5	25 ± 1	D_ThinICE_2L
Discharge	ThinICE	4	5	25 ± 1	D_ThinICE_4L
Discharge	FlatICE	2	5	25 ± 1	D_FlatICE_2L
Discharge	FlatICE	4	5	25 ± 1	D_FlatICE_4L

To perform a charging process, HTF was first circulated through the PCM tank until all sensors inside the tank reached a temperature of 5 ± 1 °C. Then, the HTF inlet temperature was set at 25 ± 1 °C and the flow rate was set to the corresponding value of the experiment shown in Table 3. The charging process was considered complete when the HTF temperature at the outlet of the tank reached 25 °C. To perform a discharging process, HTF was first circulated through the PCM tank until all sensors inside the tank reached a temperature of 25 ± 1 °C. Then, the HTF inlet temperature was set at 5 ± 1 °C and the flow rate was set to the corresponding value of the experiment in Table 3. The discharging process was considered complete when the HTF at the outlet of the tank reached 7 °C. This value was used instead of 5 °C because a minimum temperature difference of 2 °C was assumed between inlet and outlet of the storage tank as a constraint from the demand side.

2.4. Uncertainties Analysis

The impact of the uncertainties in the calculated parameters from the different measurements was evaluated by performing an uncertainty analysis using the Kline McClintock method. The uncertainties of the different monitored parameters are shown in Table 4. HTF specific heat capacity and density were calculated following the correlations presented in Equations (1) and (2) [42]:

$$\rho_{HTF} = 1.38{\cdot}10^{-5} \cdot T_{HTF}^3 - 5.63{\cdot}10^{-3} \cdot T_{HTF}^2 + 3.6{\cdot}10^{-3} \cdot T_{HTF}^1 + 1000 \tag{1}$$

$$Cp_{HTF} = 2.69{\cdot}10^{-9} \cdot T_{HTF}^4 - 6.63{\cdot}10^{-7} \cdot T_{HTF}^3 + 6.67{\cdot}10^{-5} \cdot T_{HTF}^2 - 2.67{\cdot}10^{-3} \cdot T_{HTF}^1 + 4.21 \tag{2}$$

Table 4. Uncertainties of the different parameters involved in the analyses of the present study.

Parameter	Units	Sensor	Accuracy
Temperature	°C	Pt-100 1/5 DIN class B IEC 60751	$\pm 0.3 + 0.005 \cdot T$
Temperature	°C	Pt-100 1/5 DIN class A IEC 60751	$\pm 0.15 + 0.002 \cdot T$
Flow rate	L/min	Badger meter type ModMAG M1000	±0.25%

By applying Equation (3) to the different parameters [43], the uncertainties of the HTF thermophysical properties (density and specific heat) as well as of the heat transfer rates and total stored/released energy were estimated. The uncertainty of the HTF thermophysical properties and heat transfer rates was estimated at each registered time step, and then the mean value was used. Table 5 shows the average uncertainties of the HTF density, specific heat, heat transfer rate, and stored/released energy during the different processes carried out:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1}{\cdot}w_{x_1}\right)^2 + \left(\frac{\partial R}{\partial x_2}{\cdot}w_{x_2}\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}{\cdot}w_{x_n}\right)^2\right]^{1/2} \tag{3}$$

where W_R is the estimated uncertainty in the final result, R the function which depends on the measured parameters, x_n is the different independent monitored parameters, and w_x is the uncertainties associated to those independent parameters.

Table 5. Estimated uncertainties of the HTF thermophysical properties, heat transfer rate, and cumulated energy.

Test	Density [$\pm$kg/m^3]	Specific Heat [$\pm$kJ/kg · °C]	Heat Transfer Rate [$\pm$kW]	Accumulated Energy [$\pm$kJ]
C_ThinICE_2L	±1.28	$\pm 2.44 \cdot 10^{-2}$	±0.039	±19
C_ThinICE_4L	±1.28	$\pm 2.42 \cdot 10^{-2}$	±0.055	±19
C_FlatICE_2L	±1.27	$\pm 2.43 \cdot 10^{-2}$	±0.038	±23
C_FlatICE_4L	±1.28	$\pm 2.45 \cdot 10^{-2}$	±0.054	±24
D_ThinICE_2L	$\pm 5.5 \cdot 10^{-2}$	$\pm 2.95 \cdot 10^{-3}$	±0.039	±19
D_ThinICE_4L	$\pm 5.6 \cdot 10^{-2}$	$\pm 3.05 \cdot 10^{-3}$	±0.055	±20
D_FlatICE_2L	$\pm 5.3 \cdot 10^{-2}$	$\pm 2.77 \cdot 10^{-3}$	±0.039	±23
D_FlatICE_4L	$\pm 5.6 \cdot 10^{-2}$	$\pm 3.21 \cdot 10^{-3}$	±0.055	±23

3. Results and Discussion

3.1. Temperature Evolution during the Charging Process

Figure 5 shows the charging temperature profile of all sensors placed at the surface of the slabs for the two PCM encapsulation design at different flow rates. To analyze the effect of the encapsulation design in the charging duration, both slabs types were compared at the same flow rate. Due to the higher heat transfer surface and the reduced amount of PCM (30% less according to Table 3) when using ThinICE slabs, at both flow rates, the experiment with the ThinICE slabs reached full charge (T_out = 25 °C) 14% faster than with FlatICE. Furthermore, when analyzing the impact of the flow rate, in both slab designs the experiments show that at 4 L/min the full charge is reached 60% faster than at 2 L/min.

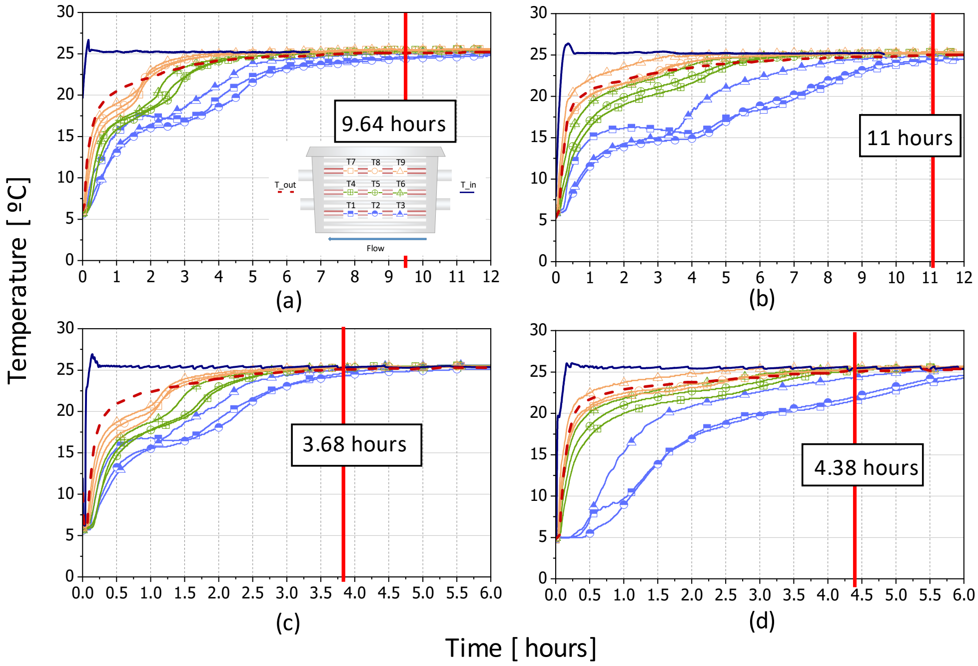

Figure 5. Charge PCM slab temperature profile for different slabs and HTF flow rates: (**a**) C_ThinICE and 2 L/min, (**b**) C_FlatICE and 2 L/min, (**c**) C_ThinICE and 4 L/min, and (**d**) C_FlatICE and 4 L/min. Note: The red line denotes the end of the charging experiment (T_out = 25 °C). The time axis is not presented on the same scale in all the figures.

When comparing temperature distribution inside the tank (Figure 5), a constant stratification profile between the top, middle, and bottom slabs was observed in all the experiments. This effect was more pronounced in the tests performed with FlatICE slabs in which the lower part of the tank takes longer to charge, obtaining a temperature gradient up to 15 K between the coldest and hottest regions of the tank. This can be explained by the fact that the tank with FlatICE fits a lower number of slabs, as well as presenting smaller HTF channels compared with the tank with the ThinICE design (Figure 3, Table 2). Therefore, in this tank, the opposition to the HTF flow is higher, enhancing the distribution of the latter towards the regions of the tank where the density is more similar to the HTF inlet one (i.e., upper and middle region of the tank).

3.2. Heat Transfer Rate Evolution and Total Energy Stored in the Charging Process

Figure 6 presents the evolution of the heat transfer rate (HTR) during the charging process of the four studied cases. Due to the characteristics of the experimental set-up, at the beginning of the experiment, the inlet temperature of the tank oscillated ±2 °C with respect to the desired temperature, affecting the initial peak of the heat transfer rate. However, the inlet temperature stabilized (with Tin standard deviation lower than 0.3) before the temperature inside the tank reaches the latent range of the PCM. The HTR profiles showed an exponential behavior with significantly higher values during the first 20 min of the process when the heat is mainly transferred to the HTF inside the tank and, therefore, rapidly increases its temperature. Afterwards, while the PCM temperature increases, the values of the heat transfer exponentially decrease until minimum values.

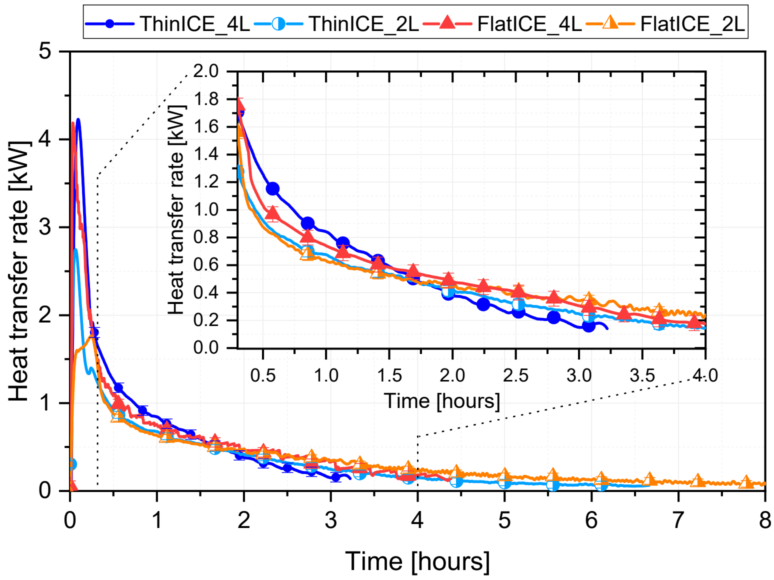

Figure 6. Evolution of the HTF heat transfer rate during the charging processes of the four study cases presented in this study.

During the first 1.5 h of operation, ThinICE_2L and FlatICE_2L showed similar HTR values, which indicates that, due to the low flow rate, the heat transfer by convection is low. Therefore, the higher heat transfer surface area existing with ThinICE slabs is not fully exploited. Moreover, after 1.5 h the HTR delivered to the ThinICE_2L decreases faster than the one delivered to the FlatICE_2L due to the higher amount of PCM introduced into the tank with FlatICE slabs. At a higher flow rate, heat transfer by convection increases. Therefore, during the first 1.5 h of operation, the bigger heat transfer surface area present with ThinICE_4L slabs increases its HTR over FlatICE_4L. After this period, and similar to the results at 2 L/min, the power delivered to the ThinICE_4L decreased faster than the one delivered to the FlatICE_4L.

When analyzing the effect of the flows in each slab type, the influence is greater in the tank with ThinICE slabs obtaining, after the initial peak, up to 0.4 kW more in ThinICE_4L than in ThinICE_2L. In the case of the tank with FlatICE, this increase drops to 0.1 kW when comparing FlatICE_4L vs FlatICE_2L. The latter results corroborate the statement above; the increase in heat transfer by convection, as the flow rate increases, is more pronounced in the tank with ThinICE slabs due to the larger heat transfer surface and the lower thickness of the PCM layer using this type of slab.

Figure 7 reports the total energy stored for each experiment condition. The results with ThinICE slabs show that the flow variation did not affect the total stored energy, suggesting the correct utilization of the energy storage capacity of the PCM. Conversely, when analyzing the tank with FlatICE slabs, the charging experiments at 4 L/min stored 10% less energy than the same experiment at 2 L/min. This is due to changes in the flow rate distribution between the slab channels inside the tank when increasing the flow rate. At the end of the experiment, (T_out 25 °C) with FlatICE at 4 L/min, the PCM in the bottom slabs of the tank had not completed the phase change (Figure 5) and therefore stored 8% less energy.

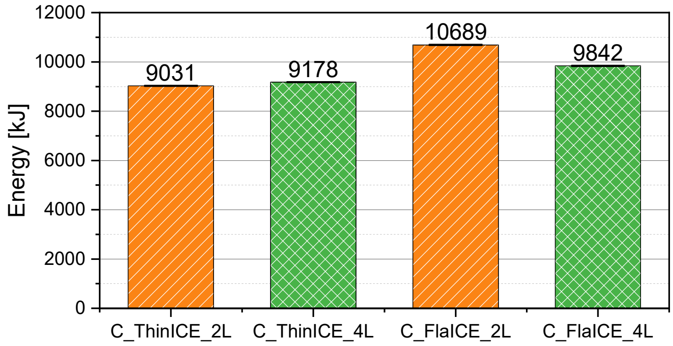

Figure 7. Total energy delivered to the PCM storage tank during the charging processes of the four study cases presented in this study.

3.3. Temperature Evolution during the Discharging Process

Figure 8 shows the discharging temperature profile of all sensors placed at the surface of the slabs at two different mass flow rates. Analyzing the influence of the PCM encapsulation design on both flow rates, the tank with ThinICE slabs finished the discharging process 30% faster than with FlatICE slabs. This can be explained by the higher heat transfer surface and the lower amount of PCM (30% less according to Table 3) when using ThinICE. Moreover, when analyzing the influence of the flow rate, Figure 8 shows that for both slab types at 4 L/min the experiments were completed 50% faster than at 2 L/min.

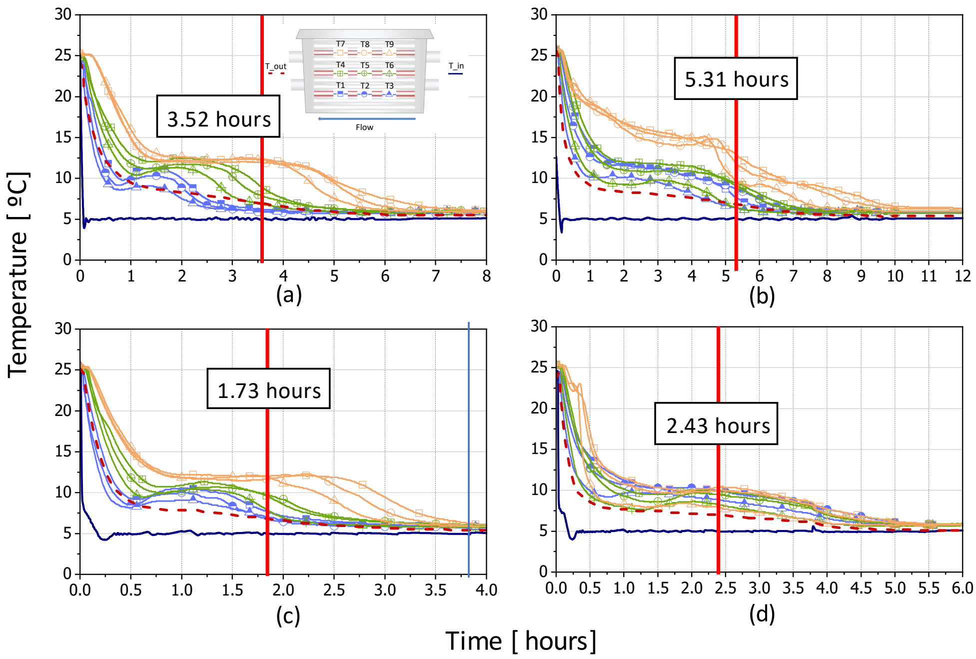

Figure 8. Discharge process PCM slab temperature profile for different slabs and HTF flow rates: (**a**) ThinICE and 2 L/min, (**b**) FlatICE and 2 L/min, (**c**) ThinICE and 4 L/min, and (**d**) FlatICE and 4 L/min. Note: The red line denotes the end of the charging experiment (T_out = 25 °C). The time axis is not presented on the same scale in all the figures.

When comparing temperature distribution inside the tank (Figure 8), a similar temperature profile between the top, middle, and bottom slabs was observed in all the experiments performed with ThinICE slabs. Moreover, this behavior changed with the use of the FlatICE, where the stratification and the profile temperature inside the tank depends on the mass flow rate.

3.4. Heat Transfer Rate Evolution and Total Energy Released in the Discharging Process

The HTR evolution during the discharging process for all the experimental cases is shown in Figure 9. In all the experiments the profiles showed a similar trend. Significantly higher values were obtained during the first 20 min of the process when the heat is mainly transferred from the HTF inside the tank followed by an exponential decrease while the PCM decreases its temperature until minimum values are reached. Furthermore, in this case, due to the characteristics of the experimental facility, at the beginning of the experimentation the inlet temperature of the tank oscillates ±2 °C around the desired temperature, affecting the initial peak of power. However, the inlet temperature stabilizes (T_in standard deviation lower than 0.3 °C) before the temperature inside the tank reaches the latent range of the PCM. After the initial peak and during the first 1.5 h of operation, ThinICE_2L shows slightly better performance getting up to 0.1 kW more HTR than FlatICE_2L. Moreover, due to the lower amount of PCM in the storage tank with ThinICE slabs, after 1.5 h the HTR delivered by ThinICE_2L decreases faster than the one delivered by FlatICE_2L. At 4 L/min, after the initial peak and during the first 1.5 h, similar results to 2 L/min are obtained. Moreover, after 1.5 h the HTR of ThinICE_4L drastically decreases, therefore for the next 2 h (from 1.5–3.5 h) FlatICE_4L maintains an HTR up to 0.4 kW higher than ThinICE_2L.

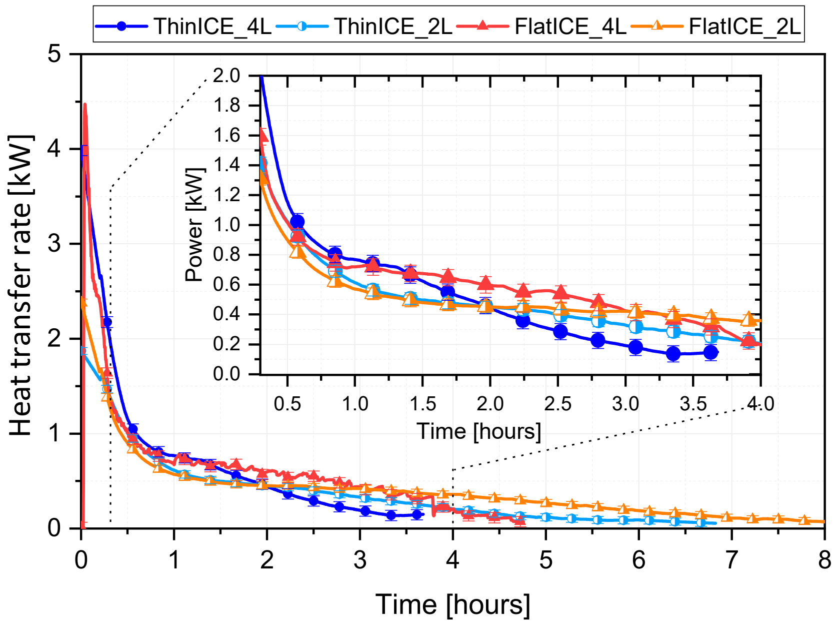

Figure 9. Evolution of the HTF heat transfer rate during the discharging processes of the four study cases presented in this study.

Figure 10 reports the total energy released for each experiment conditions, and the percentage it represents with respect to the energy stored in the charging process (Figure 7) in each case. Analyzing the effects of flow rate, similar to the charging, both experiments with ThinICE slabs showed a comparable energy release, suggesting a correct utilization of the energy stored in the PCM. In the case of FlatICE slabs, experiments at 2 L/min released 10% more energy compared with 4 L/min. This is supported by the fact that in the charging process the tank at 2 L/min manages to store 10% more energy than at 4 L/min (Figure 5). In addition, it is interesting to note that in all cases of the selected operating threshold approximately 85% of the energy stored in the tank was discharged.

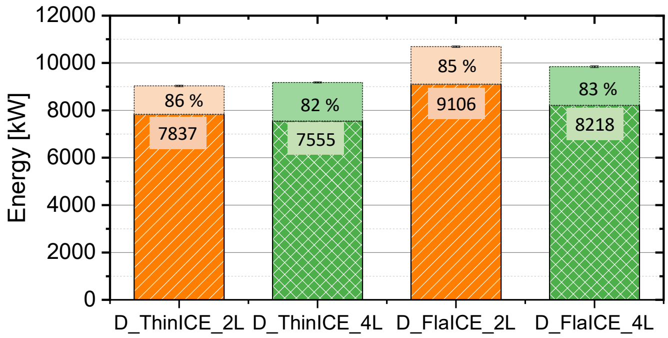

Figure 10. Total energy released by the PCM storage tank during the discharging processes of the four study cases presented in this study.

4. Conclusions

Macro-encapsulation of phase change materials (PCM) represents one of the most widely used techniques for the implementation of latent heat thermal energy storage systems. The design of the macro-encapsulation is fundamental to archive the best compromise between optimal heat transfer performance and energy stored. However, current literature lacks experimental data on the effect of macro-encapsulation in the performance of latent heat thermal energy storage.

This paper analyzed, through an experimental study, the effect of the design of macro-encapsulated PCM on the thermal behavior of a latent heat thermal energy storage tank during both the charging and discharging processes. In this study, external dimensions of the energy storage tank were fixed and two different types of commercial slabs with different thickness filled with the same PCM were tested. The results could be particularly useful to evaluate the best configuration of storage medium when the storage tank is limited with a fixed volume.

The results were compared in terms of temperature profile, heat transfer rate, and energy stored/released. The results and the conclusions obtained from this study can be applied to similar configuration of the PCM storage that aim to use rectangular macro-encapsulated slabs as storage medium. The lesson learnt from this study suggests that macro-encapsulation design has a relevant impact on the heat transfer during both charging and discharging processes, so the design of the TES unit should be done and analyzed according to the requirements of the application.

The use of a thinner macro-encapsulation design (ThinICE) allowed fitting a larger number of slabs inside the tank. However, the higher amount of encapsulation material and the larger distance between the slabs (i.e., higher HTF channels height) resulted in a 30% less amount of PCM introduced inside the tank with this encapsulation design.

With ThinICE slabs, the temperature profiles were less affected by the influence of the mass flow rate, promoting a stratified temperature profile inside the tank in both the charging and discharging processes. Using FlatICE, this effect is more pronounced at low flow rates due to the smaller height of the channels that obstructed the flow at the bottom of the tank during charging and at the top of the tank during discharging. However, at high flow rates, the stratification is reduced with the use of thicker slabs, especially during the discharging process.

In all the discharging tests, when the outlet temperature of the tank reached 7 °C, approximately 85% of the energy previously stored in the tank was discharged.

The effect of increasing the heat transfer surface using ThinICE slabs on the power delivered by the storage tank is mostly appreciated at a higher flow rate where the heat transferred by convection is higher. Furthermore, using thinner slabs, the higher heat transfer surface area achieves a higher discharging power but is delivered for a shorter period of time. Therefore, for longer discharging periods and for higher storage capacity given a fixed volume of storage tank, the use of FlatICE should be preferred.

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Key Challenges for High Temperature Thermal Energy Storage in Concrete—First Steps towards a Novel Storage Design

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Abstract: Thermal energy storage (TES) allows the existing mismatch between supply and demand in energy systems to be overcome. Considering temperatures above 150 °C, there are major potential benefits for applications, such as process heat and electricity production, where TES coupled with concentrating solar power (CSP) plants can increase the penetration of renewable energies. To this end, this paper performs a critical analysis of the literature on the current and most promising concrete energy storage technologies, identifying five challenges that must be overcome for the successful exploitation of this technology. With these five challenges in mind, this paper proposes an approach that uses a new modular design of concrete-based TES. A preliminary study of the feasibility of the proposed system was performed using computational fluid dynamics (CFD) techniques, showing promising results.

Keywords: concrete; modular system; thermal energy storage; high temperature; new concept

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1. Introduction

Thermal energy storage (TES) addresses the mismatches between energy supply and demand, which involve time, temperature, power, and location [1]. Therefore, TES has multiple applications. If high temperature is considered, i.e., above 150 °C, where water cannot be used as storage medium, high temperature TES applications include process heat and electricity production by concentrating solar power (CSP) plants.

The demand for process heat in industry can be met by fossil fuels, as is common practice today, but it could also be supplied by solar energy or the recovery of waste heat (on-site or off-site). The integration of solar energy with industry requires TES systems using any of the available technologies (sensible, latent, and thermochemical TES) [2]. Similarly, to efficiently use industrial waste heat as the input for industry requires a TES system [3]. The potential of waste heat recovery in the European non-metallic mineral industry for the period 2007–2012 was estimated by Miro et al. [4] using a bottom-up approach, showing an average of 0.33 PJ/year. This estimation highlights the high potential of this energy source.

Today, solar energy represents the main renewable source of both thermal and electric power. One of the main large-scale technologies that can convert solar energy into electricity is represented by CSP plants. According to REN21 [5], in 2020 the total capacity installed worldwide amounted to 6.2 GWe, and it is expected to continue growing. In order to deal with the intermittency of the sun, thermal energy storage is an essential component. Current commercial CSP technologies mainly rely on the use of molten salts as a storage medium [6]. However, the main drawbacks of this medium consist of corrosion issues and a limited operating temperature range (up to 360 °C), which limits CSP in terms of global performance and cost [7]. Amongst storage medium alternatives, the use of concrete represents a viable option due to its versatility, relatively low cost, and the ability to reach a high operating temperature above 500 °C [8].

Although concrete has a high potential as a storage solution, there are still challenges posed by this technology that need to be addressed, including its fabrication techniques, material formulation, and design, which limit construction feasibility and thermal performance. In order to improve the actual configurations, this study proposes a novel concept for thermal energy storage using concrete based on a modular concept, improved concrete formulation, and a direct contact design. Moreover, a preliminary assessment of the thermal performances of the new concept proposed in this study were analysed using CFD analysis to determine temperature distribution in the modules.

2. Innovative Concrete Formulations for High Temperature TES

According to Laing et al. [9], the concrete to be used for high temperature TES should fulfil numerous requirements, such as high thermal durability, high heat capacity, high thermal conductivity, low cost, and be easily workable. Therefore, different approaches can be found in the literature for the development of new concrete formulations that can withstand harsh conditions, such as high temperature and thermal cycling. These approaches include the use of different cements (i.e., ordinary Portland cement, OPC; calcium aluminate cement, CAC), geopolymers, or the selection of different additives. A summary of such efforts can be found in Table 1. Enormous efforts have been made in the study of the aggregates to use, but the use of fibres or other additives have attracted much less attention. Results show that innovative concretes showed a change in properties after the first thermal cycle, especially when temperatures above 350 °C were reached, but then they remained constant with temperature and thermal cycling.

Seeing the results of these efforts, a lot of research is still needed, since the formulations reported up until now do not meet requirements listed above, but there are still options to be tested (such as the use of other aggregates, fibres, or the inclusion of additives to increase thermal conductivity).

Table 1. Summary of innovative concrete formulations for high temperature TES.

Formulation	Cement	Water-Cement Ratio	Sand	Aggregate	Super-Plasticizer	Curing And Drying Protocol	Thermal Cycling	Compression Strength (MPa)	Porosity	Thermal Properties	Reference
Cement paste	OPC	0.34	—	—	—	28 days curing in water	20–200 °C 20–400 °C 20–600 °C 20–800 °C	Loss of stability in thermal cycling above 400 °C	Open porosity decreases with thermal cycles	Decrease in the thermal conductivity from 1 W/m·K to around 0.5 W/m·K after thermal cycling	[10]
Cement paste	CAC	0.34	—	—	—	28 days curing in water	20–200 °C 20–400 °C 20–600 °C 20–800 °C	Decrease after first thermal cycle with stabilisation later on	Open porosity increased with temperature and thermal cycling	Lower thermal conductivity than OPC but higher heat capacity	[10]
Mortar	70% CAC + 30% blast furnace slag (BFS)	0.44	Standard siliceous	—	1%	3 days @105 °C	290–550 °C	72.67 ± 1.97 (after 7 days curing)	—	—	[11]
Concrete	Blast furnace cement	—	—	Iron oxides, flue ash, and other	—	—	—	Medium material strength with several cracks	—	916 J/kg·K (@350 °C) 1.0 W/m·K (@350 °C) 9.3 $\cdot 10^{-6}$/K (@350 °C)	[12]
Concrete	70% CAC + 30% blast furnace slag (BFS)	0.5	Standard siliceous	Natural from crash stone, silicon calcareous aggregate (SCA)	0.8%	3 days @105 °C	290–550 °C	50% decrease after first thermal cycle with stabilisation later on	100% increase after thermal cycles	—	[11]
Concrete	70% CAC + 30% blast furnace slag (BFS)	0.57	Standard siliceous	Natural SCA + industrial waste slag	0.8%	3 days @105 °C	290–550 °C	50% decrease after first thermal cycle with stabilisation later on	100% increase after thermal cycles	—	[11]
Concrete	CAC	0.43	—	Basalt 0–6 mm	0.9%	Left @95% RH and @20 °C until testing	300–600 °C	—	—	1.2–2 W/m·K Decrease of 20–40% in the thermal conductivity after first thermal cycle	[13]
Concrete	CAC	0.43	—	CAT 0.25–4 mm	0.9%	Left @95% RH and @20 °C until testing	300–600 °C	—	—	1.2–2 W/m·K Decrease of 20–40% in the thermal conductivity after first thermal cycle	[13]
Concrete	CAC	0.43	—	Slag 0.25–2 mm	0.9%	Left @95% RH and @20 °C until testing	300–600 °C	—	—	1.2–2 W/m·K Decrease of 20–40% in the thermal conductivity after first thermal cycle	[13]
Concrete	CAC	0.43	—	Slat 3–7 mm	0.9%	Left @95% RH and @20 °C until testing	300–600 °C	—	—	1.2–2 W/m·K Decrease of 20–40% in the thermal conductivity after first thermal cycle	[13]

Table 1. *Cont.*

Formulation	Cement	Water-Cement Ratio	Sand	Aggregate	Super-Plasticizer	Curing And Drying Protocol	Thermal Cycling	Compression Strength (MPa)	Porosity	Thermal Properties	Reference
Concrete	CAC	0.43	—	Calcareous 0–6 mm	0.9%	Left @95% RH and @20 °C until testing	300–600 °C	—	—	1.2–2 W/m·K Decrease of 20–40% in the thermal conductivity after first thermal cycle	[13]
Concrete	CAC	0.43	—	Siliceous 0–3 mm	0.9%	Left @95% RH and @20 °C until testing	300–600 °C	—	—	Up to 5 W/m·K Decrease of 50% in the thermal conductivity after first thermal cycle	[13]
Concrete	CAC	0.43	—	Siliceous + polypropylene fibres	1%	Left @95% RH and @20 °C until testing	300–600 °C	Loss of 74% after one thermal cycle	—	Decrease of 50% in the thermal conductivity after first thermal cycle	[14]
Concrete	CAC	0.43	—	Calcium aluminate (CAT) + polypropylene fibres	1%	Left @95% RH and @20 °C until testing	300–600 °C	Loss of 63% after one thermal cycle	1.6–2 μm Increase to 24–27 μm after thermal cycling	Decrease of 50% in the thermal conductivity after first thermal cycle	[14]
Concrete	CAC	0.43	—	CAT + crushed basalt + polypropylene fibres	1%	Left @95% RH and @20 °C until testing	300–600 °C	Loss of 69% after one thermal cycle	0.7 μm Increase to 24–27 μm after thermal cycling	Decrease of 50% in the thermal conductivity after first thermal cycle	[14]
Concrete	CAC	0.43	—	CAT + crushed basalt + 15% waste slag + polypropylene fibres	1%	Left @95% RH and @20 °C until testing	300–600 °C	Loss of 69% after one thermal cycle	1.6–2 μm Increase to 24–27 μm after thermal cycling	Decrease of 50% in the thermal conductivity after first thermal cycle	[14]
Concrete	CAC	0.43	—	CAT + crushed basalt + 30% waste slag + polypropylene fibres	1%	Left @95% RH and @20 °C until testing	300–600 °C	Loss of 61% after 1 thermal cycle	1.6–2 μm Increase to 24–27 μm after thermal cycling	Decrease of 50% in the thermal conductivity after first thermal cycle	[14]
Concrete	Cement	0.32	9% washed sand 0–4 mm	Aggregate + metal and synthetic fibres	0.43%	28 days in a tank @100% HR and @15–20 °C	50–200 °C 50–300 °C 50–400 °C (1 cycle)	Higher values at low temperature	Density was characterised	Specific heat is constant with temperature treatment Thermal conductivity around 2 W/m·K	[15]
Concrete/PCM	Cement	0.37–0.41	9% washed sand 0–4 mm	Aggregate + metal and synthetic fibres + PCM impregnate in porous material	0.43%	28 days in a tank @100% HR and @15–20 °C	50–200 °C 50–300 °C 50–400 °C (1 cycle)	PCM content helps in maintaining higher values after thermal treatment	Density was characterised	Specific heat increases with temperature treatment Thermal conductivity decreases strongly with PCM content	[15]
Geopolymer concrete	20% OPC + 80% inorganic geopolymer	0.6	—	Steel slag	—	1 day @100% RH + 28 days @room temperature	—	—	—	More stable thermal properties than OPC as temperature increases	[16]

3. Conventional TES Concept

One of the first concepts for TES based on concrete for high temperature applications was developed and studied by DLR. Laing et al. [12] built a prototype with high-temperature concrete and a storage capacity of approximately 280 kWh. The unit comprised two parallel storage modules with a heat-exchanger composed of 36 tubes of high-temperature steel with a nominal diameter of 21 × 12 mm distributed in a square arrangement of 6 × 6 tubes with a separation of 80 mm. Each storage unit had a total volume of 23 m^3. The prototype (Figure 1) was tested at the Plataforma Solar de Almeria in Spain in 2003–2004 [9,12,17].

Figure 1. DLR concrete storage concept. Reprinted/adapted with permission from Ref. [9]. 2009, American Society of Mechanical Engineers.

Concrete storage modules were also used in the project EDITOR funded by the solar ERA-NET framework. The storage was coupled with a parabolic through collector and installed in the KEAN drinks factory in Limassol, Cyprus. The HTF employed is a silicone-based thermal oil named HELISOL®XA with reduced environmental impact. The objective of this system was to produce thermal energy for industry, not electricity, and the results for this design were presented in Ktiskis et al., 2021 [18].

4. Challenges

A state-of-the-art TES system made of concrete for high temperature applications should address the following challenges:

(i) On-site construction.

In 2009, Laing et al. [9] already highlighted that the first heating cycle of a new concrete TES is crucial in the process. During this first cycle, any free water and a certain amount of chemically bonded water evaporate, which can create excessive vapor pressure that can damage to the storage module. This pressure increases with the size of the TES module; similarly, on-site production means higher water content in the concrete than production and curing in a controlled environment. This problem was also identified by Martins et al. [19] and Hoivik et al. [20].

The problem of scaling-up concrete preparation from the laboratory for an on-site installation has already been highlighted by Prieto et al. [21]. It is widely accepted that for concrete with special requirements, such as the formulations presented in this paper, heterogeneity in its properties can be a challenge. For the same concrete mixture, compressive strength results can present a variability higher than 10%, even in the same quality control laboratory [22].

Another problem with construction on site is related to the complexity of casting a large pipe register in a block of concrete. In order to enhance flexibility in scaling up a high temperature TES, EnergyNest developed and tested a 2 × 500 kWth thermal energy storage system based on a modular design with HEATCRETE vp1 concrete as the storage medium, offering improved thermal conductivity, heat capacity, and compressive strength able to resist temperatures up to 400 °C. The storage system included cast-in steel pipe heat exchangers, as shown in Figure 2. The TES system was commissioned in October 2015.

Figure 2. Concrete thermal element design for the HEATCRETE vp1 concept [20].

(ii) Different thermal expansion coefficient of steel and concrete.

According to Laing et al. [12], thermal expansion in the axial direction of one module of concrete with a steel heat exchanger is 120 mm; therefore, the length of a modules can expand by approximately 60 mm at each end. During cycling at operating temperatures, the temperature difference should be only about 40 K, so the expansion would be less than 10 mm at each end. In this instance, two metal sheets acting as sliding planes were used to compensate for this expansion.

Hoivik et al. [20] also mentioned the fact that different thermal expansion coefficients have to be considered, without giving further details.

Moreover, even if concrete and metallic pipes with similar thermal expansion coefficients were used, the thermal conductivity of the two materials is different, so that, during cycling, the temperature of the steel will increase before the concrete, which will generate differential expansion.

(iii) Poor thermal conductivity of concrete.

According to Asadi et al. [23], concrete has a thermal conductivity between 0.4 W/m·K and 1.01 W/m·K. The addition of components such as copper wires or phase change materials (PCM) may bring this thermal conductivity up to 3.84 W/m·K, but it can also decrease it to 0.21 W/m·K.

Efforts to increase the thermal conductivity of concrete for high temperature TES (Table 1) have shown that the use of CAC can increase thermal conductivity up to 5 W/m·K [13], compared to a maximum of 2 W/m·K with the use of metal fibres [15]. Finally, the literature shows that thermal cycling can lead to a decrease in thermal conductivity, usually attributed to an increase in open porosity [10,14].

Therefore, it is possible to increase the thermal conductivity of concrete with improved formulations.

(iv) HTF thermal oil or molten salts with limited operating temperature range.

Vignarooban et al. [24] presented the thermophysical properties of commonly used heat transfer fluids (HTFs) in CSP plants, which are shown in Table 2. As it can be seen, thermal oils (mineral or synthetic) can only withstand 450 °C; therefore, they cannot be used in CSP plants working at higher temperatures. The other common commercial HTF, molten salts, can theoretically withstand 600 °C, but there is a lot of literature showing that impurities seriously compromise this limit, since their decomposition starts at around 380–400 °C [25]. Therefore, future CSP plants are considering the use of air as a HTF [26].

Table 2. Thermophysical properties of heat transfer fluids used in CSP plants [24,26].

HTF	Melting Point (°C)	Stability Limit (°C)	Viscosity (Pa·s)	Thermal Conductivity (W/m·K)	Heat Capacity (kJ/kg·K)
Air	—	—	0.00003 (@ 600 °C)	0.06 (@ 600 °C)	1.12 (@ 600 °C)
Water/steam	0	—	0.00133 (@ 600 °C)	0.08 (@ 600 °C)	2.42 (@ 600 °C)
Thermal oils	−20	300	—	~0.1	—
Mineral oil	−20	350	—	~0.1	—
Synthetic oil	−20	400	—	~0.1	—
Biphenyl/diphenyl oxide	12	393	0.00059 (@ 300 °C)	~0.01 (@ 300 °C)	1.93 (@ 300 °C)
Solar salt (60 wt.% $NaNO_3$-40 wt.% KNO_3)	220	600	0.00326 (@ 300 °C)	0.55 (@ 400 °C)	1.1 (@ 600 °C)

(v) HTF thermal oil or molten salts in direct contact with concrete: migration of oil/salt in concrete.

The use of thermal oils or molten salts as HTFs when there is direct contact between the HTF and concrete can lead to migration of the HTF into the concrete, but also contamination of the HTF by concrete components. The use of air as the HTF avoids migration and contamination issues; however, the low conductivity of air presents new challenges to overcome.

In the design by Laing et al. [17], the idea of using a tubeless design was investigated. The advantages of this approach, low cost and direct heat transfer, were identified as the main drivers of this design. Nevertheless, according to the authors, concrete did not allow for a high enough level of impermeability, even when restressed, causing oil leaks. Moreover, in this design, the pipe-storage unit junction became a technical challenge, which is difficult and expensive to solve. In this paper, the problem of thermal oil (the HTF) absorption by the concrete was also identified, along with the challenge of final disposal of the storage unit after use.

5. New Concept Proposal

To address the challenges presented in Section 4, a new concrete TES design performed in Autodesk inventor [27] is presented in this paper. The new concept is designed to work with air as the HTF, and it is based on concrete blocks measuring 100 mm × 100 mm × 1000 mm (Figure 3) with a modular design and simple direct-fit male-female connections (Figure 4a). The blocks were designed to be stacked (Figure 4b) and interlocked (Figure 4c) to fit the thermal needs of the installation and the available space. To address challenge (i), the design is based on a modular concept with blocks of relatively small dimensions that allow them to be produced in a controlled industrial environment and then transported to the installation site. Moreover, to overcome challenge (ii), the design is made exclusively in concrete, eliminating the need for metal piping and thus the problem of thermal expansion differences between materials. Challenge (iii) will be addressed in future work by modifying the thermophysical properties of the simulated concrete using new materials currently being validated at an experimental level. Finally, the temperature limitation of molten salts and thermal oils, and their migration into the concrete due to the non-use of metal pipes (challenges (iv) and (v)) are solved by using air as the HTF.

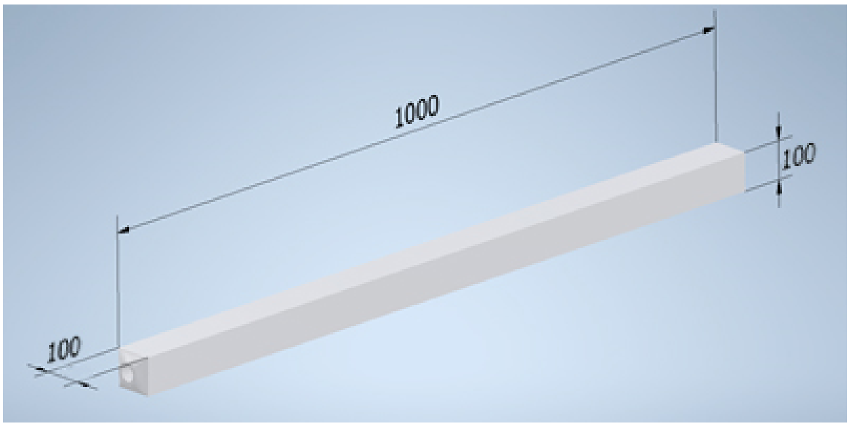
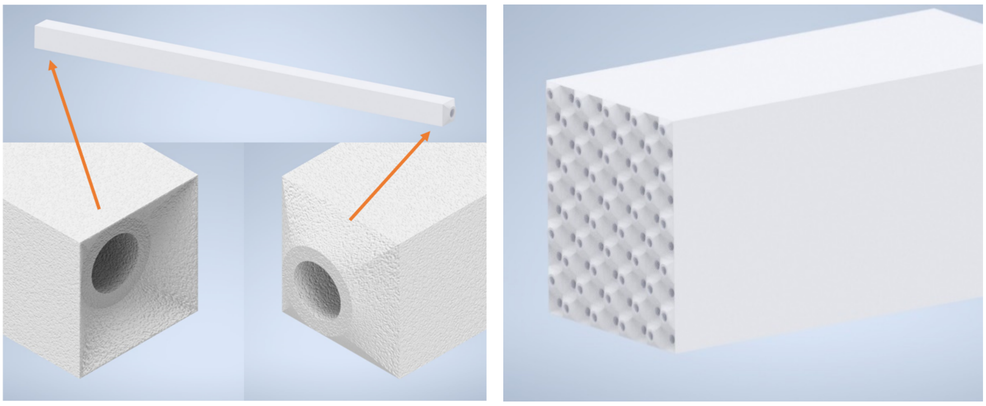
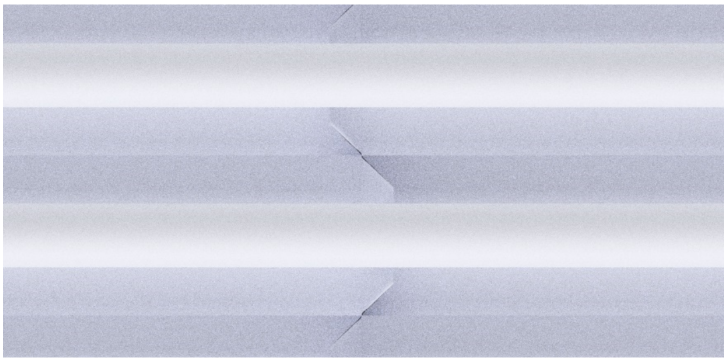


Figure 3. Concept of concrete block and block dimensions [mm].



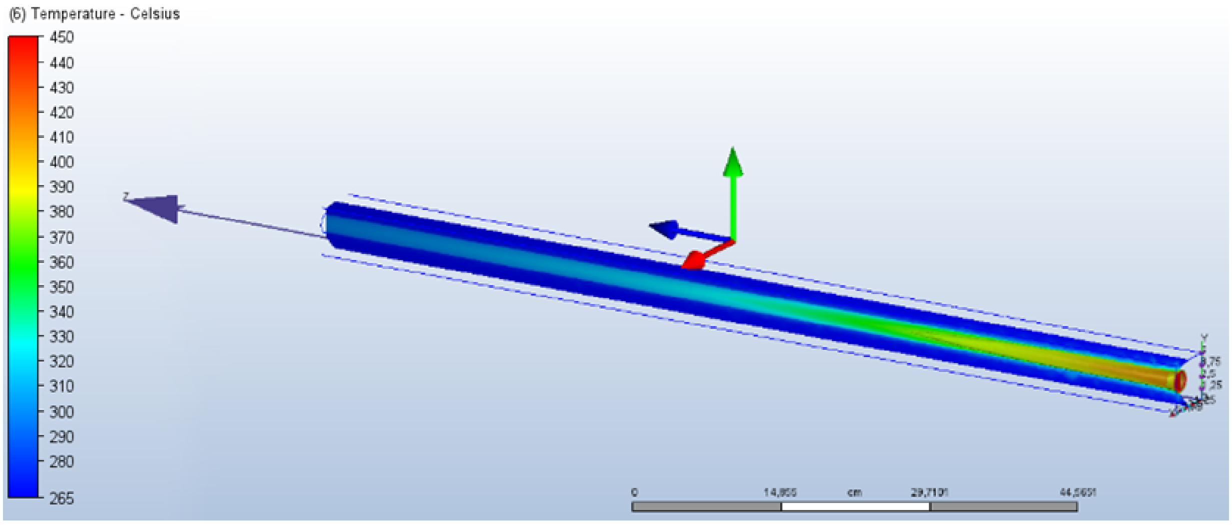
(**a**) (**b**)



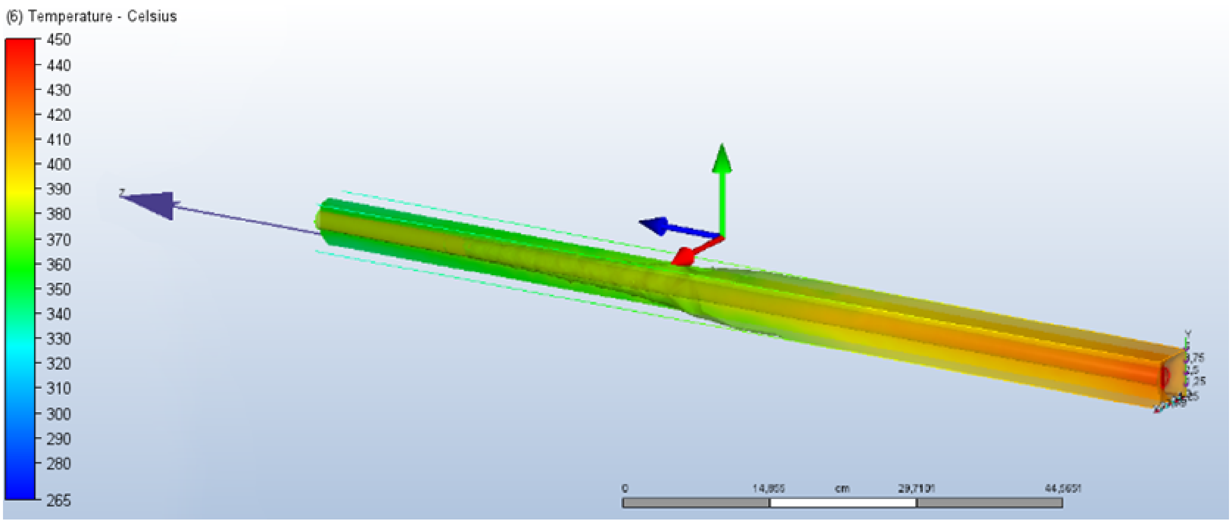
(**c**)

Figure 4. Concrete block concept: (**a**) fitting connections, (**b**) stacked distribution example, (**c**) connection points.

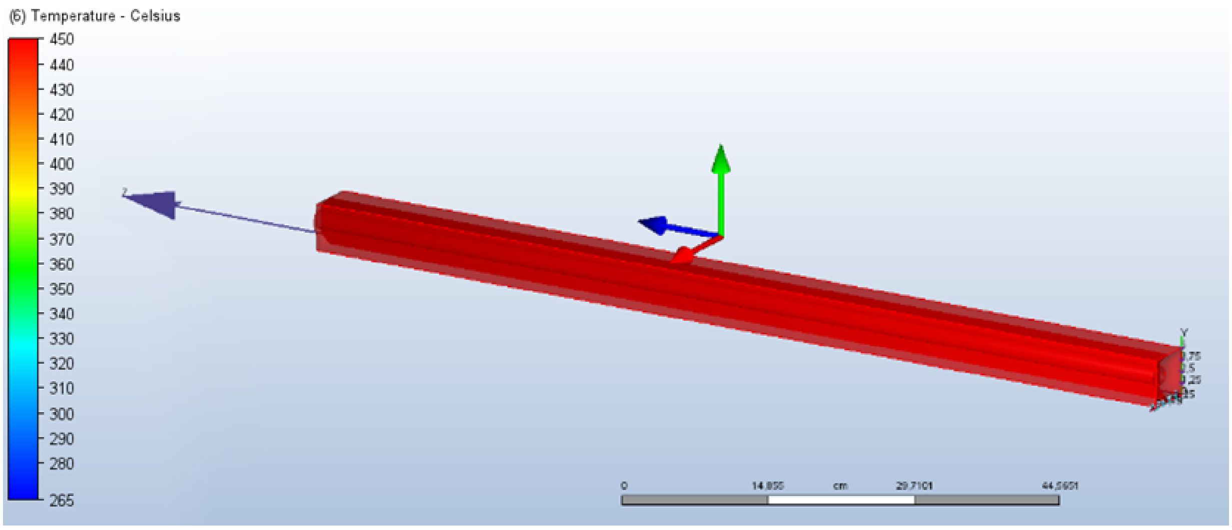
A computational fluid dynamics (CFD) model of the proposed concrete block was developed in Autodesk CFD [28] to validate its feasibility in terms of thermal performance during operation of the module (Figure 5). As a preliminary study, conventional concrete was used. The thermophysical properties of the concrete and heat transfer fluid (air) used are shown in Tables 3 and 4, respectively. Moreover, the equations governing fluid flow and heat transfer are the Navier–Stokes equations and the first law of thermodynamics, respectively. A k-epsilon turbulence model was selected with a turbulent laminar ratio of 100, and finite element discretisation was performed using "ADV 5: Modified Petrov–Galerkin". Finally, the mesh dimensions were set to automatic with the parameters set out in Table 5.



(**a**)



(**b**)



(**c**)

Figure 5. Computational fluid dynamics of the proposed concrete block: (**a**) initial charge, (**b**) mid-charge, (**c**) full charge.

Table 3. Thermophysical properties of concrete implemented in CFD.

Property	Concrete
Thermal conductivity x, y, z direction [W/m·K]	1.01
Density [kg/m^3]	2306
Specific heat [kJ/kg·K]	0.837
Emissivity [-]	0.95
Transmissivity [-]	0
Electrical resistivity [ohm·m]	0
Wall roughness	0

Table 4. Thermophysical properties of the HTF (air) implemented in CFD.

Property	Air
Density	Equation of state
Viscosity [poise]	0.0001817
Thermal conductivity [W/m·K]	0.02563
Specific heat [kJ/kg·K]	1.004
Compressibility [Cp/Cv]	1.4
Emissivity	1
Wall roughness	0

Table 5. CFD mesh parameters.

Parameter	Value
Resolution factor	1
Edge growth rate	1.1
Minimum points on edge	2
Points on longest edge	10
Surface limiting aspect ratio	20

The analysis was carried out by performing a complete charging process on a concrete block. The process started with the block at an initial temperature of 265 °C, simulating a real storage cycle, and injecting HTF at 450 °C and 0.33 m^3/s (optimised for improved air transfer coefficient) until the concrete block was fully charged (Figure 5). The figure shows that the concrete block reached 450 °C homogeneously, where the difference between the inlet section and the outlet section of the module was about 50 °C in the middle of the charging period (Figure 5b). The total energy stored in the concrete block was 4266 kJ (1.185 kWh).

6. Conclusions and Future Work

High temperature thermal energy storage has shown great potential for increasing the penetration of renewable energies in the energy mix. The use of concrete represents a viable option due to its versatility, relatively low cost, and the ability to reach an operating temperature above 500 °C. However, to become technologically and economically feasible, concrete storage systems must overcome a number of challenges.

This paper, through a comprehensive literature review, identified and analysed the five key issues that affect current systems. These are: (i) in-situ construction, (ii) different thermal expansion coefficient of steel and concrete, (iii) poor thermal conductivity of concrete, (iv) HTF thermal oil or molten salts with limited operating temperature range, and (v) migration of oil/salt by direct contact with the concrete.

Considering the challenges identified, a novel design for a high temperature thermal energy storage system with concrete was proposed and analysed using CFD techniques. The new design is composed of modular concrete blocks with direct-fit male-female connections. These were designed to be stacked and interlocked, thus enabling quick and easy customised sizing according to energy needs. The proposed design was able to overcome four of the five challenges identified. Only the low conductivity of concrete remains to be addressed in future works. In addition, the plug-and-play design facilitates construction of the modules, which can be manufactured under controlled conditions, guaranteeing the properties of the concrete.

Moreover, the streamlined design of the modules, the abundance of the material used, the potential low manufacturing cost once implemented on an industrial scale, as well as the results of the simulations favour the proposed design as a highly competitive thermal energy storage solution. However, this new design also presents new challenges that must be overcome, such as the low specific heat capacity and convective heat transfer coefficient when air is used as the heat transfer fluid, the tight junction between modules, and the interaction of concrete debris with the HTF.

Future work will address the following topics: analysis of the proposed design with other concrete formulations or the addition of aggregates to increase the thermal conductivity of the storage material while maintaining specific heat values; optimise the design to improve the coefficient of internal convection to overcome the low conductivity of air when air is used as the HTF; and analysis of the connection between the modules and the heat supply/demand.

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