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Seasonal Thermal Energy Storage System provided with an Adsorption Module

Dissertação no âmbito do Mestrado Integrado em Engenharia Mecânica, ramo de Energia e Ambiente, orientada pelo Professor Doutor Adélio Manuel Rodrigues Gaspar e pelo Professor Doutor Marco Alexandre dos Santos Fernandes e apresentada ao Departamento de Engenharia Mecânica da Faculdade de Ciências e Tecnologias da Universidade de Coimbra

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Seasonal Thermal Energy Storage System provided with an Adsorption Module

Submitted in Partial Fulfilment of the Requirements for the Degree of Master in Mechanical Engineering in the speciality of Energy and Environment

Sistema de Acumulação Sazonal de Energia Térmica com Módulo de Adsorção

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Abstract

Global energy production and use has been increasing significantly in the past few years, and is set to increase even further in the coming future, with the energy for Domestic Hot Water (DHW) representing a significant portion in the building sector. With that in mind, it is of particular interest to improve and develop new thermal energy storage systems that increase the efficiency and the renewable fraction of such systems.

By using Seasonal Thermal Energy Storage (STES) systems it is possible to store energy over long periods of time, presenting themselves as interesting solutions to store intermittent energy sources such as solar energy. By employing such systems, it is possible to store excess heat during the summer, that would otherwise be wasted, for later use during winter, when the availability is lower and the demand is higher. Although there are nowadays some commercial STES systems, their use is not yet spread, being their relatively low energy density an important limitation. Therefore, more research should be conducted to develop new technological solutions, with the sorption principle presenting promising results.

This work presents a Seasonal Thermal Energy Storage System provided with an Adsorption Module, that has been developed with the objective of increasing the efficiency and energy density of the traditional sensible thermal energy storage systems. The system is based on the adsorption heat pump concept, inserted into a hot water tank which supports the main DHW system. For the present study a previous developed model using TRNSYS and MATLAB was adapted to simulate the seasonal storage, tested under different configurations and conditions, and compared to a conventional sensible heat storage system.

A single-family house of four people located in Lisbon with a system composed of a 250 L DHW tank and 12.15 m^2 of solar collectors, and a storage period between April and October was considered as the base case study. Different numbers of collectors were tested, with the area being increased up to 17.01 m^2. Starting with a seasonal storage tank of 3000 L, several seasonal storage capacities were tested with the adsorption module integrated. The highest savings of backup energy were observed for a seasonal storage capacity of 1800 L, presenting relative savings of 17% in comparison to the conventional system (in which the 3000 L were maintained). This shows that the adsorption module allows better energy performance and the use of smaller tanks. Furthermore, the analysis of the seasonal storage duration and the usage shows that considering a storage period comprising only the months of July and August, relative savings of 24.2% were reached, as well as a renewable fraction of nearly 85%. Energy density is relatively low, however, due to low discharging amplitudes.

The performance of the system in different climates was also assessed. The system performs better for climates with warmer summers, and higher average mains water temperatures. The system with the adsorption module again presented better results, but far from desired, requiring further optimization.

Keywords: Domestic How Water, Seasonal Thermal Energy Storage, Adsorption, TRNSYS

Resumo

A produção de energia a nível global tem vindo a aumentar significativamente, com tendência a agravar-se ainda mais nos próximos anos, representando a energia para preparação de Águas Quentes Sanitárias (AQS) no sector dos edifícios residenciais uma parcela significativa. Assim, é de particular interesse desenvolver sistemas de armazenamento de energia térmica que contribuam para a melhoria da eficiência dos sistemas de AQS e aumento da captação de energia de origem renovável.

Os sistemas de Acumulação Sazonal de Energia Térmica (STES) possibilitam o armazenamento de energia térmica durante longos períodos de tempo, sendo assim soluções interessantes para aumentar a captação e aproveitamento da energia solar, dada a sua natureza intermitente. Ao implementar um sistema deste tipo, é possível acumular energia térmica em excesso no verão, que seria de outra forma desperdiçada, e aproveitá-la para o inverno quando a disponibilidade é menor e as necessidades maiores. No entanto, a maior parte dos sistemas disponíveis no mercado apresentam densidades de armazenamento e eficiência relativamente baixas. Pelo contrário, os sistemas que utilizam tecnologias de sorção, ainda que relativamente imaturos, apresentam melhores características.

Este trabalho apresenta um Sistema de Acumulação Sazonal de Energia Térmica com Módulo de Adsorção, desenvolvido e estudado com o objetivo de aumentar a eficiência, poupança de energia e densidade de armazenamento de um sistema típico de acumulação sazonal, bem como para contribuir para o desenvolvimento da tecnologia de adsorção para comercialização futura. O sistema baseia-se no conceito de bomba de calor de adsorção inserida dentro de um depósito de água quente, que apoia diretamente um sistema solar térmico de AQS. Para atingir os objetivos propostos, um modelo anteriormente desenvolvido nos programas TRNSYS e MATLAB foi adaptado ao caso de acumulação sazonal, sendo simulado em várias configurações e sob diversas condições, e comparado com um sistema convencional equivalente, i.e., sem módulo de adsorção.

Considerou-se, como caso de referência, uma moradia unifamiliar de quatro pessoas em Lisboa, com um período de acumulação entre abril e outubro, com o sistema composto por um reservatório de AQS de 250 L, 12.15 m^2 de coletores solares, e partiu-se de um reservatório de acumulação sazonal de 3000 L. Diferentes números de coletores utilizados foram testados, aumentando a área até 17.01 m^2. Foram analisados vários volumes do depósito de acumulação sazonal ao se integrar o módulo de adsorção, tendo-se verificado uma redução na utilização da energia de apoio ao se reduzir o volume do depósito. A maior poupança foi verificada para um depósito de 1800 L, o que se traduz em cerca de 17% em relação ao sistema convencional (onde se mantiveram os 3000 L). Conclui-se que o módulo de adsorção não só permite uma poupança significativa de energia auxiliar, como também permite a utilização de depósitos menores. O valor de poupança também varia consoante os períodos considerados para acumulação e o perfil de utilização do depósito de acumulação sazonal. Considerando um período de acumulação apenas entre julho e agosto, a poupança relativa da energia de apoio é de 24,2%, verificando-se uma fração renovável de aproximadamente 85%. No entanto, a densidade de energia obtida é baixa, devido a amplitudes de descarga também baixas.

O desempenho do sistema foi também avaliado para diferentes climas. O sistema apresenta melhor desempenho para climas que apresentam Verões mais quentes e temperaturas médias de água da rede mais elevadas. O sistema com módulo de adsorção apresenta melhores resultados em todos os parâmetros analisados, porém estes continuam longe dos desejados e portanto requerem otimização adicional.

Palavras Chave: Água Quente Sanitária, Acumulação Sazonal de Energia Térmica, Adsorção, TRNSYS

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Nomenclature

A	area [m^2]
C	output control function [-]
c	specific heat [J/(kg·K)]
D	diameter [m]
d	distance [m]
E	porosity [-]
e	thickness [m]
E_d	energy density [J]
h	height [m]
k	thermal conductivity [W/(m· K)]
L	length [m]; specific latent heat [kJ/kg]
m	mass [kg]
N	number [-]
n	node [-]
P	pressure [Pa]
p	pitch [m]
$P2$	pump 2 [-]
Q	thermal energy [J]
S	spacing between fins [m]
T	temperature [K, ° C]
t	time [s]
V	volume [m^3]
X	adsorbate content (mass of adsorbate by unit mass of dry adsorbent) [$\mathrm{kg_{adsorbate}/kg_{adsorbent}}$]

Greek Symbols

α	angle of the condenser rows
Δ	difference; variance [-]
ρ	density or volumetric mass density or specific mass [kg/m^3]

Subscripts

1	main seasonal storage tank; controller
2	secondary pre-heating tank; controller 2
a	adsorption; adsorbent; adsorbate
c	condensation; condenser; collector; corrected
ct	control function
d	desorption/regeneration
e	evaporation
f	interior or inner fin
H	upper dead band
h	hollow
i	inner
L	lower dead band
o	outer
p	constant pressure; potential
t	tube
w	wall; water
x	horizontal
y	vertical
conv	conventional
evap	evaporator
fext	exterior or outer fin
high	upper input
low	lower input
max	maximum
med	tube’s axis level
min	minimum

List of Abbreviations and Acronyms

ATES Aquifer thermal energy storage

BTES Borehole thermal energy storage

DHW Domestic Hot Water

EU European Union

LHS Latent Heat Storage

PCM Phase change materials

PTES Pit thermal energy storage

SHS Sensible Heat Storage

STES Seasonal Thermal Energy Storage

TES Thermal Energy Storage

THS Thermochemical Heat Storage

TTES Tank thermal energy storage

1. Introduction

1.1. Framework

According to the International Energy Agency - 2021, global energy demand is set to increase by 4.6% in 2021, pushing demand 0.5% above levels registered in 2019, before the COVID-19 pandemic. Due to this increase, demand for all fossil fuels is expected to grow significantly as well. This will in turn increase carbon emissions and worsen the global warming and climate change effects on our planet. To counter these effects and reduce greenhouse gas emissions, there are many directives in place to implement renewable energy systems. In fact, during 2020 a growth in demand was registered for renewables (3%), set to increase across the power, heating, industry and transport sectors in 2021 ("Global Energy Review - IEA" 2021).

The European Commission set a Renewable Energy Directive that defines rules for its member countries to achieve a target of 32% of energy production to be met by renewable sources by 2030, ensuring the energy and climate goals of the European Union (EU) are met. These targets and measures include stimulating investments and driving cost reductions in these technologies, and are set in place in order to reduce greenhouse gas emissions by 55% by 2030. With that in mind, Thermal Energy Storage (TES) systems, and in particular Seasonal Thermal Energy Storage (STES) systems, present themselves as an interesting technology to explore and implement to contribute for these goals. These systems are particularly relevant to hot water production in the residential sector.

Water heating represents 14.8% of final energy consumption in the residential sector in the EU, according to Eurostat. In Portugal alone, the share of the total energy consumption in households for water heating is 17.6%. Adding to this, renewables cover roughly 13% of the energy needs for water heating. Gas is the most used fuel to provide water heating, with 41% of the energy consumed for water heating coming from this source. These values are summarized in Figures 1.1 and 1.2 ("Energy Consumption in Households - Eurostat" 2021).

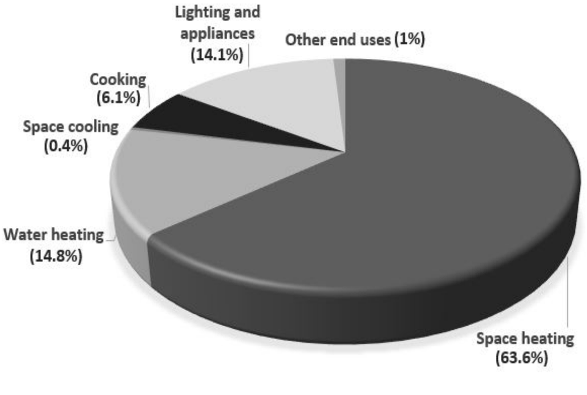

Figure 1.1: Final energy consumption in the residential sector by use in the EU (adapted from Eurostat (2021)).

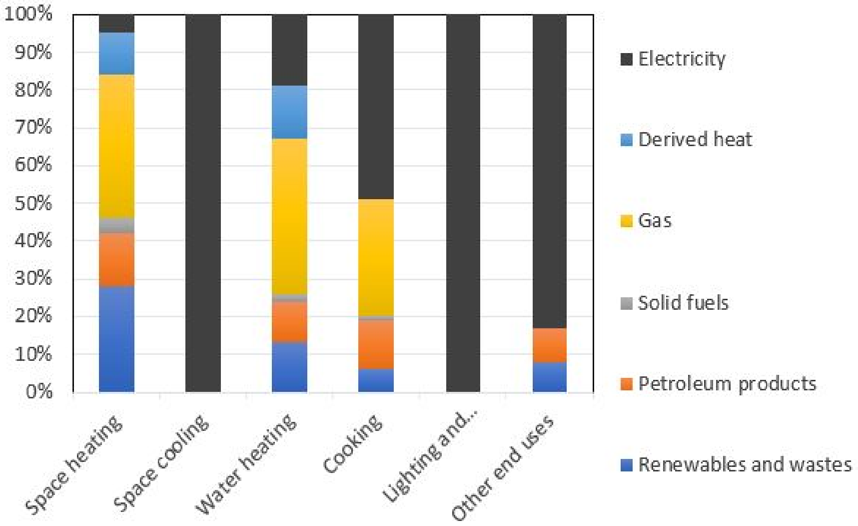

Figure 1.2: Part of the main energy products in the final energy consumption in the residential sector for each type of end-use in the EU (adapted from Eurostat (2021)).

STES concerns the storage of heat over long periods of time. Solar energy, due to its availability and intermittent nature, is ideal for these type of systems. From May to September, the sun supplies the majority (approximately 65%) of the incoming solar energy in Central Europe, which could cover all of the heat demand during this period. However, most of the heat consumption is during the winter months, from October to April, with the sun only covering approximately 7% of this demand. There is then a necessity for storing heat during the hotter months to use in the colder season. To achieve this, STES systems are employed, which are implemented by setting a large collector field to capture the energy from the sun, which is used to charge the stores of the system over the summer months. The energy is released at a later time, during winter, when there is a larger heat demand, either for space heating, or water heating, as is the case with the system modelled in the present thesis. The diagram in Figure 1.3 shows the connection between the supply of solar energy in the summer and the demand during winter ("Guidelines for STES systems in the Built Environment" 2016).

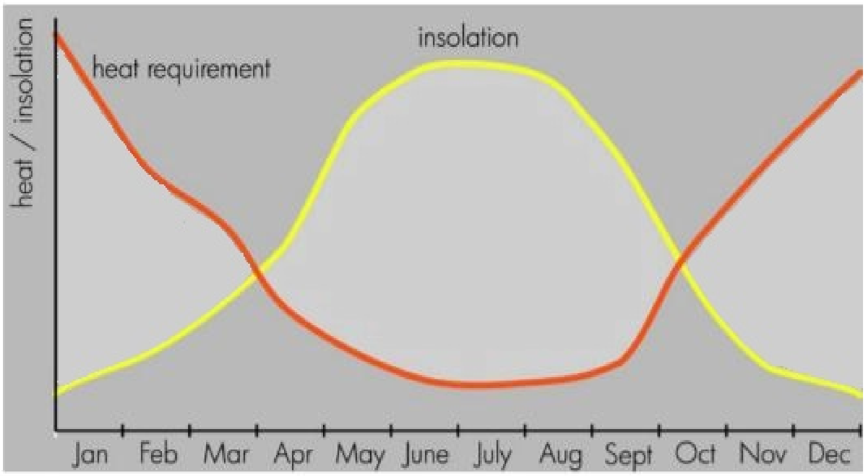

Figure 1.3: Solar heat supply in the summer (middle) and heating demand during the winter (left and right) (adapted from Solites (2016)).

If the targets set by the EU to reduce CO_2 emissions mentioned previously are to be met, then there is a need to make use of seasonal thermal energy storage in the future energy supply of the European Union.

STES systems can be subcategorized in three types: Sensible Heat Storage (SHS), Latent Heat Storage (LHS) and Thermochemical Heat Storage (THS). In the first type, the increase in the system's internal energy is translated directly to an increase of temperature in the storage material. LHS systems, on the other hand, take advantage of the heat released during phase change in the storage materials, such as Phase change materials (PCM). THS systems make use of the heat released during reversible reactions between two substances to promote the storage of energy. Most DHW systems require rather large tanks to store sensible energy. In the case of long periods of storage and low water consumption, this can lead to high temperatures being recorded in the tanks, leading to a decrease in efficiency. In addition, during the winter months, when solar energy is no longer sufficient, a backup system is required to fulfill the heat demand. Considering this, a system that presents minimal thermal losses as well as a high energy density is required.

Adsorption-based thermal energy storage systems have therefore been the object of several studies and research in the past few years, leading to some interesting developments, and making this a promising alternative to conventional DHW systems (Antoniadis and Martinopoulos 2019; Fernandes et al. 2017; Köll et al. 2017; Schreiber et al. 2018). In these type of systems, a heat source promotes the dissociation of two substances that make up the working pair, an adsorbent and an adsorbate. These two substances can stay separated for long periods of time, which promotes the storage of energy. The energy is later released when the substances come into contact again, energy which can be used for heating purposes, such as water heating (Fernandes et al. 2017).

1.2. Motivation and Objectives

This work falls within the scope of the project AdsorTech, with the objective of conducting research into systems that reduce energy consumption from non-renewable sources, and present higher efficiency and minimal thermal losses. In 2017, Fernandes et al. developed a Thermal Energy Storage system provided with an adsorption module, achieving significant results in backup energy savings when considering the case of a family of four people with a given DHW consumption and profile. The objective of the present work is to adapt the previous simulation model developed in TRNSYS to study the performance of seasonal systems.

In the defined system, seasonal thermal energy storage using adsorption works as a supplement to the conventional DHW system. This way, further savings in backup energy use can be achieved. Priority is given to the main DHW storage tank, and once charged, the excess of energy captured by the solar collectors is rerouted to a secondary storage tank, which houses an adsorption system fundamentally working as a heat pump, where energy is stored for later use.

To implement the system described some modifications have to be made to the TRNSYS model, namely the addition of a new tank, as well as a more complex control system. This control system is responsible for activating the charge of the seasonal storage tank:

- when the main DHW tank is itself already fully charged;
- when the water from the mains flows into the seasonal storage tank for pre-heating purposes, only during the designated consumption period (i.e. winter months).

A number of performance metrics are used to assess the system's operation, and assure an optimal configuration for a given case (number of collectors, storage capacity of the tank and seasonal storage period).

As fossil fuels become increasingly more expensive and rare with the growth in global energy demand, and its burning aggravates the issue of climate change, this proposed system presents itself as a promising alternative to conventional DHW systems, and further contributing to the development of adsorption systems, still very immature and limited in marketable applications.

2. Literature Review

2.1. Seasonal Thermal Energy Storage Systems

In order to reduce the carbon footprint, sustainable energy systems are employed, utilising higher shares of renewable energy, integrating storage concepts and a smart coordination between centralised and decentralised supply. However, the dependency of renewable resources on environmental conditions, for example, slows the sustainable energy transformation. Thermal Energy Storage (TES) systems present a solution to collect and store energy from different sources independent of the demand, allowing it to be used later (Bott et al. 2019).

Energy storage can be classified into short-term storage and long-term storage, depending on how long it is intended to store energy. Seasonal Thermal Energy Storage (STES) concerns the storage of thermal energy for periods of up to several months, typically when it is available in large sums, to be used whenever needed most. To compensate for the heat supply insufficiency during the wintertime, excess heat collected in the summer can be used (J. Xu et al. 2014). This way, STES systems hold great promise for storing summer heat for winter use, allowing the seasonal heat demand to be met without resorting to fossil-based fuels as back up (Yang et al. 2021).

The applications of these types of systems facilitate the transition of conventional fossil fuel-based heat supply to alternative, renewable sources such as solar thermal energy, geothermal energy and waste heat from industrial processes. In STES systems, the thermal energy generated from sustainable systems, such as solar collectors which capture the Sun's energy, is harvested and stored during the summer to be used in the winter, accomplishing the coordination of the seasonal mismatch between the heat supply and demand (Hesaraki et al. 2015; Yang et al. 2021).

Solar energy systems are particularly interesting to explore in this context, due to the incompatibility between the energy supply and the consumption, caused by the Sun's energy intermittent nature (Fernandes et al. 2018; J. Xu et al. 2014).

STES systems can be classified into three types: Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Heat Storage (THS), which will be analyzed more carefully in the next few subsections.

2.1.1. Sensible heat storage

The SHS method collects thermal energy and converts it into sensible heat in selected materials, retrieving heat whenever necessary. The material's specific heat and its temperature increase determines the amount of heat stored. It is a simple, inexpensive and relatively mature technology (J. Xu et al. 2014).

The stored thermal energy can be calculated using the following equation:

$$Q = m \cdot c_p \cdot \Delta T \tag{2.1}$$

where m is the mass (kg), c_p is the specific heat capacity at constant pressure (J/kg$\cdot$ K) and ΔT is the temperature change during the charging process (Koçak et al. 2020).

STES technology has mainly been used in space heating and Domestic Hot Water (DHW) supply. For these applications, the temperature ranges from 40 to 80 °C, becoming water, rock-sort materials and ground/soil the most popular solutions for storage media (J. Xu et al. 2014).

Typical SHS systems can be classified into Tank thermal energy storage (TTES), Pit thermal energy storage (PTES), Borehole thermal energy storage (BTES) and Aquifer thermal energy storage (ATES). In TTES systems, thermal energy is stored in tanks with water being used as the main storage medium, while the tanks are usually fabricated in pre-stressed concrete or stainless steel (Dahash et al. 2019; Pinel et al. 2011). These tanks operate using stratification, meaning that the water inside the tank is hotter at the top and colder at the bottom, due to thermal buoyancy. It is a mature and highly-commercialized technology mostly used in small commercial and residential buildings. Its main restrictions consist in space constraints as well as heat destratification, which causes more heat loss in the system (Yang et al. 2021).

PTES systems also use stratification for storing energy, but in this case, the energy is stored in an excavated ground enclosed with watertight lines or in an artificial store constructed out of reinforced concrete or stainless steel below the ground surface, or near to it (Chang et al. 2017; Dahash et al. 2019; Novo et al. 2010). It is a mature technology, presenting high energy density and system efficiency, although it must be insulated efficiently to prevent heat loss. Another barrier to PTES applications which causes higher heat losses is the degradation due to vapor condensation (Yang et al. 2021).

BTES systems store excess heat using the soil and/or rock, with the ground serving as the storage medium. First, the boreholes are drilled into the ground, with a certain depth, and subsequently, U-shaped pipes are inserted in the boreholes, forming borehole heat exchangers, through which a heat transport medium, such as water, passes (Alva et al. 2018; Dahash et al. 2019). The development of these systems is limited by certain barriers such as geological conditions and a very low efficiency in its first years of operation (Yang et al. 2021).

An ATES system stores the collected heat in an underground layer, using a mixture of natural water and ground. Water is chosen as the main storage medium, to avoid contamination risk by chemical hazardous, since the aquifers are permeable. These systems cannot be insulated, a restriction that implies higher heat losses to the ground (Dahash et al. 2019; Pavlov and Olesen 2012). A system of this type requires suitable hydrogeological conditions to implement as well as high thermal loads (Yang et al. 2021).

To sum up, TTES and PTES systems are mature technologies that present a suitable solution as they offer an edge in storage temperature and efficiency due to being insulated. Yet, their applications are limited by space requirements and possibility of leakage. BTES and ATES can be used for both heating and cooling purposes, but present a low thermal conductivity and energy density. In general, SHS technologies are more mature than LHS and THS technologies and are largely commercialized in the current market (Yang et al. 2021).

2.1.2. Latent heat storage

LHS systems use the phase transition of a material (such as the transformation from gaseous, liquid, and solid states) to store thermal energy. The heat is stored in the form of potential energy between the particles of the substance of the storage medium. Systems that employ LHS present an advantage comparatively to SHS systems since they can store the same amount of heat in much smaller volumes. This is because the latent heat of a substance is much greater than its specific heat (Hall 2010).

Using Eq (2.2), we can calculate the thermal energy stored by latent heat:

$$Q = m \cdot L \tag{2.2}$$

where L is the specific latent heat (kJ/kg) (Alva et al. 2018).

Typically, three parts make up a latent energy system: a Phase change material (PCM), where the heat is stored, a surface upon which the heat is exchanged and a container that encloses the material (Hasnain 1998; Lefebvre and Tezel 2017). Examples of PCMs include ice, salts and organic materials.

Soares et al. (2013) concluded that TES systems with PCMs increase indoor thermal comfort by reducing energy demand for heating and cooling as well as heating and cooling peak loads, can take advantage of renewable energy sources and contribute to the reduction of carbon dioxide emissions related to heating and cooling.

Certain systems developed and studied have presented high energy density and a relatively constant temperature during the phase-change process. However, these types of systems have not been commercialized to the same extent as the SHS systems due to a lack of fully commercial PCMs, and to their potential corrosion, flammability, and toxicity, which greatly reduces their usage (Yang et al. 2021).

2.1.3. Thermochemical heat storage

THS is a promising alternative to other storage tecnhologies, as it can overcome the barriers in LHS and SHS systems, presenting high energy storage and low heat losses. Thermochemical storage can be split into two categories: Chemical reaction and sorption storage, which includes absorption and adsorption (Lefebvre and Tezel 2017; J. Xu et al. 2014).

Chemical reaction is based on the principle of reversible reactions between two substances, with the energy being stored through the reaction and then recovered once that reaction is reversed. In order to release the heat and control the reaction, a catalyst is usually required, which is not always desirable, even though chemical reactions provide high amounts of energy per unit volume of material (Lefebvre and Tezel 2017).

On the other hand, absorption occurs when atoms, molecules or ions of a liquid or gas are taken up by the volume of another material. A binary working pair is typically used in the case of THS systems. For absorption systems, the working pair consists of an absorbent and an absorbate, with H_2O-$LiBr$, H_2O-$LiCl$, H_2O-$CaCl_2$, H_2O-$NaOH$ and NH_3-H_2O being commonly used. The concentration of the solution is closely linked with the storage energy density. Hui et al. (2011) concluded that the H_2O-$LiCl$ pair achieves the best storage capacity and efficiency results. However, its further application is restrained by its high price. Absorption systems are suitable for STES since they can store thermal energy in the form of chemical potential energy for long periods, avoiding heat losses. Z. Xu and Wang (2019) proposed absorption seasonal thermal storage cycles with multi-stage output in order to increase the energy storage density, which was possible due to the large concentration glide achieved.

Adsorption relates to the interaction between the atoms, ions or molecules of a fluid and a solid surface. The solid material is the adsorbent, with the adsorption taking place upon its surface, and the gas or liquid is the adsorbate. Typical working pairs are Activated Carbon-Methanol, Activated Carbon-Ammonia, Zeolite-Water and Silica-gel-Water (Fernandes et al. 2017). The adsorption is promoted during the discharge phase, with the heat being released due to the process being exothermic. During the charge phase, heat is supplied to the adsorbent, promoting the separation between the working pair, with the adsorbate being stored separately. This storage occurs without losses, making adsorption systems a very suitable alternative for STES (Köll et al. 2017).

Given the context of this work, in the next sections, Adsorption systems and particularly Adsorption-based STES systems will be covered in more detail.

In general, THS systems provide high energy density and low heat losses, but further studies are required considering that these systems are very difficult to implement and the storage materials present instability problems (Yang et al. 2021).

2.2. Adsorption

Adsorption consists in the adhesion between the atoms, ions or molecules of a surface and a fluid (gas or liquid) or dissolved solid. It is based on either a physical or a chemical reaction.

Physical adsorption, or physisorption, takes place when the interaction between the molecules of the working pair occurs due to van der Waals forces or electrostatic attraction. In this case, the energy released is in the order of magnitude of the latent heat of vaporization. When heat is applied, the adsorbate molecules can be released from the surface of the adsorbent, making this a reversible process.

Chemisorption results from the ionic or covalent bonds formed between the surface of the solid material and the adsorbate. The amount of heat released is generally much bigger in this case, due to the forces in chemical bonds being much greater as well than the forces involved in physical adsorption. Because of this, this is not an easily reversible process, since it is also necessary to provide a huge amount of energy to promote the dissociation of the working pair during the charge phase. Due to this, as well as the fact that chemical reactions promote the chemical alteration of the adsorbate substance involved in the process, most adsorption systems are based on physical adsorption (Fernandes et al. 2014).

2.3. Adsorption systems

Adsorption systems can be split into two categories: open systems and closed systems. In open systems, the passage of air which transports water vapor promotes heat and mass transfer. The working fluid is released directly to the environment. In closed systems, a heat source and a heat sink are needed, with only the condensation heat being released to the environment. They operate on a closed, isolated circuit.

In closed systems, generally made up of an adsorber, a condenser and an evaporator, the process works typically under vacuum, which allows for the vaporization of the working fluid to occur in a temperature range compatible with the system's operation. The system's pressure varies between two established limits, the condensation pressure in the condenser and the vaporization pressure in the evaporator.

The thermodynamic cycle consists then of 2 isosteric phases (constant specific volume) and 2 isobaric phases (constant pressure). The cycle can be represented in a Clapeyron diagram, which can be seen in Figure 2.1. The cycle is composed of the 4 mentioned phases taking place in the following order:

- Isosteric heating phase (1-2)
- Isobaric desorption phase (2-3)
- Isosteric cooling phase (3-4)
- Isobaric adsorption phase (4-1)

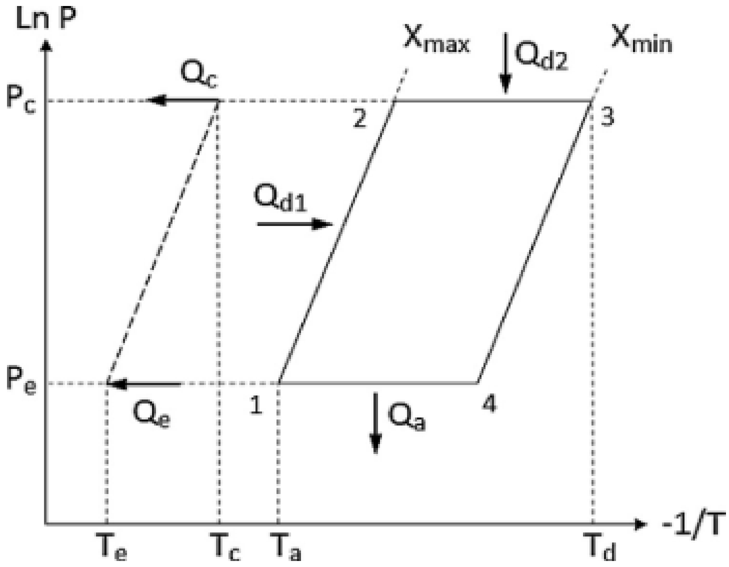

Figure 2.1: Thermodynamic basic adsorption cycle [Fernandes et al. 2014].

In the isosteric phases, the temperature and pressure increase or decrease while the adsorbate content in the adsorbent is constant. In the isobaric phases, the pressure is considered constant, with the first isobaric phase, between points 2 and 3 in the diagram, representing the desorption phase, with the pressure in question being the condensation pressure. Between points 4 and 1, the pressure is the vaporization pressure, with this phase representing the adsorption phase. In order to achieve vaporization, energy (Q_e) is absorbed from the environment by the evaporator. The cycle works intermittently, between the desorption and adsorption phases.

Between 1 and 2, the adsorber receives energy from a heat source (Q_{d1}), with its temperature and pressure increasing (first isosteric phase). The dissociation of the working pair is promoted, with the adsorbate being released in the form of vapour to the condenser, when the condensation pressure, P_c, is achieved. The adsorber continues to receive energy (Q_{d2}) during this phase until the adsorbent possesses the minimum amount of adsorbate. As the vapour condenses, the heat from the condensation, Q_c, is released to the surrounding environment. This corresponds to the desorption phase, or the first isobaric phase.

While the adsorbate is stored in either the condenser or the evaporator, the adsorbent is regenerated, having the minimum amount of adsorbate (X_{min}). This means the system is charged, and will remain as such as long as the connection between the evaporator and the adsorber remains closed. Since the system remains charged under a potential of adsorption, and as long as the working pair remains separated, it is possible to store thermal energy for long periods of time with minimal losses. As the adsorber cools over time (isosteric phase from 3-4), it will eventually reach the vaporization pressure P_e, at which point the connection with the evaporator will be opened, allowing the adsorbate to be fully adsorbed by the adsorbent (X_{max}), resulting in the adsorption phase or the isobaric phase from 4-1. As mentioned previously, the energy necessary for vaporization to take place is removed from the surrounding environment, allowing the transformation from the liquid adsorbate into vapour, at T_e and P_e. Because adsorption is an exothermic process, the energy Q_a is released to the exterior of the adsorber (Fernandes et al. 2017).

The viability of adsorption systems has been studied on several applications, such as cooling systems (Brites et al. 2016; Li et al. 2015; Sah et al. 2017), thermal energy storage systems (Cabeza et al. 2017; Lefebvre and Tezel 2017), heating and cooling hybrid systems (Zhang and Wang 2002) and desalination systems (Wu et al. 2014).

2.4. Adsorption-based Seasonal Thermal Energy Storage Systems

2.4.1. Description and operation

Adsorption-based TES Systems essentially operate on an adsorption heat pump cycle, where a period of interruption takes place between the adsorption and desorption phases, which is when the energy storage occurs. As long as the connection between the adsorber and the evaporator remains closed after the charging phase, this period of energy storage can happen for an indeterminate amount of time. As pointed out before, adsorption does not take place as long as the adsorbate and the adsorbent do not come into contact, allowing for energy to be stored for long periods of time.

A major advantage of this kind of system is the ability to store energy at ambient temperature, since, unlike in a SHS system, it does not result in the system's discharge happening over time due to exchanges with the environment, which is especially beneficial for long-term storage, such as seasonal storage (Fernandes et al. 2017; Pinel et al. 2011). Figure 2.2 offers a visualization of the operation of a TES system employing adsorption technology.

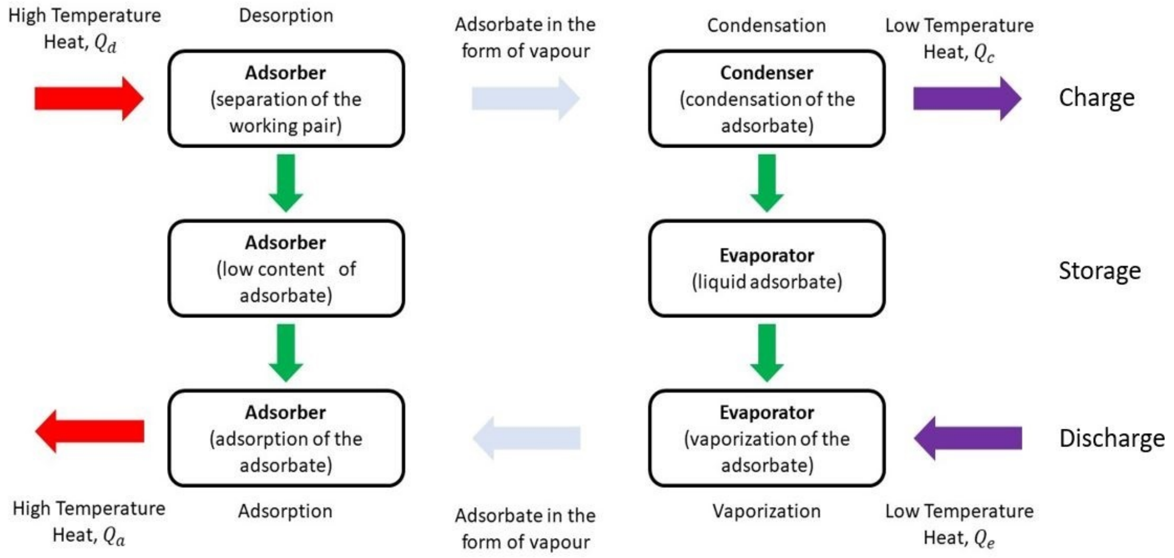

Figure 2.2: Operation principle of an adsorption-based thermal energy storage system (adapted from [Fernandes et al. 2017]).

Charging phase

High temperature heat is supplied to the adsorber, promoting the desorption phase, in which the adsorbate is separated from the adsorbent in the form of vapour. The connection between the adsorber and the condenser is opened as the adsorber reaches the condensation pressure, allowing the adsorbate to be condensed. The condensation heat is then released to the environment surrounding the condenser. The valve is then closed.

Storage phase

The system is considered fully charged when the adsorbent is regenerated, possessing as little adsorbate as possible. The adsorbate is stored in the condenser/evaporator, and as long as the valve connecting the evaporator and the adsorber remains closed, adsorption cannot take place, allowing for thermal energy to be stored as an 'adsorption potential', for long periods of time with minimal losses.

Discharging phase

When the connection between the evaporator and the adsorber is opened, adsorption is instantaneously promoted. The evaporator vaporizes the adsorbate by supplying low temperature heat, typically captured from air in the environment. The heat from the adsorption process is then released, which can then be used for heating purposes.

Solar energy is particularly interesting to explore in the context of STES systems, as previously mentioned, due to the seasonal discrepancy between the heat demand, and the majority of the supply. There is an excess of thermal energy captured by the solar collectors, which can be stored for long periods of time, for later usage during winter, with minimal losses, using an adsorption system.

2.4.2. Working pairs

There are several possible working pairs that can be used in adsorption systems. The selection of this pair needs to be carefully studied, since the system's efficiency and performance will vary with the pair chosen. Factors such as the heat source temperature, the system's predicted features and the properties of the pair's substances should be taken into account when selecting the pair. With this in mind, four different combinations, the more frequently used, are analyzed.

Silica-gel - Water

Silica-gel is typically used for water filtration and for moisture removal from air. This pair possesses low regeneration temperature (around 85 °C), making it a perfect candidate for solar collector applications. It also presents high latent heat of phase change, bigger than methanol and other conventional fluids. However, it has low adsorption capacity, and the fact that to employ this pair in a system, vaccum is necessary, can present an obstacle. Low vapour pressures can restrain mass transfer in silica-gel.

Zeolite - Water

Zeolite is used for water purification and gas separation. This pair presents high stability at high temperatures and has a high latent heat of phase change, but requires efficient heat sources since it possesses a rather high regeneration temperature. Vaccuum conditions are needed, and just as the Silica-gel - Water pair, the low vapour pressures restrain the mass tranfer in zeolite. The high adsorption heat makes it harder to dissipate, a disadvantage in cooling systems, but an advantage in heating and thermal energy storage systems. Systems that employ this pair present low cooling capacity.

Activated Carbon - Methanol

Activated carbon is used mainly for air and mains water purification purposes. Methanol possesses high latent heat of phase change, and the pair presents low regeneration temperatures and low adsorption heat. Methanol also presents a low freezing point, making this pair a very suitable solution for ice production. However, methanol is toxic and flammable, making it a less than ideal adsorbate in situations where leaks might occur. It starts decomposing above 120 °C. Activated carbon possesses low thermal conductivity, which in turn reduces the system's Coefficient of Performance. Vacuum conditions are necessary.

Activated Carbon - Ammonia

Stability at high temperatures and low adsorption heat make this a suitable pair for cooling applications, as well as the high cooling capacity of ammonia. It requires conditions of overpressure, increasing heat and mass transfer and avoiding system infiltrations. Nevertheless, regeneration temperatures can reach 150 °C and ammonia is toxic and corrosive. Activated carbon's adsorption capacity is smaller with ammonia than with methanol.

Due to its availability, low cost, accessibility, low regeneration temperature (which allows the usage of cheaper flat collectors as a heat source instead of more expensive, more efficient ones like evacuated tube collectors), and the fact that water is not corrosive and not toxic, an advantage in case of leaks, the system studied in this work uses the Silica-gel - water pair (Fernandes et al. 2017).

2.4.3. Brief historical background

Interest for THS began in the 1970's, due to the oil crisis that took place. That initial interest eventually faded, with a renewal in the 1990's, and only recently the construction of prototypes with storage solutions due in part to the rise in technologies that use solar energy. There is now a rising interest in sorption-based TES technologies, given the high energy density and low heat losses, calling for further studies due to the difficulty of implementation as well as its immaturity as a solution, compared to SHS and LHS systems (Nan Yu et al. 2013).

In the past, several systems employing adsorption technology for seasonal storage purposes have been implemented, to varying degrees of success. Between 1998 and 2001, the European Union financed the HYDES (High Energy Density Sorption Heat Storage for Solar Space Heating) project, the objective being to develop a seasonal thermal energy storage system using adsorption with high energy density, for DHW production and space heating, using the silica-gel - water pair. The system consisted of several independent storage units (modules), industrially prefabricated and combined to a suitable system on the location. With the financial aid of the European Commission, research work was continued in the project mentioned, which in turn led to the MODESTORE (Modular High Energy Density Sorption Heat Storage) project, also funded by the European Commission. The main improvement of this project consisted in the integration of an evaporator/condenser and a reactor into one single container, enabling the system to operate in a wide variety of applications. For this project, a first generation prototype system was installed in a laboratory in Austria, seen in Figure 2.3, and two new modules were developed (Gartler et al. 2004).

Figure 2.3: Sorption storage tank plant (EV/CO: evaporator/condenser) [Gartler et al. 2004].

In Figure 2.4 we can see the protoype for the second generation module, which integrated the key components into one single container, in order to reduce costs and making installation straight forward. This allows for a vacuum connection between the components to no longer be needed. A reduction in size and weight for the modules was also an objective, which led to the adsorption units being designed smaller as well. U-shaped finned tubes were used to increase the heat exchange. The ratio area to volume is also greater in this second generation prototype, due to the silica-gel area being surrounded by the evaporation/condensation area (Gartler et al. 2004).

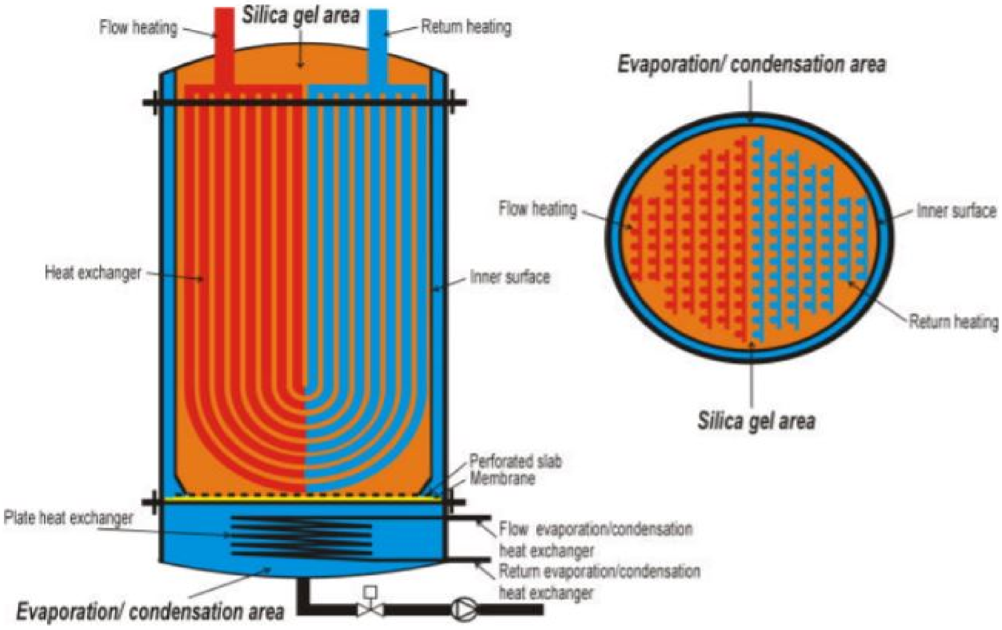

Figure 2.4: Second generation prototype module developed [Gartler et al. 2004].

Schwamberger et al. (2011) conducted a study into a novel adsorption cycle for high-efficiency adsorption heat pumps and chillers, using the zeolite-water pair. This cycle takes advantage of the thermal stratification effect occurring in a storage tank which in turn increases the recovery of internal heat between the desorption and adsorption half cycle. An external heat source is used to preserve this stratification effect. This stratified thermal storage allows for temperature-based extraction and insertion of storage fluid, being hydraulically coupled to a single adsorber. The regeneration of the adsorber is achieved by reusing the released heat of adsorption, which increases overall efficiency.

Using the zeolite - water pair, a seasonal thermal energy storage prototype employing sorption technology was tested (Helden et al. 2014). The system consisted of a tank that possessed the adsorbent element and a heat exchanger in its upper area, connected to an evaporator/condenser at the bottom. It achieved storage densities of 77 kWh/m^3, superior in over 30% to water storage densities between 25 °C and 75 °C, making it a viable system for domestic water heating.

In 2015, Yu et al. developed a prototype and a computational model of an adsorption-based thermal energy storage system using LiCl and activated carbon. It presented a storage density of 874 kJ/kg of consolidated adsorbent, with charging happening at 85 °C and discharging taking place at 40 °C, 4.6 times superior to the storage density presented by water in the same temperature range.

Köll et al.(2017) demonstrated a system for DHW and space heating for a single family house with a heat demand of 30 kWh/m^3 and a living area of 140 m^2 using the zeolite-water pair. An energy density of 178 kWh/m^3 was achieved, which, when compared to a conventional sensible storage energy density, is almost 3 times higher. Also, 83.5% of solar fraction was reached. A schematic of the system design developed can be seen in Figure 2.5.

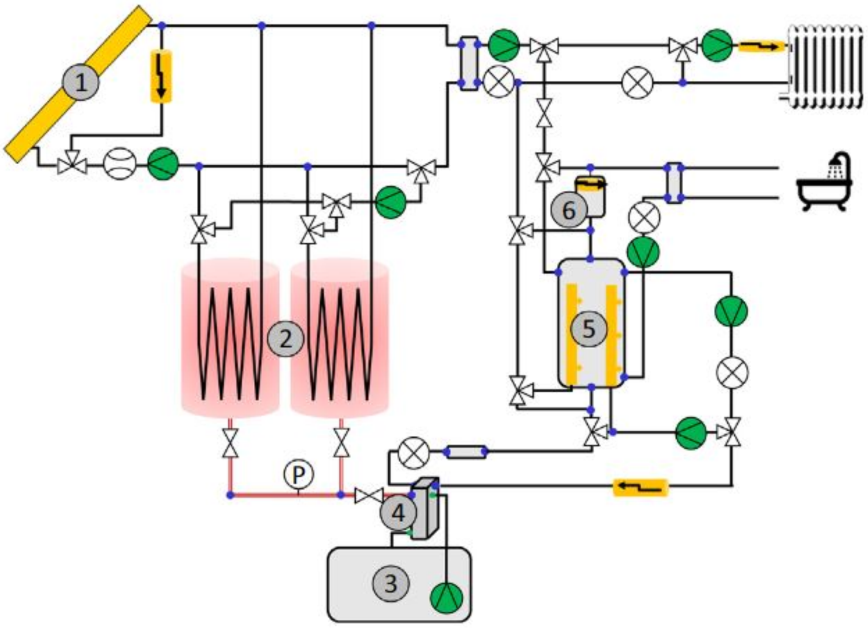

Figure 2.5: Scheme of the demonstration system [Köll et al. 2017].

Solar energy is captured by evacuated tube collectors (1). Two cilindrical tanks are filled with 1 m^3 of zeolite 13XBF (2). Also present in the system are two storage tanks, one with 660 L (5) for space heating and the other with 80 L (6) for DHW. There is also another reservoir (3), used to house water in liquid form, necessary for the adsorption process. Via a piping system, it is connected to a baffle heat exchanger (4), which acts as an evaporator/condenser, with the closed sorption storage working similarly to a heat pump. By providing low temperature heat from a heat source to the evaporator, water vapour is produced, which will flow to the storage and be adsorbed by the dry zeolite during winter. The released heat is extracted by the fixed bed heat exchanger. During summer, the material is dried and the released water vapour flows back to the heat exchanger now acting as a condenser. The condensed water then runs back to the reservoir, where it is stored. The stratified storage acts as buffer for the heat demand and a as heat source/sink for evaporation/condensation.

The work on this thesis is based on a system developed by Fernandes et al., in which the adsorber is placed in the top part of a DHW tank, and the condenser is placed in a secondary tank directly beneath the main DHW tank, with the intent of pre-heating the mains water, essentially working as a heat pump. The evaporator is outside both tanks, extracting energy from the surrounding environment. This way, it works as a combination between conventional storage systems and adsorption-based solar refrigeration systems (Fernandes et al. 2017). The schematic for this system can be seen in Figure 2.6.

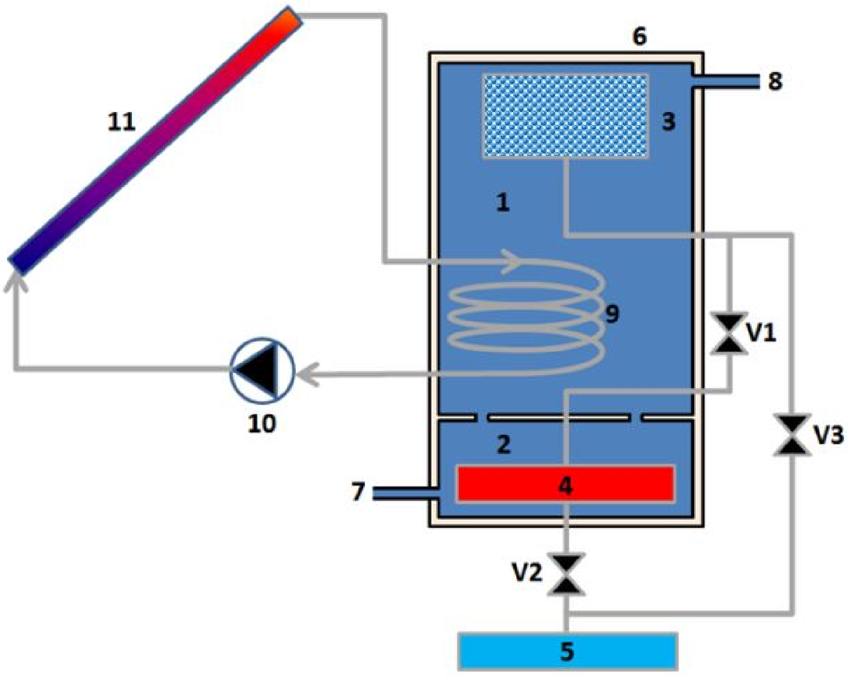

Figure 2.6: Schematic of the solar thermal energy storage system provided with an adsorption module 1 - Storage tank; 2 - Secondary pre-heating tank; 3 - Adsorber; 4 - Condenser; 5 - Evaporator; 6 - Thermal insulation; 7 - Mains water; 8 - DHW outlet; 9 - Solar coil; 10 - Solar circuit pump; 11 - Solar collectors; V1, V2, V3 - operating valves [Fernandes et al. 2017].

Energy from the air or surrounding environment is captured and then later released in the adsorber and/or condenser for the production of DHW. The sensible heat losses from the adsorber are in this way recovered to heat up the water in the tank, effectively increasing the system's efficiency. With this in mind, it is this work's objective to adapt this system into a seasonal thermal energy storage system, implementing a new main DHW tank, with the adsorption system being used to store energy in excess in the summer, for later usage in the winter, in a secondary seasonal storage tank.

3. Modelling of the Seasonal Storage System

To overcome the mismatch between the available solar energy during summer, and the heat demand in winter, an STES is proposed, provided with an adsorption module. To that end, two tanks will be employed, one for short term storage, and the other for long term storage. The first tank ensures the DHW needs for a single family house of four people throughout the year, having a capacity of 250 L. Priority is given to this tank, with the thermal fluid heated by the solar collectors flowing via a valve to a heat exchanger placed inside the DHW tank, ensuring heat transfer to the water flowing into the tank from the mains. Once this tank is charged, the flow of solar fluid is redirected to the secondary seasonal storage tank. Figure 3.1 shows a basic schematic of the system proposed.

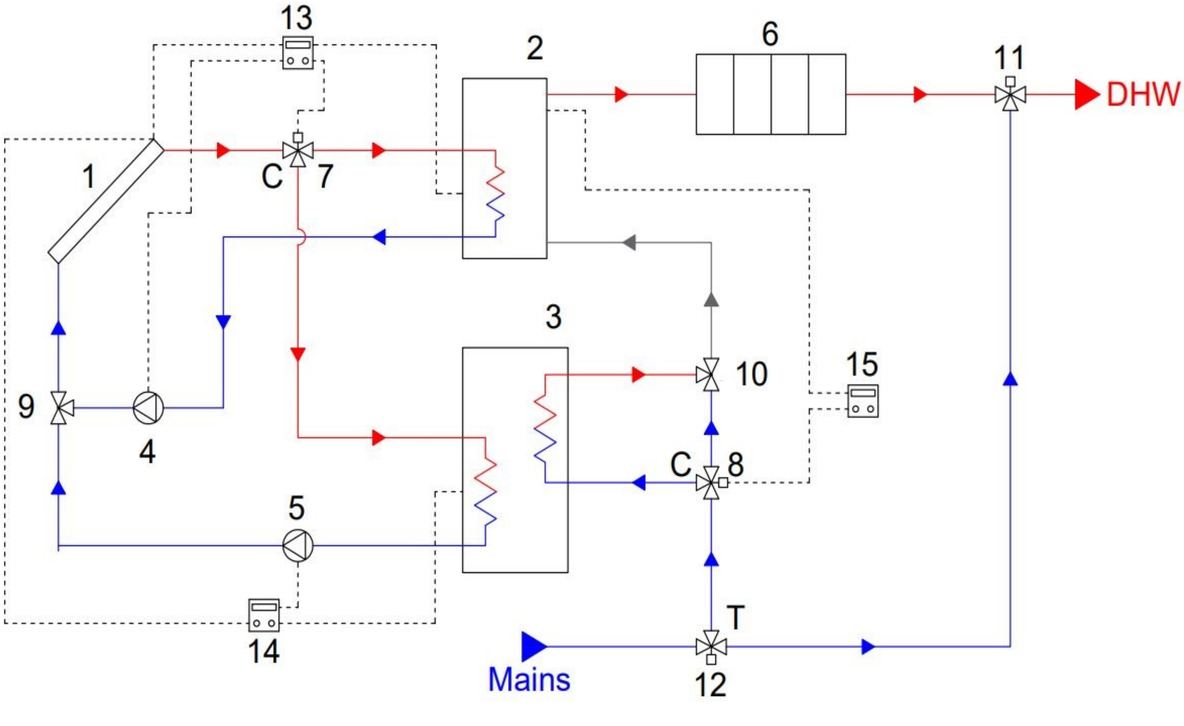

Figure 3.1: Schematic of the Seasonal Thermal Energy Storage System with its main components. (1) solar collectors; (2) DHW tank; (3) Seasonal storage tank; (4), (5) Pumps; (6) the auxiliary electrical heater; (7), (8) Flow control valves; (9), (10) Tee-pieces; (11) Thermostatic mixing valve; (12) Temperature control valve; (13), (14) and (15) Differential controllers for pumps and valves.

The adsorption system, working essentially as a heat pump, is placed within the seasonal storage tank, in order to increase efficiency and diminish thermal losses. Excess heat is stored during the hotter months, and during the winter a secondary consumption circuit is in place to reroute water from the mains to the seasonal storage tank whenever the temperature from the main DHW tank drops below a certain level. Since in practice a heat exchanger is needed, this simulation model means that the seasonal storage tank acts as a perfect heat exchanger, effectively pre-heating the water which then flows to the main tank, avoiding or, at least, reducing the necessity of the water being heated via the external backup electrical heater. The adsorption system itself is composed of an adsorber, placed at the top of the seasonal storage tank, to take advantage of the stratification effect, a condenser set within a secondary tank placed directly beneath the seasonal storage tank for pre-heating purposes, and an evaporator, outside the tank, removing energy from a low temperature source. Both the adsorption and desorption processes, and the charging and discharging of the seasonal storage system are controlled by a set of valves. A detailed description of the adsorption system and its components is given in the next section.

3.1. Description and operation of the adsorption storage system and its components

Figure 3.2 shows a schematic representation of the secondary seasonal storage circuit only. When the seasonal storage tank is being charged, the thermal fluid passes through a heat exchanger inside the tank, with energy being transferred to the water inside. Once the water reaches a certain temperature level, heat is transferred to the adsorber. The adsorber contains the adsorbate and the adsorbent, in this case water and silica-gel respectively. As the adsorber is heated, the dissociation of the working pair is promoted, with the adsorbate flowing to the condenser, drying the adsorbent. Since the condenser works fundamentally as a heat sink, the adsorbate that left the adsorbent in the form of vapour, passes through valve V1 and is condensed here, with the heat released being used to pre-heat the water coming directly from the mains in the pre-heating tank. Water then flows to the evaporator through valve V2, where it is stored as long as the valve between the evaporator and the adsorber (V3) remains closed. Thermal energy is then stored as a potential of energy, with very minimal losses.

Whenever necessary, valve V3 is opened, allowing the passage of the adsorbate back to the adsorber. During this phase, the adsorbate is in its vapour form. The evaporator extracts heat from its surroundings, vaporizing the water. Adsorption then takes place as the two substances of the working pair come back into contact, with the heat of the process being released to the water inside the seasonal storage tank, as long as it is at a lower temperature than the adsorber.

The main seasonal storage tank consists of a conventional cylinder water tank, with a solar heat exchanger inside, as well as the adsorber, and remaining necessary connections between components (Figure 3.2). A secondary tank housing the condenser is placed beneath the seasonal storage tank, where water from the mains enters and is pre-heated by the condenser operating as a heat sink. During the winter, when the temperature from the main DHW tank falls below a certain level, water from the mains is redirected to this seasonal storage tank, where it will be heated by the hot water there stored, following then its course to the main DHW tank via a tee-piece valve.

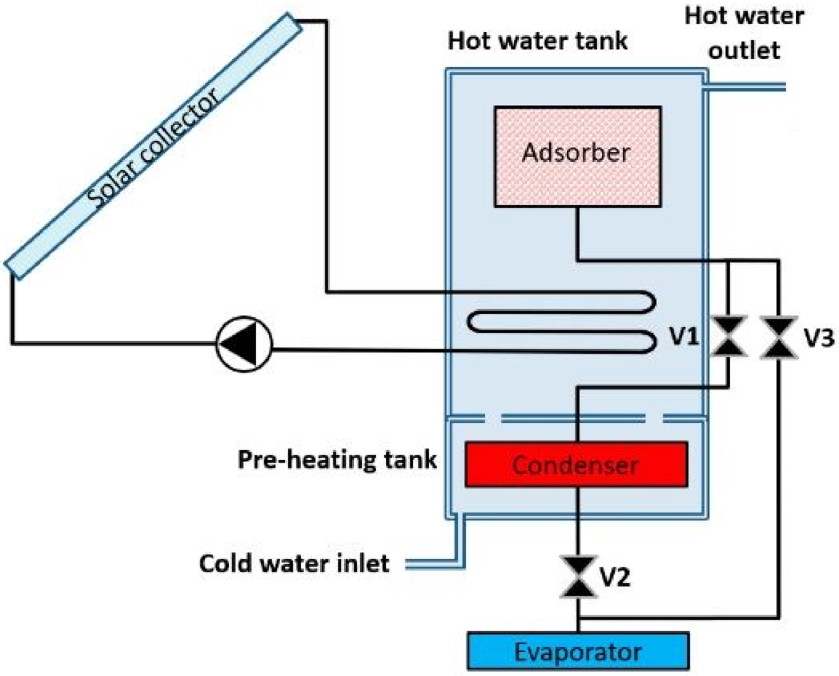

Figure 3.2: Solar thermal seasonal storage circuit with the adsorption module (Fernandes et al. 2019).

3.1.1. Seasonal storage tank

The original TRNSYS type developed with adsorption module (Fernandes et al. 2017) will be used to model the seasonal storage tank. In this tank, the water may be stationary for long periods, thus not proper for DHW. Therefore, a second heat exchanger would be required inside the storage tank, through which the mains water would enter, gather the stored heat, and be routed to the short term DHW tank, during winter. However, since the referred TRNSYS type does not allow a second heat exchanger, it is considered in this work that the mains water enters the seasonal storage tank and mixes with the hot water there stored, thus operating as a perfect heat exchanger.

3.1.2. Secondary pre-heating tank

The secondary tank set directly beneath the seasonal storage tank also consists of a conventional vertical cylinder water tank, albeit with smaller dimensions. The diameter remains the same, but the height is altered to ensure that the storage capacity is always 25% of the capacity considered for the main seasonal storage tank. Figure An.1 in Annex A shows a representation of the two tanks.

3.1.3. Adsorber

The adsorber, where adsorption takes place, is essentially a finned metallic cylinder. In its interior, it houses the adsorbent (silica-gel), itself traversed by longitudinal fins to increase heat transfer between the cylinder and the material. In its central area, there is a hollow section, where water vapour flows. The adsorbent bed is fixed by means of a perforated steel plate. It also fixes the adsorbent, separating the bed from the hollow section. The adsorber is connected to a metallic tube, one side leading to the condenser, and the other to the evaporator. To take advantage of the stratification effect occurring inside the tank, the adsorber is set horizontally, near the top. Figure 3.3 displays the adsorber.

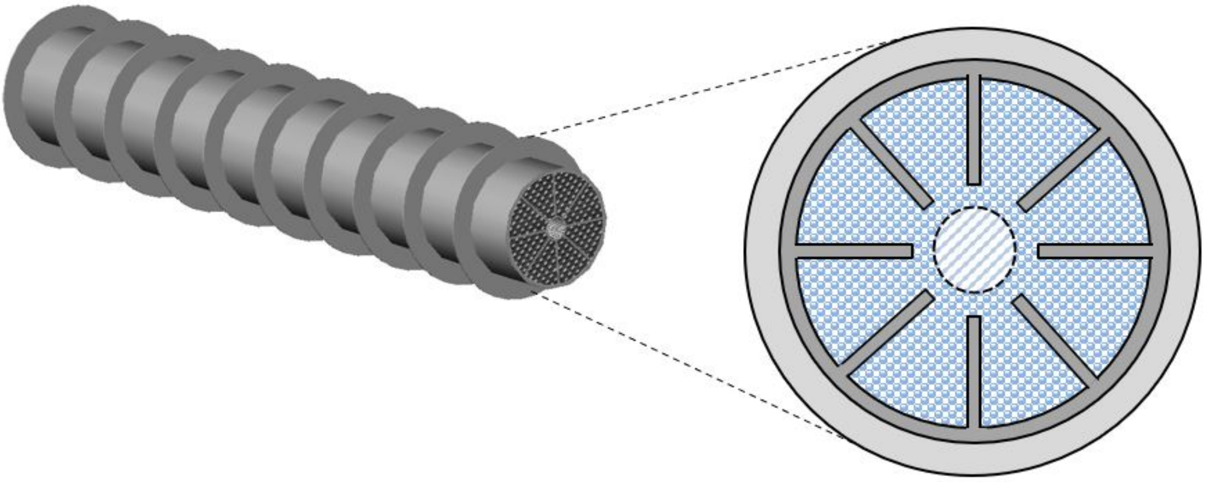

Figure 3.3: Adsorber component placed within the seasonal storage tank.

A previous parametric study (Fernandes et al. 2018) demonstrated that a slender and lengthy adsorber is desirable, with a large number of thin fins. The thinner the fins, the more can be placed for a fixed length of the adsorber, increasing the surface area of heat exchanging, and subsequently overall system efficiency. The number of external and internal fins considered for the various configurations tested and simulated are the maximum values that allow for a 10 mm spacing between the outer fins, and 6 mm spacing between the tip level of the inner fins. The hollow section diameter is considered to be 25% of the adsorber inner diameter. These assumptions are also considered in the present study.

3.1.4. Condenser

The condenser is a helical metallic tube, functioning as a heat sink, immersed in the secondary pre-heating tank. The water vapour flowing from the adsorber is condensed here, during the desorption phase (energy charging phase). The condensation rate is higher in this setup, due to the high water-side convection coefficient, and the condensation heat released is used to preheat the mains water, increasing system efficiency (Fernandes et al. 2016). Figure 3.4 shows the condenser housed inside the secondary pre-heating tank.

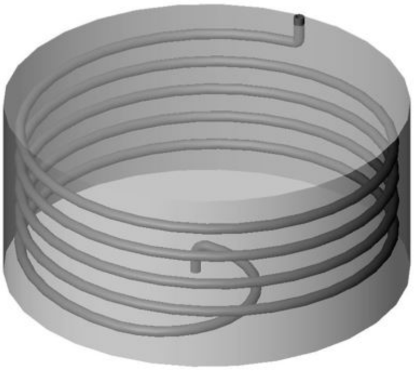

Figure 3.4: Condenser inside the secondary pre-heating tank.

Fernandes et al. (2018) showed that a thick and lengthy condenser leads to better results. The volume of the secondary pre-heating tank is always considered 25% of the main seasonal storage tank, therefore, the water volume present inside the secondary tank is dependent on the volume occupied by the condenser.

3.1.5. Evaporator

The evaporator is composed of a set of vertical tubes with rectangular longitudinal fins. These fins increase the surface area of heat convection from the surrounding environment. Its total diameter is equal to that of the seasonal storage tank. The bigger the number of tubes, the more facilitated is the vaporization process.

The volume of the evaporator is such that it is able to store all of the adsorbate present in the system. Figure 3.5 shows a representation of the evaporator.

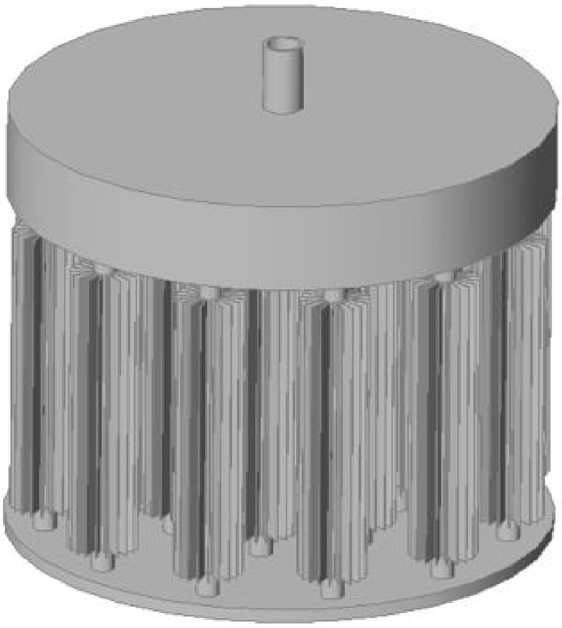

Figure 3.5: Evaporator.

As with the previous components, the parametric study conducted by Fernandes et al. (2018) showed that a large number of lengthy tubes increases heat transfer of the heat exchangers and the mass of adsorbent, as this leads to larger water tanks (larger cross-sections, thus shorter for the same volume). The study also concluded that for smaller tube diameters, and taller external fins, heat exchanging surface area is bigger, thus increasing system performance.

3.2. Dynamic modelling of the Seasonal Thermal Energy Storage System

As with the system developed by Fernandes et al. (2017) in TRNSYS, the STES system with the adsorption module incorporated is modelled. TRNSYS is a simulation program developed at the University of Wisconcin, that possesses a varied library of components used in energy systems, such as thermal energy storage, heating, ventilation and air conditioning and combined heat and power systems. It is split into two parts: one that reads and processes the input data, solves the system in an iterative manner and determines the convergence and outputs of the system; and a library of components, or types, that allows the user to specify the equipments that make up the system, as well as the way all of them are connected between each other ("TRNSYS 17" 2012).

However, TRNSYS lacks a type that allows the simulation of adsorption. Nevertheless, it has a function to 'Call MATLAB', which permits the user to use a component modelled using the MATLAB software. Therefore, Fernandes et al. (2017) modelled the tank with the adsorption system described in section 3.1, by inputing the balances of energy and mass of each component into MATLAB. For this work, that same type was used to model the seasonal storage tank.

The mathematical model of the adsorption system and its components, as well as the numerical model, are described in detail in Fernandes et al. (2017). For the purposes of this work, only certain geometrical parameters of each component were adjusted to suit any alteration in the STES system configuration, following recommendations based on the conclusions of posterior work (Fernandes et al. 2018, Fernandes et al. 2019). The geometrical parameter equations of each component can be found in Annex A.

In order to adapt the developed DHW system into a STES system, a new tank model was implemented. Based on the work of Antoniadis and Martinopoulos (2019), who developed a solar thermal system for seasonal energy storage purposes integrated on a building in Greece. This system is composed of two tanks, one for DHW, and the other for STES for space heating. Priority is given to the DHW tank, with the other tank being charged only once the former is fully charged. The system is controlled by a complex set of valves and differential controllers. In this case, both tanks aim to fulfill the DHW needs of a single family house, with the seasonal storage tank acting as a backup to the conventional auxiliary electrical heater, during the season with higher heat demand (winter).

3.2.1. TRNSYS model

The implemented TRNSYS model for dynamic simulation can be found in Figure 3.6. A weather file contains information regarding hourly mean temperature levels, solar energy and mains water temperature for a selected location. Solar energy is captured by flat-plate collectors (type 1), and transferred to the thermal fluid that then flows to the flow diverter (type 11f). This diverter is responsible for directing the flow to either the DHW tank (type 60c) or the seasonal storage tank (type 463, developed in MATLAB, with tank each divided into 3 nodes). Since priority is given to the DHW tank, thermal fluid is only rerouted to the seasonal storage tank once the former is charged. To that end, a differential controller is used (type 2b), which is directly linked to the flow diverter. This controller receives inputs of the fluid temperature exiting the collector, T_{high}, and the temperature of the water on the bottom node of the DHW tank, T_{low} . The difference of temperature is measured and compared with two predefined dead band temperature differences, generating an output control function which may be ON (1) or OFF (0). These dead band temperature differences are ΔT_H and ΔT_L. In case that the last controller status was off, it will be on when:

$$T_{\text{high}} - T_{\text{low}} \geq \Delta T_{\text{H}} \tag{3.1}$$

It shall remain on until:

$$T_{\text{high}} - T_{\text{low}} \leq \Delta T_{\text{L}} \tag{3.2}$$

The controller will also monitor the outlet temperature, that is, the temperature of the water exiting the tank. If it surpasses a certain limit, the output control function will be 0, shutting down the Pump (type 3).

When the controller is on the flow diverter will deviate all of the fluid exiting the collectors towards the DHW tank. Once the controller is shut off, the valve diverts the flow onto the other tank, effectively charging it, as long as Pump 2 (type 3) is on. A tee-piece (type 11h) is used to connect both circuits back to the collectors, since two outputs cannot be linked to the same input.

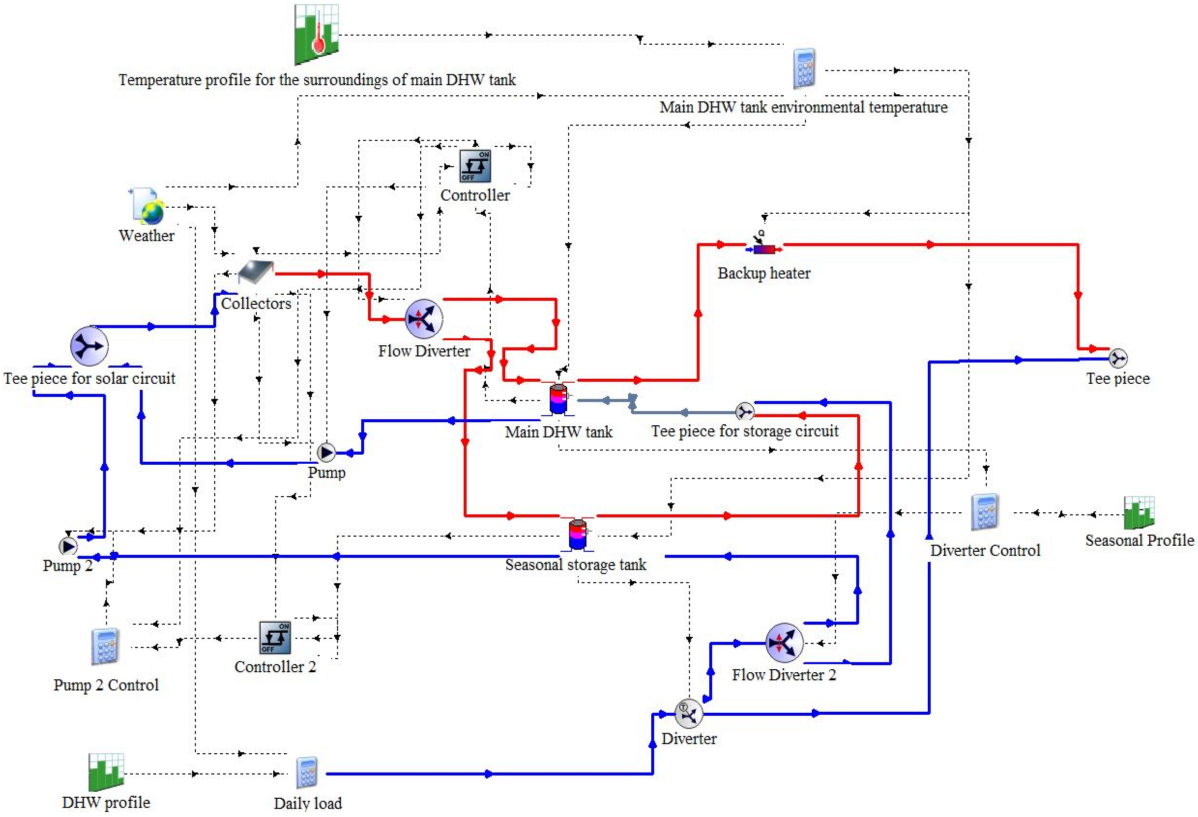

Figure 3.6: STES system modelled on TRNSYS. Continuous lines represent flow of fluid and dotted lines represent flow of information.

A second controller (type 2b) functions exactly as the first, receiving inputs from the fluid exiting the collectors as well as the temperature of the water on the bottom node of the seasonal storage tank. The differences are measured and compared to a set of predefined dead band temperature differences, generating output control functions, just as with the previous controller. This controller activates Pump 2 whenever the flow is redirected towards the seasonal storage tank, and only then, remaining off whenever the DHW tank is being charged. To ensure this, the output control functions of both controllers are linked to an equation type (Pump 2 Control), to guarantee that when one pump is working, the other is off. May the output control function of the first controller be C_1, and the output control function of the second controller C_2. The following equation establishes a new output, $P2_{ct}$, which when linked to Pump 2 certifies that it is only turned on when the other pump is off:

$$P2_{\mathrm{ct}} = C_2 \cdot (1 - C_1) \tag{3.3}$$

The flowchart presented in Figure 3.7 shows the operation of the pumps and their respective control.

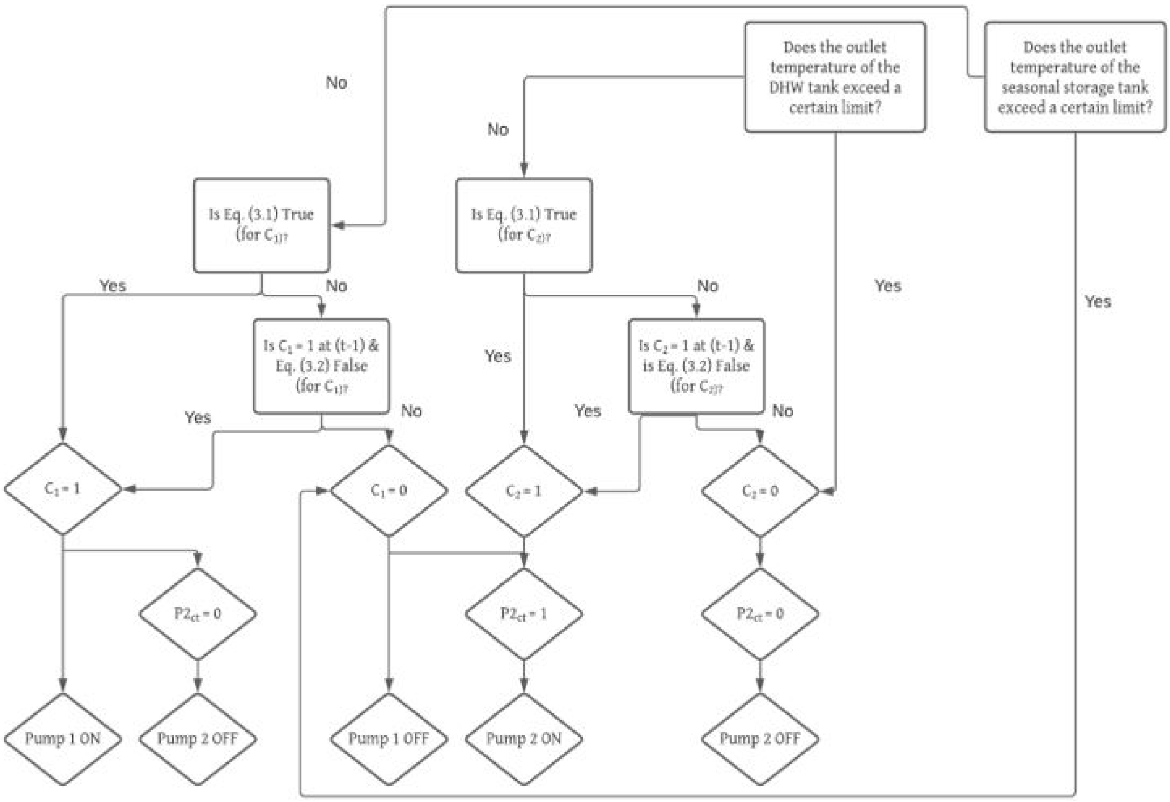

Figure 3.7: Flowchart of operations for the control of the pumps.

The environmental temperature of each tank is given by another equation type. It is assumed that both tanks are situated in a space with no environmental control. A single temperature profile was modelled (type 14), considering the tanks are in the same room, with a temperature of 20 °C during winter and 25 °C during summer. This temperature profile shall be T_{int}. Another input is the dry bulb temperature given by the weather file, which shall be T_{env}. In accordance with REH (2013), the environmental temperature in a space with no environment control (T_{NCS}) is given by:

$$T_{\text{NCS}} = T_{\text{env}} + (1 - b_{tr})(T_{\text{int}} - T_{\text{env}}) \tag{3.4}$$

b_{tr} is the coefficient that relates the temperature of an air-conditioned space with that of a non-air-conditioned one. An intermediate value of 0.5 was considered.

A DHW profile is implemented by means of another type 14, which is linked to another equation type, which defines the temperature of the mains water, as well as the expected flow rate based on the consumption profile. The water will flow towards Flow Diverter 2 (type 11f), which directs it to either one tank or the other. The control of this valve is accomplished by equation type 'Diverter Control', which has two inputs: a seasonal profile, and the outlet temperature from the DHW tank. The mains water is only directed to the seasonal storage tank when:

- the seasonal storage tank is charged;
- the exiting temperature of the main DHW tank falls below a certain level.

To ensure the charge of the seasonal storage tank, a seasonal storage profile is implemented. For the first tests, a period of storage between the beginning of april and the end of september was considered, with this period being adjusted in later configurations to optimize results. Considering this, the seasonal storage tank can be used to heat up water from the mains, which then exits the tank outlet towards the tee piece for storage circuit (type 11), between the months of october and march.

Hence, during winter, water from the mains can enter the DHW tank directly, bypassing the seasonal storage tank, or it can be pre-heated in the seasonal storage tank by being redirected by the flow diverter, reducing the use of backup energy provided by the electrical heater (type 6), should the temperature of the DHW tank fall below a certain level, considered in this case to be 50 °C.

4. Results and Discussion

After implementing the model, several different configurations were tested in order to determine the one that allows to obtain the best results, first for the conventional system, and then for the system with the adsorption module implemented. For the present study, a single-family house of four people in Lisbon (38.73° N, 9.14° W) was considered. The DHW profile considered for this case is present in Appendix A, in Figure Ap.1, based on the profile utilized by Fernandes et al. 2017. A consumption of 40 litres per occupant was considered.

The solar collectors used have an aperture area of 2.43 m^2, an optic efficiency of 0.794, an efficiency slope of 3.863 $\mathrm{W/m^2 \cdot K}$ and an efficiency curvature of 0.013 $\mathrm{W/m^2 \cdot K^2}$. The collector's inclination angle is 37.8°.

During the simulations, a setpoint temperature of 45 °C for consumption was used. If the water exiting the DHW is lower than this value, then backup is necessary, either by the seasonal storage tank acting as a pre-heater or by the backup electrical heater. An upper dead band temperature difference of 6, and a lower dead band temperature difference of 2 were used in the differential controllers, in accordance with reccomendations in "Guia para Instaladores de Colectores Solares" (2004).

4.1. Performance metrics and first sensitivity analysis

To better study the performance of the system modelled, a set of different performance metrics were used. Considering the main objective of the present work is to develop a system that reduces the necessity to use backup auxiliary energy from a conventional source, the equation that expresses the annual energy savings obtained from a system with the adsorption module relatively to a conventional system is:

$$Q_{\text{savings}} = Q_{\text{backup, conv}} - Q_{\text{backup, ads}} \tag{4.1}$$

where Q_{savings} represent the absolute savings in backup energy or heat (MJ), $Q_{\text{backup, conv}}$ is the backup energy necessary in the conventional system (MJ) and $Q_{\text{backup, ads}}$ is the backup energy necessary in the system with the adsorption module (MJ). To obtain the relative savings, one must divide the absolute savings by the backup energy obtained for the conventional system. Another metric used was the renewable fraction, expressed in the equation below:

$$f_{\text{REN}} = \frac{Q_{\text{solar}} + Q_{\text{evap}}}{Q_{\text{solar}} + Q_{\text{evap}} + Q_{\text{backup}}} \tag{4.2}$$

where f_{REN} is the renewable fraction, Q_{solar} is the solar energy transferred from the thermal fluid to the water inside the seasonal storage tank by way of the heat exchanger inside the tank (and therefore given as the difference between the energy input from the heat exchanger and the thermal losses from the tank) and Q_{evap} is the energy removed from the environment by the adsorption module's evaporator to vaporize the adsorbate

(Q_{evap} is obviously not considered for the calculation of the renewable fraction for the case of the conventional system).

The energy density of the conventional seasonal tank and the one with adsorption module will also be assessed. The conventional system is a Sensible Heat Storage system, and, therefore, the thermal energy stored is given by equation 2.1. To obtain the energy density, one must simply divide by the volume of storage, as given by the following equation:

$$E_d = \rho \cdot c_p \cdot \Delta T \tag{4.3}$$

where E_d is the energy density and ρ is the volumetric mass or density of the storage material (kg/m^3). However, since the system with the adsorption module comprises two distinct storage materials, which store energy by way of different phenomena, the overall energy density is not so simple to calculate. By considering only the adsorbent medium, the energy density can be obtained by dividing the adsorption energy released considering the weighted average duration of each discharge period, which is variable, by the volume of the adsorber:

$$E_{d,ads} = \frac{Q_{ads}}{V_{ads}} \tag{4.4}$$

where Q_{ads} is the weighted average of the energy released by the adsorber for the analyzed period and V_{ads} is the adsorber volume.

Thus, in order to compare the global energy density of both systems, a specific heating potential is defined in this work. This parameter is the amount of energy supplied (or amount of water that the STES system can heat) by unit of volume, i.e., the difference between the energy removed by the seasonal storage tanks outlet and the energy entering the tank via the inlet (cold water inlet), divided by the total storage volume, as given by equation 4.5. This difference represents the heat supplied to the water, both solar and by way of adsorption during the discharging process.

$$\Delta Q_p = \frac{\sum[(\dot{m}_{out} \cdot c_{p_{out}} \cdot T_{out} - \dot{m}_{in} \cdot c_{p_{in}} \cdot T_{in}) \cdot dt]}{V} \tag{4.5}$$

where ΔQ_p is the specific heating potential, $\dot{m}_{out}$ is the flow rate, $c_{p_{out}}$ is the specific heat and T_{out} is the temperature of the water exiting the tank via the outlet, $\dot{m}_{in}$ is the flow rate, $c_{p_{in}}$ is the specific heat and T_{in} is the temperature of the water entering the tank from the mains, and dt is the time at each instant or timestep. V represents the volume of the seasonal storage tank in this case.

A sensitivity analysis was performed on the storage capacity of the conventional seasonal storage tank (i.e., without adsorption module), with 3 different volumes being considered: 3000, 4500 and 6000 L. The volume of 250 L for the DHW tank was maintained from the previous work (Fernandes et al. 2017), while the volume for the seasonal storage tank was assessed in a first phase of this analysis. For this first analysis, a period of storage between April and October (and therefore, of utilization of the seasonal storage tank between November and March), as well as 5 collectors (or 12,15 m^2) were considered. Previous analysis conducted using a type 60c to simulate the seasonal storage tank showed that using 5 collectors provided better results. The results are presented in Figure 4.1.

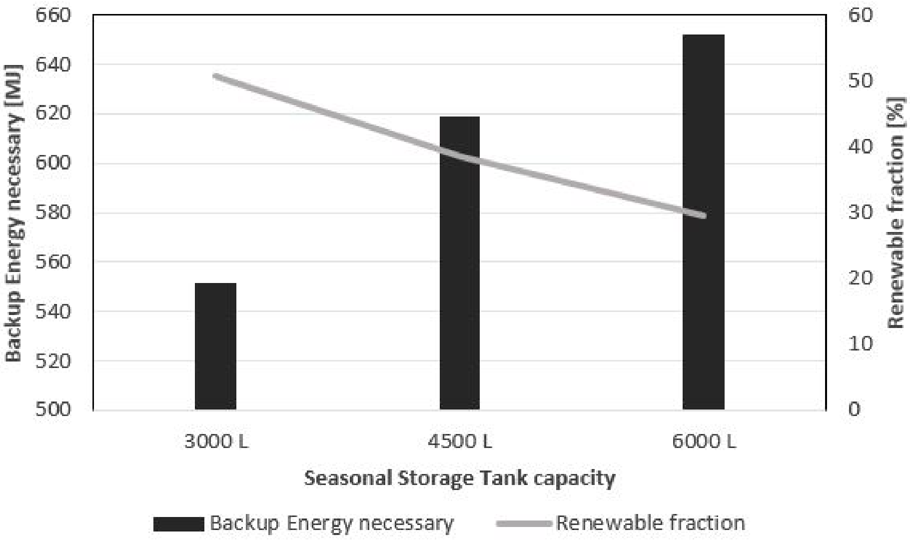

Figure 4.1: Variation of the annual backup energy and renewable fraction for different storage capacities of the seasonal storage tank, for a conventional system with 5 collectors and a storage period from April to October.

The increase in the storage capacity leads to greater values of backup energy necessary to heat water for consumption. While there is only a difference of approximately 30 MJ between the system with 4500 L of and the one with 6000 L of seasonal storage capacity, the system with 3000 L allows for savings of more than twice as much in comparison with the system with 4500 L (approximately 70 MJ). In addition, the renewable fraction also decreases with an increase in storage capacity. While results showed that thermal losses were more or less the same for the different configurations, the decrease in the energy transferred from the heat exchanger to the water inside the tank, as well as the increase in backup energy necessary, lead to lower renewable fractions. Therefore, for further analysis, a seasonal storage capacity of 3000 L was considered.

4.2. Performance analysis for different configurations

4.2.1. Number of collectors

Initially, 5 collectors were considered for the previous analysis. However, due to the still relatively low renewable fractions obtained for the system with 3000 L of seasonal storage capacity, a second sensitivity analysis is conducted regarding the number of collectors, adjusting, for each configuration, the flow rate of thermal fluid in each pump. The performance of the adsorption system is also assessed during this analysis. Figure 4.2 shows the variation of the annual backup energy for a different number of collectors (5, 6, 7 and 8) for both configurations, with and without the adsorption module.

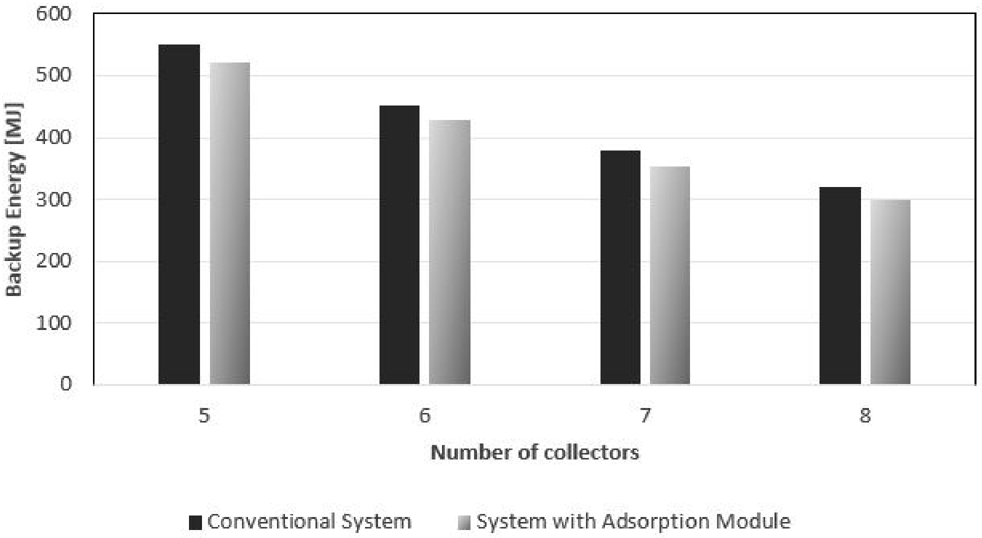

Figure 4.2: Variation of the annual backup energy for a different number of collectors, for the conventional system and the system with the adsorption module.

As expected, the higher the number of collectors, the smaller the amount of backup energy necessary for both systems. However, as the number of collectors increases, the gap of backup energy necessary between configurations decreases. For example, for the conventional system, increasing the number of collectors from 5 to 6 decreases backup energy used by approximately 100 MJ, but an increase from 7 to 8 allows for savings of approximately half as much. To better compare the two configurations, Figure 4.3 shows absolute and relative savings.

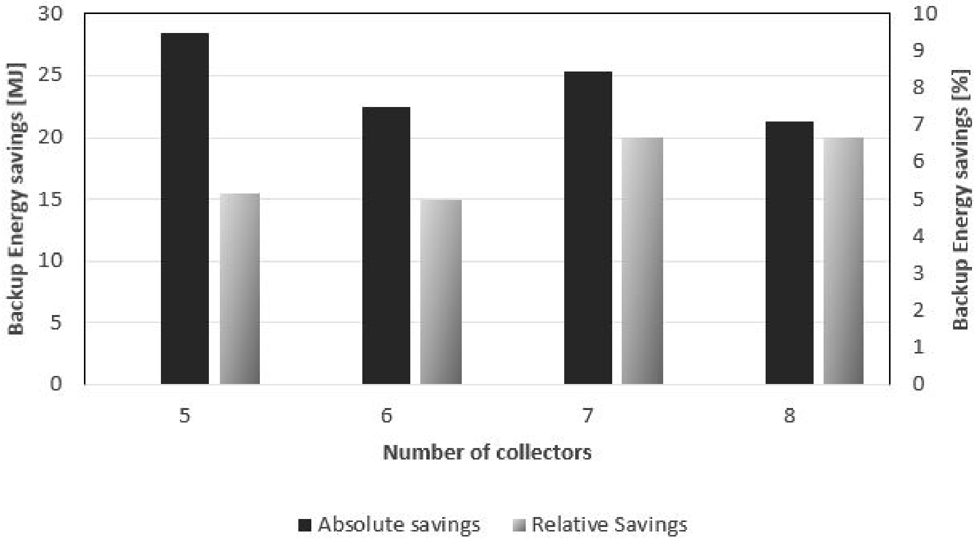

Figure 4.3: Variation of the annual backup energy savings, both absolute and relative, for a different number of collectors, for the system with the adsorption module in comparison with the conventional system, considering a storage capacity of 3000 L and a storage period from April to October.

The configuration with 5 collectors allows for bigger absolute savings, followed by the configuration with 7 collectors, which itself presents bigger relative savings. The configuration with 8 collectors presents the lowest absolute savings, but the second best relative savings.

Figure 4.4 shows the variation of renewable fraction for both configurations for the different number of collectors considered. Since the backup energy required to heat water decreases with the increase of the number of collectors, and more thermal energy is transferred from the heat exchanger to the water inside the seasonal storage tank, the renewable fraction also increases, despite the fact that there are also more thermal losses (more solar energy is being wasted since the system [with or without adsorption module] cannot store the bigger energy input due to the increase in collectors, since the storage volume is kept constant).

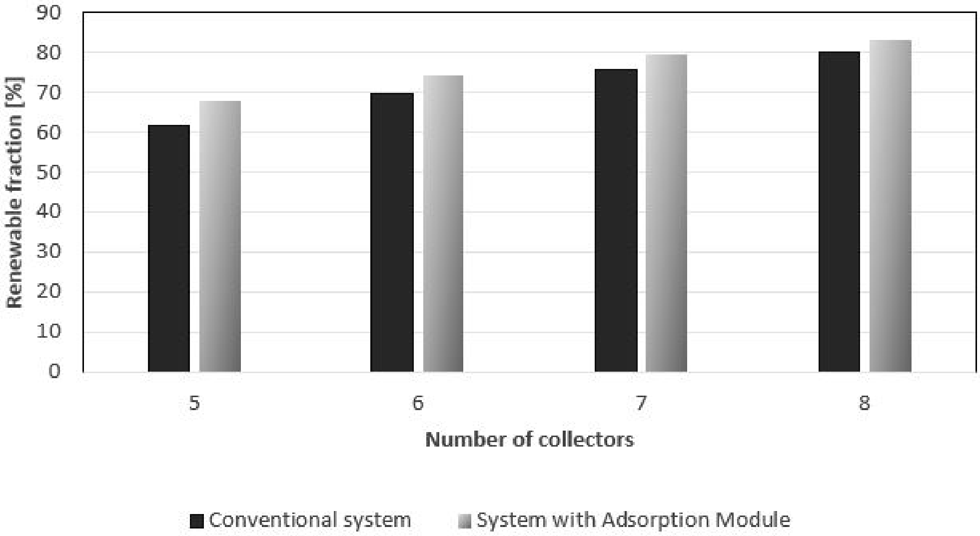

Figure 4.4: Variation of the annual renewable fraction for a different number of collectors, for the conventional system and the system with the adsorption module.

When calculating the renewable fraction for the system with the adsorption module, thermal losses from the secondary tank also have to be considered. Nevertheless, these correspond to only 5-7 % of the total energy transferred from the heat exchanger to the water, causing little impact. Energy removed by the evaporator from the environment also slightly increases with the number of collectors, and contributes to better results in the system with the adsorption module since the conventional system does not have an evaporator.

Considering all the different analysis, a compromise must be made. Further analysis use 7 collectors (or 17.01 m^2), the configuration that allows for better relative savings and allows for better absolute savings and renewable fraction, presenting satisfying results on its own, with a backup energy use of 378.6 MJ and a renewable fraction of 75.7 %. Thus, the conventional system with a seasonal storage capacity of 3000 L and 7 collectors serves as the reference system for future comparisons.

4.2.2. Seasonal storage tank volume

Considering the first sensitivity analysis (section 4.1) showed that smaller tanks lead to better results in terms of backup energy required and renewable fraction, the same analysis is conducted, this time to the system with the adsorption module. Results are compared to the conventional system with 7 collectors and 3000 L of seasonal storage capacity. The adsorption system and its parameters will have to be adjusted to each volume. Table 4.1 provides a list of different parameters used for each different seasonal storage capacity.

Table 4.1: Adsorption system's geometrical parameters input for different seasonal storage tank volumes.

Component	Parameter	Seasonal storage tank volume			
		3000 L	2400 L	2100 L	1800 L
Adsorber					
	$D_{o,a}$ $[m]$	0.21908	0.21908	0.21908	0.21908
	N_{fext}	1800	1440	1250	1080
	N_f	24	24	24	24
	m_a $[kg]$	455.5	364.4	318.8	273.3
Condenser					
	$D_{o,c}$ $[m]$	0.04216	0.04216	0.04216	0.04216
	L_c $[m]$	41.407	32.671	30.465	27.182
	N_c	10.749	8.576	8.576	8.065
Evaporator					
	D_{evap} $[m]$	1.282	1.268	1.186	1.128
	$D_{o,evap}$ $[m]$	0.04826	0.04826	0.04826	0.04826
	e_{evap} $[m]$	0.00368	0.00368	0.00368	0.00368
	$N_{t,evap}$	178	174	152	137
	$e_{f,evap}$ $[mm]$	0.889	0.889	0.889	0.889
	$N_{f,evap}$	36	36	36	36
	V_{evap} $[L]$	1000	809	706	607

While the value of some parameters remains the same for the different capacities studied, the number of exterior fins of the adsorber, for example, is adjusted, to allow for 10 mm spacing between them in each configuration. The diameter of the evaporator, on the other hand, is the same as the diameter of the tanks, and by decreasing the volume of the tanks, the number of tubes that can be placed in the evaporator also decreases, as well as its volume. The height of the tanks was adjusted so that for each volume the decrease in diameter would not be as significant, allowing for a still relatively high amount of tubes to be placed, and subsequently attain a better performance from this component, hindering, however, the stratification effect of the tank.

Figure 4.5 shows the variation of the annual backup energy savings obtained for the different capacities. With the decrease in seasonal storage capacity, an increase in backup energy savings is verified. The configuration which presents better results is the one with a capacity of 1800 L for the seasonal storage tank, with savings of 64 MJ, or approximately 17 % in comparison with the conventional system. While all configurations allow for bigger savings in auxiliary energy required, the one with 1800 L is particularly interesting considering that the total volume of the entire system (seasonal storage tank (1800 L) + secondary pre-heating tank (450 L) + evaporator (607 L)) is lower than that of the seasonal storage tank alone in the conventional system (3000 L).

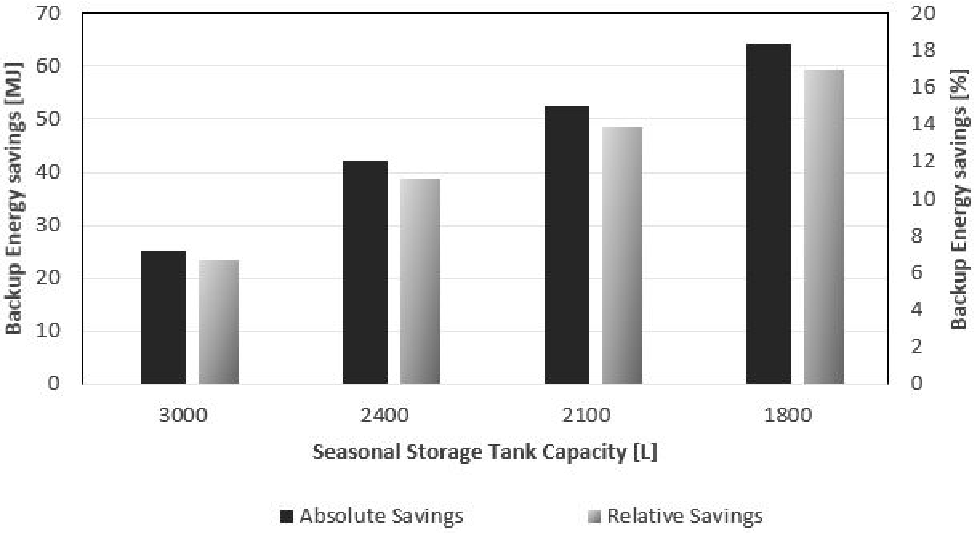

Figure 4.5: Variation of the annual backup energy savings for different storage capacities of the seasonal storage tank, for the system with the adsorption module in comparison with a conventional system with 7 collectors and a storage capacity of 3000 L with a storage period from April to October.

Figure 4.6 shows the variation of the annual renewable fraction for each capacity tested. The renewable fraction increases with the decrease of the storage capacity, but only slightly. While the evaporator does remove as much energy from the environment, thermal losses are significantly smaller the smaller the tank is. In the first analysis (section 4.1), results showed that thermal losses did not present a significant variation with a decrease in volume, but with the adsorption system, this is no longer true. Reducing the volume from 3000 L to 1800 L, approximately 1250 MJ are recovered from thermal losses, due to the implementation of the adsorption system.

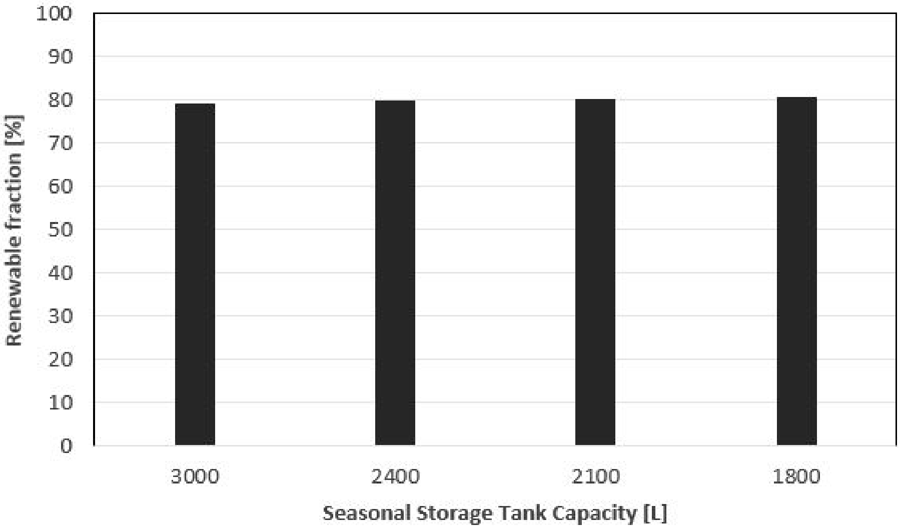

Figure 4.6: Variation of the annual renewable fraction for different storage capacities of the seasonal storage tank, for the system with the adsorption module.

4.2.3. Seasonal storage tank utilization period

The seasonal storage and utilization periods are now analyzed. For previous analysis, the seasonal storage tank was being used to pre-heat water from the mains from November to March, storing thermal energy from April to October. Three different utilization periods will now be analyzed and compared with the reference case (conventional system with usage from November to March): from November to April, October to May and September to June. Figure 4.7 shows the variation of the annual backup energy savings obtained for each period:

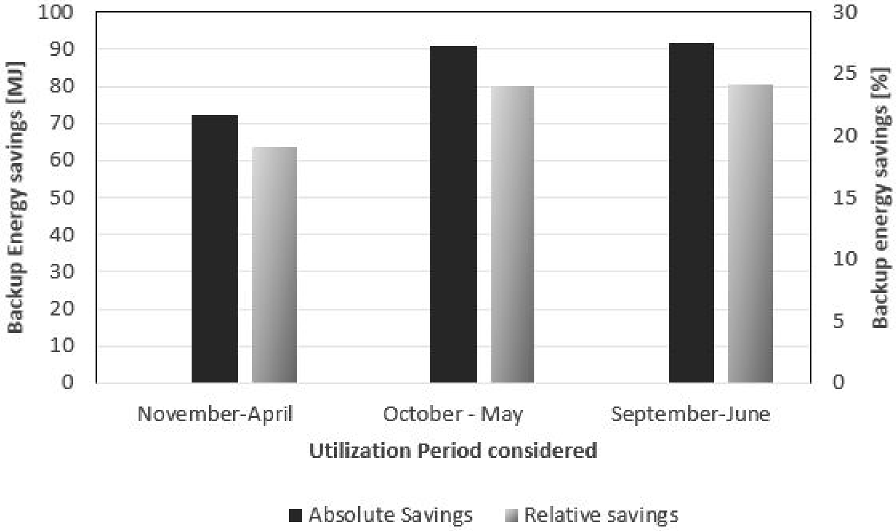

Figure 4.7: Variation of the annual backup energy savings for different seasonal storage and utilization periods of the seasonal storage tank, for the system with the adsorption module in comparison with a conventional system with 7 collectors and a storage capacity of 3000 L, with a storage period from April to October.

The more the seasonal storage tank is used throughout the year, the bigger the energy savings. While there is a significant increase from the first period to the second, from the second to the third the backup energy usage only decreases by 0.2 % in comparison with the conventional system. This is due to the fact that in June and September there is not a significant energy demand for water heating that cannot be supplied by the solar DHW system on its own. By using the seasonal storage tank to pre-heat water from September to June, relative savings of 24.2 % are obtained.

Figure 4.8 presents the variation of the annual renewable fraction for the different periods considered. It also increases for larger usage periods. By considering bigger storage periods, there were timesteps in the simulations in which, while the DHW tank was fully charged, fluid was not redirected to the seasonal storage tank because it was still at the maximum cut-out temperature considered (and thus, fully charged as well) from previous timesteps. By increasing the usage of the seasonal storage tank, the water inside it is cooled more often, allowing for more energy to be transferred to the water by the heat exchanger, stored by the adsorption system, and removed by the evaporator from the environment, thus increasing renewable fraction and the overall system's efficiency.

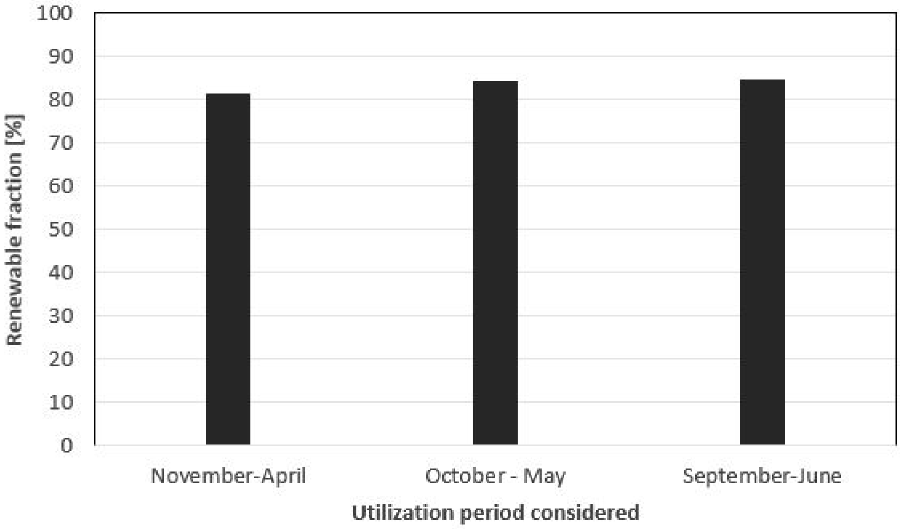

Figure 4.8: Variation of the annual renewable fraction for different seasonal storage and utilization periods of the seasonal storage tank, for the system with the adsorption module.

4.2.4. Specific Heating Potential and Energy density

The conventional system presents an annual specific heating potential of 94.5 kWh/m^3, while the system with adsorption module presents a value of 184.1 kWh/m^3. It should be noted that the volume considered for the system with the adsorption module is lower (2250 L, compared to the 3000 L of the conventional SHS system), and that its utilization period is different, meaning that there is a higher flow of water into and out of the tank.

Figure 4.9 shows the annual evolution of the total energy released from the adsorber to the water inside the seasonal storage tank at the end of each discharge period, considering the usage period of September-June. Most of that energy is adsorption heat (approximately 89 %), while the rest is sensible heat released during the cooling phase. The adsorber released 793.2 MJ to the water throughout the year. The energy density pertains to the adsorber only and can be obtained by applying equation 4.4. The volume of the adsorber is 0.4548 m^3 for the system considered, obtaining an average annual energy density of 10.8 kWh/m^3. The peak value is of 32.6 kWh/m^3, which occurs for a discharge period when ΔX = 0.067 kg/kg$_{silica-gel}$. Both of these values are extremely low, in particular when in comparison with other values found in literature for these types of systems (Fernandes et al. 2017). This is likely due to the fact that the assessed adsorption system was still not optimized for its intended operation (seasonal storage), thus presenting small discharging amplitudes (ΔX; the theoretical maximum is 0.4 kg/kg$_{silica-gel}$), which translates in low adsorption heat released when compared with the adsorption material volume used. In addition, the large adsorber volume may difficult the release of energy, thus decreasing energy density as well.

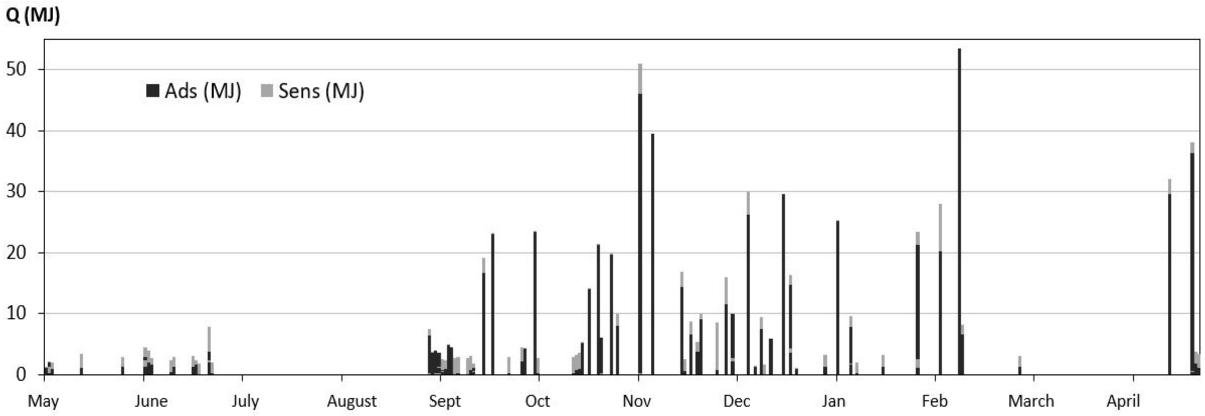

Figure 4.9: Total energy released from the adsorber component to the water at the end of each discharge period, for a year.

4.3. Performance analysis in different European climates

Mains water temperature is a significant parameter when assessing these types of systems. The higher the mains temperature, the lower the flow rate of hot water necessary to obtain the desired consumption temperature. Climate and season both affect the temperature of the mains water, thus impacting hot water consumption patterns (Fuentes et al. 2018).

Europe is characterized by a temperate climate. Most of Western Europe features an Oceanic climate, presenting mild summers and cool but not cold winters. Southern Europe has a Mediterranean climate, featuring warm to hot summers and cool to mild winters. Central-Eastern Europe has a Continental climate, which features warm to hot summers and cold winters. Considering this, 4 different locations were chosen to assess the system's performance under different climates: London, England, which features a Continental climate, with a hot summer and no dry season; Berlin, Germany which features a Continental/Oceanic climate, a warm summer and no dry season; Zurich, Switzerland, which also features a Continental/Oceanic climate; and Helsinki, Finland, which features an Oceanic climate and cold summers with no dry season.

Each location presents different DHW consumption values per occupant as well as profiles, expected average mains water temperature and solar exposition. Different profiles were constructed for each location, presented in Appendix A (Figures Ap.2 - Ap.5, in accordance with Fuentes et al. (2018). The solar collectors' inclination angle considered is the same as in the previous analysis. Table 4.2 presents the main parameters input for the different climates. In order to determine the optimal configuration for each climate (namely, seasonal storage tank volume and number of collectors), several simulations of the conventional system were performed, arriving at an optimal capacity of 1000 L for each (adjusting the adsorption system components' parameters accordingly).

In comparison with the Portuguese case, a decrease in the seasonal storage tank volume as well as an increase in the number of collectors increase the overall system's performance. However, backup energy required is now quite significant, for either the conventional system or the system with adsorption module, which also uses a seasonal storage tank with a capacity of 1000 L, once the optimal configurations were obtained and simulations using the type with the adsorption component were run. This is due to the fact that the average mains water temperature in the case of Lisbon was much higher than that of the climates in the present analysis (average mains water temperature in Lisbon is of approximately

Table 4.2: Parameters for the different locations and climates analyzed.

Parameter	Location			
	London, ENG	Zurich, CH	Berlin, DE	Helsinki, FI
DHW consumption [L/occup.]	39	55	64	43
Average mains water temperature [$^\circ C$]	11.9	10.3	9.9	8.1
No. of collectors	12	12	12	15
DHW tank volume [L]	250	350	350	250
Seasonal storage tank volume [L]	1000	1000	1000	1000
Storage period	July-August	July-August	July-August	July-August

20.1 °C). Moreover, there is not as much solar energy available, impacting the energy released from the heat exchanger to the water, as well as fluid flowing to the seasonal storage tank, since for this to happen, the main DHW tank has to be fully charged, which can be rare in winter. DHW consumption per occupant is also significantly higher in Switzerland and Germany, which can also affect the results. Adjusting several parameters of the DHW tank was necessary for these locations, as it required a larger volume than the one considered for the other analysis. Figure 4.10 shows the variation of the annual backup energy required for the conventional systems and system with adsorption module, as well as the renewable fraction.

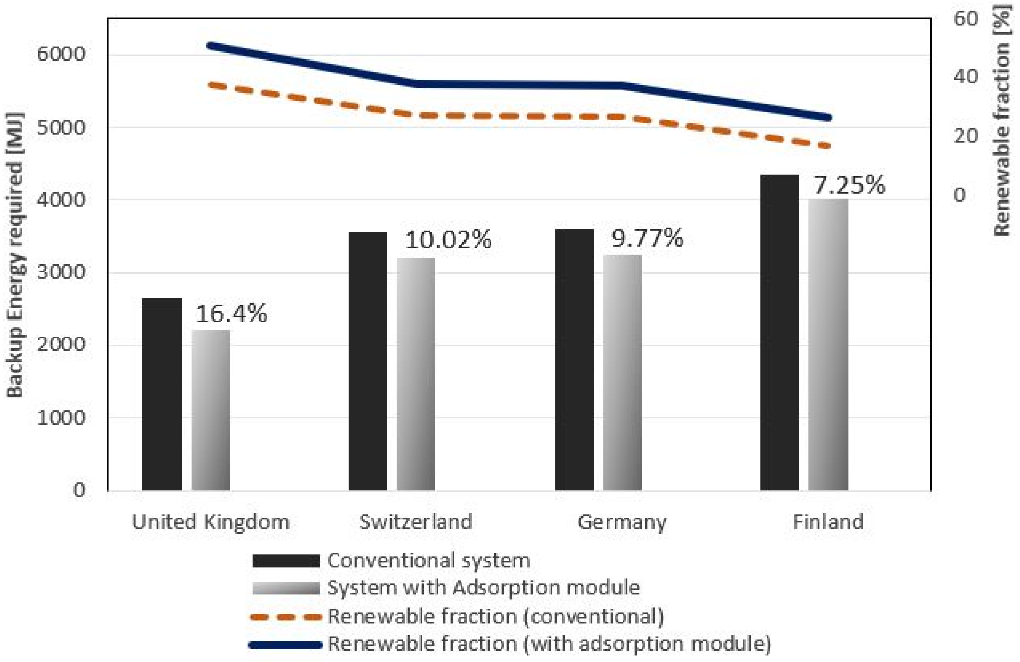

Figure 4.10: Variation of the annual absolute backup energy and renewable fraction for different climates in Europe. Relative backup energy savings values presented on the top of the bars.

In terms of total backup energy required for water heating and relative backup energy savings when using the system with the adsorption module, as well as renewable fraction for both configurations, the location that presents the best results is London in England, which features the warmer summers of all climates considered, as well as the higher average mains water temperature. Germany and Switzerland both present very similar results in all analysis targets, as expected due to their very similar climate. Helsinki presents by far the worst results, as it features cold summers and the lowest mains water temperature. Renewable fractions obtained are slightly higher for the systems with the adsorption module, proving once again the system benefits from the module, although its values are still far from the desired. Further optimization of the system's configuration and parameters is required for the different climates.

5. Conclusions

A Seasonal Thermal Energy Storage System provided with an Adsorption Module is modelled in TRNSYS and analyzed in this work, based on a previous system which stored thermal energy for short-term use in a solar DHW system, also provided by an adsorption module. The proposed system features two tanks, one for short-term use, and the other for long-term storage, allowing excess heat in the summer to be stored and used in the winter. The adsorption module is implemented inside the seasonal storage tank, allowing energy to be stored under a potential of energy, reducing thermal losses and improving the overall system's efficiency. The seasonal storage tank acts as a perfect heat exchanger, pre-heating water from the mains which then enters the main DHW tank, whenever the temperature of the latter drops below a certain level, effectively reducing the necessity for backup energy from a conventional source. The main conclusions from the different analysis conducted are:

- For the conventional sensible heat storage system, increasing the storage capacity leads to greater values of backup energy required to heat water for consumption. Results also showed that renewable fractions decrease with the increase of the storage capacity, as the energy transferred from the heat exchanger is lower, despite the thermal losses being more or less the same.

- As the number of solar collectors is increased, the less backup energy is required, although the amount of energy recovered diminishes with each increment. The configuration with 7 collectors obtained the best relative savings, and the second best absolute savings behind the configuration with 5 collectors. The configuration with 8 collectors presented the lowest values of backup energy required for both the conventional and the system with adsorption module, but the lowest absolute savings.

- Despite there being more thermal losses, the renewable fraction increases with the number of collectors due to the increase in the energy transferred from the heat exchanger and decrease in backup energy required. Thermal losses from the secondary tank present on the system with adsorption module represent only 5-7 % of the total energy transferred from the heat exchanger, therefore causing little impact.

- The conventional system with 17.01 m^2 and 3000 L of seasonal storage capacity that served as a comparison term for further analysis achieved an annual specific heating potential of 94.5 kWh/m^3, while the system with the adsorption module achieved a specific heating potential of 184.1 kWh/m^3. In the system with the adsorption module, besides the energy from the thermal fluid transferred through the heat exchanger, energy released from the adsorber is considered, allowing for bigger values of specific heating potential, not to mention the seasonal storage tank's lower volume, and bigger utilization period (allowing for higher flows of water).

- Decreasing the seasonal storage volume in the system with the adsorption module results in an increase in backup energy savings. The configuration which presents better results is the one with a capacity of 1800 L for the seasonal storage tank, with relative savings of approximately 17 % in comparison with the conventional system of 3000 L. This demonstrates that the implementation of the adsorption not only leads to bigger savings, but also allows the use of smaller tanks. The total added volume of the system, comprised of the two tanks and evaporator, is also smaller than the volume of the seasonal storage tank alone in the conventional system.

- The adsorption module's evaporator removes more energy the bigger it is in volume, as it possesses more tubes, and thermal losses are significantly lower the smaller the tank is (1250 MJ are recovered by reducing the volume from 3000 L to 1800 L and introducing the adsorption module). As such, the renewable fraction also increases with the reduction of the seasonal storage capacity.

- Relative savings of 24.2 % and a renewable fraction of 85 % were achieved for a system with an utilization period of the seasonal storage tank between September and June. The difference of only 0.2 % of savings from this configuration to the one with an utilization period from October to May is due to the fact that in June and September there is not a significant energy demand for water heating that cannot be supplied by the solar DHW system on its own.

- The energy density obtained for the adsorption system is relatively low, with the peak value (32.6 kWh/m^3) being much lower than the peak value in Fernandes et al. (2017). This is due to the low discharging amplitudes of ΔX, which translate in low adsorption heat being released, particularly when compared to the large volume of the adsorber.

- Parameters such as DHW consumption and average mains water temperature proved to be relevant in addition to the solar energy available for the different climates considered. The lower the mains water, the more energy is required to heat water, and, in colder climates, it could prove challenging to charge the seasonal storage tank, since this is only possible once the DHW has been fully charged. The analysis conducted led to the same conclusions of higher backup energy savings and renewable fractions with the use of an adsorption module, despite the results being far from the desired, requiring further parametric analysis and optimization.

6. Suggestions of future work

Several simplifications were adopted throughout the development of this work, completely based on modelling and simulation. As such, in this chapter, some suggestions of future work are presented:

- The seasonal storage tank behaves as a perfect heat exchanger, as the type modelled first in MATLAB and called to TRNSYS does not allow for a second heat exchanger. As such, it would be of interest to adjust the seasonal storage tank programmed to feature a second heat exchanger through which the mains water would pass, and be effectively heated by the hot water inside the tank. This would allow obtaining more realistic results, since the water inside the seasonal storage tank would not be optimal for consumption after long periods of storage, due to stagnation.
- An optimization study on the parameters of the STES system (number of collectors, storage capacity of both tanks, setpoint temperatures, utilization periods) is required in order to determine the optimal values that would lead to the best results in terms of backup energy savings and renewable energy. Such a study could be conducted by way of optimization software such as GenOpt. Another optimization study would then be required for the adsorption system, in order to determine the optimal parameters for each component, considering the seasonal storage capacity used. The study could also determine the configuration that allows for a higher energy density, considering the significantly low energy density obtained for the present system, in part due to the large adsorber volume considered.
- Most STES systems aim to supply both DHW and Space Heating needs, which in Europe make up almost 80% of energy demand in the residential sector. As such, it would be interesting to adapt the current system to also provide space heating in a single-family house. The volume of the seasonal storage tank would have to be increased significantly considering the needs are much higher, and the system would have to be adapted to suit the parameters which allow for the simulation of the considered dwelling's conditions. For a large seasonal storage capacity, implementing the adsorption module in this tank would not be feasible anymore. In this case, the adsorption module could be maintained in the DHW tank for which it was originally developed, and the seasonal storage system could be analyzed separately to meet the space heating needs by way of supplying hot water to radiators or radiant floors.

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Annex A. Parameters of the adsorption system's components

Main seasonal storage tank

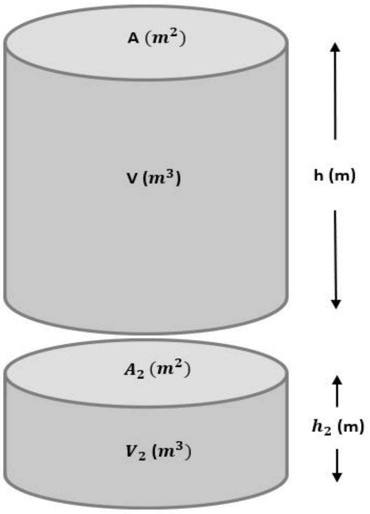

Figure An.1: Seasonal storage tank and secondary pre-heating tank placed directly beneath the main seasonal storage tank, with main geometrical properties.

Table An.1: Main seasonal storage tank's geometrical parameters.

Parameter	Equation
Cross section area	$A = \frac{V_1}{h_1}$
Diameter	$D = \sqrt{\frac{4 \cdot A}{\pi}}$
Volume of one node	$V_{node} = \frac{V_1}{n}$
Volume of water	$V_{w1} = V_1 - V_a$

Secondary pre-heating tank

Table An.2: Secondary pre-heating storage tank's geometrical parameters.

Parameter	Equation
Height	$h_2 = \frac{V_2}{A_2}$
Volume of water	$V_{w2} = V_2 - V_c$

Adsorber

Adsorber tube

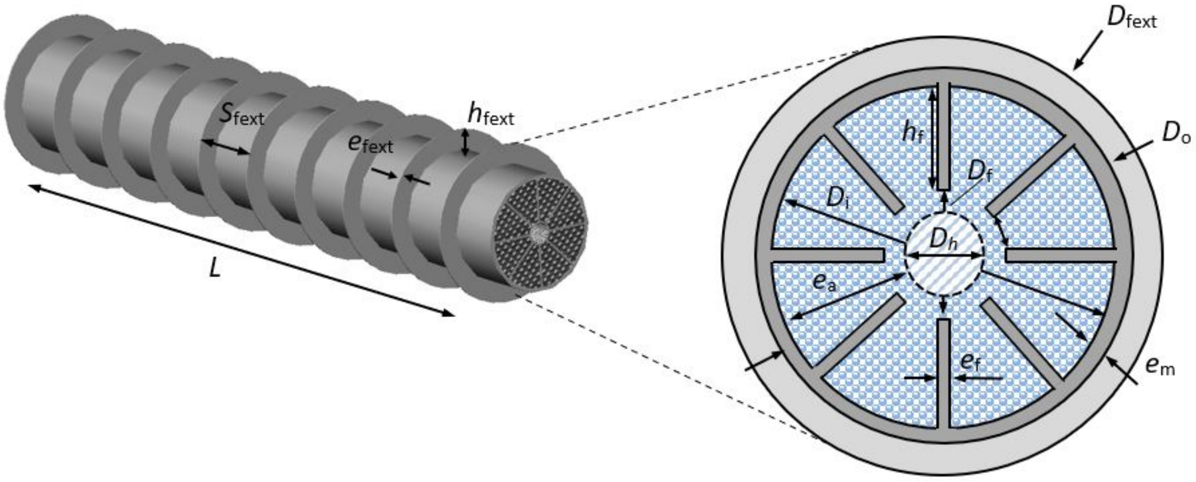

Figure An.2: Adsorber tube and cross section, with main geometrical properties.

Table An.3: Adsorber tube's geometrical parameters.

Parameter	Equation
Length	$L = \frac{0.9 \cdot 4 \cdot V_{node}}{\pi \cdot D_{fext}}$
Internal diameter	$D_i = D_o - 2 \cdot e_m$
Hollow diameter	$D_h = D_i \cdot 0.25$
Hollow volume	$V_h = \frac{D_h^2 \cdot \pi \cdot L}{4}$
Adsorber tube's volume	$V_{a,t} = \frac{D_o^2 \cdot \pi \cdot L}{4}$
Adsorber's volume (tube + fins)	$V_a = \frac{D_o^2 \cdot \pi \cdot L}{4} + V_{fext}$

Adsorbent properties

Table An.4: Adsorbent's properties.

Parameter	Equation
Adsorbent thickness	$e_a = \frac{(1-0.25) \cdot D_i}{2}$
Adsorbent volume	$V_a = \frac{(D_i^2 - D_h^2) \cdot L}{4} \cdot V_f$
Adsorbent mass	$m_a = \rho_a \cdot (1 - E) \cdot V_a$

Inner fins (longitudinal)

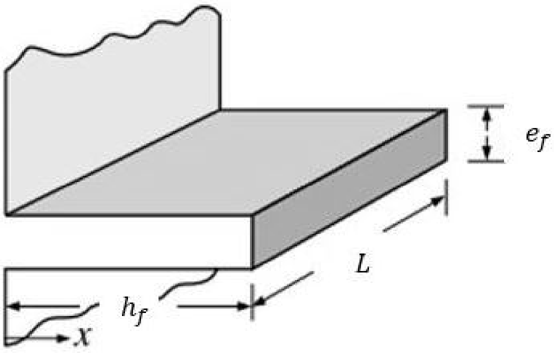

Figure An.3: Rectangular fins [adapted from Çengel 2003].

Table An.5: Adsorber inner fins' geometrical parameters.

Parameter	Equation
Inner diameter limited by the fins	$D_f = D_h$
Fin area	$A_f = 2 \cdot L \cdot h_f + L \cdot e_f$
Spacing between fins	$S_f = \frac{(\pi \cdot D_f - N_f \cdot e_f)}{N_f}$
Fin volume	$V_f = N_f \cdot e_f \cdot L \cdot h_f$
Fin height	$h_f = \frac{D_i - D_f}{2}$

Outer fins (annular)

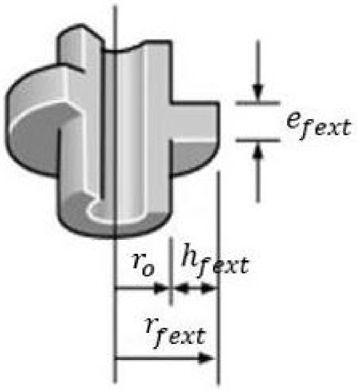

Figure An.4: Annular fins [adapted from Çengel 2003].

Table An.6: Adsorber outer fins' geometrical parameters.

Parameter	Equation
Outer diameter of the fins	$D_{fext} = D_o + 0.1 \cdot D_o$
Outer fin area	$A_{fext} = \frac{2 \cdot \pi \cdot (D_{fext}^2 - D_o^2)}{4} + D_{fext} \cdot e_{fext} \cdot \pi$
Spacing between outer fins	$S_{fext} = \frac{L - N_{fext} \cdot e_f}{N_{fext}}$
Outer fin volume	$V_{fext} = \frac{N_{fext} \cdot e_{fext} \cdot \pi \cdot (D_{fext}^2 - D_o^2)}{4}$
Outer fin height	$h_{fext} = \frac{D_{fext} - D_o}{2}$

Condenser

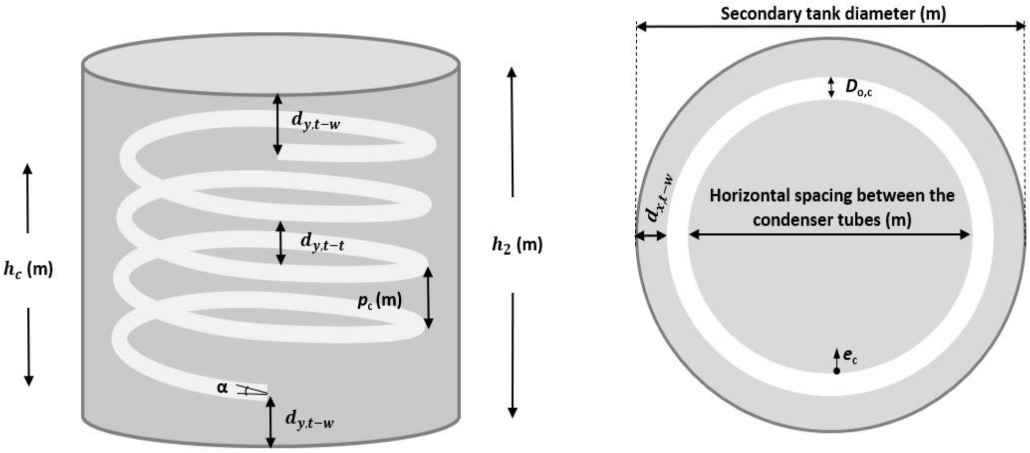

Figure An.5: Condenser inside the secondary pre-heating tank, with main geometrical parameters.

Table An.7: Condenser's geometrical parameters.

Parameter	Equation
Vertical distance between the tube and tank wall	$d_{y,t-w} = d_{x,t-w}$
Vertical distance between rows of the tube	$d_{y,t-t} = d_{x,t-w}$
Tube's inner diameter	$D_{i,c} = D_{o,c} - 2 \cdot e_c$
Coil's total diameter at tube's axis level	$D_{x,med} = D_2 - D_{o,c} - 2 \cdot d_{x,t-w}$
Condenser height at tube's axis level	$h_c = h_2 - D_{o,c} - 2 \cdot d_{y,t-w}$
Pitch	$p_c = D_{o,c} + d_{y,t-t}$
Number of helical turns	$N_c = \frac{h_c}{p_c}$
Angle of the condenser rows	$\alpha_c = \arctan \frac{h_c}{\pi \cdot D_{x,med} \cdot N_c}$
Length of the condenser tube	$L_c = \sqrt{(\pi \cdot D_{x,med} \cdot N_c)^2 + h_c^2}$
Volume occupied by the condenser	$V_c = \frac{\pi \cdot D_{o,c}^2 \cdot L_c}{4}$

Evaporator

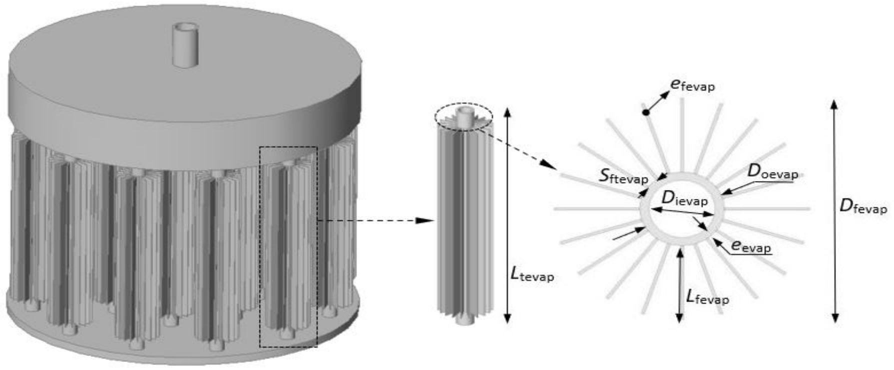

Figure An.6: Evaporator with main geometrical parameters.

Evaporator tube

Table An.8: Evaporator tube's geometrical parameters.

Parameter	Equation
Maximum adsorbate volume removed	$V_{w,max} = m_a \cdot q_m$
Inner volume of the evaporator	$V_{evap} = V_{w,max}$
Tube's inner diameter	$D_{i,evap} = D_{o,evap} - 2 \cdot e_e$
Sum of the height of all tubes	$L_{evap} = \frac{4 \cdot V_{evap}}{\pi \cdot D_{i,evap}^2}$
Evaporator's outer surface area	$A_{o,evap} = \pi \cdot L_{evap} \cdot D_{o,evap}$
Height of each tube	$L_{t,evap} = \frac{L_{evap}}{N_{t,evap}}$
Outer surface area of each tube	$A_{o,t,evap} = \pi \cdot D_{o,evap} \cdot L_{t,evap}$

Longitudinal fins

Table An.9: Evaporator tube's longitudinal fins' geometrical parameters.

Parameter	Equation
Corrected thickness	$e_{f,evap,c} = D_{o,evap} \cdot \arcsin \frac{e_{f,evap}}{D_{o,evap}}$
Diameter of each tube (including fins)	$D_{f,evap} = D_{o,evap} + 2 \cdot L_{f,evap}$
Surface area of each fin	$A_{f,t,evap} = 2 \cdot (L_{t,evap} + e_{f,evap}) \cdot L_{f,evap} + L_{t,evap} \cdot e_{f,evap}$
Spacing between evaporator fins	$S_{f,evap} = \frac{\pi \cdot D_{o,evap} - N_{f,evap} \cdot e_{f,evap,c}}{4}$

Appendix A. DHW profiles for different climates

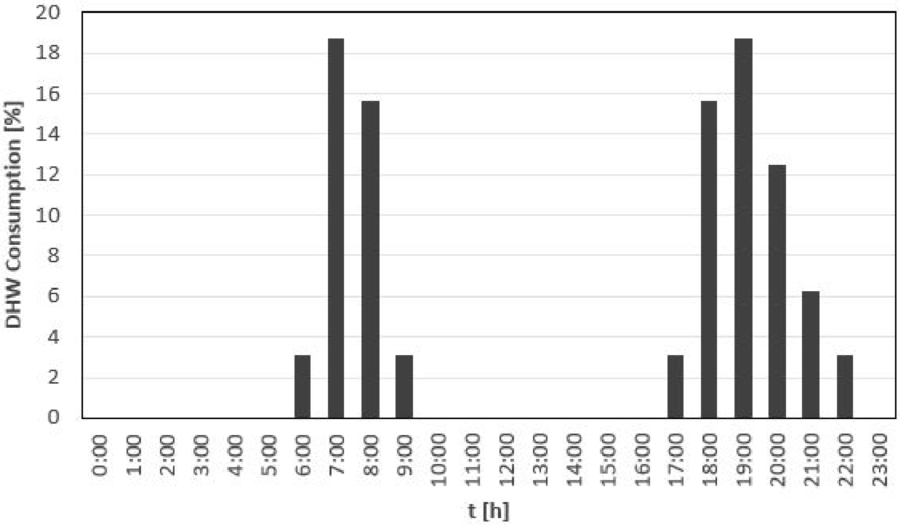

Figure Ap.1: DHW profile considered for Lisbon, Portugal.

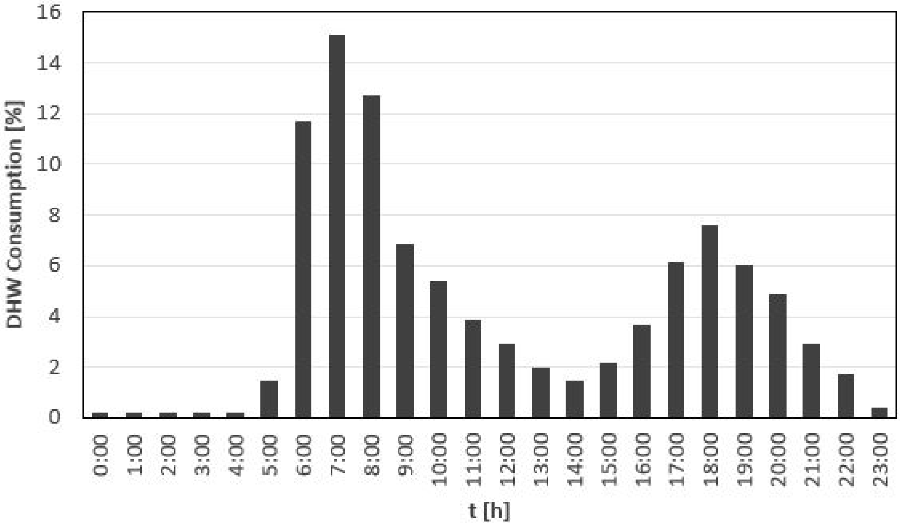

Figure Ap.2: DHW profile considered for London, England.

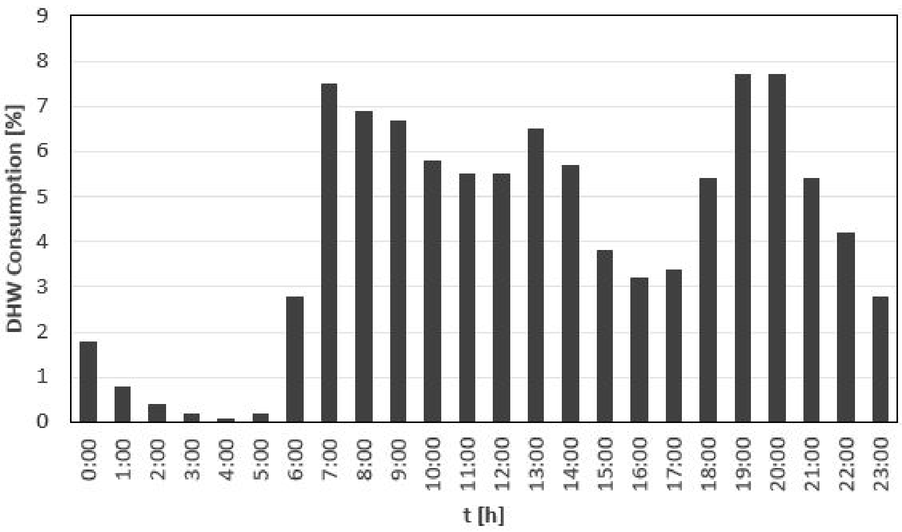

Figure Ap.3: DHW profile considered for Zurich, Switzerland.

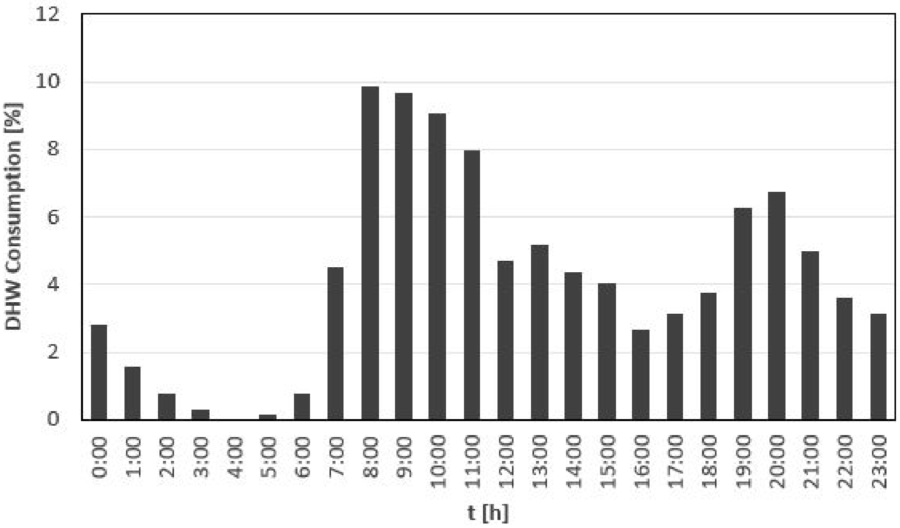

Figure Ap.4: DHW profile considered for Berlin, Germany.

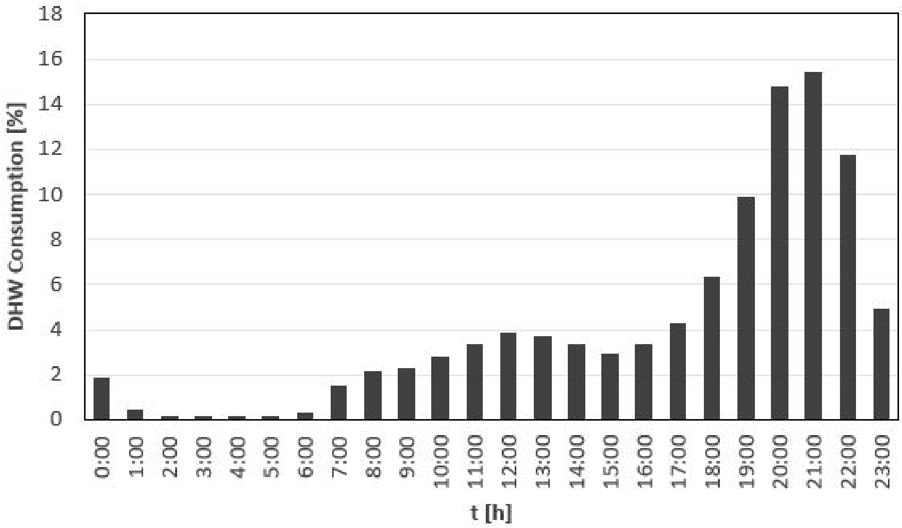

Figure Ap.5: DHW profile considered for Helsinki, Finland.