Department of Mechanical and Aerospace Engineering

AN EXPERIMENTAL INVESTIGATION OF AN ELECTRICAL STORAGE HEATER IN THE CONTEXT OF STORAGE TECHNOLOGIES

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Signed: *Ignacio Becerril Romero* Date: 22nd September 2013

Abstract

This project is divided in two different parts: an investigation of energy storage and an experimental analysis of a storage heater.

The “20 20 20” targets dictate that the share of renewables in EU’s energy consumption has to be increased to a 20% by the year 2020 (European Commission, 2012). More flexibility needs to be added to the grid in order to integrate the increasing amount of variable generation. Energy storage is especially well suited to respond to this challenge (Teller et al., 2013). However, the role that storage is to play in the future grid needs to be evaluated meticulously. A detailed investigation of the services that storage can provide to the grid and of the main storage technologies is carried out in this thesis. The analysis shows that storage is a very valuable element of the energy grid since it can provide numerous services at the same time. It plays a fundamental role within the integration of renewables and is particularly useful combined with wind power to avoid curtailment and minimum generation constrains. In addition, it is realised that only a combination of different storage technologies can deliver all the services that energy storage will need to provide in the future.

State-of-the-art storage heaters can provide demand side management (DSM) services in small isolated grids with significant wind generation. The charging periods of the heater can be scheduled by the utility provider based on wind output and demand forecasts. At the same time, storage heaters can also provide frequency response. However, they present some features that may affect their performance. No relevant publications were found about the topic, so an experimental analysis of the thermophysical properties of the storage medium and of the temperature distribution inside the core of the heater is performed. The first shows that the specific heat and conductivity of the storage material are higher than expected with values of $C_P = 1.58$ J/g·K and k = 4.3 W/m·K. It is concluded that the storage material presents good qualities for heat storage. On the other hand, the temperature distribution is shown to be very inhomogeneous during a standard charging cycle. Nevertheless, the method used overestimates the average temperature of the core of the heater by a 50% showing that a 3D approach is necessary to study absolute temperatures. Likewise, the data obtained are insufficient to study the performance of the heater as DSM and, due to the lack of time and equipment, this is left as future work.

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Contents

List of figures

List of graphs

List of tables

List of equations

1. Introduction

In December 2008, the European Parliament and the European Council agreed upon the so called *Climate and Energy Package*, more commonly known as the 20 20 20 targets. These are a set of binding legislation which aims to ensure the European Union meets its ambitious climate and energy targets for 2020 (European Commission, 2012). The three key objectives of this legislation are, namely:

- A reduction in greenhouse gas emissions of at least 20% below 1990 levels
- An increase of the share of renewable energy to 20% in the overall energy consumption
- An improvement of the overall EU's energy efficiency of a 20%

The second bullet point of the previous list implies that the energy network will have to cope with high amounts of unpredictable and variable renewable generation. The current energy grid only possesses a limited degree of flexibility provided, mainly, by conventional rapid cycling gas turbines or hydro power plants (Denholm, 2012). Increasing the share of RES in the generation mix will inevitably require a higher flexibility to avoid situations in which, from time to time, generation largely exceeds demand or vice versa, and the problems this can pose to transmission and distribution networks.

Energy storage is especially well suited to respond to this challenge and ensure a continued security of energy supply at any time by storing energy in times of excess supply and releasing power when there is not enough generation.

However, in order to understand the role that storage will play in the future energy grid and, especially, within the integration of renewable energy, it is first necessary to investigate and understand the following topics:

1. What are the services that energy storage currently provides to the grid
2. What are the potential services that storage could further provide
3. How these services are currently carried out without energy storage
4. What are the present and future technologies that can provide these services

It is difficult to find an exhaustive analysis where all these elements are reviewed and gathered together although it is fundamental to understand the potential of energy storage. Thus, this situation has motivated the first part of this thesis in which a deep investigation of all the subjects listed above is presented.

Demand side management (DSM) is another effective way of providing flexibility to the grid but its large-scale implementation is very complex (Strbac, 2008). In contrast, isolated communities with small self-managed energy grids (like islands) and abundant wind resources offer a great potential for DSM.

These communities are often not connected to the gas grid. Thus, electric heating commonly represents a high percentage of the total energy consumption. Storage heaters are the preferred choice for electric heating due to their reduced running costs when combined with off-peak tariffs. Moreover, state-of-the-art models feature automated charging controls that can be remotely programmed by the utility provider. This allows their use as DSM.

In already mentioned small isolated communities with significant amounts of wind generation, two main types of DSM services are identified for ‘smart’ storage heaters:

- Charging scheduling - utility providers can use wind output and demand forecasts to schedule optimum charging times in the heater.
- Frequency response - by monitoring the frequency of the grid, heaters can automatically detect imbalances and modify their energy consumption.

However, storage heaters also present a number of issues that can affect their performance as DSM:

- Core temperature distribution – ceramic bricks used in storage heaters as storage medium exhibit low thermal conductivities that can lead to very uneven temperature distributions in the core of the heater.
- Standing losses – storage heaters exhibit unwanted heat losses that reduce their efficiency.
- Human factors – a wrong programming of the heater can result in significant amounts of wasted energy.

A ‘smart’ storage heater was experimentally analysed in the second part of this thesis.

The thermophysical properties of the storage medium determine the behaviour of the storage heater to a large extent. However, there is a lack of relevant publications about this topic. This motivated the first part of the experimental analysis in which the main thermal properties of the storage material are analysed in detail.

Likewise, the same situation occurs with the temperature distribution inside the core of the heater. The second part of the experimental analysis, thus, investigates the temperature distribution and studies how it can affect the overall performance of the heater. In addition, it is used to assess its storage capacity and standing losses.

2. Energy Storage

2.1 Applications of Energy Storage within the Energy Grid

2.1.1 Introduction

Energy storage plays a very important role in the current grid providing services such as operating reserves, energy arbitrage and frequency control just to mention a few.

The main historical reason for research on and application of energy storage was the need of matching demand and supply. Energy could be stored during off-peak periods from base-load plants (large coal and nuclear plants, mainly) and be released during peak periods to meet demand. Pumped hydro storage (PHS) plants were developed for this purpose and, actually, they are still the dominant energy storage technology today. According to Strbac et al. (2012), PHS currently provides the 99% of the global energy storage capacity.

In the 1970s, there was a strong interest in energy storage due to dramatic increase in the price of oil entailed by the oil crisis. Many of the current PHS plants were built during that period since they were a cheaper way to meet peak demand than fossil-fuel based peaking plants (Denholm et al., 2010). Likewise, many other storage technologies were also researched and developed like flywheels, several types of batteries, capacitors or electromagnetic superconducting storage (DOE, 1977). However, the drop in the price of natural gas set and end to this situation and global interest shifted from energy storage technologies to flexible generation gas turbines, both open and combined cycle, which became the cheapest peaking technology (Denholm et al., 2010).

Nevertheless, energy storage has remained as a key element of the energy grid thanks to the numerous services it can provide. These can be classified into five different classes (Eyer and Corey, 2010): electric supply, ancillary services, grid system, end user and renewable integration applications. In this section, the services most widely discussed in the literature are listed and briefly explained in order to investigate the importance of energy storage in the current and future energy grid.

2.1.2 Electric Supply Applications

Electric energy time-shift/Energy arbitrage

Off-peak low-cost energy is stored during low demand periods (especially at night) and released to meet peak demand. The energy stored comes mainly from base-load plants that are desirable to be operated continuously at maximum capacity since they achieve their highest efficiency and lowest running-costs when working in this regime.

Energy arbitrage favours the use of efficient and expensive base-load plants instead of inefficient peaking plants. Thus, fuel consumption, emissions and overall running costs are reduced. The capital cost of the global system may be also reduced because of the fewer peaking plants required to meet the peak demand. (Walawalkar et al., 2004)

Electric supply capacity

Strongly related to the previous one, stored energy is used to ensure a reliable generation capacity to meet the demand during peak periods. Energy storage could be used to defer and/or to reduce the need to buy new generation capacity and/or to 'rent' generation capacity in the wholesale electricity marketplace (Eyer and Corey, 2010).

2.1.3 Ancillary Services Applications/Frequency Response Services

Any imbalance between electric power generation and consumption results in a frequency change within the entire network of the synchronous area. Stored energy can be used to maintain the frequency of the grid constant (i.e. match supply and demand) in case of predicted or unpredicted events. The energy stored is usually referred to as operating reserves (Denholm et al., 2010). Unlike the applications just mentioned above, the response time of the operating reserves has to be low. Due to the long time required to put a generator online and the fuel expenses associated to it, the usual solution to deal with these issues is the use of partially loaded generators synchronised with the grid that can detect and correct variations in the frequency of the grid (sensitive mode); and, also, by load reductions from some industrial customers (Strbac et al., 2012). There are three basic frequency response services: load following, area regulation and reserve capacity. Voltage control and black-start are also two services highly related to frequency and, thus, they are also included in this section.

Load Following

In order to operate the energy grid, supply must be able to match demand at every time. Since demand varies throughout the day, a variable output supply is necessary as well. The figure below depicts how demand is met by different types of generation and the role that load-following generation plays within the total generation mix.

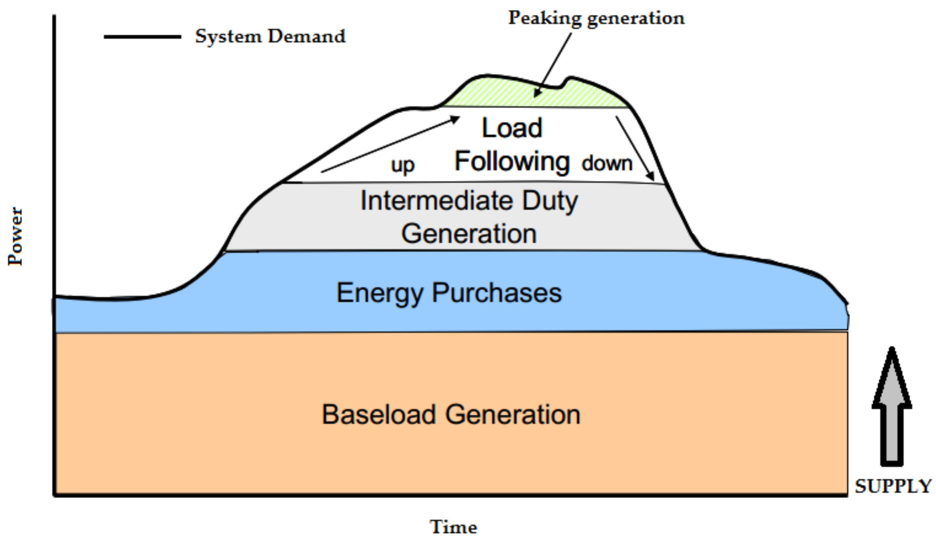


Figure 1 - Matching supply and demand. Load following. Ref: Eyer and Corey (2010)

The traditional solution to provide load-following services is to use of partially loaded generators synchronised with the frequency of the grid that can increase (follow-up) or decrease (follow-down) their output rapidly. However, partially loaded generators are less fuel efficient and have higher emissions than generators operating at their rated output. Maintenance costs associated to modulated generators are also higher than those of constant output generators. (Callaway and Hiskens, 2011)

Storage may be an attractive alternative to most generation-based load following for at least three reasons (Eyer and Corey, 2010):

- Storage has superior part-load efficiency
- Efficient storage can use twice its rated capacity (i.e. it can stop discharging and start charging at the same time) providing an efficient service both for follow-up

(energy is discharged from storage) and follow-down (energy is charged) operations.

- Storage output can be varied very rapidly (e.g., output can change from 0 to 100% or from 100 to 0% within seconds)

Area regulation

Regulation is the response to momentary and unpredicted variations in the energy demand (Denholm et al., 2010). The difference with load following lies on its momentary and unpredictable nature as well as on its smaller amplitude (see Figure 2). However, area regulation is usually addressed by the use of partially loaded thermal generators just like load following (Eyer and Corey, 2010). It has been already remarked that the efficiency of partially loaded generators is quite low and implies high fuel consumption and air emission rates.

Energy storage is particularly useful for area regulation for the three reasons mentioned above. The fast response and the capability of providing twice its rated capacity (charge plus discharge) are vital for area regulation due to the rapid and random nature of the frequency variations (see figure below).

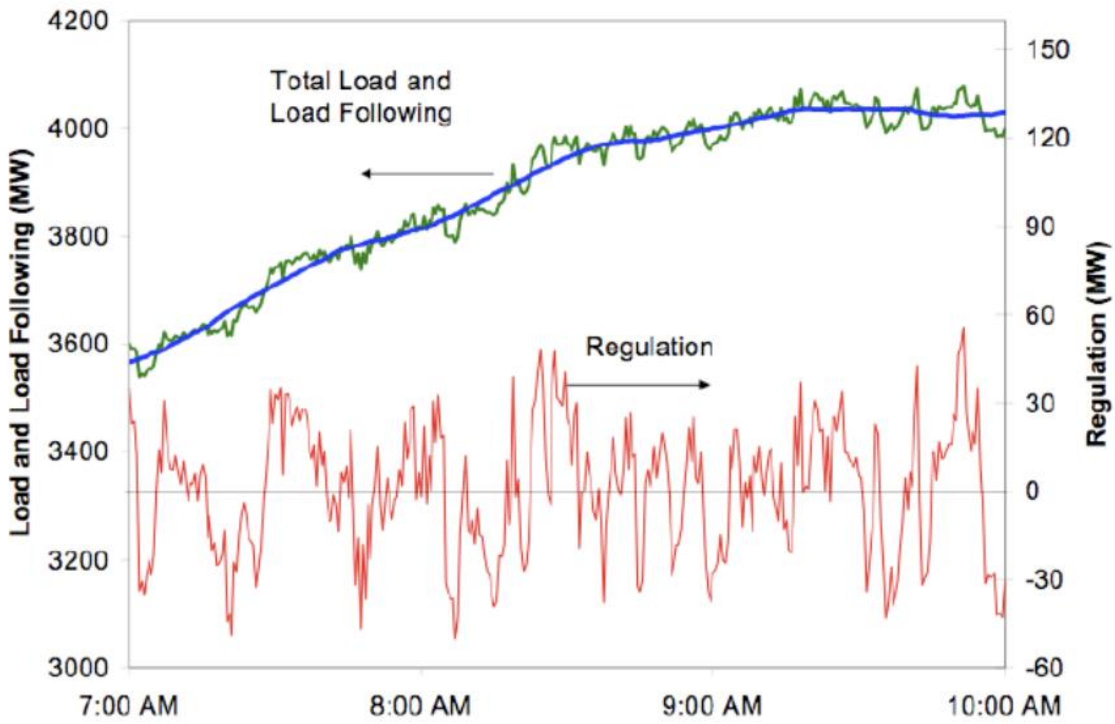


Figure 2- Area regulation. Ref. Denholm et al., (2010)

Electric supply reserves capacity

Every electric power system needs to have some reserve generation to back-up unexpected losses of power, e.g. a generator failure. These reserves are known as contingency reserves (Denholm et al., 2010). There are three types of contingency reserves (Eyer and Corey, 2010):

- *Spinning reserves* - they are the first type of reserves used when a shortfall occurs. They are comprised by generators that are online (synchronised) but unloaded so they can increase their output very rapidly.
- *Supplemental reserves* - they are used after all spinning reserves are online and can be available within 10 minutes. Supplemental reserves are not synchronized with the grid.
- *Back-up Supply* - It can pick up load within one hour. Its role is, essentially, a backup for spinning and supplemental reserves.

Again, its rapid response and firm supply makes storage an ideal option for contingency reserves. Furthermore, spinning reserves need to be online even when they are not needed while storage technologies do not start discharging until the fault is detected.

Black-start capability

National Grid (n.d.) defines a black start as "the procedure to recover from a total or partial shutdown of the transmission system which has caused an extensive loss of supplies. This entails isolated power stations being started individually and gradually being reconnected to each other in order to form an interconnected system again."

Only power plants with no or very low start-up energy needs have the ability to black-start (Zach et al., 2012). PHS plants and diesel engines are commonly used as black start units. However, other bulk energy storage technologies could also be used for this type of service.

Voltage support

Inductors and capacitors in AC systems produce a phenomenon called reactance. Energy is stored and released in the form of magnetic (inductors) and electric (capacitors) fields which, in turn, generate opposing electromotive forces. As a result, current stops being in phase with voltage and, thus, the effective voltage and power delivered by the grid is reduced (see figure below).

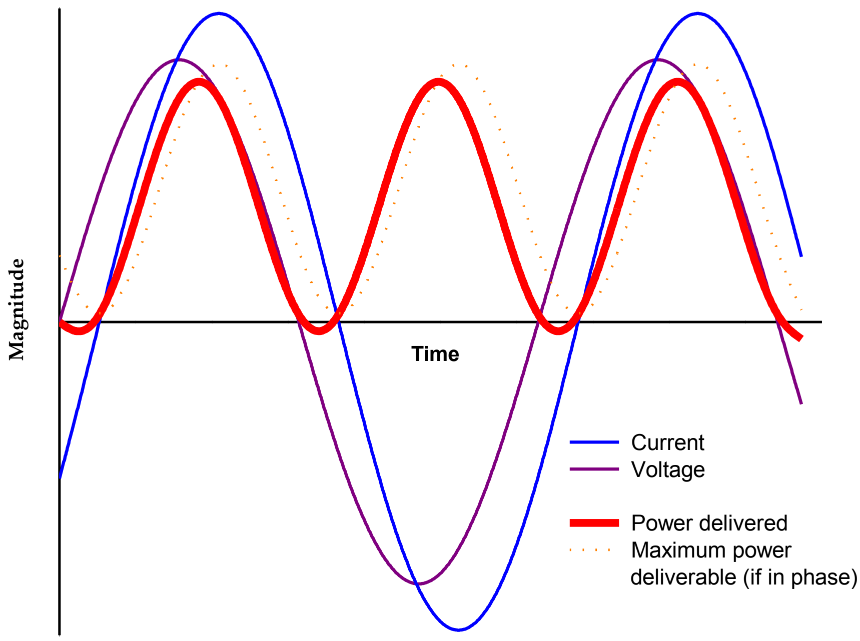


Figure 3- Reactance

Voltage must be maintained within an acceptable range for both customer and grid equipment to function properly. This can be controlled by generating or absorbing reactive power to compensate the effect of reactance. Both generation and transmission equipment can be used for this purpose. However, when generators are required to supply excessive amounts of reactive power, their real-power production must be curtailed. (Kirby and Hirst, 1997)

According to Eyer and Corey (2010), many major power outages are attributable to problems transmitting reactive power to load centres. Using distributed storage near load to create reactive power can be a particularly good alternative since this type of power cannot be transmitted efficaciously over long distances (Kirby and Hirst, 1997).

2.1.4 Grid System Applications

Transmission support

The electricity transmitted through transmission and distribution (T&D) networks is not a perfect sine wave. It can present several anomalies like voltage dips, unstable voltage or sub-synchronous resonances that can compromise the performance of transmission.

The rapid response of storage technologies is well-suited for this purpose. Energy storage can be used to improve the performance of T&D systems by correcting the disturbances and anomalies in the transmitted electricity (Eyer and Corey, 2010).

Transmission congestion relief

Transmission congestion decreases the system efficiency and increases electricity prices through congestion charges or locational marginal pricing. It occurs when peak load is higher than the transmission system's maximum capacity. Furthermore, congestion increases the need of enlarging transmission lines and has an elevated cost associated. (Samant, 2011)

Energy storage systems can be deployed downstream from the congestion point. They would be charged during low demand periods and discharge during peak demand to alleviate congestion and, thus, mitigate upwards pressure on electric prices and defer and/or eliminate the need for further transmission expansion. (Eyer and Corey, 2010; Samant, 2011)

Transmission and distribution upgrade deferral

T&D systems are designed for maximum peak demand. However, this high demand typically occurs only during a few hours a year (Denholm et al., 2010). The upgrading of T&D systems to accommodate the increasing peak demand can be delayed or even avoided if energy storage is placed near load (downstream from the T&D overloaded node) to be used during peak times (Nourai, 2007). It can report great savings since the elevated capital cost of building new substations, transformers, lines, etc. would be avoided. At the same time, energy storage near load can also reduce the large line-losses that take place during high peak demands (Nourai et al., 2008; Denholm and Sioshansi, 2009).

It is important to note that a small amount of storage can provide enough incremental capacity to defer the need for a large investment in T&D equipment (Eyer and Corey, 2010). This can be observed in the following example provided by EPRI-DOE (2003, p.53):

Assuming a load increase of 2.5% per year, the upgrade of a 9 MWac system (in California) to 12 MWac could be deferred for one year by building a storage plant of just 225 kW. This would result in 150000$ benefit. If the cost of storage is equal or less to this quantity, the repayment period of the storage plant would be equal or lower than one year.

In addition, not only T&D upgrading is deferred but also the lifetime of the T&D equipment can be substantially improved by reducing maximum load or load swings. (EPRI-DOE, 2003)

Substation on-site power

Energy storage provides power at electric utility substations for switching components as well as for substation communications and control equipment when the grid is not energized. (Sandia Corporation, 2012)

The vast majority of these systems use lead-acid batteries, mostly vented valve-regulated, with 5% of systems being powered by NiCd batteries. Lead-acid batteries are a low-cost and extremely entrenched in the market technology and users are satisfied with their lifetime and operational performances. Therefore, advances in energy storage technologies are not likely to make an important change in this service. (Eckroad et al., 2004)

2.1.5 End User Applications

It should be noted that the storage systems described in this section need to use time-varying prices and/or be very site-specific in order to be economically feasible for end users (Denholm et al., 2010). TOU and demand charge management will be further discussed when talking about demand side management in section 3.2.1.

Time-of-use (TOU) energy cost management

TOU energy cost management is the equivalent to energy arbitrage but at a customer level. Costumers use and/or store energy during off-peak periods, when the price of electricity is low, in order to get an economic benefit. Obviously, this requires that the electricity provider offers a time-variable tariff like UK's "Economy 7 tariff" which charges electricity cheaper overnight (for seven hours) than during the day.

Two technologies widely used for this purpose are storage heaters and hot water cylinders. Electricity is stored in the form of thermal energy during night and released during the day to provide space heating and hot water respectively.

Demand charge management

Similarly to the previous service, utility users can use storage to avoid the use of electricity during peak hours that may be penalised with "demand charges". This usually affects only to large electricity consumers (more than 2 MWh/month). These costumers are forced to have installed a demand meter that takes readings every 15 minutes. Accordingly, their electricity tariff varies every 15 minutes too. (National Grid, 2005).

Energy can be stored throughout the day and be used to reduce the overall demand during peak periods. Therefore, storage can make a significant difference in the energy bill for large customers by avoiding expensive demand charges at peak hours.

Electric service reliability

Energy storage can be used as on-site back-up supply in the event of a power outage. It should provide enough energy to ride through outages of extended duration; to complete an orderly shutdown of processes; or to transfer to on-site generation resources (Eyer and Corey, 2010). All these options lead to a highly reliable electric service and can be of particular interest for costumers like hospitals or other facilities where energy supply is critical for their operation. Energy storage can complement (or even substitute) traditional back-up generators (usually diesel generators) providing, in addition, a very rapid response.

UPS (uninterruptible power supply) units used to protect computers, data centres or telecommunication equipment are a good example of this service. They are an extended technology and can provide power almost instantaneously.

Electric service power quality

Voltage spikes, dips or harmonics are common issues in the electricity supply and they are said to worsen the power quality. They can produce malfunction in electrical devices and can even cause severe damage in sensitive equipment. Storage is commonly used by the customer at load site to buffer and protect sensitive equipment (Denholm et al., 2010).

2.1.6 Renewables Integration Applications

Most of renewable energy generation is highly unpredictable and the variability of its energy output poses control, response and other energy management challenges to the utility operators. Energy storage has the capability of firming and backing up the variable and intermittent nature of renewables by smothering its supply profile and extending its useful generation time (Denholm et al., 2010). That way, storage could also help to stabilise the price of renewable energy avoiding its curtailment when its price is too low (Denholm and Sioshansi, 2009).

Storage appears, thus, to be the ideal solution to accommodate variable generation. However, the role that it will play in the future grid is not so clear. The viability of storage will depend on many factors like the penetration and type of renewable generation or the cost of deployment of storage versus other technologies. There are other ways of integrating variable generation within the grid like flexible generation, interconnection and demand side management (Strbac et al., 2012). Either way, surely energy storage is very beneficial when combined with renewables.

Renewables energy time-shift

One of the main issues of renewable generation is that it is usually not produced when it is needed. As an example, wind generation usually blows most intensely at night and early morning (Bentek Energy, 2010). Energy generated during off-peak periods has a very low price in the energy market. Storage could be used to store this low-price energy and sell (release) it during on-peak times when it is more valuable (Eyer and Corey, 2010).

The characteristics of time-shifting vary from technology to technology. Wind, solar and base-load renewables are briefly explained to illustrate these differences

Wind

As stated above, wind usually has a large output overnight. In addition to its low value, excessive wind generation during off-peak periods can also cause minimum load constrains which are a serious operational challenge (this will be explained in section 2.2.3). Energy could be stored overnight and be released during peak demand so it is more valuable and minimum load constrains are avoided.

For the case of wind generation, the required discharge duration ranges from two and one-half hours to as much as four hours, depending on the amount of energy from wind generation that occurs during on-peak times. (Eyer and Corey, 2010)

Solar

The case of solar energy is totally different to wind. Generally, solar energy is produced when it is needed (see Figure 4) and, thus, it is already valuable. In addition, the output from solar energy can be predicted to some extent so minimum load violations are not likely to occur. Nevertheless, as will be analysed later on, energy storage plays a really important role to firm solar generation capacity.

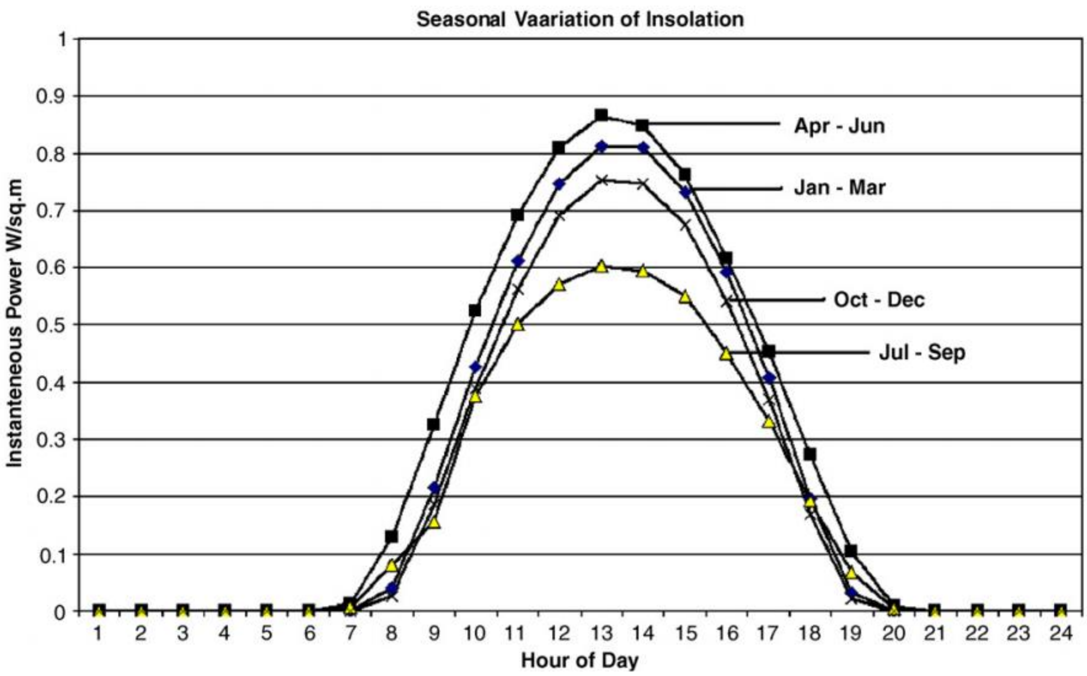


Figure 4- Diurnal variability of solar radiation. Ref. Pradeep and Mohan (2007)

Base-load renewable energy generation

Renewable generation with a fairly constant and predictable output is sometimes referred as base-load renewable. It includes technologies such as geothermal, biomass, biogas or solar thermal.

Time-shift in this case works very similar to wind power. Energy is stored during off-peak periods (usually at night) and used at peak times when it is more valuable.

Renewables capacity firming

As it has been stated many times before, one of the major concerns of renewable generation is its unpredictable intermittency. It has been already explained how these output variations imply the use of rapid-response dispatchable generators as back-up supply such as open cycle gas turbines.

The combination of variable generation and storage can provide a constant output from intermittent sources of energy. This is known as capacity firming. Wind and solar energy are the most extended technologies and, thus, for which storage offers a higher potential.

Solar PV

PV generation suffers from two equally important types of intermittency: short-duration and diurnal (Eyer and Corey, 2010).

Short-duration intermittency accounts for temporary shading of the PV panels due to objects or, more importantly, clouds (Sayeef et al., 2012). When shading occurs, the output from the solar panels decreases substantially. Storage can be used to “fill” these momentary generation gaps so the overall output remains constant (Eyer and Corey, 2010).

On the other hand, diurnal intermittency of solar generation is basically due to the variable amount of radiation that PV panels receive during the day as the sun moves in the sky. A typical profile of this variability can be found in Figure 4. It can be observed that the bulk of solar generation occurs during on-peak times. It is especially during on-peak periods when it is important for the grid operators to count with constant energy outputs. Storage can be used to provide this service by discharging during on-peak times when the power output is lower than the rated power of the plant.

Energy storage plays, thus, a fundamental role to make PV generation reliable and useful.

Wind

Wind power also presents short-duration and diurnal intermittency although less markedly than in the case of solar. Short-duration intermittency is due to rapid variations in the wind speed and diurnal intermittency comes from the tendency of wind to blow stronger during some parts of the day (or night) (Bentek Energy, 2010).

Storage could be used, as in the case of solar, when the output of the power plant falls below its rated power during on-peak periods to provide a constant and reliable output.

Capacity of storage needed for firming of renewables

The capacity of the storage system needed for firming of renewables depends on the maximum power drop-off (Eyer and Corey, 2010). The next figure illustrates the meaning of drop-off.

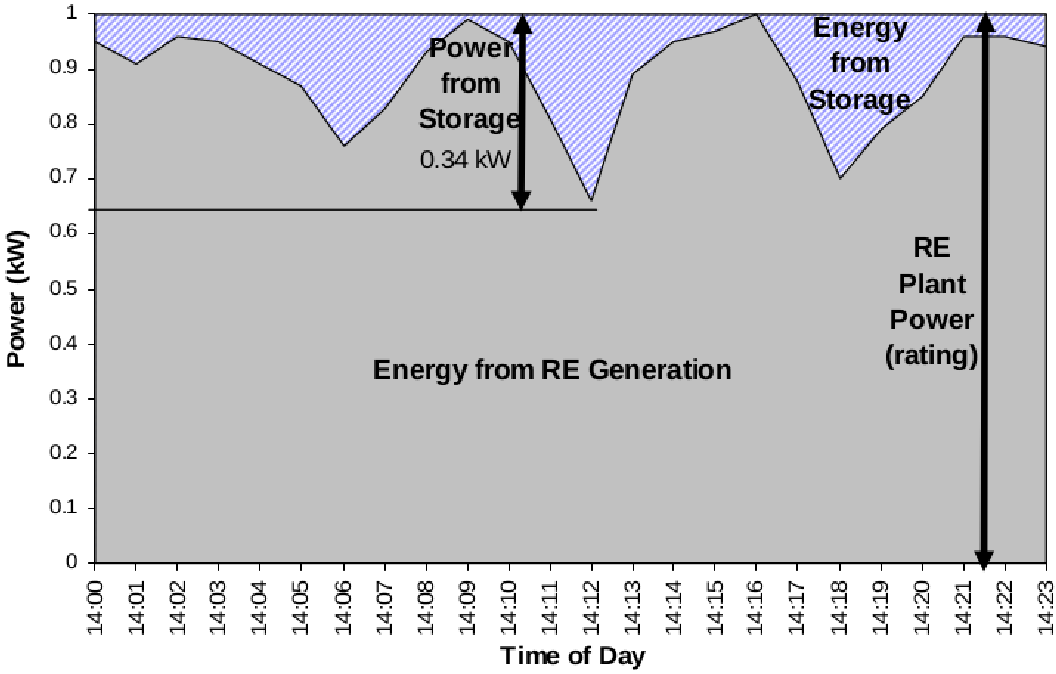


Figure 5 - Renewable energy firming. Ref: Eyer and Corey, 2010

In the case of the figure above, a storage power of 0.34 kW would be necessary to provide enough firming since it is the maximum difference between rated power of the plant and the real power output.

Eyer and Corey (2010) indicate that the duration of the discharge should be from one and a half to two hours for solar and from three to four hours for wind.

Bottom line

Energy time-shifting and capacity firming are the only two applications of storage that can be considered specific to renewable generation. However, every service listed before is totally connected with and useful for the integration of renewable energy. E.g. variable generation poses load-following and area regulation challenges, needs contingency reserves, can worsen power quality, produce congestion in T&D systems, etc. Therefore, storage and renewable generation are very interrelated and will be even more with the growth of variable generation.

2.2 Storage and Wind Power

2.2.1 Introduction

Wind energy is growing very fast. According to Carrington (2013) it grew a 20% globally in 2012. Thus, it is the renewable technology which is starting to pose the biggest integration challenges.

According to Denholm et al. (2010) the integration costs of wind power arise mainly from:

- *Area regulation* - the increased costs that result from providing short-term ramping resulting from wind deployment.
- *Load-following* - the increased costs that result from providing the hourly ramping requirements resulting from wind deployment.
- *Wind uncertainty* - the increased costs that result from having a suboptimal mix of units online because of errors in the wind forecast.

However, different studies (Denholm et al., 2010) show that area regulation and load-following do not have a significant impact in the overall integration costs. This is due to the current capacity of the grid to supply variable output in order to match demand. Thus, wind uncertainty is the main cause for wind integration costs.

2.2.2 Wind uncertainty

Supply needs to be planned in advance according to the forecasted demand. Only the precise number of generators required to meet demand are scheduled so that they are online at the right time. This is known as unit commitment. Large base-load generators need a particularly good planning due to the long time and high fuel requirements necessary to bring them online. The combination of base-load, load-following and peaking generators that provides the right supply with the highest efficiency is usually referred to as the optimal generation mix.

Because of the unpredictable nature of wind, wind power is often regarded as an unexpected reduction in the demand profile more than like part of the supply scheme (Denholm et al., 2010). Therefore, wind power with relatively high degree of penetration becomes a very important part of the planning for unit commitment (see Figure 6 left). If there is a large difference between real wind output and the prediction, the following scenarios can occur[1]:

If the wind output is lower than predicted (Figure 6 centre), there is not enough scheduled supply to meet demand. Back-up generation (e.g. contingency reserves) need to be brought online and/or some large costumers be asked to reduce their load. This scenario represents elevated costs that could have been avoided by scheduling cheaper base-load generation.

On the other hand, if the wind out is higher than predicted (Figure 6 right), there is an excess of supply. Customers will be encouraged to use electricity by very low, zero, or even negative prices and/or wind production will need to be curtailed. Again, the costs associated to this situation are high. The expenses of scheduling too much large base-load generation are high and, at the same time, fuel-free wind power is being wasted.

Storage could significantly reduce the costs associated to prediction inaccuracy by providing additional supply in the case of an underestimation (Figure 6 right) or by absorbing the excess of generation in the case of an overestimation (Figure 6 centre) avoiding supply shortages and undesirable wind power curtailment respectively.

[1] A similar analysis can be found in Denholm et al., (2010)

Nevertheless, storage is expensive and its implementation should be economically evaluated. As an example, many renewable integration studies (Denholm et al., 2010) show that with a wind generation up to a 30% of the total there is no need for additional storage.

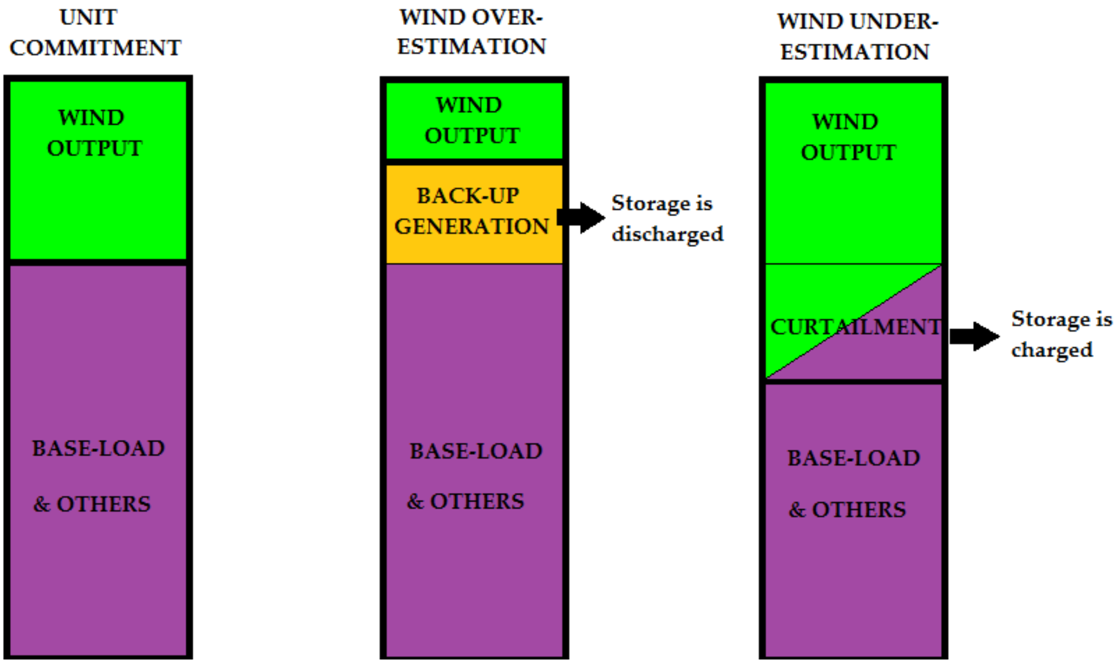


Figure 6- Power scheduled and wind prediction

2.2.3 Minimum generation constrains

It is often assumed that renewable generation only displaces load-following generation (see Figure 1). This is true only for low penetration levels. Load-following generators are designed to modulate their output so renewable energy does not pose a significant integration problem. It can be accommodated easily by just varying the output of load-following generators properly.

Nevertheless, in some countries wind power starts to represent a high percentage of the total generation. Just to mention a couple of examples, wind power accounted for 18.1% of the total generation during 2012 in Spain (Red Eléctrica de España, 2012) and 30.08% in Denmark (Energinet, 2013). For elevated amounts of wind generation, it is possible that not only load-following but also base-load generation needs to reduce its output in order to accommodate wind. However, it is not an easy task and an unsuccessful base-load modulation can lead to wind power curtailment. A study by

Ackermann et al. (2009) shows that wind curtailment is a common issue in the Danish energy power system during periods of high wind output.

This is usually referred to in the literature as minimum generation constrains. Its origin lies in the fact that base-load generators are not designed to be modulated and, furthermore, they have a minimum output they need to provide to operate safely. As an example, large coal-fired power plants are often restricted to operating in the range of 50-100% of full capability, although the lack of experience cycling these plants makes that limit very uncertain (Denholm et al., 2010).

Logically, renewable energy curtailment due to minimum generation constrains will occur more frequently with higher penetrations of wind power. This can put a limit to the growth of renewable energy. The only way of avoiding this situation is to add flexibility to the grid. Conventional rapid-response generators, interconnection, demand side management and storage are the most common solutions proposed to do this (Lannoye, 2012).

Energy storage can be a key element in avoiding curtailment and reducing (or even eliminating) minimum generation constrains. Storage technologies can absorb excess generation, that would be wasted (curtailed) otherwise, and shift it to times of high demand. Furthermore, Denholm et al., (2010) suggest that storage could effectively replace base-load generation as it provides firm capacity. This would eliminate minimum loading limitations totally.

Minimum generation constrains are very site-specific Thus, the cost of storage technology versus other options will define its ultimate role in the future grid in every specific case.

2.3 Location of storage

It has been shown in previous sections that energy storage is likely to be a key element of the future grid because of all the useful services it can provide as well as its capacity to accommodate large amounts of variable generation. However, it has not been discussed so far a crucial aspect of storage: its optimum location.

It is quite common to think of storage units coupled directly to renewable generators. Energy could be stored in times of excess generation and released when necessary for every individual renewable energy plant. This would result in lots of renewable and dispatchable generators, what seems a desirable situation. Surprisingly, if that was case, the overall efficiency of the global energy power system would be compromised. However, there are some situations in which it is beneficial to tie generation and storage together.

Micro-grids and highly distributed storage are not considered in this discussion. However, they can provide very useful services and add flexibility to the grid. The role that storage heaters can play as demand side management distributed storage will be analysed later on.

2.3.1 Separated generation and storage

It is easy to see that the way storage operates when coupled to a single generator is totally analogous to energy arbitrage (see section 2.1.2) but in an individual basis. Nevertheless, energy arbitrage is more efficient when the energy operator can choose what type of generation to store based on cost and efficiency (Denholm et al., 2010). If arbitrage is restricted to only one energy source, the optimal generation mix (the one that ensures maximum generation efficiency) is lost and the flexibility of the overall system decreases.

The concept behind storage location is resource aggregation. This concept is quite easy to understand when talking about energy demand. The demand of a single customer can vary very abruptly and is highly unpredictable. Using a power plant to supply electricity to a single customer would be, thus, quite absurd and inefficient. There would be many times of excess and lack of power supply while, at the same time, other customers would be in the opposite situation. Hence, if many different loads are aggregated, the combined demand profile is much smoother and easy to match.

The same situation is applicable to storage. Let’s use the case of wind power. The output of a single plant is highly variable. If a storage facility is tied to a single plant it will be discharging when there is not enough wind and charging when there is an excess. However, other plants can be in the opposite situation at the same time. Thus, it would be very likely that energy was being stored at some facilities and discharged at others simultaneously. This is a total waste of the capabilities of storage resources and, in addition, the losses associated with the storage process make the operation highly inefficient.

Likewise, the supply profile for an aggregation of wind power plants located at different places tends to be smoother since the wind has different blowing patterns at different locations.

For those reasons, an aggregation of both loads and variable generation sources would lead to an optimum use of storage resources reducing, consequently, both capital and running costs.

Besides energy arbitrage, it is of extreme importance to note that a storage plant not tied to a variable generation plant can also provide many other high-value grid services as it was explained in the previous section (see section 2.1). Therefore, co-locating generation and storage is also a waste of the potential of storage technologies.

The following picture illustrates the scenario of variable generation plant and storage facility in different locations.

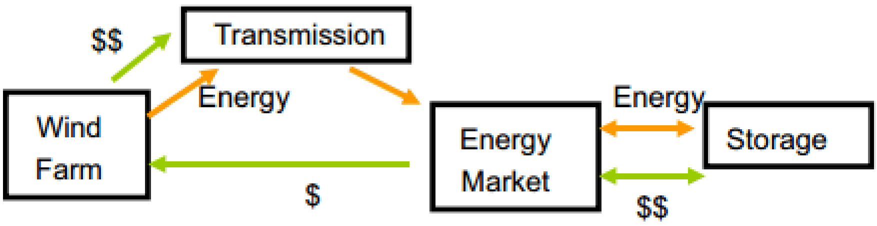


Figure 7 – Separated generation and storage. Ref. Denholm and Sioshansi (2009)

2.3.2 Co-location of generation and storage

Nevertheless, co-location of storage and renewable generation can be beneficial in some situations. A good example is the integration of thermal storage within concentrated solar power plants (Denholm et al., 2010).

A particularly interesting case is that of wind farms located at very low populated areas where the transmission network is weak (Denholm and Sioshansi, 2009). The transmission capacity of the local grid can be a limit to the size of the power plant.

However, it has been already mentioned (see section 2.1.4) that upgrading T&D lines has an elevated capital cost.

Integration of storage within the wind farm (i.e. upstream the transmission line) can downsize the maximum power supplied by the plant and, consequently, it can avoid the upgrading of the transmission line. The question here is whether the reduced transmission costs exceed the penalties associated with a suboptimal use of the energy storage plant (Denholm and Sioshansi, 2009).

The following picture illustrates the scenario of generation and storage co-location

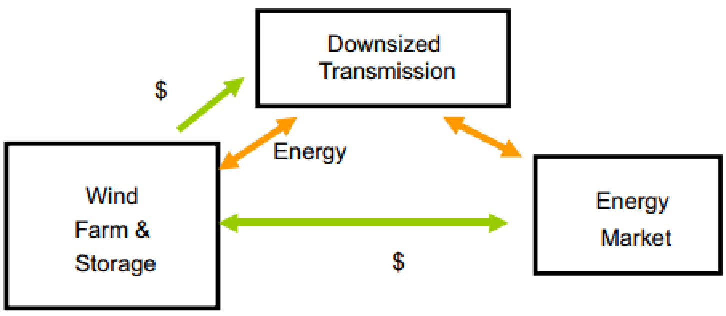


Figure 8 – Co-location of generation and storage. Ref. Denholm and Sioshansi (2009)

2.3.3 Bottom line

A good bottom line to this discussion can be found at Denholm et al. (2010): "Just as loads are balanced in aggregate, the net load in the future grid – after all variable generation sources are included – will be balanced by a mix of conventional generation, plus flexibility options that include energy storage".

2.4 Energy Storage Technologies

2.4.1 Introduction

So far, only the services that storage can provide to the grid have been analysed. However, it is equally important to examine the different storage technologies used for those services, their performance and potential.

The figure below gives an idea of the wide range of technologies available for energy storage. This section investigates the most common ones found in the literature focusing mainly on how they work, their positive and negative characteristics, their limitations and the services they can provide to the operation of grid.

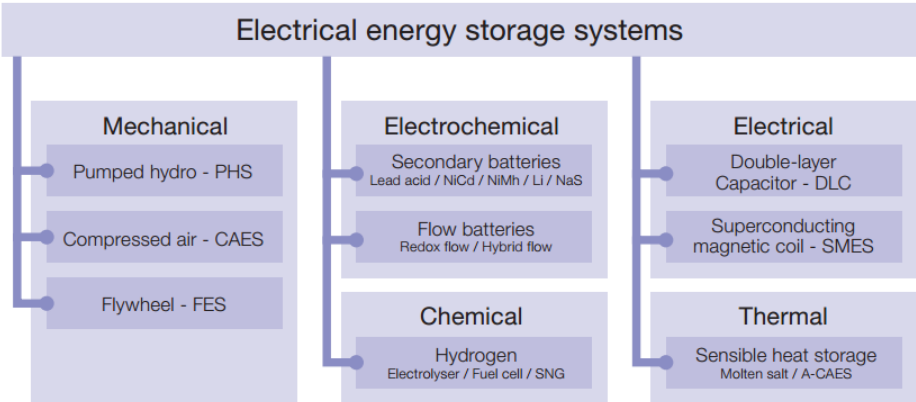


Figure 9 - Storage technologies. Ref. IEC (2011)

2.4.2 Mechanical energy storage

Compressed air energy storage (CAES)

CAES plants store energy in the form of air elastic potential energy (compressed air). Electricity is taken from the grid to drive a compressor. Compressed air is then stored in tanks above the ground or in underground geologic formations (caves, mines…). To convert the stored energy back into electricity, the compressed air is heated and expanded through a gas turbine attached to a generator. The diagram below illustrates a typical operation CAES plant.

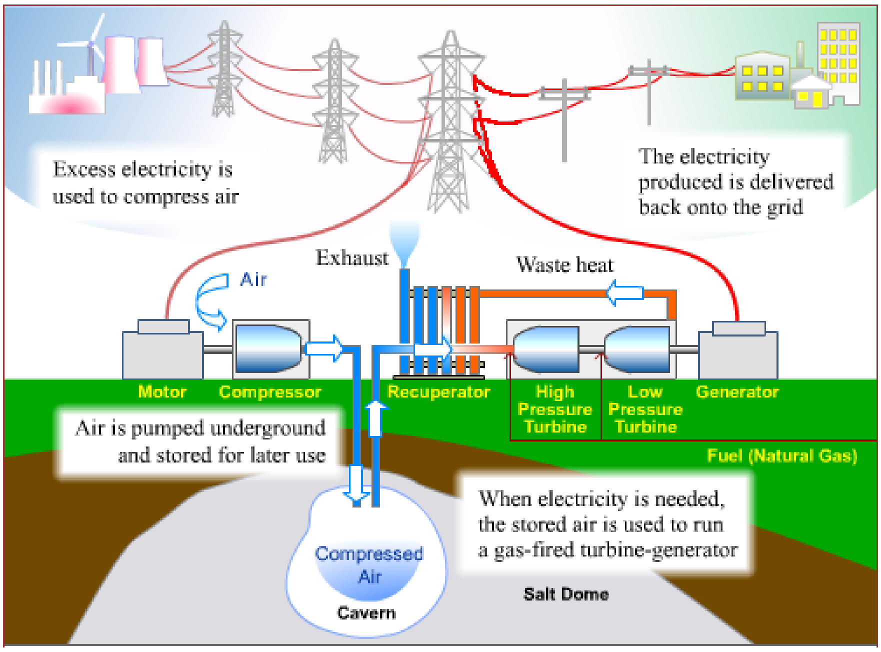


Figure 10- Typical operation of a CAES plant. Source: http://www.ridgeenergystorage.com/

Heat is released as result of the compression process. Nevertheless, the air must be preheated before expansion in order to avoid ice formation in the turbine (due to the Joule-Thomson effect). Natural gas or other fuels are used for this purpose. If the heat arising from the compression is released to the atmosphere, the storage process is called diabatic CAES and has a 40-50% efficiency (Teller et al., 2013). On the other hand, that heat could be stored and used to preheat the air before its expansion. This concept is called adiabatic CAES and should result in round-trip efficiencies of up to 65% (EPRI-DOE, 2003).

The main features of CAES systems are: an efficient partial load operation, the ability to start up without an external power input, reaching of full power within minutes and quick transition from generation to compression mode. (Chen et al., 2013)

Applications

The main advantage of CAES is its large capacity when using underground storage. This large scale potential makes CAES a very suitable technology for future energy arbitrage like PHS. However, CAES is not only suitable for large but also for small scale storage applications. For example, decentralised CAES technology could be deployed at difficult accessible places with considerable share of fluctuating renewable electricity generation. (Teller et al., 2013)

It can be particularly useful in combination with wind power. Markets are expected in northern Europe close to off-shore wind farms (Teller et al., 2013). CAES can be applied within wind farms to balance generation and demand and can be used to reduce the size (and capital cost) of transmission lines. Some authors, like Denholm and Sioshansi (2009), have already explored the potential of co-location of wind power and CAES with positive results.

Regarding standard grid services, EPRI-DOE (2003) lists the following services currently provided by the only CAES facility in the U.S.: load management, ramping, peak generation, synchronous condenser duty and spinning reserve duty. In addition CAES can be applied to provide secondary and tertiary balancing power as well as black start capability (Teller et al., 2013).

Limitations

Similarly to PHS, the major barrier for CAES is the need of favourable geographic formations for its deployment. (Chen et al., 2013)

Another limitation when compared to PHS or other storage technologies is that CAES requires a gas combustion turbine to operate. This leads to emissions that make CAES less environmentally friendly. (Chen et al., 2013)

In addition, the low efficiency of diabatic CAES is also a limitation for investment in this technology. Nevertheless, the new CAES schemes proposed, like adiabatic CAES, are likely to improve the efficiency of CAES to levels comparable to those of PHS and reduce emissions. (Chen et al., 2013; Teller et al., 2013)

Finally, CAES is today not economically viable when only single applications are used to generate revenues. This means that CAES will probably have to act on different markets simultaneously in order to justify the necessary investments, limiting its potential (Teller et al., 2013).

Flywheels

Flywheels store energy in the form of kinetic energy of a spinning mass, called a rotor. The amount of energy stored in a spinning body depends only on its rotational speed and on its mass. Motor-generators are used to convert electricity into kinetic energy and vice versa.

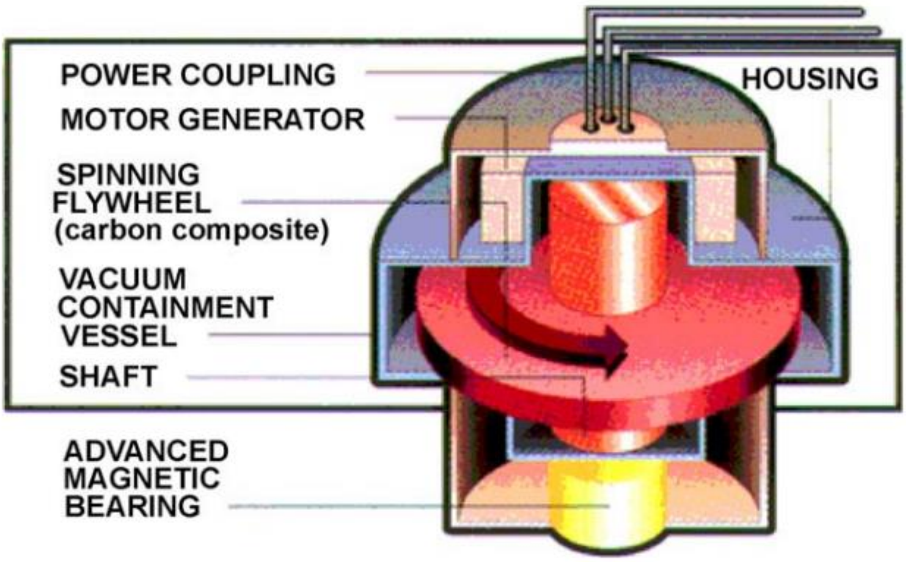


Figure 11 - Flywheel structure. Ref. Hadjipaschalis (2009)

The following features make flywheels an attractive storage technology:

- They can act as high-power devices, which absorb and release energy at a high rate. Most power flywheel products can provide from 100 to 2000 kWac for a period of time ranging between 5 and 50 seconds (EPRI-DOE, 2003).
- They have a long life, which is unaffected either by the frequency of cycling or by overcharging or deep discharges. Most developers estimate cycle life in excess of 100,000 full charge-discharge cycles (EPRI-DOE, 2003).
- Energy and power density in flywheels are almost independent variables, as opposed to other systems like batteries. They have thus flexibility in design and unit size (Dell and Rand, 2001).
- They have high round-trip efficiencies: 80-85% (Teller et al., 2013)
- They work very well as power devices and are well suited for applications which involve the frequent charge and discharge of modest quantities of energy at high-power ratings. (Dell and Rand, 2001)
- They require very little maintenance.
- They are constructed from readily available materials.
- They have no environmental impact in use or in recycling.

Conversely, flywheel systems have high self-discharge ratings, must be housed in robust containment for safety reasons and require high engineering precision components which currently results in a relatively high cost (Strbac et al., 2012)

Applications

Flywheels are mainly used nowadays for power quality applications, mainly for short-term bridging through power disturbances or from one power source to an alternate source. (EPRI-DOE, 2003)

Other applications include frequency and voltage support, renewables firming and stabilization, transport applications for light rail and large road vehicles and as UPSs for industrial uses. (Denholm et al., 2010; Teller et al., 2013; EPRI-DOE, 2003; Strbac et al., 2012)

For the latter application, flywheels are usually sold as a clean, reliable and long cycle life alternative to batteries. However, some studies show the potential of combining flywheels and batteries to improve the reliability as well as the overall efficiency and lifetime of power conditioning systems (Richey, 2004).

For renewable integration applications, flywheels are of particular interest for localized storage of electricity generated by wind turbines and photovoltaic arrays. A flywheel-based buffer storage could remove the need for downstream power electronics to track the fluctuations in power output improving the overall efficiency of the system. Rechargeable batteries would seem to be a more appropriate storage medium and, in fact, these are widely used today. However, a battery–flywheel combination (as just stated above) is worthy of consideration for this application. (Dell and Rand, 2001)

Limitations

The most significant limitation of flywheels lies in their relatively modest capability for energy storage although they work very well for high power applications. An increase of power and energy density is required in order to reduce the high investment costs and make them competitive against other technologies (Liu and Jiang, 2007)

Technical restrictions arise mainly from bearings and friction that limit the potential of flywheels. The bearings, which support the flywheel rotor, are a significant source of friction, the most life-limiting part and if they fail there can be serious incidents. Some developers have introduced magnetic bearings to improve all those issues.

Finally, another limitation comes from the heat generated by the friction between the rotor and the medium it which it is enclosed. Besides leading to energy losses, it can increase the temperature of some parts of the flywheel system reducing the safety and reliability of the system. Many different cooling systems have been proposed to address this problem, like hydrogen cooling similar to the one use in large generators (EPRI-DOE, 2003).

Pumped hydro storage (PHS)

PHS is the most established storage technology. It represents around 99% of the global grid scale energy storage capacity. It is also the storage technology with highest storage capacities. It can be sized up to several GW and its efficiency is usually around 70-85% although it depends on the operation and characteristics of the plant. (Strbac et al., 2012)

The basic elements of a PHS plant include the turbine-pump equipment attached to a motor-generator, a waterway, an upper reservoir and a lower reservoir (see Figure 12). Pure PHS plants only shift the water between reservoirs. Though, there also exist combined plants that can generate their own electricity like conventional hydroelectric plants through natural steam-flow besides pumping storage (Hadjipaschalis et al., 2009).

The main advantages of PHS are its very long lifetime and practically unlimited cycle stability of the installation. It also has a high flexibility and can ramp up to full production capacity within minutes. The typical discharge times range from several hours to a few days. However, it has a relatively low energy density and requires either a very large body of water or a large variation in height and its capital cost is very high. (IEC, 2011; Teller et al., 2013; Hadjipaschalis et al., 2009)

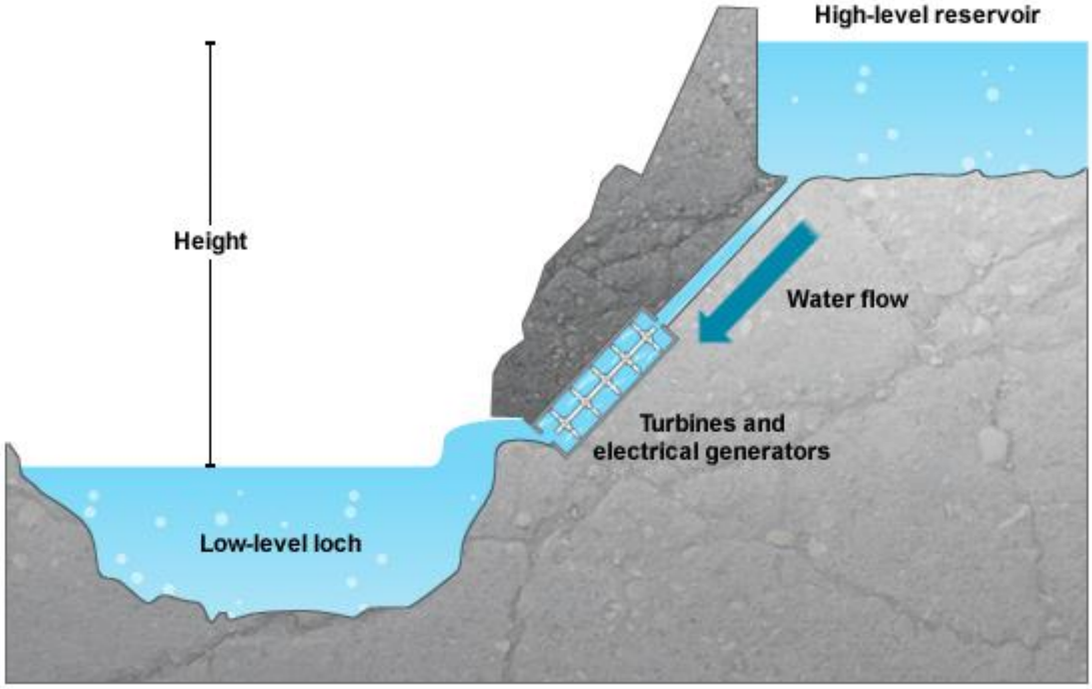


Figure 12 - Typical PHS plant. Source: http://www.bbc.co.uk/bitesize/standard/physics/energy_matters/generation_of_electricity/revision/3/

Applications

The main application of PHS is energy arbitrage. By storing energy in times of low demand, it enables fossil-fired and renewable energy plants to be operated at their most efficient levels more often. Apart from the economic benefit arbitrage reports, it also helps to reduce emissions and fuel consumption. (Teller et al., 2013)

Furthermore, its flexibility in power and short response time make PHS a useful tool to balance the grid during unplanned outages of other power plants acting as non-spinning reserves. Thus, PHS plants are already being currently used for both primary and secondary regulation in the European electricity grid. (Teller et al., 2013; IEC, 2011)

Limitations

The main weakness that limits the future potential of PHS is the inherent dependence on very specific topographical conditions for its deployment. It also has a large environmental impact since it requires an extensive use of land (IEC, 2011).

In addition, the future potential of PHS will be also determined by the capacity of this technology to improve its flexibility to accommodate the increasing amount of variable generation and even to help with the ultra-fast regulation that will be needed with the introduction of large HVDC electric highways. (Teller et al., 2013)

2.4.3 Chemical energy storage

Chemical energy storage comprises, mainly, the use of excess electricity generation to produce hydrogen via water electrolysis. The hydrogen produced from this process can be used directly or be further transformed into synthetic natural gas (SNG) by reacting it with CO_2.

Hydrogen

A chemical storage system based on hydrogen consists of an electrolyser to produce hydrogen from pure water electrolysis, a storage tank to store the hydrogen produced and a fuel cell to combine the hydrogen with air (oxygen) to obtain electricity again.

In addition to fuel cells, gas motors, gas turbines and combined cycles of gas and steam turbines are in discussion for power generation. (IEC, 2011)

SNG

In this case, after the electrolysis there is a process called methanation in which hydrogen is reacted with CO_2 to obtain methane. This methane can then be stored or released into the gas grid.

The most common source of CO_2 considered for methanation are fossil-fuelled power plants, some large industries and biogas plants. In order to minimize losses, it is recommended the co-location of the electrolyser, the CO_2 source and the storage tanks (or pipelines).

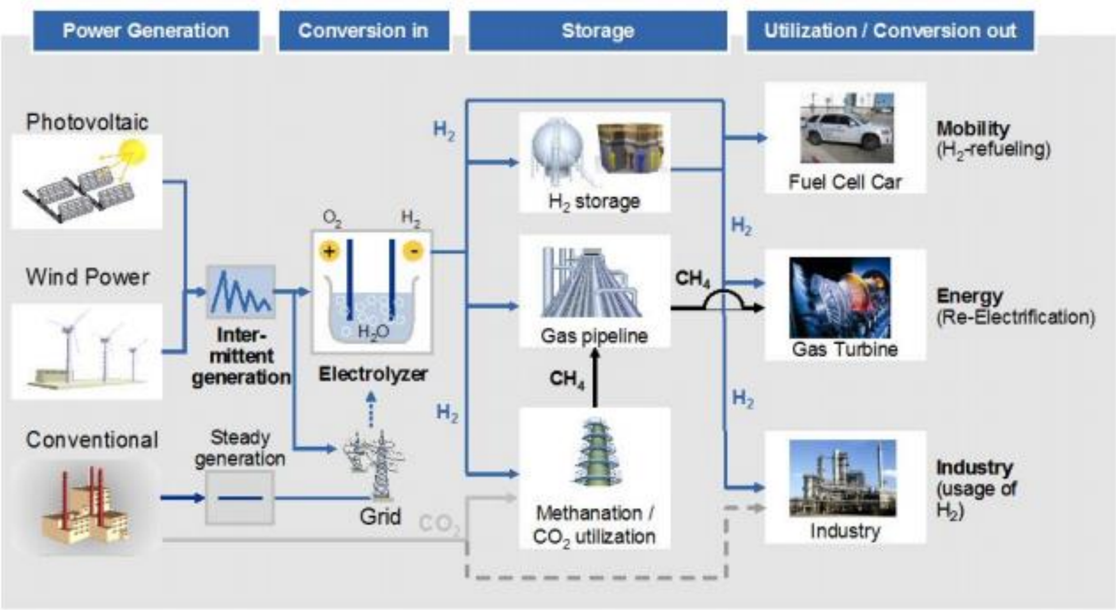


Figure 13 - Chemical storage cycles. Ref. Teller et al. (2013)

Efficiency

The efficiency of the complete cycle can be as high as 40%, similar to coal fired steam power plants (Teller et al., 2013). The most significant losses take place during electrolysis, methanation and re-electrification (see figure below).

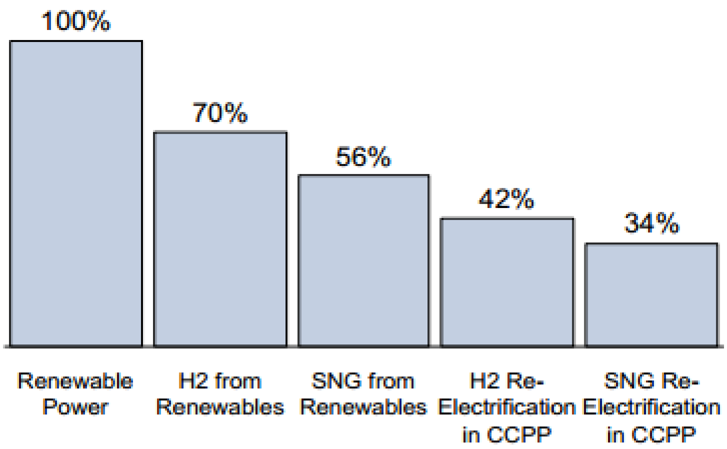


Figure 14 – Chemical storage efficiency. Ref. Teller et al. (2013)

The overall efficiency is lower than other bulk energy storage technologies such as CAES, PHS or Li-ion batteries. However, chemical energy storage is the only concept that allows storage of large amounts of energy, up to the TWh range, and for greater periods of time – even as seasonal storage (IEC, 2011).

Applications

The high energy density and the potential large scale of storage facilities make chemical storage suitable for energy arbitrage and seasonal storage. Moreover, electrolysers have the ability to react within a second or lower upon changes in electricity supply/demand, both up and down (Teller et al., 2013). They are therefore well suited for provision of ancillary services for the future electrical grid with high penetration of variable generation.

In addition, hydrogen and SNG can be used directly as fuels for transport and industrial applications as well as for synthesising several chemical compounds (Teller et al., 2013) or could be used on gas and steam turbines in peaking power plants (IEC, 2011).

Limitations

The limitations for this technology arise from its elevated cost and as well as the inexistent infrastructure although there are many technological and efficiency aspects that need to be overcome too.

2.4.4 Electrochemical energy storage - Secondary batteries and supercapacitors

Electrochemical batteries use reversible redox reactions to store energy. They consist of different cells that contain two electrodes and an electrolyte material (see figure below).

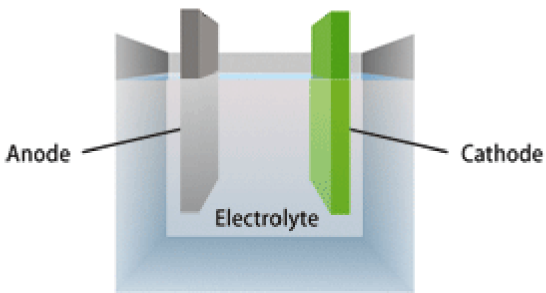


Figure 15 - Basic cell battery structure. Source: http://www.spring8.or.jp/en/news_publications/research_highlights/no_49/

When a battery discharges, negative ions in the electrolyte near one of the anodes supply electrons (oxidation) while positive ions near the cathode accept electrons (reduction). The process is reversed to charge the battery, i.e. ions are created in the electrolyte.

Lead-acid

They are the world's most widely used battery type and have been commercially deployed since about 1890 (IEC, 2011).

They are low-cost, easy to recharge, easy to recycle and they have a huge availability. However, they have many short-comes like low specific energy and power, short cycle life, high maintenance requirements and environmental hazards associated with lead and sulphuric acid. Some of these disadvantages have been overcome by improvements in chemistry and design. (EPRI-DOE, 2003)

Their most commons applications are as starter batteries in vehicles, storage for stand-alone PV houses and they can be even found in wind farms to smoother output fluctuations. (IEC, 2011)

Nickel based batteries (NiFe, NiCd, NiMH)

Nickel based batteries were invented around 1900 and are therefore almost as old as lead–acid. These alkaline batteries have not been as successful as the later because of their higher cost. (Dell and Rand, 2001)

Nickel-iron batteries suffer from numerous defects and thus have never been very popular However their high extreme durability and relative tolerance of nearly any kind of abuse, physical or operational, have made the suitable for several applications like mining or railroad signalling. (EPRI-DOE, 2003; Battery University, 2013)

By contrast, nickel–cadmium have an overall better performance than lead–acid and other beneficial features like flat discharge voltage, long life, overcharge capability, low water maintenance and high reliability (Dell and Rand, 2001). However, they have a high cost and, because of the toxicity of cadmium, these batteries are presently used only for stationary applications in Europe and they have been prohibited for consumer use since 2006 (IEC, 2011).

NiMH batteries have all the positive properties of NiCd and much higher energy densities but their maximal nominal capacity is ten times less when compared to NiCd and lead acid. They have been extensively replaced by lithium ion batteries although hybrid vehicles operate almost exclusively with NiMH batteries as these are far safer than lithium ion batteries. NiMH batteries currently cost about the same as lithium ion. (IEC, 2011)

Lithium-ion batteries

Lithium-ion batteries are currently the most important storage technology in mobile applications. They have a high efficiency (95 % - 98 %) and energy density, a cell voltage three times higher than Ni-based batteries and can achieve nearly any discharge time which makes them a very flexible and universal storage technology (IEC, 2011). In addition, they are low maintenance batteries and have little self-discharge (Battery University, 2013)

However, they are fragile, have aging problems and require built-in voltage and charge level control protection circuits to maintain a safe operation. As a consequence of this, Li-ion batteries have a high cost and are challenging for large-scale applications. However, the costs are likely to drop with mass production. Likewise, safety, storage capacity and performance are likely to improve in the near future as an intense research is being carried out on this technology in the present time. (IEC, 2011; Battery University, 2013)

Since lithium-ion batteries are currently still expensive, they can only compete with lead acid batteries in those applications which require short discharge times (e.g. as primary control backup). (IEC, 2011)

Sodium-based batteries (NaS, ZEBRA) batteries

NaS is a high-temperature battery that uses molten sulphur and sodium as electrodes and solid beta alumina ceramic as electrolyte. The operational temperature usually ranges from just below 300°C to near 400°C so the electrodes remain molten (Dell and Rand, 2001). They have a long lifetime and discharge times, an efficiency around 75% and fast response. Thus, they can be used and have been already applied (mainly in Japan) in power quality, grid stabilisation and time-shifting applications (IEC, 2011).

One of the drawbacks of the battery is the need of a heat source and a good insulation in order to maintain its operational temperature. This is usually made by using battery’s own energy, decreasing its overall efficiency (IEC, 2011). However, the major concerns are related to safety. If there was a fracture and sodium and sulphur mixed, there would and exothermal reaction with a potential fire hazard that would damage the whole battery, not just the faulty cell. In addition, other problems arising mainly from the use of sulphur as an electrode (like corrosion) have led to the development of safer batteries like the so-called ZEBRA batteries. (Dell and Rand, 2001)

Similarly to the NaS battery, the NaNiCl or ZEBRA (Zero Emission Battery Research) battery is also a high-temperature battery. Its operating temperature is lower than for NaS, around 270°C, and it uses nickel chloride instead of sulphur for the positive electrode. They have better safety characteristics and a higher cell voltage than NaS batteries. As an example of its improved safety, when a fault occurs it only results in the loss of the voltage of the cell affected instead of damaging the whole system. (IEC, 2011)

These batteries have been successfully implemented in several electric vehicle designs and present research is in developing high-energy versions for storing renewable energy for load-levelling and industrial applications (Espinar, 2011).

Flow batteries (RFB, HFB)

The main characteristic of flow batteries is that the electrolyte is stored in tanks that are separated from the battery cell. The capacity of the battery is therefore determined only by the size of the tanks, while the power output is determined by the size of the electrochemical cell stack. This separation of energy and power is not possible in a conventional battery, but is similar to that of a fuel cell. This makes them suitable for numerous stationary applications. (Dell and Rand, 2001; IEC, 2011)

RFB

Redox flow batteries (RFB) have two liquid electrolyte dissolutions, catholyte (positive electrode) and anolyte (negative electrode) stored in separate tanks that flow in two separate circulation loops through the electrochemical cell (see figure below). The electrolytes react (redox reaction) with the porous electrodes producing an exchange of charge. A membrane permeable only to specific ions separates the two halves of the cell to equilibrate the redox reaction and close the circuit.

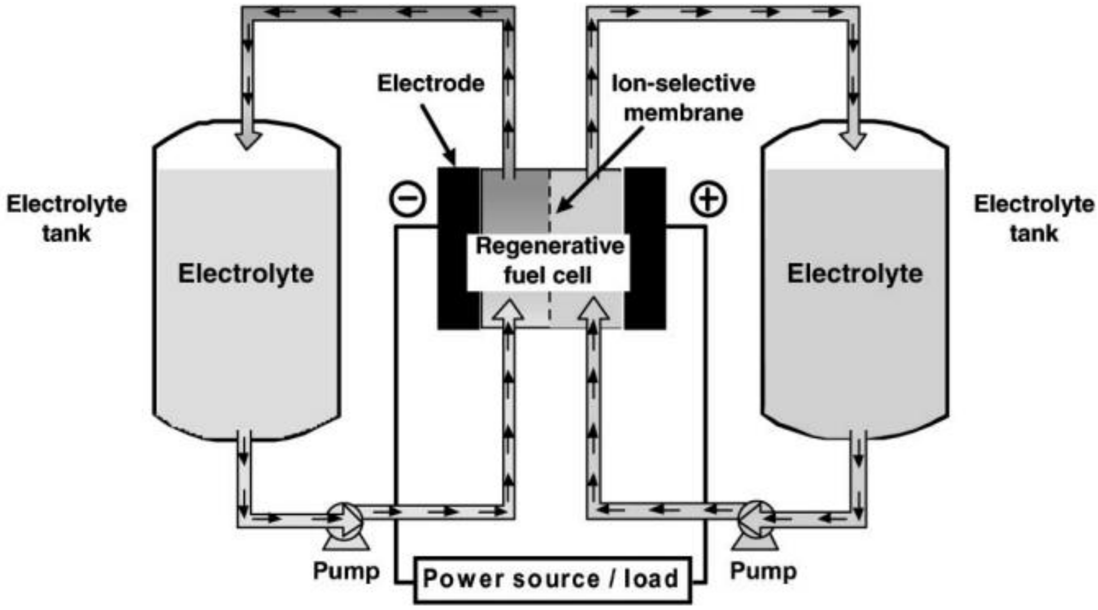


Figure 16 – Redox Flow battery. Ref. Dell and Rand (2001)

Zinc-bromine and vanadium are the most common types of RFB (Eyer and Corey, 2010). An advantage of flow batteries is that the discharge duration can be increased by adding more electrolyte and even a battery could be recharged by replacing the depleted electrolyte by charged electrolyte. They have a long life, short response time, low maintenance costs and an efficiency near 75% (EPRI-DOE, 2003).

HFB

A hybrid flow cell combines features of conventional secondary batteries and redox flow batteries. One of the active masses is internally stored within the electrochemical cell, whereas the other remains in the liquid electrolyte and is stored externally in a tank. Typical examples of a HFB are the Zn-Ce and the Zn-Br systems. (IEC, 2011)

Supercapacitors

A capacitor is a device used for storing electrical charge. There are three distinct types of capacitors: electrostatic, electrolytic and electrochemical. Electrochemical capacitors are also known as supercapacitors or double layer capacitors (DLC).

DLCs differ from the other two types of capacitor because their capacitance and energy density is several orders of magnitude larger. They are actually similar to batteries: they use liquid electrolytes and are arranged into modules consisting of various cells. Still, they are considered capacitors since they store energy via electrostatic charges on opposing surfaces and they have a very long lifetime. (EPRI-DOE, 2003)

The main features of DLCs are durability, high reliability, no maintenance, long lifetime, wide temperature-range operation, very low environmental impact and an efficiency of around 95% and discharge times from seconds to hours (IEC, 2011; Teller et al., 2013). However, they have a very high self-discharge rate (typical of capacitors), a high cost and relatively low energy densities. The use of new carbon-based materials like graphene is likely to improve these characteristics issues in the near future.

Applications

The following figure extracted from Teller et al. (2013) illustrates the applications of electrochemical storage that can be usually found in the literature

Application	Pb acid	Ni/MH	Na/S	Na/NiCl$_2$	Redox Flow	Li/ion	Super capacitor
Time-shift	Very suitable	Less suitable	Very suitable	Very suitable	Very suitable	Less suitable	Unsuitable
Renewable integration	Very suitable	Very suitable	Very suitable	Very suitable	Very suitable	Very suitable	Unsuitable
Network investment deferral	Less suitable	Less suitable	Very suitable	Very suitable	Very suitable	Very suitable	Unsuitable
Primary Regulation	Very suitable	Very suitable	Very suitable	Very suitable	Very suitable	Very suitable	Unsuitable
Secondary Regulation	Very suitable	Very suitable	Very suitable	Very suitable	Very suitable	Very suitable	Unsuitable
Tertiary Regulation	Very suitable	Less suitable	Very suitable	Very suitable	Very suitable	Very suitable	Unsuitable
Power System start-up	Very suitable	Very suitable	Very suitable	Very suitable	Less suitable	Very suitable	Unsuitable
Voltage support	Very suitable	Very suitable	Very suitable	Very suitable	Less suitable	Very suitable	Very suitable
Power quality	Less suitable	Unsuitable	Less suitable	Unsuitable	Less suitable	Less suitable	Very suitable

Very suitable *Less suitable* *Unsuitable*

Figure 17 - Applications of electrochemical storage. Ref. Teller et al. (2013)

Batteries can provide grid balancing by providing reserve capacity and ancillary services to support transmission. Batteries have a high potential because of their flexibility but they need to be correctly designed and tailored to provide effective time-shifts, peak shavings and in particular to support capacity firming of intermittent renewable sources.

DLCs are very suitable for high-power applications. Due to their extremely low response time (milliseconds) they can be easily used for transmission line stability, as spinning reserves or for area regulation (Teller et al., 2013)

Limitations

The main limitations of batteries, in general, are lifetimes (both cycle and calendar), power and energy densities, environmental friendliness and safety. These issues need to be addressed in order to develop reliable and cost-effective products.

Low energy density, high capital costs and high self-discharge rates limit the potential of supercapacitors for energy grid applications. New materials are likely to overcome some of these issues.

2.5 Conclusions

It is out of question that storage plays a fundamental role in the current grid and that its importance will grow with the increase of variable generation. However, nowadays storage is not the first choice for many of the services described in this section (e.g. load-following or contingency reserves) due to its elevated cost and technical challenges. These services are now addressed by fossil-fuel based generation technologies since they have a well-known performance and are cheaper. Nevertheless, this situation is likely to change in the near future with the growing price of fossil fuels and the need to accommodate more renewables generation.

It has also been shown the special usefulness of storage when combined with wind power. Since it is the fastest growing renewable and it is spreading rapidly all across the world, wind power is likely to be one of the motors that are going to drive the development of energy storage.

The location of storage has been shown to be a very important matter. However, it seems clear from the discussion presented above that storage can offer a larger potential when used decoupled from generation and in a distributed approach. Although it has not been addressed in this report, small scale micro-grid distributed storage can also add flexibility to the grid and it should be taken into account when considering the capabilities of storage.

Every storage technology has been analysed independently from the others and it has been shown that all of them exhibit advantages and disadvantages over the others that make them suitable for specific applications. However, the bigger picture that has to be extracted from the analysis carried out above is that only a close interrelation and combination of different technologies can deliver all the services that storage will need to provide in the future by combining the valuable features of each individual technology.

A good example of this is the combination of flywheels and batteries. Flywheels provide a very effective power delivery and absorption and at the same they buffer and protect the battery system. This, in turn, is used to store energy in a more efficient and reliable way than flywheels.

Finally, some of the most promising storage technologies are still currently in their early stages of development. Only these 'revolutionary' technologies reach a certain level of maturity and become widely used, their real potential within storage mix and, furthermore, the real role of storage in general may be assessed accurately.

In conclusion, storage has the potential to become the piece necessary to complete the puzzle of the energy grid but only after a long journey of research, development and, probably, risky bets and investments in new-coming technologies.

2.6 Thermal Energy Storage (TES)

2.6.1 Introduction

Electricity is not the only form of energy consumed, heat is also essential in homes and industrial processes. In fact, heating and cooling currently accounts for approximately 49% of primary energy use in the UK. Thermal energy storage can play a significant role in both reducing energy demand by exploiting waste heat and by enabling renewable energy resources to be utilised more efficiently. (Eames, 2013)

In contrast to the methods analysed so far, thermal storage systems do not store electric energy and transform it back into electricity when needed. Thermal energy is stored in order to use it as heat (or cold) source at another time. Thus, there are no conversion losses from one form of energy to another. Thermal energy can come from any source (solar, electricity, fossil-fuels, biomass…) and can be stored in solid, liquid or gaseous media.

TES is a very old concept. Throughout history, man has collected ice and snow during winter and stored it in well-insulated chambers to use it in hotter periods to preserve food, cool drinks, etc. As an interesting fact, the Hungarian parliament in Budapest has been using an air conditioning system based on the ice harvested from the lake Balaton during winter until recently (Dincer and Rosen, 2011).

There are three main techniques used to store thermal energy: sensible heat, latent heat and thermo-chemical reactions. The following figure illustrates the most common media used in every method.

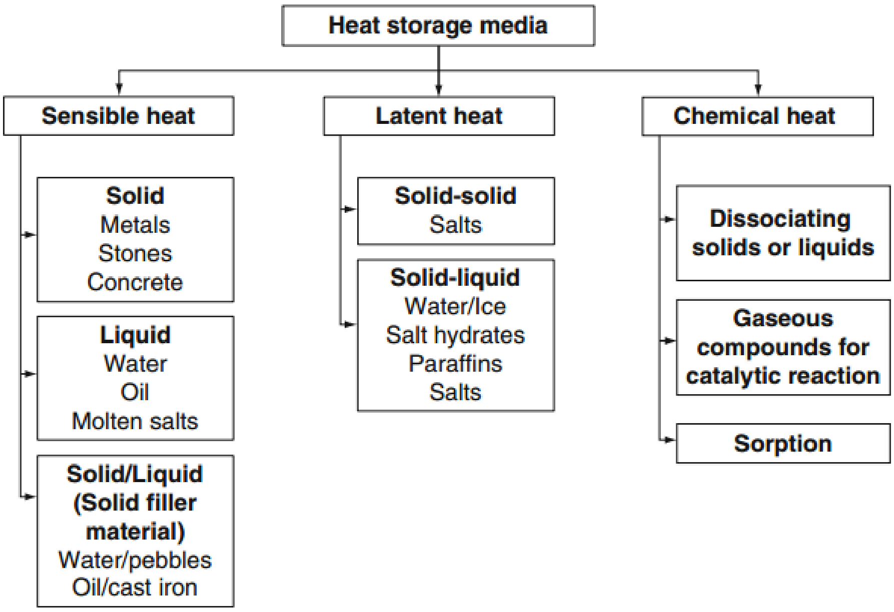


Figure 18 - Heat storage methods and media. Ref: Meyers (2012)

2.6.2 Sensible heat

Every body, every material has a certain heat capacity. Heat capacity is the ability to store heat by a change of temperature. Thus, thermal energy can be stored easily by raising or decreasing the temperature of a body. The amount of energy stored will be simply determined by the mass of the storage medium, its heat capacity and the temperature difference experimented by the medium, $Q = m \cdot c_P \cdot (T - T_0)$

Figure 18 shows a list of the most common materials used for sensible heat storage. It can be observed that very common materials like water or stones can be used as sensible heat storage media. Thus, sensible heat storage seems like a very simple technique and actually it is the most straight forward method to store heat.

However, one of its main shortcomings are the elevated surface heat losses (Teller et al., 2013). Therefore, it is desirable to keep the ratio of surface area to volume as low as possible. Surface area grows with the squared length and volume with the cubed length. Thus, the larger (in volume) the storage medium the more effective storage will be. This can be a constraint for applications where the available size is limited. As an example, the size of buffer tanks filled with water starts with about 100 litters for small applications (Teller et al., 2013).

Solids

Solid materials can be utilised in a wide temperature range and heated up to very high temperature. In addition, they do not need a container like liquids. Solid storage materials can be classified as metals and non-metals.

Metals present high conductivities that provide fast charge and discharge processes but are less attractive from an economic point of view compared to non-metals. (Meyers, 2012)

Non-metals include natural materials that are abundant and cheap like soil or rock pebbles. While they work alright for low temperature applications, more expensive materials with better thermo-mechanical stability like granite, basalt, and quartzite are needed for higher temperatures. (Meyers, 2012; Teller et al., 2013)

Besides natural materials, non-metals also include manufactured non-ceramic and ceramic bricks designed for specific applications that usually provide a better performance. An example in the low-temperature range are the construction bricks often used for passive thermal storage of buildings. At higher temperatures, refractory bricks based on oxides (silica, alumina, magnesia and iron), carbonates (e.g. magnesite) and their mixtures are commercially utilised in applications such as Cowper regenerators, storage heaters and tiled stoves. Concrete is also attractive due to its low cost and high availability. (Meyers, 2012; Teller et al., 2013)

When using solid storage media, heat transfer is usually performed by a heat carrier in direct contact with the storage medium. Designs with indirect contact of carrier and storage medium can be utilised when direct contact is not feasible. (Meyers, 2012)

Liquids

In many applications water is often the chosen thermal storage medium since it provides very favourable thermal properties (see Table 1), it is readily available, abundant, cheap, mixable... Hot water tanks can be found both in industrial and domestic applications. Very large masses of water also offer the potential for seasonal thermal storage. This includes underground thermal storage (UTES) systems where heat is stored in geologic formations like aquifers. (ASHRAE, 2003)

	Density ρ ($kg\,m^{-3}$)	Specific heat C_p ($J\,kg^{-1}\,K^{-1}$)	Volumetric thermal capacity C_p ($10^6\,J\,m^{-3}\,K^{-1}$)
Clay	1458	879	1.28
Common brick	1800	837	1.51
Sandstone	2200	712	1.57
Wood	700	2390	1.67
Concrete	2000	880	1.76
Glass	2710	837	2.27
Aluminium	2710	896	2.43
Iron	7900	452	3.57
Steel	7840	465	3.68
Gravelly earth	2050	1840	3.77
Magnetite	5177	752	3.89
Water	988	4182	4.17

Table 1 - Heat capacities of common TES media at 20°C – Ref. Norton (1992)

Water has also some disadvantages. It can only be used between 0°C and 100°C, it is corrosive and it has high vapour pressures at temperatures above 150°C. Some of these problems can be solved by the use of additives. (Meyers, 2012)

High temperature applications can be carried out by liquid molten salts. Probably one of the most well-known uses of high temperature sensible heat storage in liquids is thermal solar power plants. The two-tank molten salt concept is proven and reliable. For solar thermal electricity, power plants can store the heat for a typical 7.5 hour-period, thus feeding firm electricity to the grid during night time. (ASHRAE, 2003; Teller et al. 2013)

Other liquids like oils are also used as storage media. However, in these cases the storage liquid often becomes the largest expense of the storage system (ASHRAE, 2003).

Liquids have the advantage of acting both as storage media and heat carriers. However, the use of liquids for thermal storage requires containers or tanks for storage. Corrosion, leaks and pressurized parts of the tanks can complicate the design, reduce the performance and increase the overall cost of liquid thermal storage systems.

2.6.3 Latent heat

While a substance is undergoing a phase change, all the heat it absorbs (or releases) goes into (comes from) the rearrangement of its microscopic structure. The process usually results in a large variation of the internal energy while the temperature remains constant. This characteristic can be used for thermal storage. Since there is no change in the temperature of the storage material, the heat appears to be latent.

Latent heat storage is a particularly attractive technique since it provides a high-energy storage density and has the capacity to store and release heat at a constant temperature. For example in the case of water, 80 times as much energy is required to melt 1 kg of ice as to raise the temperature of 1 kg of water by 1°C. This means that a much smaller weight and volume of material is needed to store a certain amount of energy (see Table 2). (Verma et al., 2006)

Substances and compounds used for latent heat storage are usually known as phase change materials (PCM). Any kind of phase change process can be employed for heat storage: solid-liquid, liquid-gas, solid-gas or even transitions between different crystalline phases (solid-solid). Usually solid-liquid is the preferred choice since it does not present a large variation in volume. Liquid-gas and solid-gas will not be described in this section.

However the selection of a PCM should be determined by the following criteria (Sharma et al., 2009):

- *Thermal properties* - suitable phase-transition temperature, high latent heat of transition, good heat transfer.
- *Physical properties* - favourable phase equilibrium, high density, small volume change, low vapour pressure.
- *Kinetic properties* - no supercooling, sufficient crystallization rate.
- *Chemical properties* - long-term chemical stability, compatibility with materials of construction, no toxicity, no fire hazard.
- *Economics* - abundant, available, cost effective.

The various PCMs are generally divided into three main groups: organic, inorganic and eutectics (combinations and mixtures of both inorganic or organic PCMs).

Property	Rock	Water	Organic PCM	Inorganic PCM
Density (kg/m^3)	2240	1000	800	1600
Specific heat (kJ/kg)	1.0	4.2	2.0	2.0
Latent heat (kJ/kg)	—	—	190	230
Latent heat (kJ/m^3)	—	—	152	368
Storage mass for 10^6 J (kg)	67,000	16,000	5300	4350
Storage volume for 10^6 J (m^3)	30	16	6.6	2.7
Relative storage mass	15	4	1.25	1.0
Relative storage volume	11	6	2.5	1.0

Table 2 - PCM and sensible heat media properties. Ref: Farid et al. (2004)

Organic PCM

Organic compounds present several advantages such as non-corrosiveness, low or no under cooling, chemical and thermal stability, ability of congruent melting, self-nucleating properties and compatibility with conventional materials of construction. Organic PCM can be further classified as paraffins and non-paraffins. (Verma et al., 2006)

Paraffins

Paraffins consist of different chains of alkanes. The length of the chains determines temperature and the latent heat of the phase change providing wide ranges of operational temperatures. However, their high cost limits the use of paraffin to just some technical grade ones. (Sharma et al., 2009; Farid et al., 2004)

The advantages of paraffin are: inert and stable below 500°C, small change in volume, low vapour pressure, good nucleating properties, wide temperature ranges, relatively high latent heat, non-toxic and non-corrosive over extended periods of storage. (Verma et al., 2006; Sharma et al., 2009)

On the other hand, the main drawbacks are: low thermal conductivity, non-compatible with plastic containers and moderately flammable. Nonetheless, some of these negative characteristics can be partially palliated. (Sharma et al., 2009)

Non-paraffins

Non-paraffin organic are the most numerous PCM. Unlike paraffins, each material presents different properties. However, overall non-paraffins show high heat of fusion, inflammability, low thermal conductivity, toxicity and instability at high temperatures. (Sharma et al., 2009)

Among non-paraffins, fatty acids present a potential for heat storage, especially for space heating applications (Zalba et al., 2003; Farid et al., 2004). Fatty acids show good no supercooling and latent heats comparable to paraffin's. Their major drawback is their cost, which is 2–2.5 times greater than that of technical grade paraffin's (Sharma et al., 2009).

Inorganic PCMs

Inorganic compounds include salt hydrates, salts, metals and alloys.

Salt hydrates are the most important group of PCMs. They present high latent heat of fusion per unit volume, relatively high thermal conductivity (almost double of the paraffin's) and small volume changes on melting. They are compatible with plastics, not very corrosive and only slightly toxic. Many salt hydrates are also fairly inexpensive. (Sharma et al., 2009, Farid et al., 2004)

The major problem of salt hydrates is that most of them they melt incongruently. This decreases the performance of the medium after every charge–discharge cycle. Another shortcoming is that the rate of nucleation is generally very low leading to supercooling. (Verma et al., 2006; Sharma et al., 2009; Farid et al., 2004)

Some of the features of metals are a low heat of fusion per unit weight, high heat of fusion per unit volume, high thermal conductivity, low specific heat and relatively low vapour pressure. Generally, the high weight of metals makes them unsuitable for storage applications as PCMs. (Sharma et al., 2009)

2.6.4 Thermo-chemical storage

In thermo-chemical TES, heat is stored in the form of chemical compounds created by an endothermic reaction and it is recovered again by recombining the compounds in an exothermic reaction. The heat stored and released is equivalent to the heat (enthalpy) of reaction. Sorption systems are also considered TES.

Thermochemical energy storage has a higher energy density than other types of TES, allowing large quantities of energy to be stored in small volumes. Energy storage based on chemical reactions is suitable for short and long-term applications but it is particularly advantageous for long-term storage applications (even seasonal storage) because the process involves almost no energy losses during the storing period as long as the reactants are stored separately. Thus, with all these properties it is a promising technology for residential and commercial buildings. (Abedin and Rosen, 2011; Teller et al., 2013).

Suitable material for thermo-chemical storage should have large inner surfaces (i.e. high porosity) and be hygroscopic. Zeolite (aluminium silicates) and silica gel (based on silicon dioxide) are normally used. The operating range of zeolite is between 100 °C and 300 °C, the operating range of silica gel between 40 °C and 100 °C. It has been already proven, as an example, the capacity of zeolite in CHP biogas plants as a flexible and long term TES material. (Teller et al., 2013; Velasco, 2012).

2.6.5 Applications

TES has a huge potential and innumerable applications. Wherever heat is being produced, TES systems can store it so it can be used at some other time or even transport it to some other place. Thus, TES has the ability of totally decouple heat generation and consumption.

Within power generation, it has already be stated the important role that thermal storage plays in thermosolar plants. However, it can be equally applied to fossil-fuel fired generation, especially for CHP systems. Storing heat for its later use instead of releasing it to the environment would increase the overall efficiency of power. The main reason why TES is not widely applied yet within every means of energy production is the still cheap price of fossil-fuels and the elevated cost of thermal storage technologies. The increasing prices of fossil-fuels are likely to change this situation and make heat storage worth. (Bailey, 2010)

TES also has a great potential coupled to solar thermal storage both at small scale for domestic applications and at larger scales, even for seasonal storage. Thermal reservoirs could be used to provide hot water or space heating and, at larger scales, they could also be used for power generation by the use of organic Rankine cycles. (McMahan, 2006)

Besides power generation, distributed thermal storage in the form of domestic electric storage heaters or water heaters can act as demand side management and help to regulate the load in the grid. Flexible day-of-time tariffs would be necessary to make this application profitable for end-users.

In addition to heat, thermal storage can also provide cooling services. Again, both small and large scale applications are feasible including seasonal storage. As mentioned before, ice and snow harvesting was probably the first application of TES and it’s a very simple but good example of the “cold storage” capabilities of TES.

Related to the previous applications, PCM materials are very suitable for their integration within the structure of buildings. They could store heat during the day to avoid the use of heating systems during night and, the other way round, use the coolness of the nights to avoid the use of cooling systems during the day. This application can also be met by conventional sensible heat thermal masses but the constant temperature output/input of PCMs makes them more appropriate and effective. (Richardson and Woods, 2008)

Another interesting application can be the use of PCM as back-up systems for protection of goods. They could be used within food, chemicals or medicines storage and could provide the temperature necessary to preserve these goods in the event of a temporary power outage. This option can complete or even substitute conventional and expensive backup power generators. (Bailey, 2010)

These are just some of the most widely discussed applications in the literature. However, as stated above, heat storage can be applied in a huge number of situations.

2.6.6 Conclusions

The following table summarizes the main characteristics of and differences between TES systems.

Performance Parameter	Type of Thermal Energy Storage		
	Sensible TES	**Latent TES**	**Chemical TES (Sorption and Thermo-chemical)**
Temperature range	Up to: 110 °C (water tanks) 50 °C (aquifers and ground storage) 400 °C (concrete)	20-40 °C (paraffins) 30-80 °C (salt hydrates)	20-200 °C
Storage density	Low (with high temperature interval): 0.2 GJ/m^3 (for typical water tanks)	Moderate (with low temperature interval): 0.3-0.5 GJ/m^3	Normally high: 0.5-3 GJ/m^3
Lifetime	Long	Often limited due to storage material cycling	Depends on reactant degradation and side reactions
Technology status	Available commercially	Available commercially for some temperatures and materials	Generally not available, but undergoing research and pilot project tests
Advantages	Low cost Reliable Simple application with available materials	Medium storage density Small volumes Short distance transport possibility	High storage density Low heat losses (storage at ambient temperatures) Long storage period Long distance transport possibility Highly compact energy storage
Disadvantages	Significant heat loss over time (depending on level of insulation) Large volume needed	Low heat conductivity Corrosivity of materials Significant heat losses (depending on level of insulation)	High capital costs Technically complex

Table 3- TES systems comparison. Ref. Abedin and Rosen (2011)

Sensible heat is an already mature technology and can be readily applicable to many situations. Water is the most widely used storage medium. It makes storage simple, easily available, hazardless and economic. However, the narrow temperature range of water limits the number of possible applications. Solid materials are also an economic and effective way of storing heat but have fewer applications, normally at small scale.

The high heat surface losses, the need of good insulation and the large size necessary to make it efficient, are limit the potential of sensible heat storage. Nevertheless, it has been already applied successfully in many areas for several years. Good examples are domestic storage heaters and water cylinders. Besides some improvements in storage materials and insulation, not much progress is expected in sensible heat storage.

PCM has higher heat storage capacity than sensible heat media and a wide operational temperature range. It is also compact, has a very controllable output and a good overall performance. It is a readily available technology but only for a limited number of applications. Integration of PCMs in building construction materials or the replacement of big water tanks by smaller PCM containers are good examples of its current applicability.

The main drawbacks of latent storage are the high cost of PCMs, their low heat conductivity and some undesirable chemical properties (like corrosion or chemical instability). A lot of research on new materials suitable for heat storage is still needed to make it an economic and effective technology. In fact, an enormous research work is currently being done on PCMs, so they are likely to become the most important heat storage technology in the near future.

Finally, thermo-chemical storage has the best thermal storage properties of the three TES methods. It has very high energy densities, potential zero losses, transportability, seasonal storage capabilities... However, it is not a readily available technology. It is still being widely researched and, so far, it presents very high costs and puzzling technical complexity. However, if the challenges associated to this technology were overcome, the future potential of this technology would be enormous and could change the current role of thermal storage making it a very effective energy storage method.

In conclusion, TES is not a very extended way of energy storage although it could be very extensively applied since waste heat is a side product of many industrial processes, especially power generation. Releasing this heat to the atmosphere instead of using it limits the efficiency of these industrial processes to very low levels. One of the main reasons for not using this waste heat is because it is not immediately necessary in the place or at the time of production. TES can be used precisely to decouple generation and use of heat and, thus, it has a large potential. Furthermore, the wide range of technologies and temperature ranges that TES covers make the storage of thermal technology suitable for almost any type of application.

2.7 Summary

The following table presents a brief comparison of the main characteristics of the different storage technologies discussed in this section:

Technology	Advantages	Disadvantages	Applications	Power vs Energy
CAES	High storage capacity (underground), efficient partial-load operation, flexibility	Low efficiency, need of favourable geological formations, needs natural gas	Energy arbitrage, renewable integration, grid balancing, non-spinning reserves	Best suited for energy applications
Flywheels	High power capacity, long life, no environmental impact	High self-discharge rates, requires high engineering precision, high costs	Bridging of power disturbances, grid support, renewable firming	Best suited for power applications
PHS	Mature, very high storage capacity, long life, flexibility	Low energy density, need of favourable geological formations, environmental impact	Energy arbitrage, renewable integration, grid balancing, non-spinning reserves	Best suited for energy applications
Chemical storage: Hydrogen and SNG	High storage capabilities (TWh), can be used directly as fuel	Elevated cost, needs complex infrastructure, low overall efficiency, hydrogen storage	Energy arbitrage, seasonal storage, ancillary services	Best suited for energy applications
Lead-acid batteries	Mature technology, low cost, easy to recycle	Low specific energy and power, short cycle life, maintenance	Stand-alone systems, substation auxiliary power, renewables firming	Well suited both for energy and power applications
Ni-based batteries	Mature, good energy densities, long life, flat discharge voltage	Cost, toxicity	Renewable integration, voltage support, grid regulation	
Li-ion batteries	High efficiency, high energy density, huge potential	Cost, fragile, unsafe at large scales	Renewable integration, voltage support, grid regulation, T&D deferral	
Sodium-based	Long lifetime, good discharge times, fast	High temperature, insulation,	Power quality, grid stabilisation, time-shifting, renewable integration	

batteries	response, large potential	efficiency, fire hazard		
Flow batteries	Sizeable capacity, long life, short response time	Low energy density, efficiency, require pumps, sensor…	Time-shifting, T&D deferral, renewable integration, grid regulation	
Supercapacitors	Durability, low environmental impact, high efficiency. discharge times from seconds to hours	High self-discharge, cost, low energy density	Voltage support, power quality	Suitable for power applications
Sensible thermal storage	Mature, materials readily available, high temperature range, low cost	High surface losses, low energy densities	Efficiency improvement of industrial and power generation processes with high amounts of waste heat, solar thermal, domestic hot water and space heating with DSM and frequency response, industrial and domestic cooling	Usually suitable for thermal energy storage but, depending on the material, it can also provide high heat power outputs
PCM thermal storage	Constant temperature input/output, high efficiency, small losses, high energy densities,	Materials not readily available, limited temperature range for each material cost	Potentially similar applications as sensible heat storage but with reduced volumes and effective building integration	
Thermochemical energy storage	Very high energy density, potentially zero losses, transportability	Still in the R&D phases, cost, reactions	Potentially similar applications as sensible heat storage but with reduced volumes and effective seasonal storage	

Table 4 - Energy storage technologies comparison

It is remarkable that one of the simplest and most mature technologies with one of the widest applicability ranges, sensible thermal storage, still has a high and unexploited potential.

A very interesting application comes from the capabilities for DSM and frequency response of domestic sensible TES. These are particularly well-suited for integrating renewable generation in small isolated grids and can really make a difference in these communities. Surprisingly, there is a lack of research and publications on this topic. That is why the next part of this thesis gives an insight on how electrical sensible heat storage can play a very important role in these scenarios and also provides an experimental investigation of a storage heater.

3. Storage Heaters

3.1 Storage heater basics

3.1.1 Introduction

A storage heater is an electric heating device that stores thermal energy during low electricity demand periods, usually at night, and releases the heat stored when required during the day. They are also known as “night storage heaters”.

Heat is stored in a core formed of ceramic refractory bricks made of materials with a high density and specific heat. The bricks have several grooves so that electric heating elements can be embedded between them and heat them up. The core is well insulated to prevent undesired energy losses, making the heat output as controllable as possible and to avoid excessive temperatures in the outer surfaces of the heater.

Heat is usually released from the heater by radiation and convection processes in the surface of the heater and/or by circulating air through the core of the heater.

Storage heaters were introduced in the domestic heating scheme back in the 1950s (SotrageHeaters.com, 2013). Energy companies had a high base-load generation capacity to meet the peak demand during the day. However, the demand was much lower overnight resulting in an underutilised infrastructure and an inefficient operation[2].

Electric heating was well regarded (just like everything that was electric) and very common at that time. It was also, as it is today, very energy-consuming. The concepts of storage heater and hot water cylinder (electric hot water tank boiler) were then developed as a measure to make a better use of the energy resources at night by shifting part of the energy demand from peak to off-peak times.

However, storage heaters and water cylinders could only report benefits to the end user if off-peak energy was priced cheaper than on-peak electricity. Thus, the development of storage heaters led to the introduction of off-peak tariffs. As an example, the British economy 7 tariff was created in the late 70s for that purpose. These tariffs offered

[2] As it has been stated before, base-load generation is cheap and efficient when running at maximum capacity and the expenses of turning on or off large generators are large.

cheaper energy prices during the night so users could reduce their electricity bill by using electrical appliances overnight. Obviously, off-peak tariffs were especially attractive and designed for storage heaters and hot water cylinder users. Off-peak tariffs require the installation of an extra electricity meter for off-peak electricity.

Generally, consumers have a strong opinion about storage heaters. There are people who support them unconditionally while others are totally against any means of electric heating. Nevertheless, just like any other technology, electric storage heaters present a number of advantages and disadvantages when compared to other means of space heating like gas boilers.

Advantages

The main advantages of storage heaters are:

- They have a low capital cost
- Their installation is very simple.
- They require virtually no maintenance.
- In combination with an off-peak tariff they are more economic than conventional electric heating and the newest models claim to be comparable to gas heating systems.
- They are a good option for users out of the gas grid distribution area
- 100% of the energy consumed by the heater goes into the heating space.
- They do not produce emissions at the place of use which can be a hazard (like CO).
- The can be CO_2-free if the energy consumed is supplied renewables and nuclear sources.
- New models have the capability of being remotely controlled combined with smart heaters and act, then, as demand side management.

Disadvantages

- A large amount of heat is released by radiative and convective processes during charging.
- Also, some heat is released during the day by the same processes when not needed.

- They require planning the heating requirements for the following day. This can be a problem during warm seasons when the temperature varies widely depending on the time of the day or in case of the home owners being absent of the building unexpectedly.
- Closely related to the previous one, the controls can result complicated and, if not operated correctly, over- or under-heating are likely to occur decreasing the efficiency of the system.
- Sizing of the device is also challenging and can lead to excess or lack of heating too.
- It is not an immediate source of heat.
- If there is not an off-peak tariff available, their operation is very expensive and less efficient than conventional electric heating

3.1.2 Structure, types and operation of storage heaters

Storage heaters possess a very simple structure. They basically consist of a metallic box with a core formed by ceramic bricks. There are some heating elements embedded between the bricks and a good insulation surrounds the core (see Figure 19 and Figure 20). There two possible core configurations available in the market: with horizontal heating elements (Figure 20) and with vertical heating elements (Figure 19). These configurations usually correspond to dynamic and static heaters respectively.

Static storage heaters

Static storage heaters are designed so that around 80%[3] of the heat stored in the core is released by radiative and convective processes occurring in the surface of the heater. Another important characteristic is that the air is circulated in the core of the heater solely by natural convection processes (see figure below).

[3] This number is just an approximation based on different manufacturers’ claims. It varies from model to model.

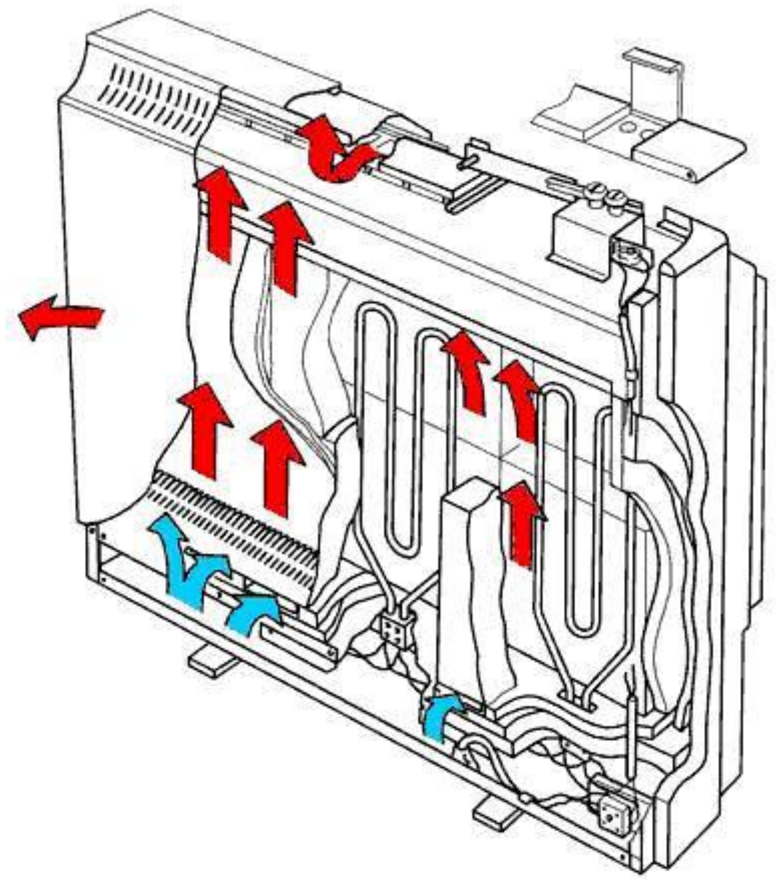


Figure 19 - Structure of a static storage heater - Source: http://www.heatersuk.com/g/48166/guide-to-storage-heaters.html

Static storage heaters commonly include two controls: input and output.

The input control determines the amount of heat stored in the heater during the charging period. It is usually a thermostatic control (Laverick, 2011) that simply sets the maximum allowable core temperature. Logically, the higher the temperature the more heat stored.

The output control regulates the air that enters (and leaves) the core of the heater by adjusting the position of a number of dampers. The dampers are usually attached to bimetal systems so that they are only opened when the core of the heater starts to cool down and a 'boost' of the heat output is required. This system only controls around the 20% of the total heat released by the heater and it is usually not well understood by the users. (Storage-heaters.com, 2013)

It is easy to see from the characteristics explained above that this kind of storage heaters provide a gradual heat output throughout the day that is not very controllable. Thus, they are recommended for spaces occupied during a large portion of the day where a constant heat supply is desirable.

Dynamic storage heaters

Dynamic storage heaters are characterised by a very good insulation that makes the heat output of the heater very controllable. Only around a 20%[4] of the heat stored is released by radiative and convective processes in the outer surface of the heater. This type of storage heater blows air into the core of the heater with the aid of a small fan to provide a well-regulated heat output (see figure below).

Figure 20 - Structure of a dynamic storage heater - Source: http://www.storageheaters.com/how-storage-heaters-work.htm

Dynamic storage heaters can have an input and an output control like static heaters but they tend to be more automatic every time. The input control works similarly to that in static heaters. The output control, however, controls the air flow coming into and going out of the core of the heater.

Many dynamic heaters come with a timer in addition to the output control that allows the user to schedule heating periods on a daily basis. Modern ones have even replaced the output control by a room temperature control. Users simply need to set a desired temperature and the heater will blow hot air into the room until it is reached.

[4] This number is just an approximation based on different manufacturers' claims. It varies from model to model.

The current tendency in dynamic storage heaters is to eliminate the input control and replace it by an automatic system. Modern heaters usually include a small built-in computer that estimates the heating requirements of the following day based on weather and usage patterns using a self-learning algorithm that charges the heater accordingly.

State-of-the-art dynamic heaters can also include a communication link system to allow remote control from the grid utility suppliers. This way, the storage heater can help to regulate the load in the grid acting as demand side management.

Finally, these heaters usually include a convector powered by a 'boost element' to provide on-peak extra heating in case the stored heat is not enough to meet the heating requirements.

Typical heat output profile

The following figure compares the typical heat output profiles from a static and a dynamic storage heater:

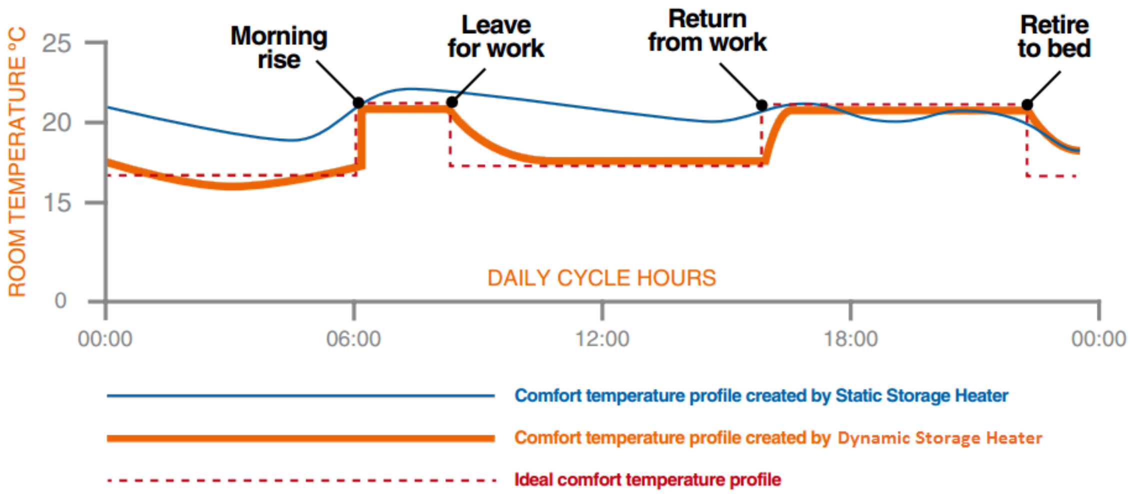


Figure 21 - Static vs dynamic storage heater. Source: Heat Book Dimplex http://www.dimplex.co.uk/assets/kb/brochure/0/Heat_Book.pdf

Their high controllability and reduced losses make dynamic heaters a more efficient and effective way of providing space heating. The difference is height between the curves gives an idea of the possible energy savings that a dynamic heater can provide compared to static models. However, as stated before, static storage heaters may provide adequate space heating in specific situations.

3.2 Storage heaters as demand side management (DSM)

3.2.1 Demand side management

Definition and basics

Qureshi et al. (2011) define demand side management as "the planning, implementation, and monitoring of distribution network utility activities designed to influence customer use of electricity in ways that will produce desired changes in the load shape, i.e. changes in the time pattern and magnitude of the network load."

Put in simple terms, demand side management is the adjustment of consumer's electricity demand for the benefit of the grid. This can be performed manually by the customer or automatically by the utility operator and can serve to accommodate an excess of supply by increasing the load on the system or, contrarily, to avoid further problems in case of a supply shortage by decreasing the demand.

As discussed in previous sections, the grid needs to provide a safe and reliable service in every situation. In order to do that, power generation and distribution infrastructures are designed to accommodate peak and not average demand. This way, it is ensured that there is enough generation and transmission capacity installed to deal with unpredicted deficits in the energy supply or sudden increases in the demand.

Historically, a capacity margin of around 20% was considered sufficient to provide adequate security levels. Nevertheless, given the typical demand throughout a year, the average utilisation of the global generation and transmission capacity is near 50% (Strbac, 2008). Furthermore, it has already been discussed that the generation reserves are mostly provided by inefficient partially-loaded generators and that the upgrading of T&D lines is highly expensive.

Hence, a considerable fraction of the overall system capacity is underutilised because it is necessary to accommodate the fluctuations of the energy demand (and variable supply). The high-level objective of DSM is to flatten the load over time by "shaving the peaks" and "filling the troughs" or, in other words: to transfer as much of the flexible demand as possible away from peak time into periods of lower activity. The main objectives of DSM are summarized in the figure below and their fulfilment would result in a much more efficient system that would make feasible to downscale the existing infrastructure without negative impacts on the power consumption. (Saffre and Gedge, 2010)

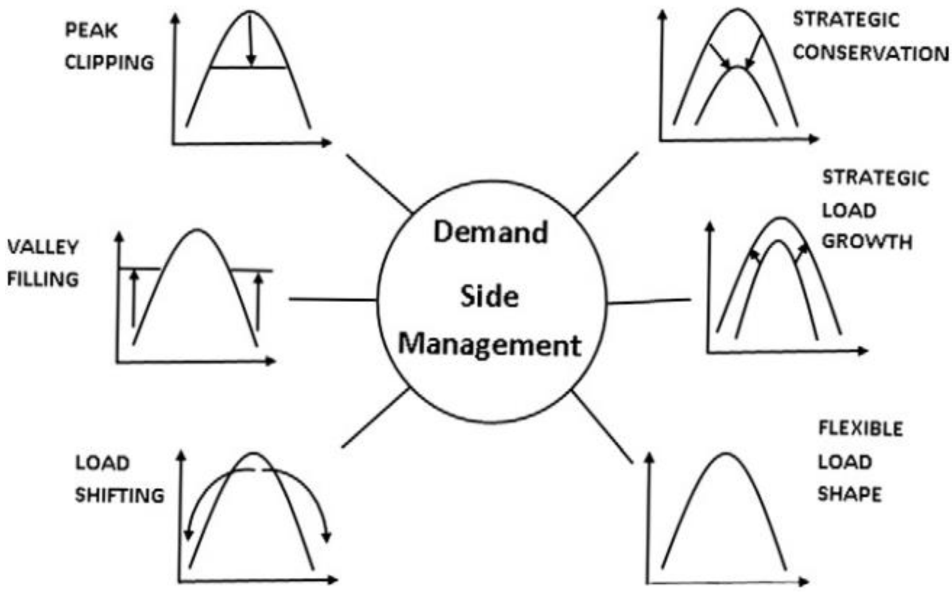


Figure 22 - Main objectives of DSM - Ref. Qureshi et al. (2011)

In order to be beneficial for the end user, DSM has to be combined with dynamic electricity prices that vary accordingly to the expected demand and supply. Nowadays, only very basic day-night tariffs are available for the average customer. However, DSM needs real-time reactive pricing mechanisms to be effective for the regulation of the grid.

Currently, large industrial customers already curtail their demand when the frequency drops below a certain value after a power loss in a generator or a similar event. They usually obtain economic benefits from it. As an example, in the UK aluminium smelters take part in this activity. Besides large industries, frequency could also be regulated by time-flexible domestic electrical appliances. HVAC systems are good candidates for this application. (Strbac, 2008)

Real-time reactive pricing mechanisms will be especially necessary with larger integration of intermittent renewables. A communication infrastructure between the load and the grid operators will be necessary to track supply and demand in real-time. Depending on how well balanced the grid is at every time-step, prices would be updated accordingly. Ideally, this would be accompanied by intelligent appliances that would switch themselves on or off therefore automating part of the load-shifting process and providing immediate benefits for the end-users. (Stifter et al., 2009; Saffre and Gedge, 2010)

DSM works, thus, very similarly to energy storage in the grid but at a distributed customer level. In fact, storage technologies at the end-user side have a very large potential as demand side management.

DSM and wind power

The main problems associated to the integration of large amounts of wind generation were analysed in section 2.2. It was concluded that they arise from the cost associated to wind uncertainty, minimum generation constrains and wind curtailment. All these are originated by the lack of flexibility of the grid. Storage appeared as an effective way to add flexibility and palliate the negative effects of wind power. Besides storage, which is usually an expensive option, DSM can be a very effective way of providing flexibility to the grid inexpensively.

With regards to the example provided to illustrate unit commitment problems associated to wind generation, DSM could help to absorb a excess in supply due to an underestimation of wind output by encouraging (or even forcing) the use of time-flexible appliances. Likewise, DSM could avoid the use of backup generation by turning off electric appliances remotely in case of an underestimation (see Figure 6).

Similarly, DSM has the capability of avoiding minimum generation constrains by scheduling time-flexible appliances in times of high wind output. Thus, the modulation of base-load generation to accommodate wind would be avoided.

Taking into account the current state of storage technologies and their elevated price, demand side management could become a green and cheap way of adding flexibility to the grid to accommodate variable generation. However, DSM requires a very complex infrastructure with continuous and dynamic communication between suppliers and clients.

Large vs. small scale DSM

The larger the network the more generation and T&D facilities, the more customers and, consequently, the more complex the creation of a DSM infrastructure. This is the main reason why DSM is not widely applied. The operational challenges, the necessary technological infrastructure, the introduction of time-varying tariffs and the social acceptance of remote control make large-scale DSM out-of-reach nowadays.

Nevertheless, DSM has a very important role to play in small isolated communities that generate and administrate their own electricity, like islands. Due to the reduced size of these grids, the implementation of a DSM infrastructure becomes more feasible. In addition, these 'experiments' in small communities can provide very valuable information for larger scale projects.

Many islands are not connected to the mainland electricity network and therefore need to rely on their own power generation resources and manage their network. The Aegean Islands in Greece, the King Island in Australia or the Shetlands and Eigg in Scotland are good examples of this type of communities.

Just like in the mainland, islands need a reliable power generation source. This can only be provided, at least currently, by fossil-fuel fired power stations. Islands usually install diesel-fired power stations as their main energy supply. However, they result in increasingly high running and maintenance costs. (Tsakiris, 2010; Hydro Tasmania, 2011; Eigg Electric, 2013; Pure energy centre, 2008).

Islands usually have greater renewable resources than the mainland. Wind is an especially abundant resource in many of them. However, the capacity to deal with large amounts of variable generation is very limited in small grids. The reduced number of conventional generation makes the grid very inflexible. Therefore, these communities cannot rely on wind or other intermittent renewables to obtain their electricity.

DSM has the potential to increase the amount of variable generation that can be integrated in small energy networks. By monitoring the frequency of the grid, smart appliances can turn on/off or increase/lower their consumption depending on the availability of renewable resources. Furthermore, the conventional generation capacity could be downsized since less generation reserves would be needed. This would reduce the cost of energy production. Electric heating has a large potential as DSM.

3.2.2 Dynamic storage heaters capabilities for DSM

In addition to not being hooked into the mainland electric power network, small communities are usually not connected to the gas grid either. Thus, electric space and water heating usually represents a high percentage of the total energy consumption.

Storage heaters and hot water cylinders are the preferred means of electric heating since they normally have low running costs if combined with night off-peak tariffs. Thus, hot water cylinders and storage heaters are numerous and offer therefore a great potential for DSM. Water cylinders will not be studied in this report although some of their characteristics are very similar to those of storage heaters.

Modern dynamic storage heaters have a very good insulation and a highly controllable output that makes them ideal candidates for DSM smart appliances. Two main types of DSM can be identified for these devices:

- *Charging scheduling:*

  It has been already stated that modern dynamic storage heaters have automated charging controls that estimate the heating requirements for the following day based on usage and weather patterns.

  Utility providers can use the available wind speed and energy demand forecasts to establish and schedule the optimum charging times for the heater.

  In addition, the weather forecast information could also be used to estimate the amount of heat necessary to meet the requirements of the household.

  This information would be ideally sent to the heater on a daily basis although updates throughout the day would be possible too.

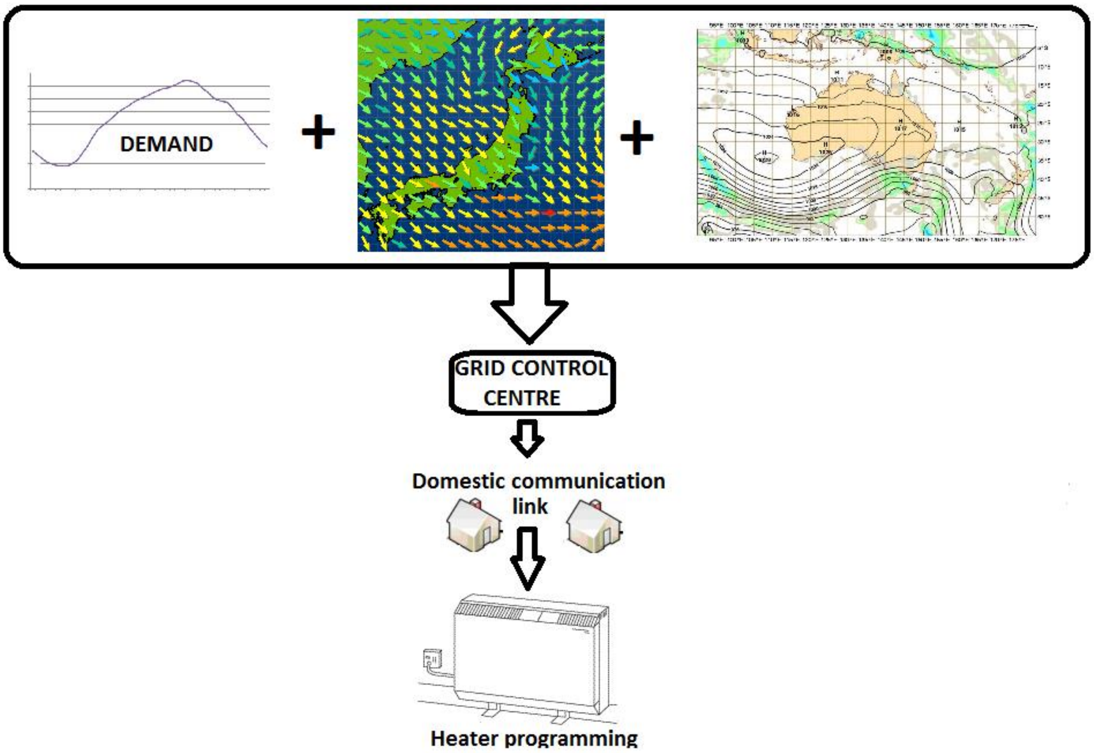


Figure 23 - Storage heater as DSM. Charging scheduling

- *Frequency response*

Short-term demand side response can potentially be performed by storage heaters too. By monitoring the frequency of the grid, heaters could detect imbalances in the grid and automatically modify their energy consumption in real time.

Storage heaters usually have 3 heating elements and a boost function. By turning on/off different numbers of heating elements, the energy consumption of the heater can be modulated in real-time as well to provide frequency response.

The usage of storage heaters as DSM seems as a very effective way of regulating the grid and making a better use of renewable resources in small communities. However, storage heaters also present a number of issues that can affect their performance and compromise their effectiveness as DSM:

- *Core temperature distribution and control*– ceramic bricks used in the core of the heaters exhibit low conductivities. This can lead to very uneven temperature distributions in the core that can affect the amount of energy stored in the heater. Furthermore, the level of charge is usually controlled by a single thermal sensor located at the bottom of the core. This sensor reads the local temperature so it may not give an accurate estimation of actual the level of stored energy. If only some of the heating elements near the sensor are used to charge the heater up, these problems are likely to be a larger concern.

- *Standing losses* – passive heat losses reduce the amount of stored energy that can be employed effectively.
- *Human factors* – users usually do not usually have a deep understanding of the operation of the heater. A wrong programming of the heater can result in significant amounts of wasted energy (e.g. by opening a window due to an excessive set temperature) and, thus, reduce the performance of heater.

The standard procedure to measure the performance of a storage heater is to use a calorimeter room at a constant temperature. 24 hour tests with different charging and discharging cycles are performed while energy is supplied to the room to keep a constant temperature. Using a simple energy balance, the power supplied by the heater can be estimated (NORDTEST, 1993)

This method can give a good idea of the heating capabilities and the heat losses in standard test conditions. However, it does not provide any information about the internal processes that take place inside the core of the heater and does not account for real-life usage conditions. No relevant information has been found in the literature about these issues so an experimental analysis of a dynamic storage heater is necessary to better understand its behaviour and its real capabilities of storage heaters.

4. Experimental Analysis of a Storage Heater

4.1 The SM heater

A state-of-the-art model of dynamic storage heater was experimentally analysed to investigate the factors that can compromise their performance as DSM. The heater chosen for the analysis has a programmable output that allows the end user to configure a room target-temperature and different heating periods. It also features automated charging controls based on usage and weather patterns. These use a self-learning algorithm to optimise their effectiveness. The heater can also be connected to a local interface controller (LIC) that monitors the frequency of the grid and sends/receives data to/from the utility control centre for DSM. For these reasons, the heater is said to be ‘smart’. From now on, the heater will be referred to as the ‘SM’ heater (SMart heater).

The SM heater is a prototype of a currently commercially available model. It has been trialled in at least one demand side management project in a small island community not connected to the mainland’s energy network. The table below summarizes the key technical data of the heater.

SM heater	
Output rating	1250 W
Heating elements rated power	3 x 800 W
Maximum storage capacity	14900 W·h / 53.6 kJ
Number of bricks in the core	24 bricks = 6 rows x 4 bricks/row
Storage medium	Feolite
Insulation (top, sides, front and rear)	Micro porous silica aero gel
Insulation bottom	Calcium silicate
Supply	240 V, 50 Hz

Table 5 - SM heater technical data

Apart from the technical information, the heater is claimed to have the following features:

- A highly insulated storage core with very limited standing losses during non-heating periods.
- An energy efficient heat output that gives an accurate control of time and temperature.
- A simple user interface for setting comfort temperature and programming heating periods.
- An electronic control fully compatible with the distribution network operator (DNO) interface, that provides:
    - A communications link to utility for charging scheduling and frequency response.
    - Mains frequency monitoring.
    - Variable frequency response.
    - Variable input power of 0%, 33%, 66% and 100%.
    - Core temperature sensing and setting.
    - Ambient and room temperature sensing and setting.

Finally, the structure and the main elements of the SM heater are presented in the figure below:

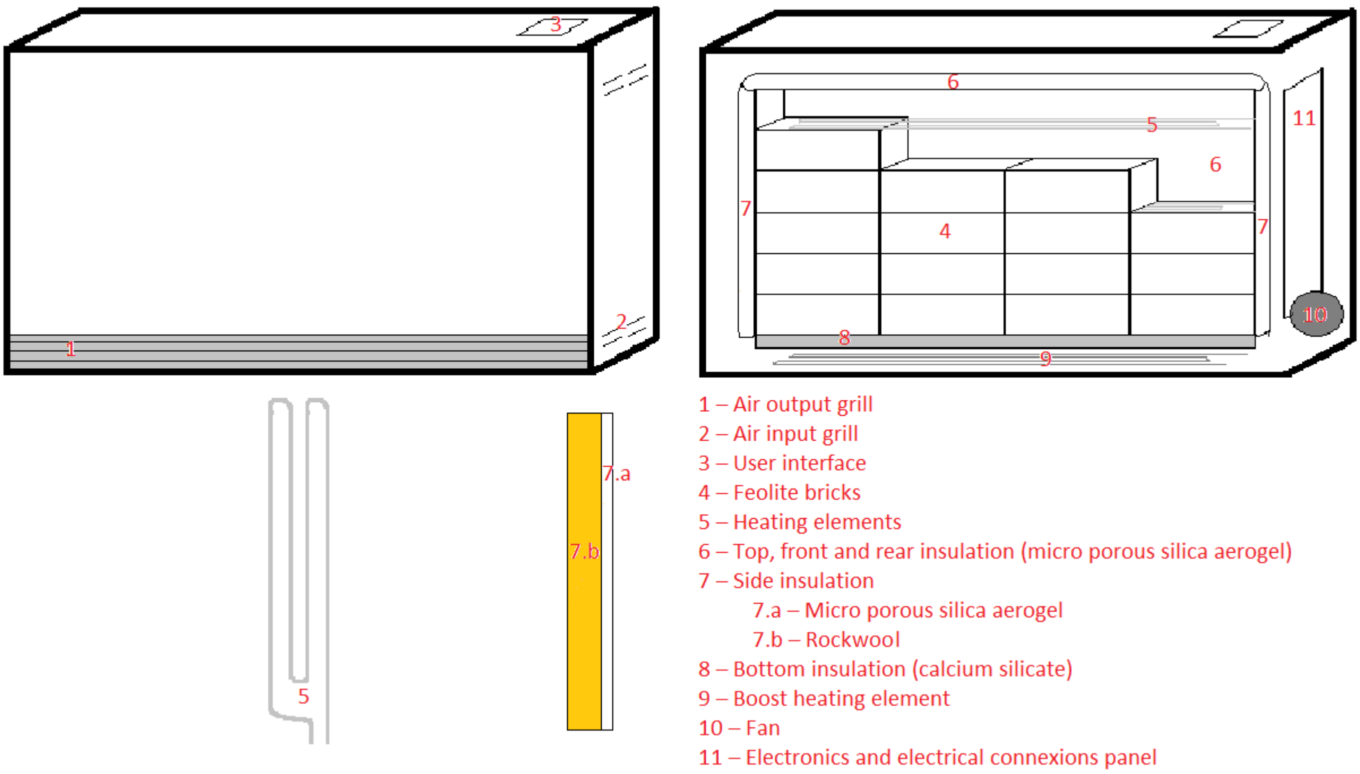


Figure 24- SM heater structure and main elements

4.2 Thermal properties of the storage medium

Table 5 indicates that the core of the heater is made of feolite bricks. Feolite is just a generic name for iron oxides (Fe_xO_y) and, in the case of storage heaters, it is commonly used to talk about high density ceramic magnetite (Fe_3O_4).

Magnetite is frequently used for TES applications due to its high volumetric heat capacity and good thermal stability at high temperatures (Gronvol and Sveen, 1974; Otero and Álvarez, 1994). Further materials employed in heat storage applications are other iron oxides, magnesia (MgO), alumina (Al_2O_3) and silica (SiO_2). However, because of the lower cost of raw materials and their superior thermal properties, iron oxides and magnesia are the best candidates for the fabrication of thermal storage bricks (see figure below).

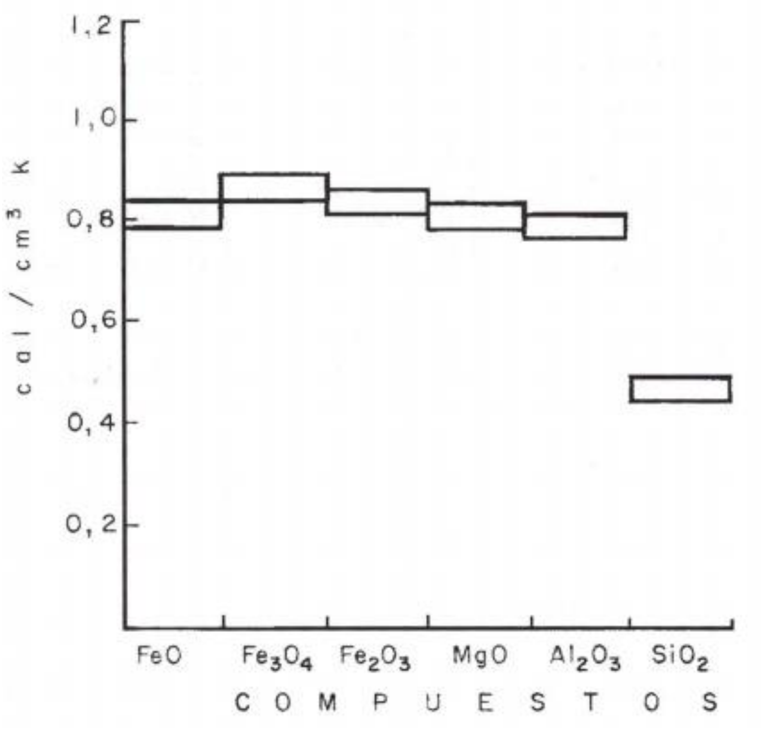


Figure 25 - Volumetric heat capacity of different materials - Ref. Otero and Álvarez (1994)

Nevertheless, magnetite ceramic bricks usually exhibit low thermal conductivities that limit the charge and discharge power they can provide in TES applications. In order to improve this and other properties, magnetite bricks manufactured for storage heaters usually contain several additives.

There is a lack of publications about the composition and thermal properties of magnetite bricks used in storage heaters due to the possible economic consequences this could bring to manufacturers. Therefore, prior to other analyses, the thermal properties of the bricks used in the SM heater were studied.

4.2.1 Experimental set-up

Three samples were cut from different bricks of the SM heater and analysed in the range from 25°C to 660°C. This is the range that can be expected in normal operational conditions. The equipment used in this analysis comprises:

- A scale and a calliper to measure the mass, volume and density of the samples at room temperature.
- A Netzsch DIL 402 C dilatometer.
- A Netzsch LFA 427 laser flash analyser.

The thermal properties investigated in this analysis are interrelated by the definition of thermal diffusivity,

$$\alpha = \frac{k}{\rho c_p}$$

Equation 1 - Thermal diffusivity

where α represents the thermal diffusivity, k the thermal conductivity, ρ the density and C_P is the specific heat capacity.

The thermal diffusivity of the three samples was directly measured by means of laser flash analysis using the LFA 427. The basics of the laser flash analysis method (based on the operation of the LFA 427) are explained below:

A small flat sample of material (*10 mm x 10 mm x 5 mm* in this case) is introduced in a furnace where it faces a pulsed laser (see Figure 27). The sample is then heated up to a certain temperature. When it attains a stable temperature, the laser emits a pulse of energy that is absorbed at the front face of the sample. This results in a homogeneous surface heating. The relative temperature increase on the rear face of the sample is then monitored and measured as a function of time by an IR detector. A typical heating profile can be found in Figure 26. These data are used to compute the thermal diffusivity of the sample using especial software. For adiabatic conditions, α can be estimated by the following equation:

$$\alpha = 0.1388\frac{l^2}{t_{0.5}}$$

Equation 2 - LFA thermal diffusivity

where l is the sample thickness and $t_{0.5}$ the time at 50% of the temperature increase in the rear face of the sample. (NETZSCH, 2013)

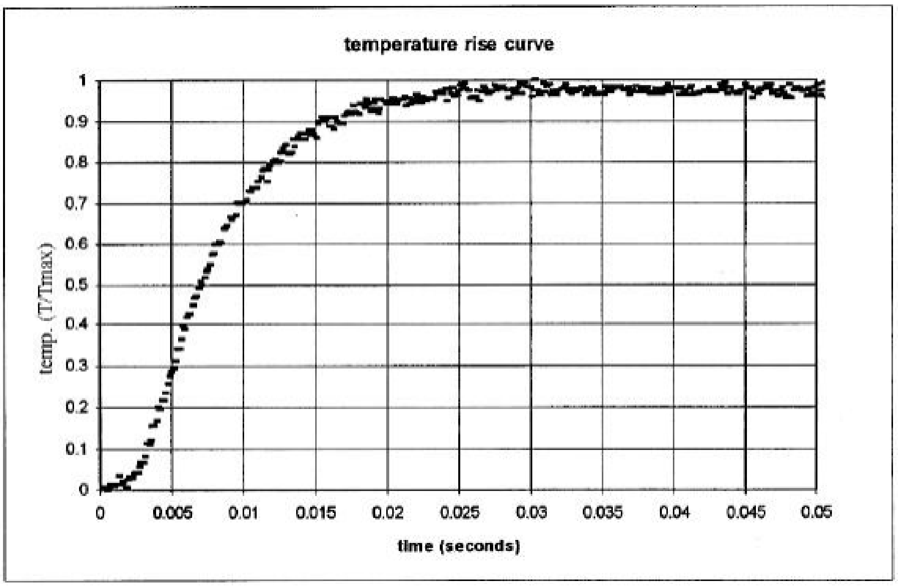


Figure 26 - Temperature increase in the rear face of a sample in LFA. Source: http://www.calce.umd.edu/TSFA/laser_flash/Results.pdf

The specific heat of the samples was also analysed by the LFA 427. To do so, the device measures the final temperature of the sample under investigation after the laser pulse has been absorbed and compares this value with a standard reference sample (graphite in this case). The basic concept behind this method is the following:

$$Q_{laser\,pulse} = (m \cdot C_P \cdot \Delta T)_{graphite} = (m \cdot C_P \cdot \Delta T)_{sample} \rightarrow C_{P_{sample}} = \frac{(m \cdot C_P \cdot \Delta T)_{graphite}}{(m \cdot \Delta T)_{sample}}$$

Equation 3 - Cp estimation by comparison with standard reference sample.

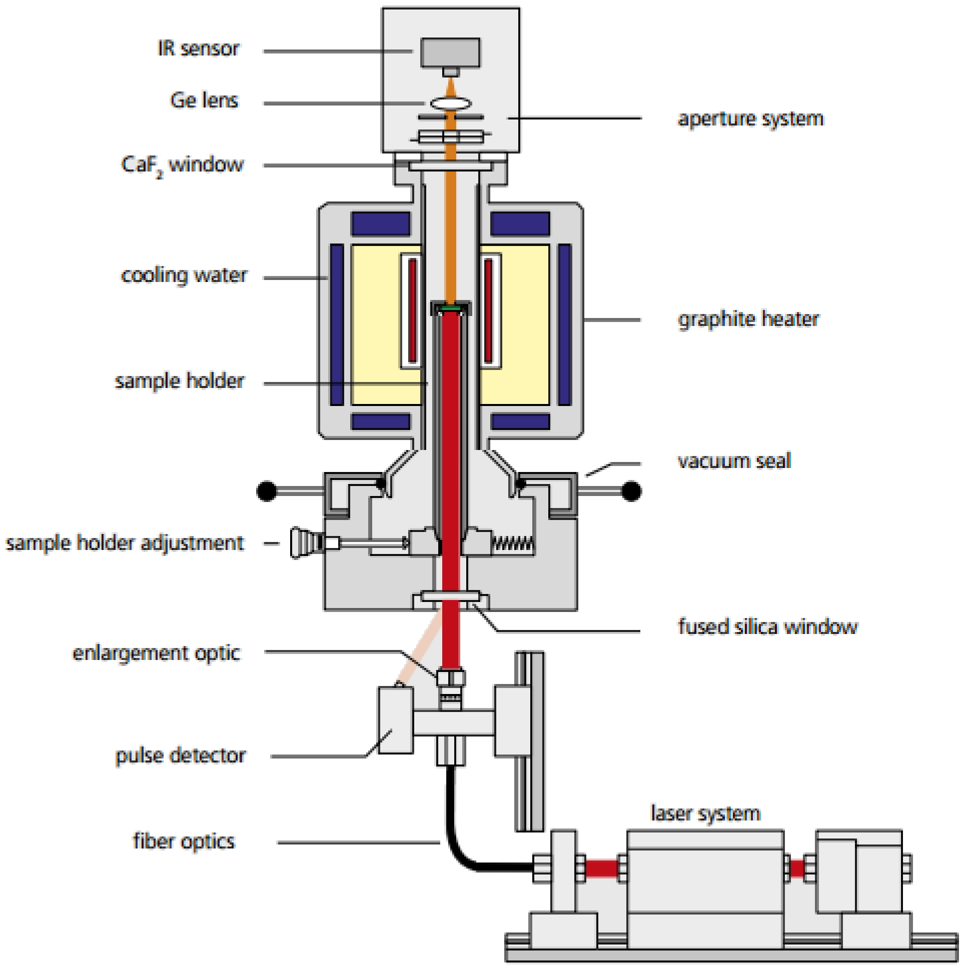


Figure 27 - LFA 427 structure. Ref. NETZSCH (2013)

The density of one of the samples was measured at room temperature by estimating its volume and weighting its mass. Then, its thermal expansion was analysed using the DIL 402 C dilatometer.

Finally, the results were combined via Equation 1 to work out the thermal conductivity of the samples.

Three individual measures were taken per temperature point. The LFA method is claimed to be have an accuracy of less than 4% for thermal diffusivity, heat capacity and conductivity. In addition, the random uncertainty (reproducibility/precision) amounts to 1–2% with three individual measurements taken per temperature point. (Müller, n.d.)

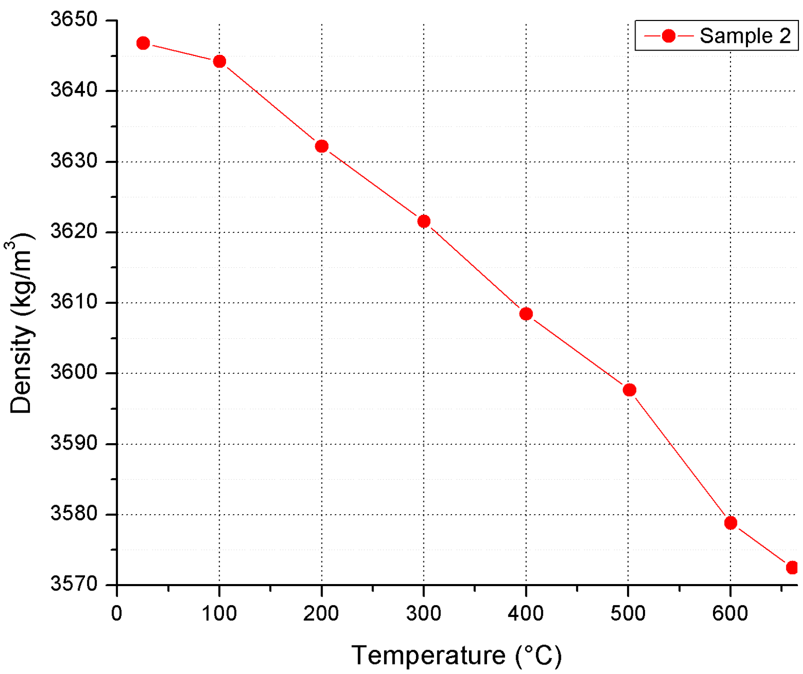
4.2.2 Results

The results presented in this section are separated into a comparison and an average of the three samples. The data shown for individual samples represent the mean value of the three measurements taken per temperature point. Since the LFA method is very precise (see above), the standard deviation is not significant in this case. However, the average of the three samples accounts for the nine measurements taken per temperature point (three per sample). The repeatability of LFA and the differences between samples are both taken into account in the standard deviation which is represented as error bars.

Density

Graph 1 shows a very linear relation between density and temperature. The values of the density of the sample at 25°C and 660°C differ roughly a 2%. Thus, it can be concluded that the magnetite used in the SM heater presents excellent thermo-mechanical properties within the studied temperature range.

These results are similar to other studies found in the literature. Densities from 3.6 to 4.0 g/cm^3 are expected in the production of magnetite ceramic bricks and the rated density of TAO-35 feolite bricks is 3.5 g/cm^3 (Otero and Álvarez, 1994; Samot, n.d.).



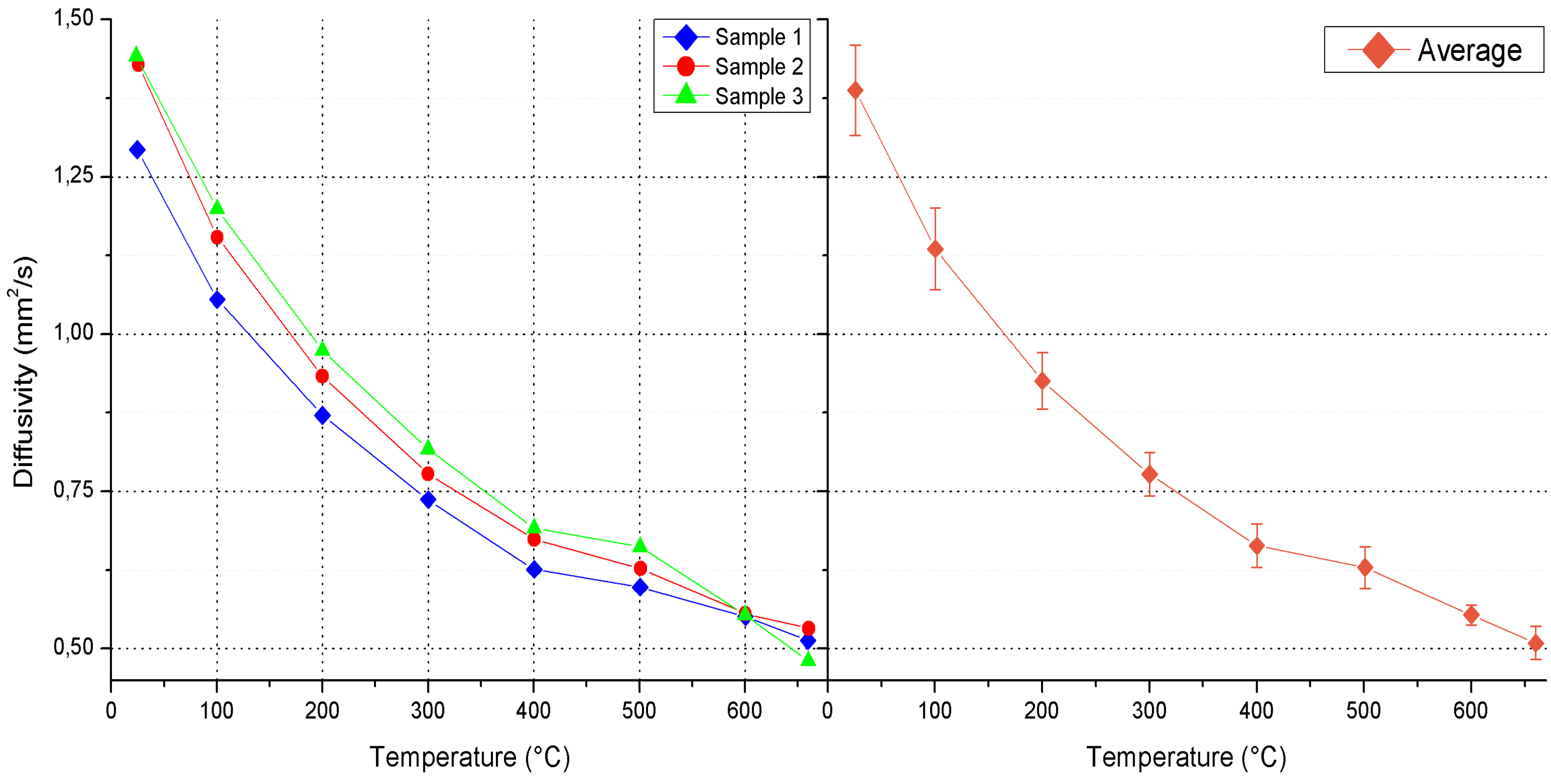
Graph 1 - Density of magnetite used in the SM heater

Thermal diffusivity

The three samples exhibit slightly different results but a very similar variation of their thermal diffusivity with temperature (see Graph 2 below). It is challenging to cut identical samples of such a reduced size (*10 mm x 10 mm x 5 mm*) from a fragile material like ceramic magnetite resulting in different masses and sizes. This is the origin of the slight dissimilarities presented by the results of the three samples.

Ceramic and stone materials typically present low thermal diffusivities (~1 mm/s^2). Diffusivity represents the thermal inertia of materials, i.e. the 'resistance' that they oppose to a change in its temperature. The lower the value of the diffusivity, the larger the thermal inertia.

Graph 2 (right) shows that the diffusivity of the samples decreases from around 1.4 mm^2/s at room temperature down to 0.5 mm^2/s at 660°C. This means that the bricks will present sharper temperature profiles at high temperatures and, therefore, the temperature distribution inside the core of the heater will tend to be more inhomogeneous as well.

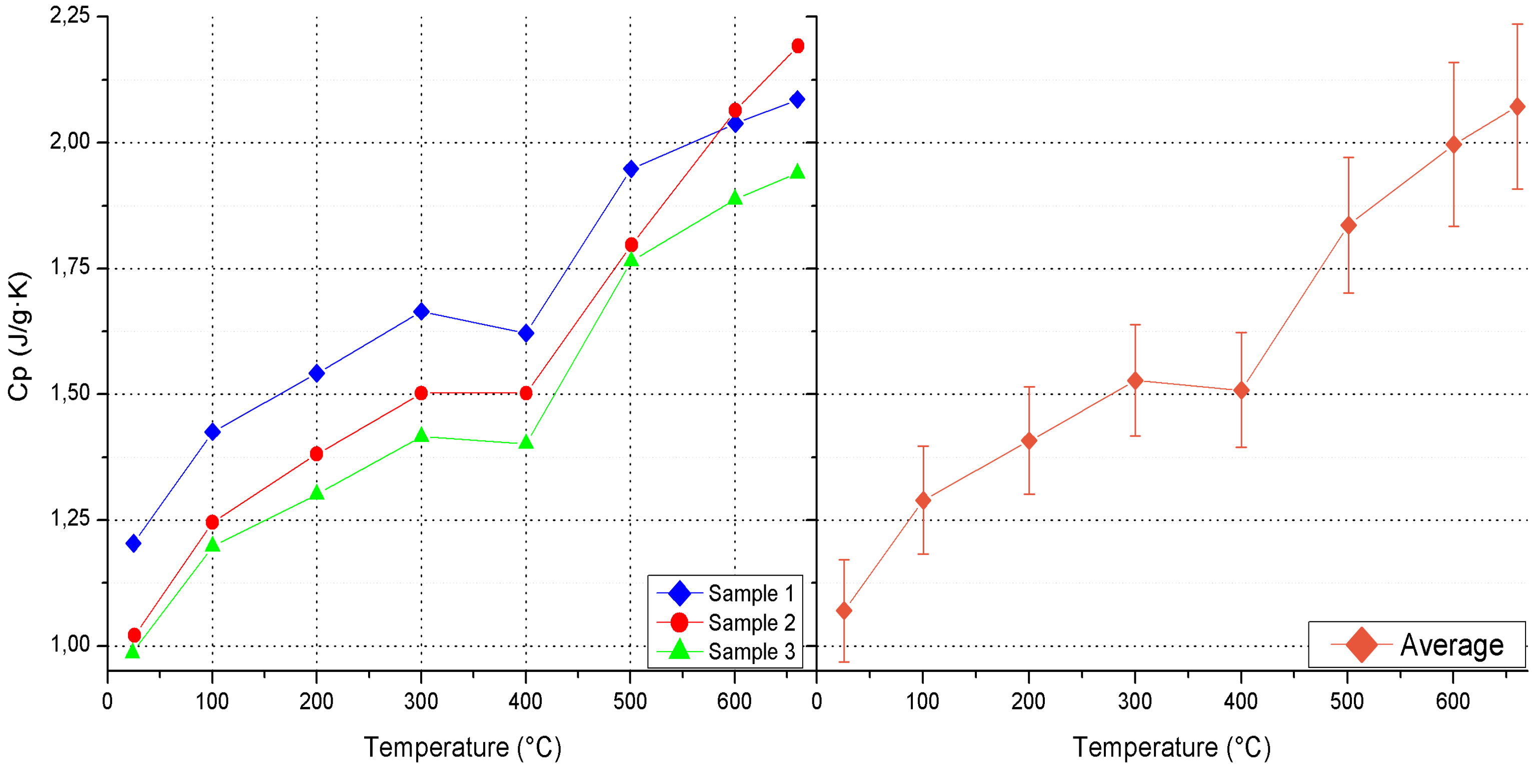


Graph 2 – Storage medium. Thermal diffusivity

Specific heat

Again, the three samples present different results and a similar variation profile. However, this time sample 1 displays significantly higher results than the other two samples. As stated in section 4.2.1, the LFA 427 estimates C_P by comparing the final temperature after the heating with a reference sample. Therefore, slight variations in the mass of the samples result in differences in the final temperature of the samples that originate the dissimilarities shown in the graph below.

The higher the heat capacity the larger the amount of energy stored for a constant temperature increase (see Equation 1). Graph 3 shows that the average specific heat of the samples increases from 1.07 J/g·K at room temperature up to 1.94 J/g·K. However, it does not grow steadily and presents a small dip at 400°C.



Graph 3 – Storage medium. Specific heat

Gronvold and Sveen (1974) carried out an extensive analysis of the heat capacity of synthetic magnetite and its ferrimagnetic phase transition back in 1974. The results of their research are summarized in the figure below:

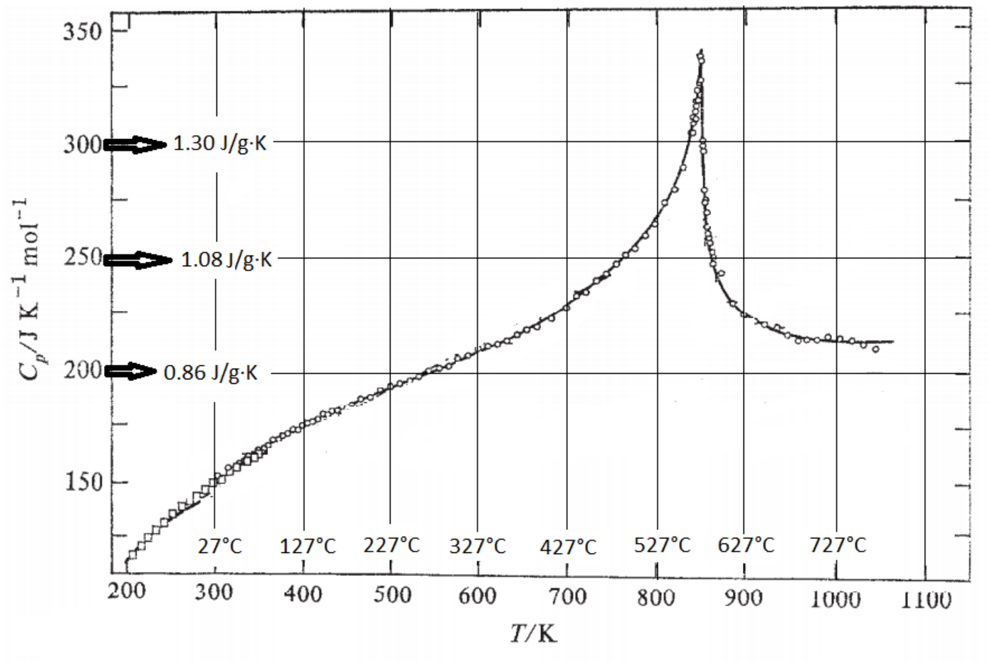


Figure 28 - Specific heat of synthetic magnetite. Source: Gronvold and Sveen (1974) [1 mol magnetite = 231.54 g]

The results obtained in the present analysis differ widely from the ones shown in the figure above. It can be easily observed that the overall heat capacity obtained for the samples is significantly higher and there is no trace of a phase transition.

In addition, Samot (n.d.) sates that the mean value for the heat capacity of feolite bricks TAO-35 in the range 20°C -700°C is 0.94 J/g·K.

In this study, the mean value of C_P can be easily estimated from the data provided in Graph 3 as:

$$\overline{C_P} = \frac{1}{T_2 - T_1}\int_{T_1}^{T_2} C_P(T)\, dT = \frac{1}{660°C - 25°C}\int_{25°C}^{660°C} C_{P_{average}}(T)\, dT = 1.6 \pm 0.2\, J/g \cdot K$$

Equation 4 - Mean value of C_P from Graph 3. [The integration was performed assuming linear variation of the heat capacity between consecutive points of Graph 3]

It is therefore clear that the heat capacity of the magnetite used in the SM heater does not behave like standard synthetic magnetite or commercial TAO-35 feolite and presents a significantly higher heat capacity.

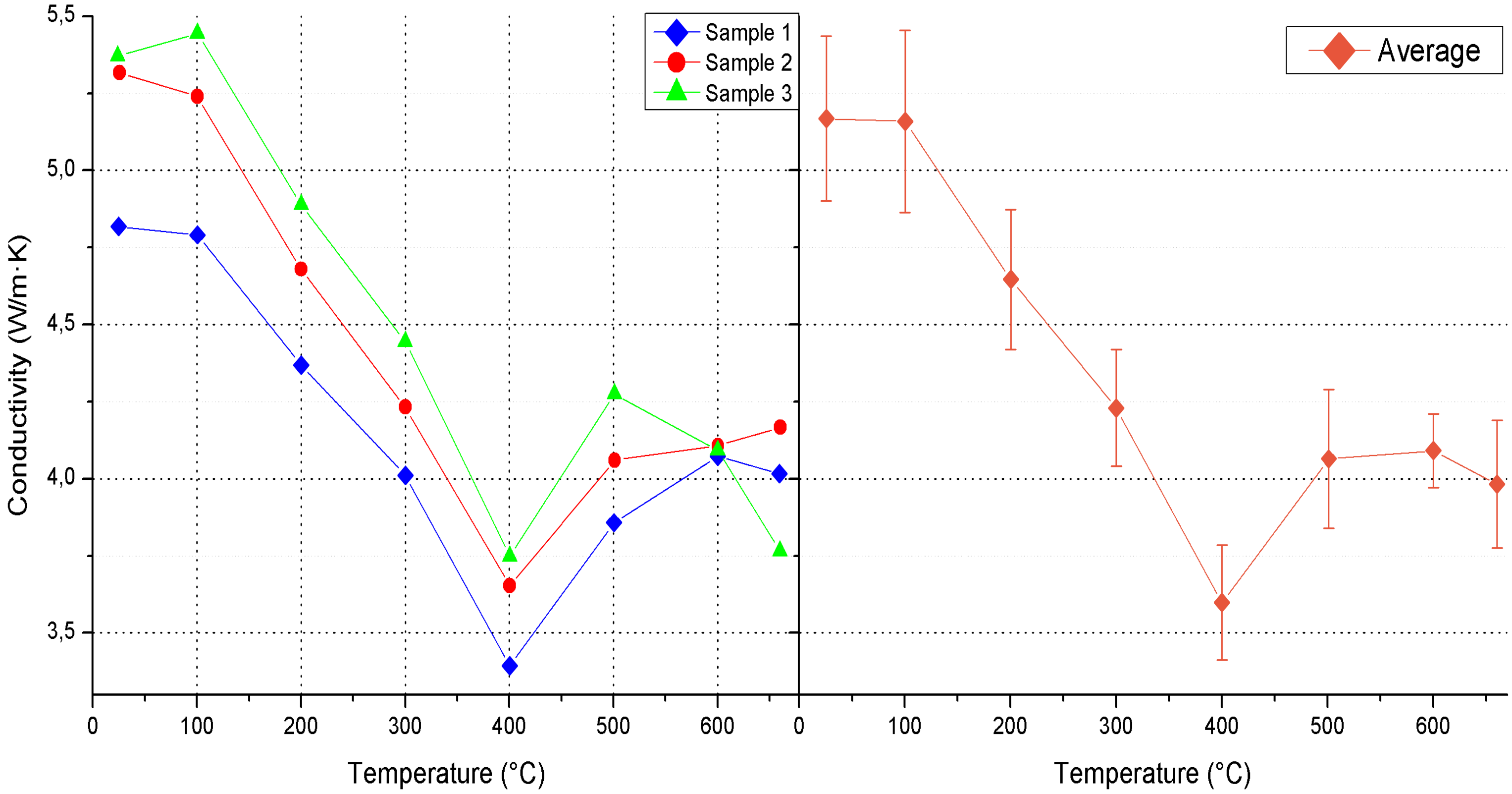
Finally, it is important to note that C_P is roughly double at high than at low temperatures and, thus, the storage capabilities of the SM heater are double too.

Thermal conductivity

Because the data from Graph 2 and Graph 3 are used together to provide Graph 4, the dissimilarities of the results found in the first two are further multiplied here (see Equation 1) resulting in larger differences between the samples. In addition, the dip observed in the analysis of C_P at 400°C becomes more evident in this case.

Samot (n.d.), gives a value for the thermal conductivity of TAO-35 feolite bricks of 1.59 W/m·K. Also, Otero and Alvarez obtained values of 2.5-3.0 W/m·K for 3.8-4.0 g/cm^3 and 1.5 W/m·K for 3.6 g/cm^3 ceramic magnetite at 100°C. These values are considerably lower than the results presented in Graph 4.

Thus, it is obvious that the magnetite used in the SM heater has improved thermal conductivity.



Graph 4 – Storage medium. Thermal conductivity

4.2.3 Discussion and conclusions

The use of the word 'feolite' instead of magnetite in the specifications of the SM heater was properly employed since the material analysed does not present any of the expected properties of magnetite, apart from density.

In the manufacture of the bricks several grinding and heating processes are required to obtain the final product. During these processes additives can be added to the raw material in order to improve its consistency and its thermal properties. As stated in sections 2.6.2 and 4.2 (see also Figure 25), MgO is also a very suitable material for energy storage with a volumetric specific heat close to that of magnetite. Its main advantage over the latter is its superior thermal conductivity (see figure below). Therefore, the higher than expected thermal conductivity of the samples can be due to MgO being used as an additive during the production of the bricks.

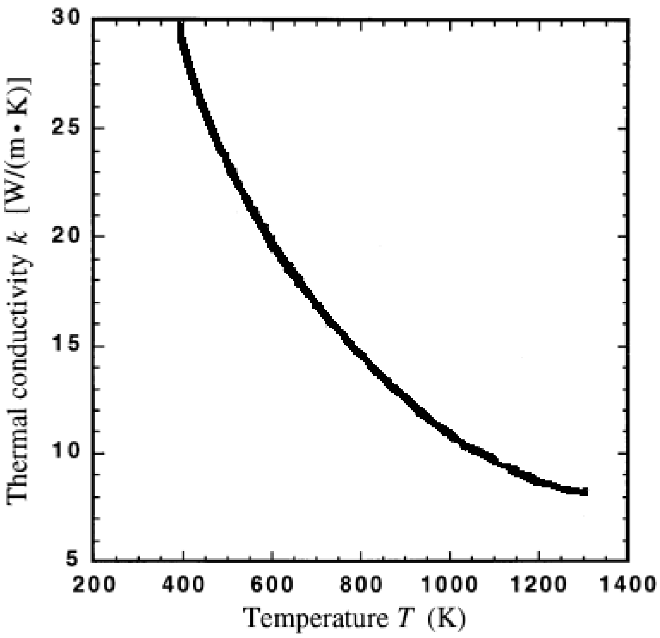


Figure 29 - Thermal conductivity of MgO. Source: http://nvlpubs.nist.gov/nistpubs/jres/103/4/j34sli.pdf

Likewise, the ferrimagnetic phase change of magnetite is not found explicitly in the results. It has probably been shifted to higher temperatures or even smoothed out as a consequence of the high temperature (above the critical temperature of magnetite) processes during the manufacture of the bricks.

As stated above, C_P represents the amount of energy that a material can store when its temperature changes. At a microscopic level this is translated into vibration of molecules in different modes. The root of the anomalous dip observed in the data at 400°C was investigated but no conclusions were attained. However, it can have its origin in the unavailability of some of those vibrational modes at that specific temperature. A deeper study of the specific heat should be performed around 400°C using a better temperature resolution in order to determine the final cause of this anomaly. Nevertheless, it does not affect significantly the storage capacity or performance of the storage material.

With regard to the margin of error of the measurements, the standard deviation of the results (around 5% for diffusivity and conductivity and 8% for specific heat) does not account for the differences encountered compared to the values found in the literature. Furthermore, a large portion of these uncertainties is due to the small differences in size and mass of the samples more than to the accuracy and repeatability of LFA method.

In summary, the properties presented by the storage material of the SM heater can be considered as very good for a ceramic storage medium. Thermal diffusivity and conductivity indicate that the overall performance of the heater is likely to be better at low temperatures with higher heat transfer rates and smoother temperatures profiles. On the other hand, the storage capacity of the heater is potentially larger at high temperatures. However, this higher capacity can be prevented by sharper temperature profiles and less effective charging and discharging processes.

In order to better evaluate the overall performance of the heater and, particularly, its effectiveness as DSM, it will be useful a direct study of the temperature distribution inside its core.

4.3 Temperature distribution

The low thermal diffusivity and conductivity of the bricks of the SM heater may prevent the heat to spread effectively from the heating elements to the rest of the core. In addition, large heat losses may as well occur in some parts of the heater. All this can cause some bricks or parts of them to be significantly colder or hotter than others.

A very inhomogeneous temperature distribution inside the core can significantly affect the performance of a storage heater. If the temperature is not evenly distributed, the high volumetric heat capacity of magnetite is under-used. This is especially true in the case of heaters, like the SM heater, in which charge control is carried out by a single thermosensor.

The temperature distribution inside the core of the heater during a typical charging cycle was studied to analyse these issues.

4.3.1 Experimental set-up

As stated above, the SM heater determines the level of charge for the following day from usage and weather patterns using smart controls and a self-learning algorithm. However, a misconfiguration (or even damage) was caused to these controls prior to this project and prevented their use in this study unfortunately.

In order to perform the experiments presented in this section, the internal controls of the heater were bypassed. The three heating elements were connected directly to the mains supply and three switches were installed to allow their individual operation.

Nevertheless, bypassing the internal controls of the heater resulted in some negative consequences. The built-in temperature/charge control was lost. Thus, the heater had to be operated manually without any knowledge about the maximum safely achievable level of charge. In order to avoid possible hazards, the local core temperature was maintained always below 650°C. However, this meant that the heater was used at random conditions that did not correspond necessarily to standard operation settings or rated storage capacity. In addition, the internal fan stopped working. Thus, it was not possible to study the heat output and discharging processes.

The equipment provided for the realisation of the experiments was rather simple. It basically consisted of 8 K-type thermocouples (TCs) and two USB interface to monitor their readings using LabView. Also, a current clamp was supplied to monitor the current going into the heater.

Due to the very reduced number of thermocouples, the heater had to be approximated to a 2D system. The thermocouples were located as close as possible to the centre of the bricks (red line in the figure below) and, thus, the temperature in this position was assumed to represent the average transversal temperature.

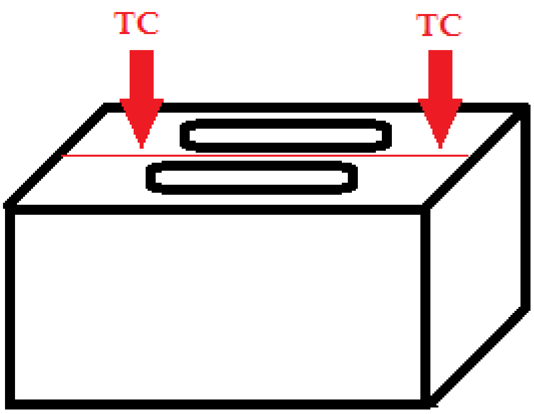


Figure 30 – Transversal location of TCs

4.3.2 Experiments and results

There were three experimental phases: an initial test to monitor local temperature distribution, a second test in which a brick-by-brick approach was developed, tried and improved; and, finally, the study of the temperature distribution of the heater brick-by-brick using the previous approach.

Initial test

TC distribution

For the initial test the thermocouples were located as shown in the following figure:

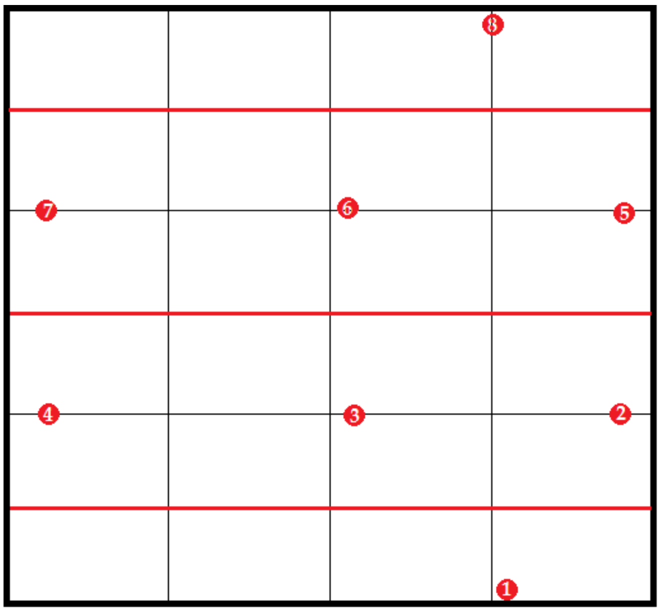


Figure 31 - Initial test. TC distribution

The figure above represents the different bricks of the core of the heater with the heating elements highlighted in red.

This distribution was chosen so that the thermocouples were as far as possible from the heating elements to protect the sensors from excessive temperatures and to avoid possible false readings caused by direct thermal radiation from the elements.

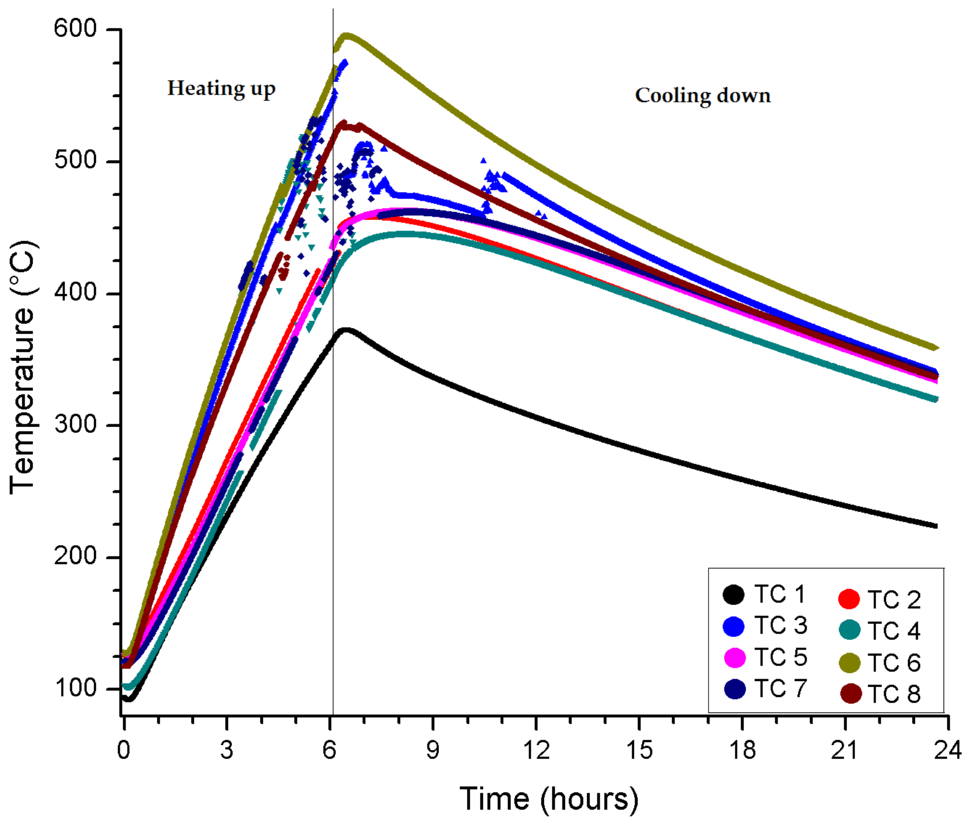
TC 1 was placed inside the bottom insulation, just where the original thermal sensor used to control the temperature of the core of the SM heater is located. This thermocouple was intended to be used as a reference temperature to compare the results of different experiments.

Experimental conditions

The test was run for a 24-hour period. Prior to the start of the test the heater was warmed up until TC1 was at around 100°C. Then, the heater was left stabilising for a couple of hours. This warming up was performed to start the test with a stable temperature distribution in approximately static conditions. When, TC6 and TC3 were giving stable and similar readings of around 120°C the heating elements were turned on for 6 hours. After the heating up period, the heater was left cooling down solely by passive heat loss processes for near 18 hours.

Results

The results of this initial test are shown in the graph below:



Graph 5 – Initial test. TC temperature distribution.

It is easy to observe that some of the thermocouples give anomalous readings during the experiment. The reason for this was discovered when the cover of the heater was removed after the experiment. The coating of the thermocouple wire had melted down. Some of the wires were in contact with others producing a mixed signal. It is difficult to estimate the actual temperature at which this happened. However, it is clear that the thermocouple wire provided for the project was not prepared for medium-high temperature applications.

Besides these strange readings, Graph 5 shows an inhomogeneous temperature distribution. The temperature is much higher in the centre of the heater than near the sides. This difference exceeds 100°C at the end of the charging period.

It is interesting to note that TC2 and TC4 as well as TC5 and TC7 are found to give similar readings throughout the experiment. This could mean that, although there is an uneven distribution of temperatures, there may exist some symmetries in it.

Overall, the differences between the readings of the thermocouples increase during the heating up period as the temperature rises and tend to be lower during the cooling down.

It can be found in the technical specifications of the heater states that the core has reached its maximum storage capacity, T_{core} = 600°C, when the thermal sensor located at the bottom insulation gives a reading of 190°C. Nevertheless, Graph 5 indicates that TC1 reached 190°C just after 2.5 hours of heating up. A typical charging period is much longer than 2.5 hours so this result is largely inconsistent with the manufacturer's claims. The original thermosensor has a protective cover while the TC1 is completely exposed. Thus, this is probably the origin of the discrepancy. Sadly, this means that the results of the project cannot really be compared with nor calibrated against previous studies and information from the manufacturer.

In summary, the temperature distribution in the core of the heater is very inhomogeneous. The temperature in the centre and sides of the heater differs in more than 100°C, roughly a 20%. However, the temperature distribution tends to homogenise with time once the heating elements are turned off.

As a final remark, when the cover of the heater was removed at the end of the experiments, besides the melted thermocouple wiring, the insulation panels of the heater were found to be slightly burned. This probably means that, although the readings of the thermocouples did not go beyond the maximum allowable core temperature (600°C), some parts of the heater exceeded this value by far. This gives an idea of how local the temperature can be and led to the design of the following test.

Second test – First brick-by-brick approach

To avoid the problems of the initial test, the thermocouples were covered in a high temperature sleeving that can stand temperatures up to 650°C.

The previous results were useful to observe the inhomogeneities in the temperature distribution at high-level. However, a more detailed study is needed to understand the performance of the SM heater. Thus, it was decided to carry out a brick-by-brick approach, i.e. to monitor every brick in an individual basis.

TC distribution

In order to carry out the brick-by-brick approach, the temperature of every brick was monitored at four (three for the top bricks) different points (see Figure 32 and Figure 33). The temperature of the brick was then estimated averaging the four temperatures.

This is equivalent to a 2D integration assuming that the temperature varies linearly from thermocouple to thermocouple.

An advantage of this method is that, inevitably, two of the thermocouples are placed very near the heating elements and provide information about the maximum local core temperature. That way, it is possible to avoid the excessive temperatures of the initial test that led to the slight burning of the insulation panels.

Obviously several experiments are needed to monitor the temperature of the 24 bricks that form the core of the SM heater using only eight thermocouples. In addition, the initial and final conditions of the experiments need to be similar in order to join the data from the different experiments together. TC1 was placed at the same location as in the initial test for this purpose.

Only two experiments were performed in this second test. The first experiment monitored the temperature of the first three bricks of the heater. The location of the thermocouples can be found in the picture below:

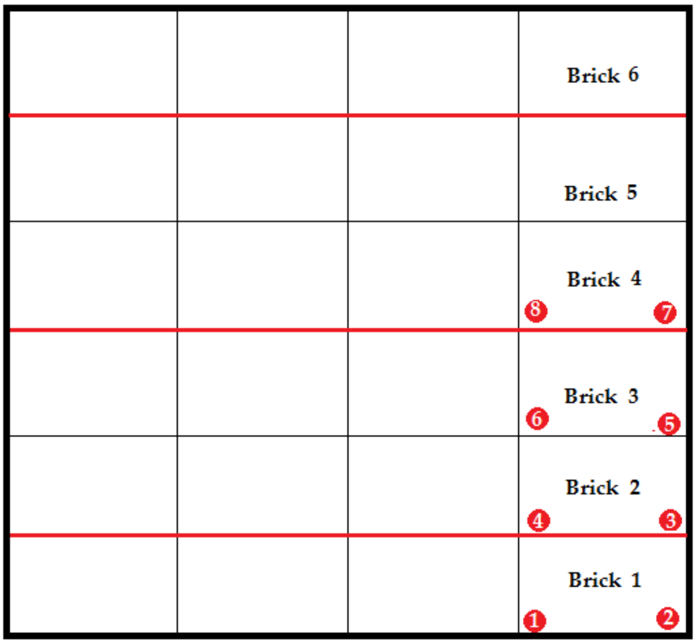


Figure 32 – Second test. Experiment 1. TC distribution.

The second experiment monitored the temperature of the three following bricks:

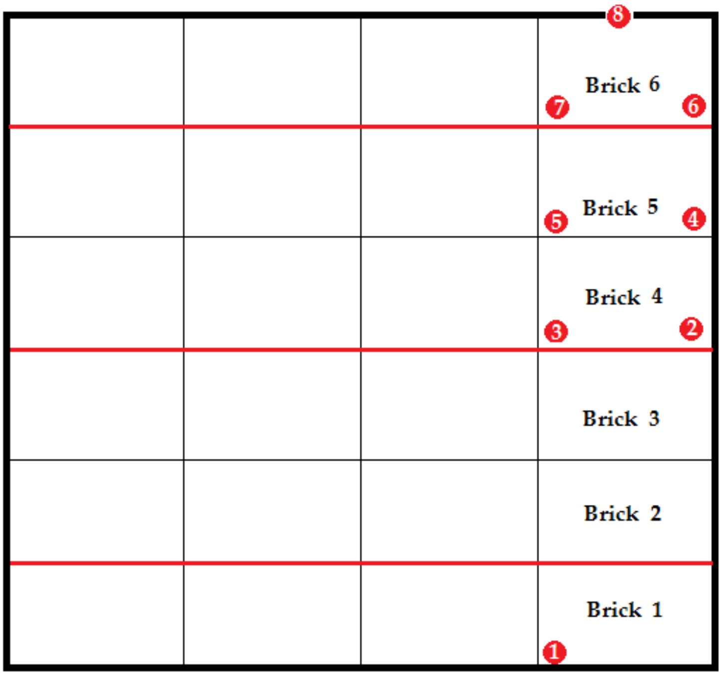
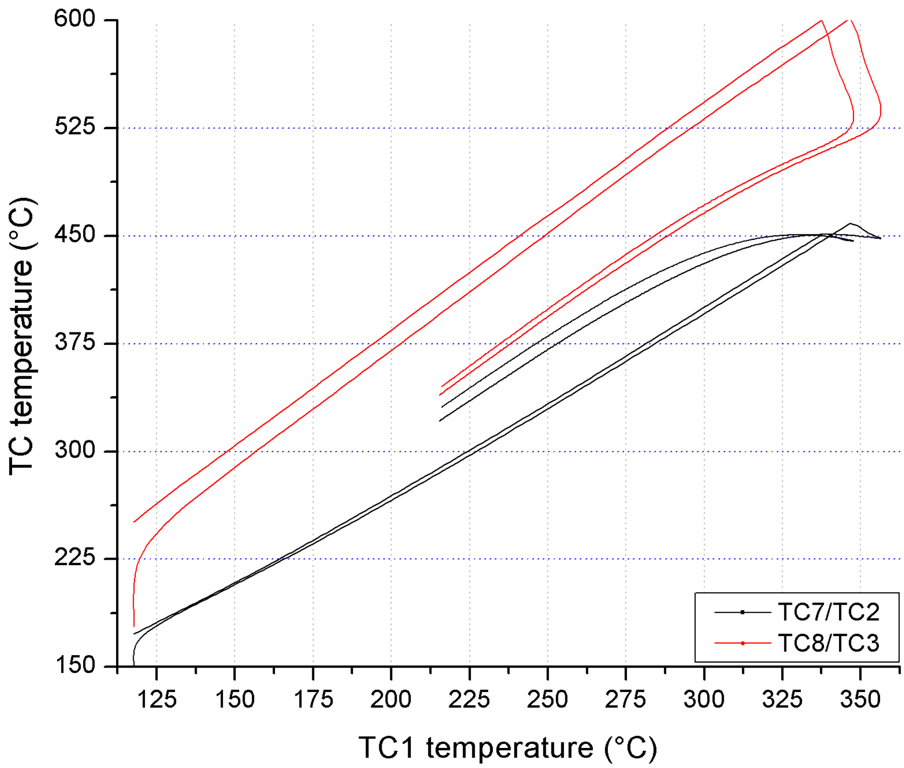


Figure 33 - Second test. Experiment 2. TC distribution.

As seen in Figure 32 and Figure 33, two extra thermocouples, TC7/TC2 and TC8/TC3 are used as an extra reference to ensure similar conditions in both experiments. However, for similar values of TC1, both experiments showed a mismatch in the reading of the extra reference thermocouples (see graph below).



Graph 6 - Second test. Reference TCs comparison in experiments 1 and 2.

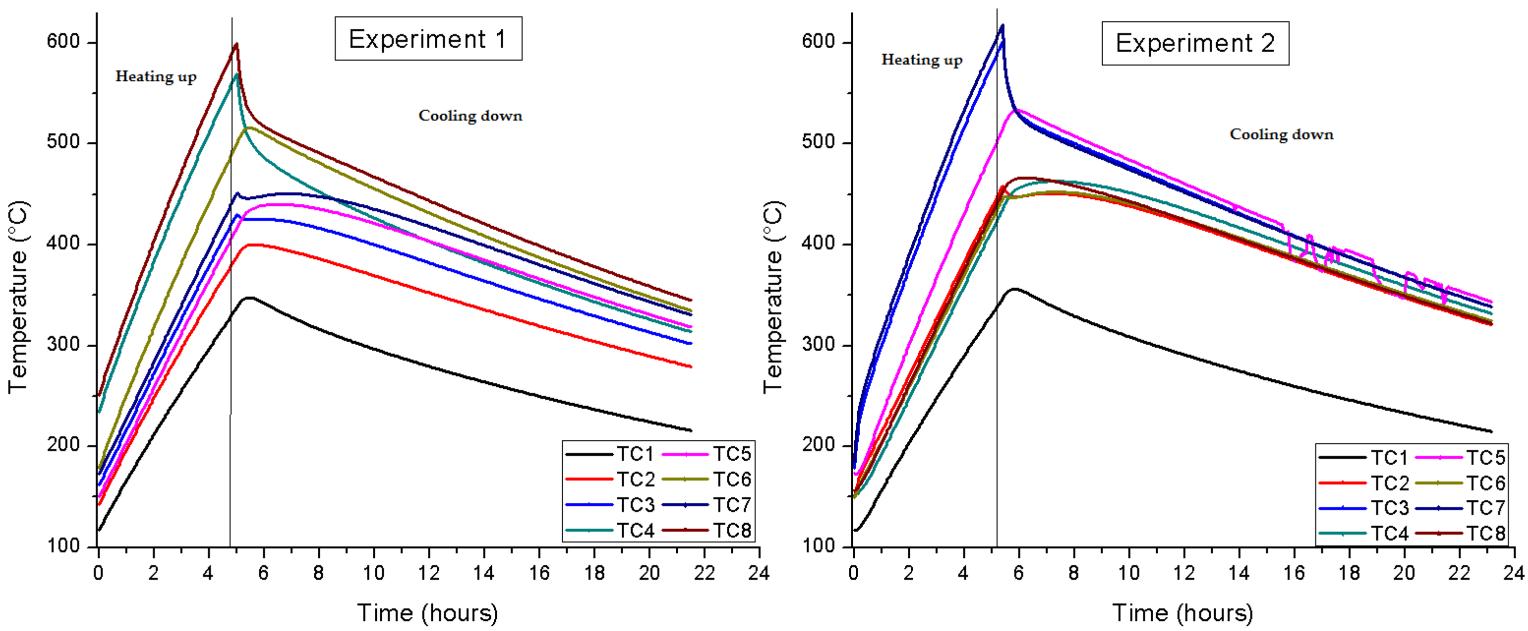
Although small, this gap represents a lack correlation between both experiments and means that the initial conditions were different in each experiment and could not be determined accurately from the reading of TC1. In order to make the results more coherent, the data of the second experiment were time-shifted to match the first experiment and the differences between the readings of T1, TC7/TC2 and TC8/TC3 were averaged.

Experiment conditions

The test was run for a 21.5 hours period. The core was first warmed up, like in the previous test, until TC1 was giving a reading of around 150°C. Then the heater was left stabilising for a couple of hours until the reading of TC1 was stable around 120°C. At that point the heating elements were turned on for 5 hours and then the heater was left cooling down solely by passive heat loss processes for 16 hours.

Results

The results of the two experiments are shown below:



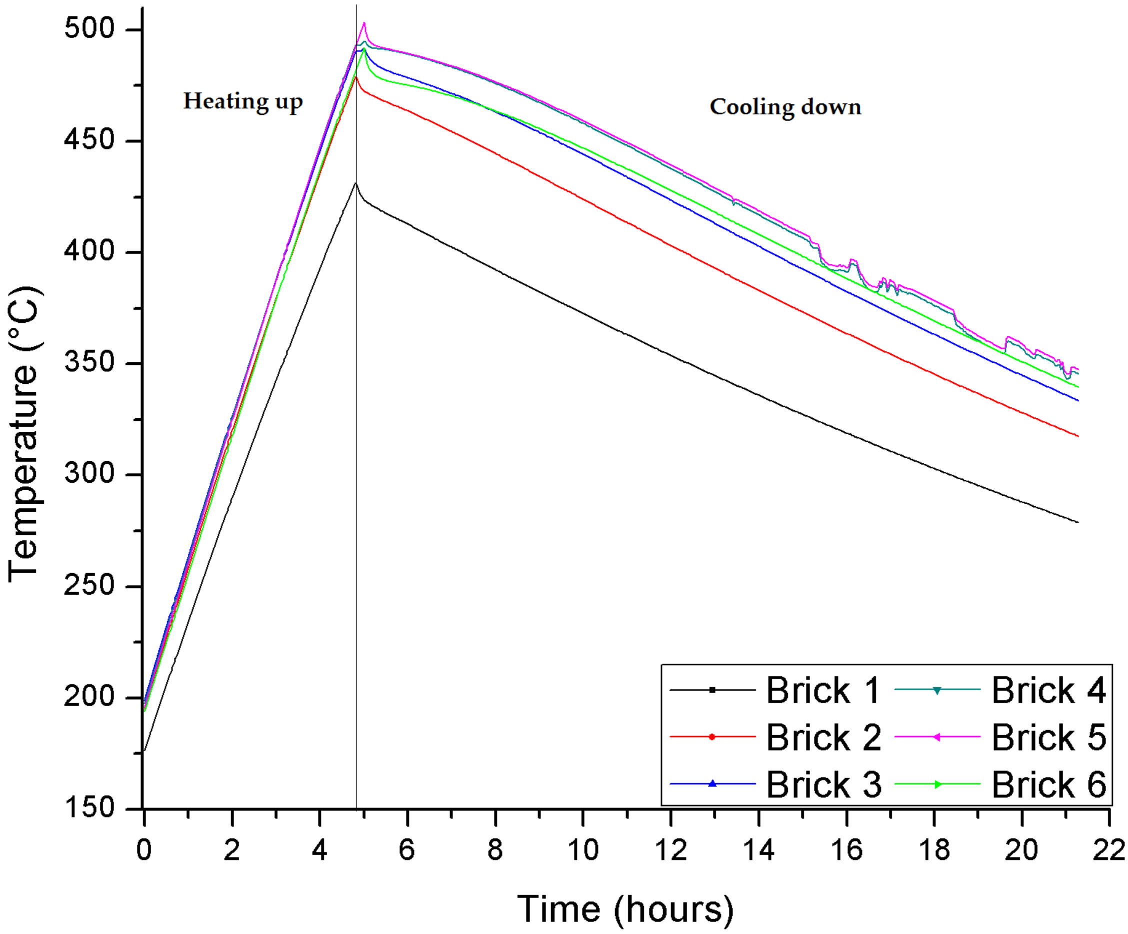
Graph 7 - Second test. TC temperatures in experiments 1 (left) and 2 (right)

The graph above shows that the temperatures near the heating elements are much higher than the others. In addition, just after the heating elements have been turned off, the temperature of these thermocouples decreases very abruptly. This temperature drop is generated by the sudden decrease of radiative heat arriving to the thermocouples as the temperature of the heating elements decreases (Stefan-Boltzmann law $E \sim T^4$). This confirms the suspicions that led to the design of the initial test (see Figure 31) to avoid false readings.

Beside these effects, experiment 1 shows a very diverse temperature distribution during the whole cycle while in experiment 2, TC2, TC4, TC 6 and TC 8 (all of them located at the right side of the heater, see Figure 32 and Figure 33) give similar readings. Furthermore, all the thermocouples tend to reduce their differences during the cooling period.

Some minor fluctuations of TC5 near the end of experiment 2 indicate that even with the high temperature sleeving, the thermocouple wire is still likely to fail.

The results for the brick temperatures are now analysed. It should be remembered that the data were modified to show coherence between experiments 1 and 2 as stated above.



Graph 8 - Second test. Brick temperature distribution

Although the temperature distribution is generally quite inhomogeneous locally, Graph 8 indicates that with a brick-by-brick approach the temperature distribution tends to be more homogeneous for these six bricks.

Brick 1 shows a low temperature compared to the others. This is mainly due to the readings of TC1. It is not in direct contact with brick 1 so its readings only account for radiative and convective processes from the surface of the brick to the thermocouple and, thus, tend to be lower.

Graph 8 also exhibits a sudden drop in the brick temperatures just after the heating elements have been switched off. Although it is lower than for individual thermocouples, it indicates that this first approach does not account for the expected behaviour of the temperatures of the bricks. These should increase or remain a bit stable just after the heating elements have been turned off since the latter are still hot and provide energy for some time.

In conclusion, the brick-by-brick approach seems a reasonable way to study the temperature distribution of the heater in detail. However, to monitor the temperature of every brick using four thermocouples offers results deviated from the expected behaviour. Thus, it should be avoided to place thermocouples near the heating elements what, in fact, is quite challenging since a direct contact between the heating element and the thermocouple wire would seriously damage the latter. In addition, too many experiments are required using this approach and very little time was available for the execution of the tests. Finally, it was quite challenging to perform the experiments in the same exact initial condition using TC1 as a reference which is not in contact with the bricks.

This is why only two experiments were performed using this method and a new approach was developed.

A new approach

The results of the second test show that monitoring the temperature of the core brick by brick provides a detailed view of the temperature distribution inside the core of the SM heater. However, a simpler approach that requires fewer experiments and avoids placing thermocouples near the heating elements is necessary.

Returning to Graph 7, it is easy to notice that the temperature of the thermocouples located near the heating elements decreases very fast just after the latter are switched off. A closer analysis reveals that their temperature does not only decrease but also tends to reach a value slightly higher than the reading of the thermocouple located directly below. As an example, on the left side of Graph 7, it can be observed that the reading of TC8 decreases to values just above those of TC6 in less than 30 minutes.

In addition, Graph 5 and Graph 7 show that the higher the thermocouples are located inside the heater the greater their readings.

Using these findings, a new approach was derived. Instead of placing four thermocouples in every brick, the effective temperature near the heating elements is now estimated as the average between the thermocouples located directly above and below that position. The following figure illustrates the new approach.

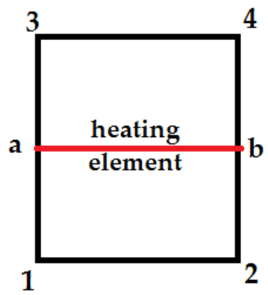


Figure 34 – Finals tests. New approach for the estimation of the temperature of the bricks

In the figure above, thermocouples are located at positions 1, 2, 3 and 4. The temperature in *a* and *b* would then be:

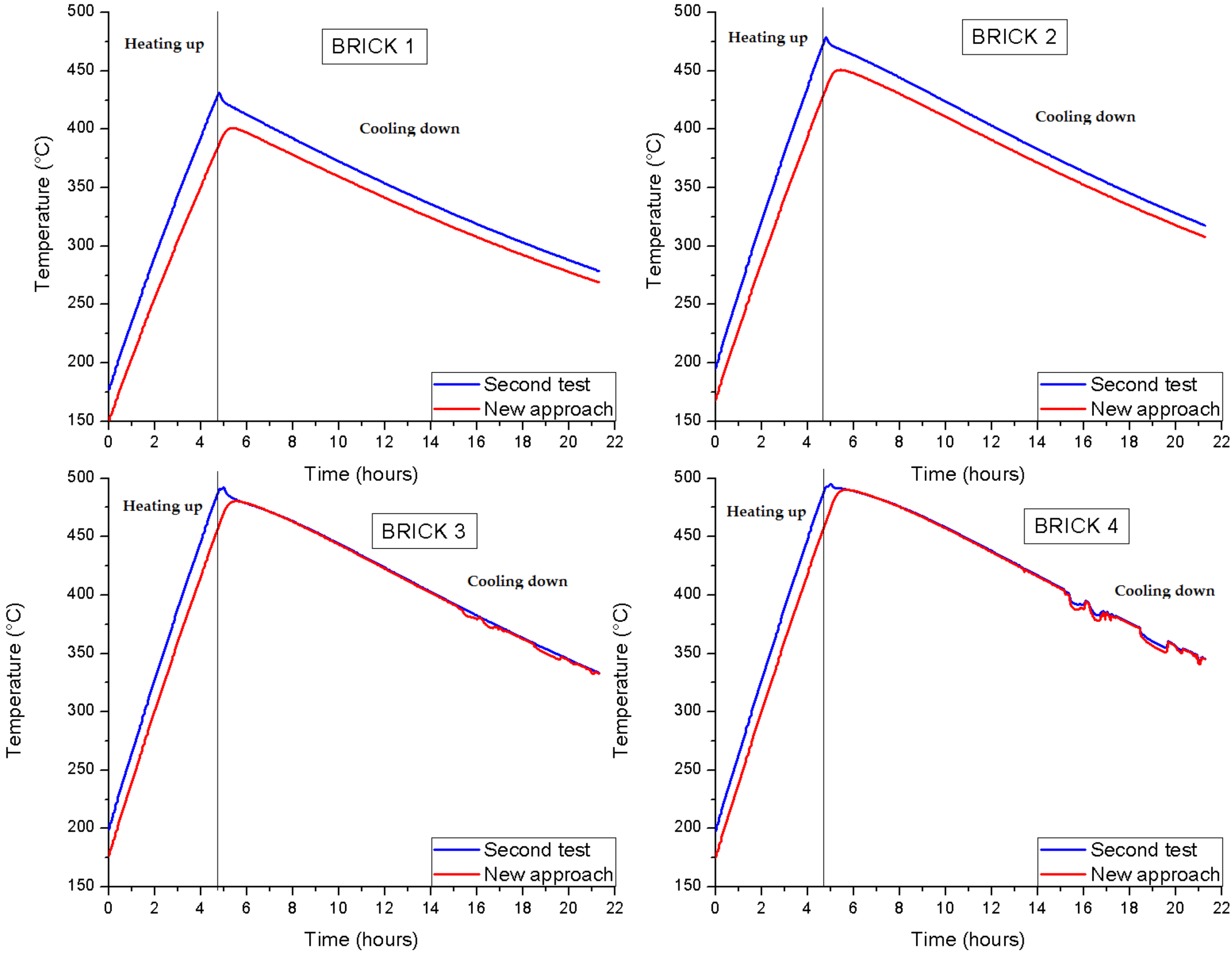
$$T_a = \frac{T_3 + T_1}{2};\ T_b = \frac{T_4 + T_2}{2}$$

T_a and T_b computed this way, present values:

- Lower than the real temperature while the heating elements are active
- Similar to the temperature after the heating elements are switched off
- Higher than the reading of the thermocouple located just below
- Lower than the reading of the thermocouple located just above

This is in accordance with the observations stated above and, thus, can be used as an effective temperature near the heating elements, i.e. as a temperature without the distorting effects of the heating elements. However, it is important to stress that they do not represent the real temperature at those locations. This is only an approximation in order to estimate of the temperature of the bricks.

The following graph shows a comparison between the results of the second test using the old approach and the new one:



Graph 9 – Final tests. Comparison between second test approach and the new one using the results from the second test

The graph shows that the temperature evolution of the bricks remains very similar to the second test but the abrupt drop after the deactivation of the heating elements is not present. Furthermore, the temperature of the bricks keeps increasing after the heating elements have been switched off. This is more like the expected behaviour. Therefore, this new approach seems a better and more effective approximation to monitor the temperature distribution inside the core of the heater.

Final test. Complete temperature distribution using a brick-by-brick approach.

TC distribution

5 experiments (plus some repetitions) were performed to obtain a complete picture of the temperature distribution during a full charging cycle of the SM heater. The results from all the experiments were joined together so that, overall, they are equivalent to a single experiment using 18 thermocouples distributed in the following manner across the core of the heater:

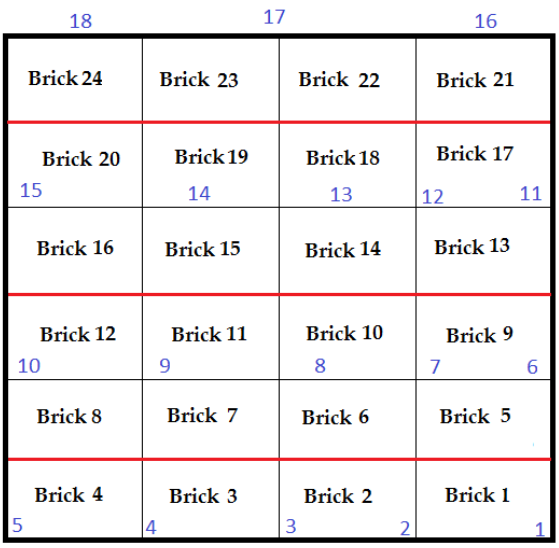


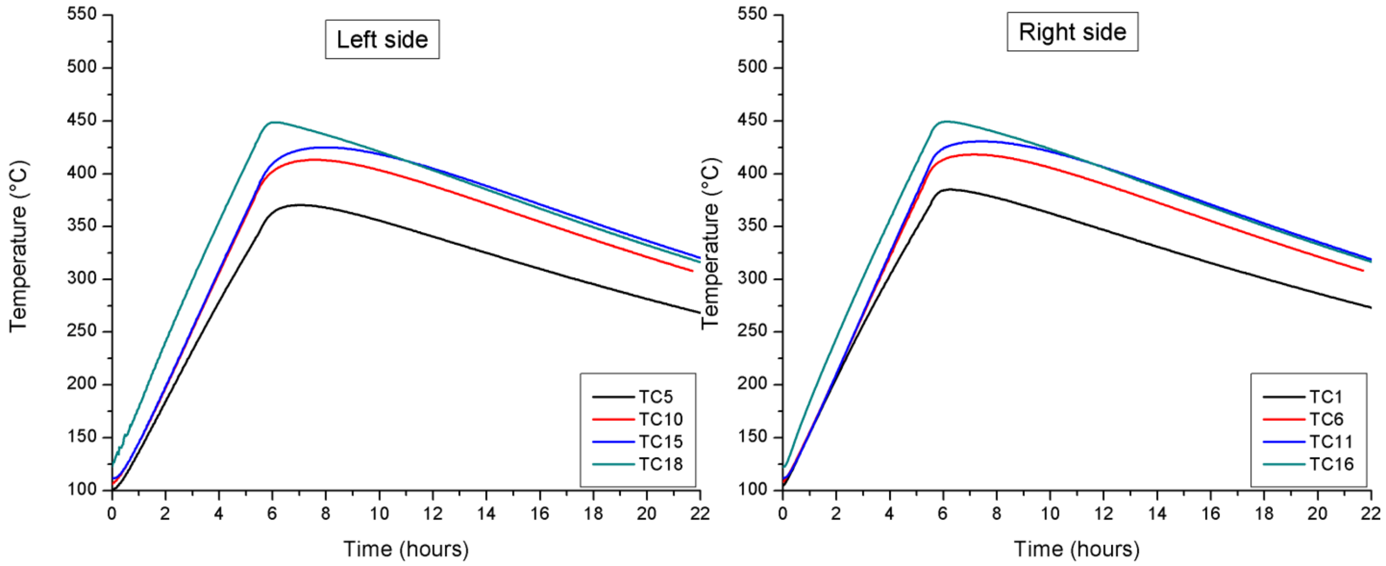
Figure 35 – Final tests. TC distribution

Experiment conditions

The tests were run for a 21.5 hours period. Prior to every test the heater was warmed up until TC3 was giving a reading of around 120°C. Then the heater was left stabilising for a couple of hours until the reading of TC3 was stable around 110°C. At that point the heating elements were turned on for 5 hours and 40 minutes and then the heater was left cooling down solely passive heat loss processes for 14 hours and 20 minutes.

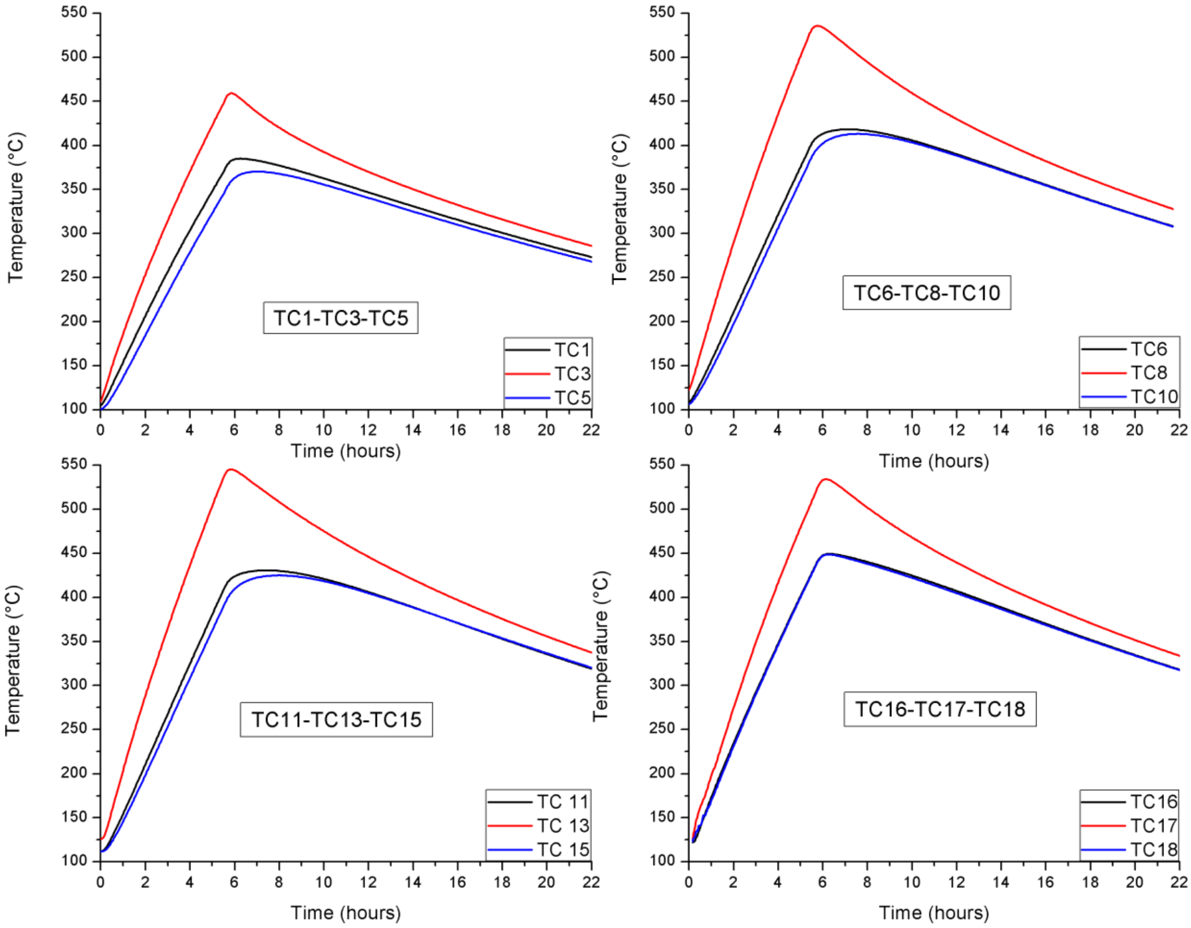
TC results

Before investigating the temperature distribution in the core of the SM heater with the new brick-by-brick approach, the results from individual thermocouples are analysed. The following graph presents the readings of the thermocouples located at the sides of the heater:



Graph 10 - Side thermocouples

The graph above shows very similar results for both sides of the heater indicating some symmetry of the temperature distribution in the edges of the heater. The following graph gathers together the readings of the thermocouples row by row:

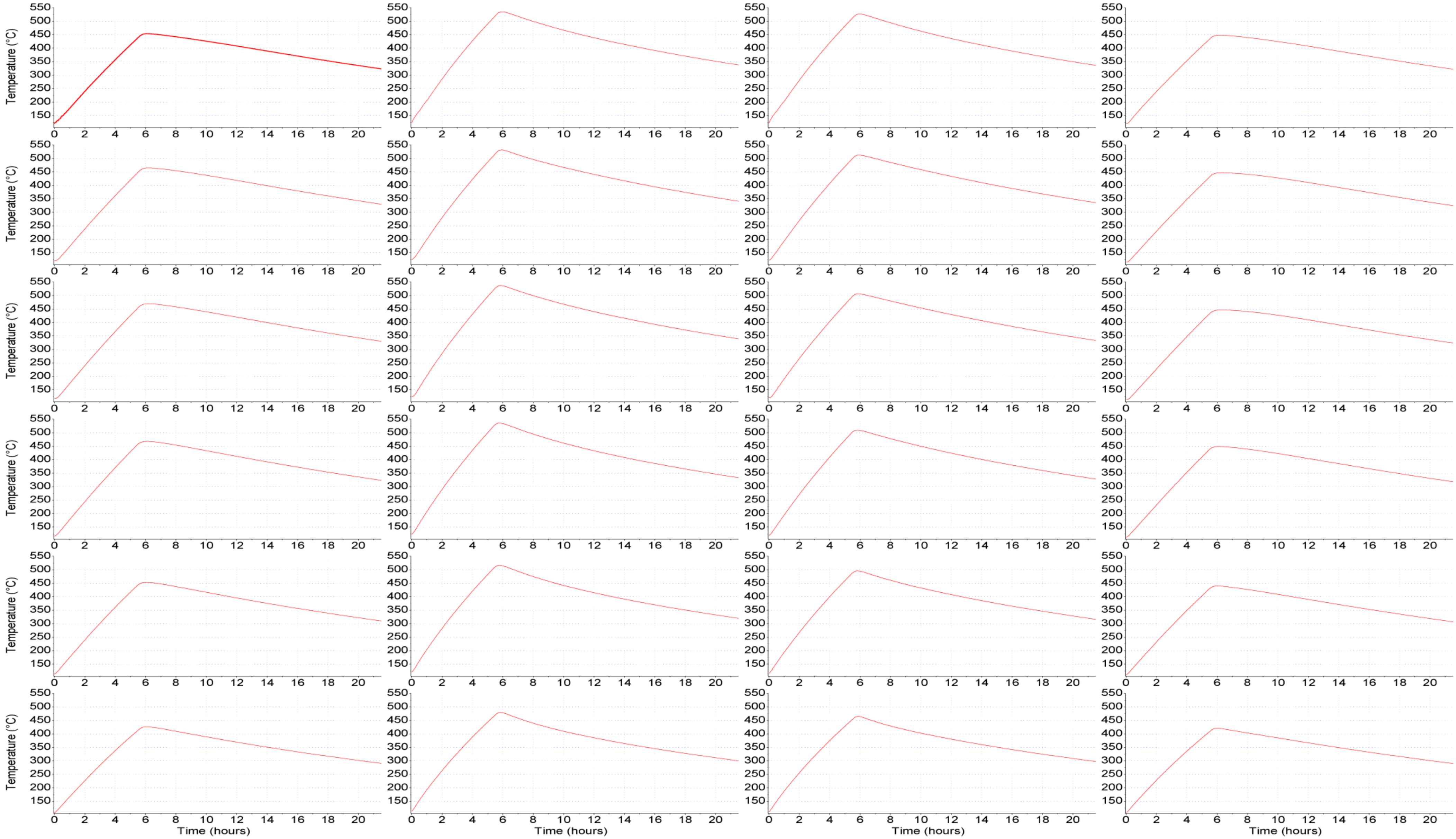


Graph 11 – TC comparison between different rows

The graph above confirms that the temperature distribution in the SM heater presents some symmetry. The lowest temperatures are found at the bottom side of the heater (TC1-TC3-TC5). In contrast, the two middle rows exhibit the highest temperatures. The top row (TC16-TC17-TC18) also presents high temperatures but slightly below the latter. Within the rows, the temperature is observed to be much higher in the middle than in the sides in all of them.

Brick-by-brick results

The temperatures of the bricks were estimated using the approach explained above. The following graph presents the evolution of the temperature in every brick during the whole cycle. The different graphs correspond to individual bricks and are located at the position that they occupy inside the core of the heater (see Figure 35).



Graph 12 - Temperature evolution of every brick within the core of the SM heater

Although it is difficult to obtain a detailed picture of the instantaneous distribution of temperature throughout the core from the graph above, it can be easily observed that the temperatures in the sides are considerably lower than in the middle columns. In addition, there is not an evident symmetry in the temperature distribution as in the case of the analysis of the individual thermocouples presented above.

The following pages contain ‘snapshots’ of the temperature distribution in the core of the SM heater taken every 30 minutes during the whole cycle. This way, it is easier to picture the instantaneous distribution of temperatures. The higher temperatures are symbolized with redder tonalities. It should be noted that all the values in the tables below are given in °C.

t = 0 hours			
122	125	123	120
120	125	122	116
118	125	121	114
116	124	120	112
113	120	117	111
108	113	112	108

t = 0.5 hours			
148	168	166	147
142	158	155	138
140	159	151	136
144	164	155	139
143	163	155	139
137	155	151	138

t = 1 hour			
178	207	204	179
174	201	194	170
174	204	192	167
178	209	196	170
176	205	195	171
168	194	189	170

t = 1.5 hours			
210	248	244	211
208	243	234	201
208	247	231	198
212	251	235	202
209	246	233	203
198	231	224	200

t = 2 hours			
241	288	283	241
240	282	272	231
242	287	268	229
246	292	273	233
241	284	269	234
228	266	257	230

t = 2.5 hours			
272	325	320	270
272	320	308	262
274	326	304	260
278	330	310	265
273	321	305	264
257	299	289	258

t = 3 hours			
300	359	353	297
301	354	341	290
304	360	337	288
309	365	343	293
302	354	336	292
284	329	318	284

t = 3.5 hours			
329	394	388	326
332	389	375	319
336	396	371	318
340	401	377	324
332	388	369	321
312	359	347	311

t = 4 hours			
358	428	421	354
362	423	408	348
367	431	404	348
371	435	410	353
361	421	401	350
339	389	376	336

t = 4.5 hours			
385	460	453	382
392	455	440	377
397	464	436	377
401	468	442	382
390	453	431	377
364	417	403	361

t = 5 hours			
413	491	483	409
421	487	471	405
427	497	468	406
430	501	474	411
418	483	461	405
390	445	429	386

t = 5.5 hours (end of heating up)			
440	521	513	435
450	519	501	433
456	529	498	434
459	531	504	439
445	512	489	431
414	471	455	410

t = 6 hours (max avg. temperature)			
454	535	527	448
465	531	512	446
469	536	506	446
468	534	509	448
453	514	495	440
426	478	464	421

t = 6.5 hours			
453	528	520	448
464	523	506	446
469	527	500	446
466	524	501	448
451	505	486	438
424	468	455	418

t = 7 hours			
450	518	511	446
461	513	499	445
466	517	493	445
463	514	493	445
447	494	477	434
420	458	445	413

t = 7.5 hours			
446	508	502	443
458	504	492	443
462	508	486	443
458	504	485	442
443	484	469	431
415	448	437	408

t = 8 hours			
443	500	494	440
454	496	485	441
458	500	480	441
454	495	478	439
438	475	461	427
410	440	430	404

t = 8.5 hours			
439	491	486	436
450	489	478	438
454	491	473	438
449	486	471	435
433	466	454	422
405	432	422	399

t = 9 hours			
435	483	478	433
446	481	472	435
449	483	467	434
444	477	463	431
427	458	446	418
399	424	416	394

t = 9.5 hours			
431	475	471	429
442	474	465	431
444	475	460	431
439	469	456	427
422	450	439	413
394	417	409	390

t = 10 hours			
426	467	463	425
437	467	458	428
440	468	454	427
433	461	450	423
416	442	433	409
389	410	403	385

t = 10.5 hours			
422	459	456	421
433	460	452	424
435	461	448	423
428	454	443	418
411	435	426	404
384	403	397	380

t = 11 hours			
417	452	449	416
428	453	446	419
430	454	441	418
423	446	436	413
406	428	420	399
379	397	391	376

t = 11.5 hours			
413	445	442	412
423	447	439	415
425	447	435	414
417	440	430	409
401	421	414	395
374	391	386	371

t = 12 hours			
408	439	436	408
419	441	434	411
420	441	430	410
412	433	424	404
396	415	408	390
370	386	381	367

t = 12.5 hours			
404	433	430	403
414	435	428	406
415	434	424	405
407	427	418	400
391	409	402	385
365	380	375	362

t = 13 hours			
399	426	424	398
409	429	422	402
410	428	418	400
402	420	412	395
386	403	397	381
360	375	370	358

t = 13.5 hours			
394	420	418	394
404	423	416	397
405	422	412	396
397	414	407	390
381	397	391	376
355	370	365	354

t = 14 hours			
390	414	412	389
399	417	410	392
400	416	407	391
392	408	401	385
376	391	386	371
351	364	360	349

t = 14.5 hours			
385	408	406	384
394	411	405	388
395	410	401	386
387	402	395	380
371	386	380	367
346	360	356	345

t = 15 hours			
380	403	400	379
389	406	399	383
390	404	396	382
382	397	390	376
366	380	375	362
342	355	351	341

t = 15.5 hours			
376	397	395	375
384	400	394	378
385	398	390	377
377	391	385	371
361	375	370	357
338	350	346	336

t =16 hours			
371	391	389	370
379	395	389	373
380	393	385	372
372	386	380	366
357	370	365	353
333	345	342	332

t = 16.5 hours			
367	386	384	366
375	390	384	369
375	388	380	368
368	381	375	362
352	365	360	349
329	341	338	328

t = 17 hours			
362	381	379	361
370	385	378	364
371	383	375	363
363	376	370	357
348	360	356	344
325	337	333	324

t = 17.5 hours			
358	376	374	357
366	379	373	360
366	378	370	359
358	370	365	353
343	355	351	340
321	332	329	320

t = 18 hours			
353	371	369	352
361	374	368	355
361	372	365	354
354	365	360	348
339	351	346	336
317	328	325	316

t = 18.5 hours			
349	366	364	348
356	369	364	351
357	367	361	349
349	361	355	344
335	346	342	331
313	324	321	312

t = 19 hours			
345	361	359	343
352	364	359	346
352	362	356	345
345	356	350	339
330	341	337	327
309	320	317	309

t = 19.5 hours			
340	356	354	339
347	360	354	342
347	358	351	341
340	351	346	335
326	337	333	323
305	316	313	305

t = 20 hours			
336	352	350	335
343	355	349	338
343	353	346	336
336	346	341	331
322	333	329	319
302	312	309	301

t = 20.5 hours			
332	347	345	330
339	350	345	333
339	348	342	332
332	342	337	327
318	328	324	315
298	308	305	297

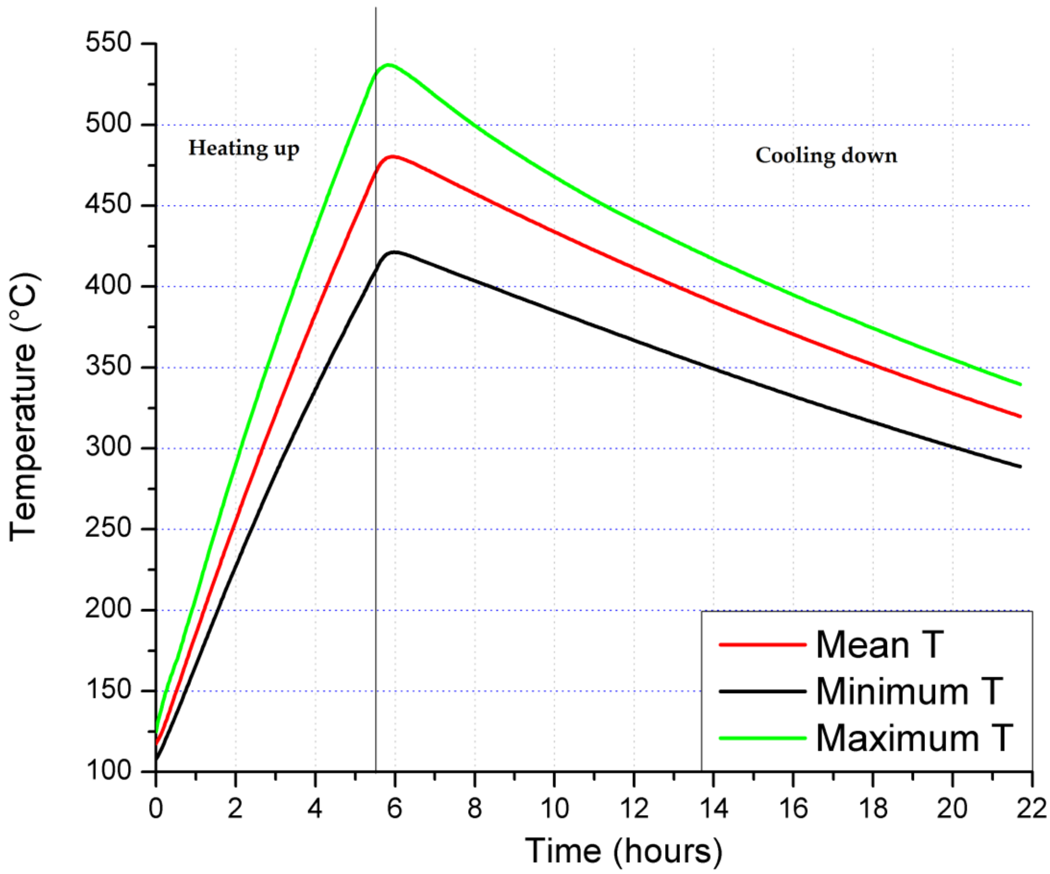
t = 21 hours			
328	343	341	326
335	346	341	329
335	344	338	328
328	338	333	323
314	324	320	311
294	304	301	294

t = 21.5 hours			
324	338	336	322
330	341	336	325
330	339	333	324
323	333	328	319
310	320	316	307
291	300	298	290

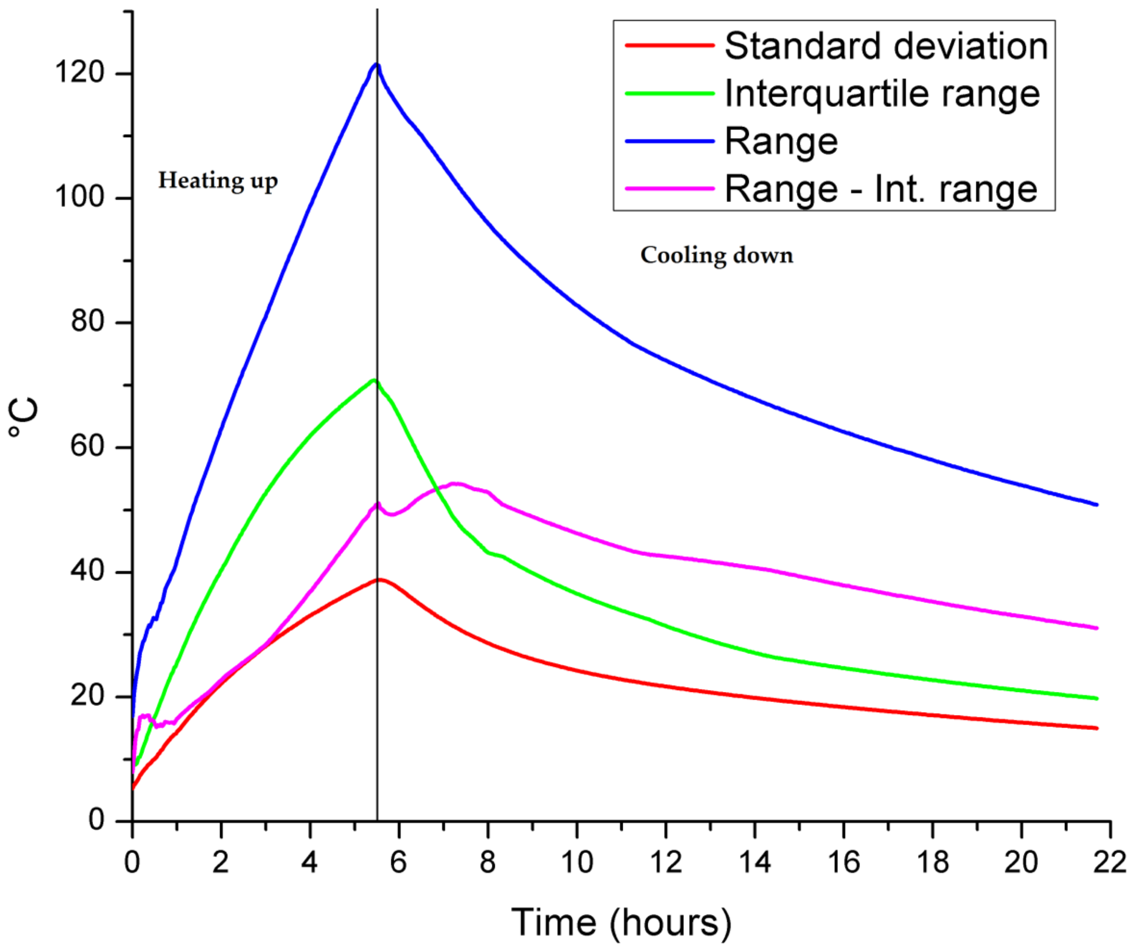
It is easy to see from the tables above that during the heating up, the temporal evolution of the temperature distribution looks very inhomogeneous. The middle columns heat up much faster than the side columns and the difference between them increases rapidly with the time. In addition, the middle-left column heats up faster than the middle-left column and achieves greater maximum temperatures. On the other hand, the left side column exhibits higher temperatures than the right side one. Thus, the temperature distribution is not symmetric during the heating up since the right hand side of the heater is appreciably colder than the left side.

In contrast, once the heating elements are switched off, the average temperature of the core keeps increasing for almost 20 minutes (see also Graph 13). After this extra heating period, the heater starts to lower its temperature. The hotter columns cool down faster. Consequently, the temperature of the core tends to be more homogeneous.

Still, the tables presented above can be tedious to interpret due the high amount of data they contain. Using very simple descriptive statistics techniques, the main features of the temperature distribution are summarized in the two graphs below:



Graph 13 – Minimum, maximum and average core temperature



Graph 14 - Measurement of the dispersion of temperatures inside the core. Descriptive statistics

In Graph 14, the range indicates the difference between the maximum and minimum temperatures inside the core (which are plotted in Graph 13). The range increases rapidly and almost linearly during the heating up until reaching 120°C and the end of it. Providing that the initial temperature of the core was around 120°C, the range shows a maximum temperature difference of roughly a 30% between the coldest and the hottest brick of the core. However, the range starts to go down just after the heating elements are turned off decreasing rather fast until it reaches a value of approximately 50°C.

The interquartile range and the standard deviation represent the degree of dispersion of the temperatures of the bricks. The larger they are, the more disperse the temperature distribution is. Thus, Graph 14 confirms what was already described above when describing the time evolution tables and the results in Graph 12: the temperature distribution becomes more and more inhomogeneous during the heating up and starts to homogenise just after the heating elements are switched off. From that point, the homogenisation level keeps increasing although more and more slowly as the time passes by.

Finally, the difference between the range and the interquartile range gives an idea of how ‘extreme’ the minimum and maximum temperatures are with respect to the mean value. Contrarily to the previous observations, this function achieves its maximum value during the cooling down around two hours after the heating elements have been switched off.

4.3.3 Storage capacity

Using the temperatures of the bricks, their masses and their heat capacity (see Graph 3) it is possible to estimate the amount of heat stored in the core of the heater at each stage of the cycle analysed above. In addition, the power input of the heater can be easily estimated as well.

Finally, it is possible to perform a rough and simple approximation of the heat losses of the SM heater during the heating up by comparing the power input and the energy stored in the heater (losses = input – energy stored). It is also possible to estimate the standing losses during the cooling down using this method at every point of the cycle (losses = initial energy – final energy).

Power input

In order to monitor the power going into the heater during the charging process, two different methods were used. On the one hand, a current clamp was used to monitor the current passing through the heater directly. On the other hand, the resistance of the heating elements and voltage were measured using a multimeter.

Both method showed rather stable power during the charging up of the heater and very similar values to the rated power provided in the technical specifications of the heater. The results are presented in the table below:

Resistance	Total resistance	Voltage	Intensity	Power	Rated Power
67Ω + 68Ω + 69Ω (in parallel)	22.7Ω	233 V (average)	10.33 A (average)	2405 W (average)	2400 W

Table 6 - Power, resistance, voltage and intensity of the SM heater

Thus, the total power input to the heater can be easily calculated as:

$$P_{input} = 2405\ W \cdot (5\ h\ 40\ min) = 2405\ W \cdot 5.67\ h = 13.6\ kWh$$

Equation 5 - Total power input to the SM heater

Evaluation of the energy stored in the core of the SM heater

The energy stored in a single brick can be estimated by means of the following integral:

$$E_{brick} = \int_{T_i}^{T_f} m_{brick} \cdot C_P(T) \cdot dT$$

Equation 6 - Estimation of the energy stored in a brick

If C_P is constant during the temperature interval, then the equation above transforms into the well-known expression $E = m \cdot C_P \cdot \Delta T$. In this analysis, C_P is assumed to vary linearly between consecutive points of Graph 3 in the form

$$C_P(T) = a \cdot T + b$$

Equation 7 - Linear variation of CP (T)

The following parameters were found for the different steps of Graph 3:

Step	a [$\cdot 10^{-3}$ J/g·°C^2]	b [J/g·°C]
100°C - 200°C	1.18	1.172
200°C - 300°C	1.20	1.169
300°C - 400°C	-0.19	1.585
400°C - 500°C	3.28	0.197
500°C - 600°C	0.160	1.037

Table 7 - Parameters of linear variation of C_P

Combining Equation 6 and Equation 7 the following expression is obtained for the determination of the energy stored in a brick in each temperature step:

$$E_{step} = \int_{T_i}^{T_f} m_{brick} \cdot (a \cdot T + b) \cdot dT = m_{brick} \cdot \left[0.5 \cdot a \cdot \left(T_f^2 - T_i^2\right) + b \cdot \left(T_f - T_i\right)\right]$$

Equation 8 - Resolution of an integration step

Summing all the integration steps for every brick and, then, the results obtained for the 24 bricks that form the core of the SM heater, the energy contained in core is obtained.

Before performing these calculations, it should be stated that the average mass of the bricks (using 6 bricks) was found to be 4.9 kg. Their original mass was 5 kg, but due to their fragility and all the tests performed with the heater before and during this project, some of them have lost part of their original mass.

Using the data of the heater at the initial conditions and its maximum temperature, the following energies were calculated:

Ti (°C)			
122	125	123	120
120	125	122	116
118	125	121	114
116	124	120	112
113	120	117	111
108	113	112	108

Tf (°C)			
454	535	527	448
465	531	512	446
469	536	506	446
468	534	509	448
453	514	495	440
426	478	464	421

Energy stored (Wh)			
670	864	847	660
699	853	810	662
712	866	797	666
713	863	806	674
684	819	777	658
632	742	711	622

With these data, the total energy stored in the heater is found to be 17.8 kWh. Obviously, there has been an overestimation of the energy stored in the heater since this value is a 31% higher than the energy input to the heater.

A simpler but less 'accurate' method to estimate the energy stored, is to use the average temperature of the heater and average C_P. That way, the energy obtained would be:

Ti average	Tf average	Energy stored
118°C	480°C	17.6 kWh

Table 8 - Estimation of the stored energy using average temperatures

The value is very similar to the one obtained brick by brick and, thus, it is an overestimation too.

The heater has been assumed to be a 2D system. It is likely that this is the main cause for the overestimation of the energy stored inside the heater.

A last-minute experiment was conducted using the last four thermocouples that were still working to monitor the temperature on the top of brick 19 (see Figure 35) at three different transversal points. The figure below shows the locations of the thermocouples:

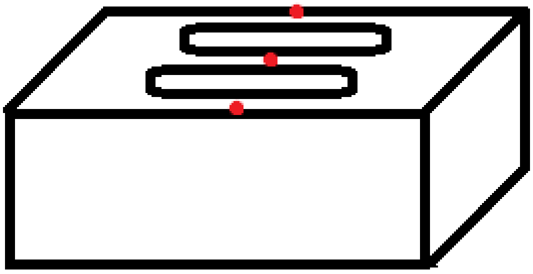
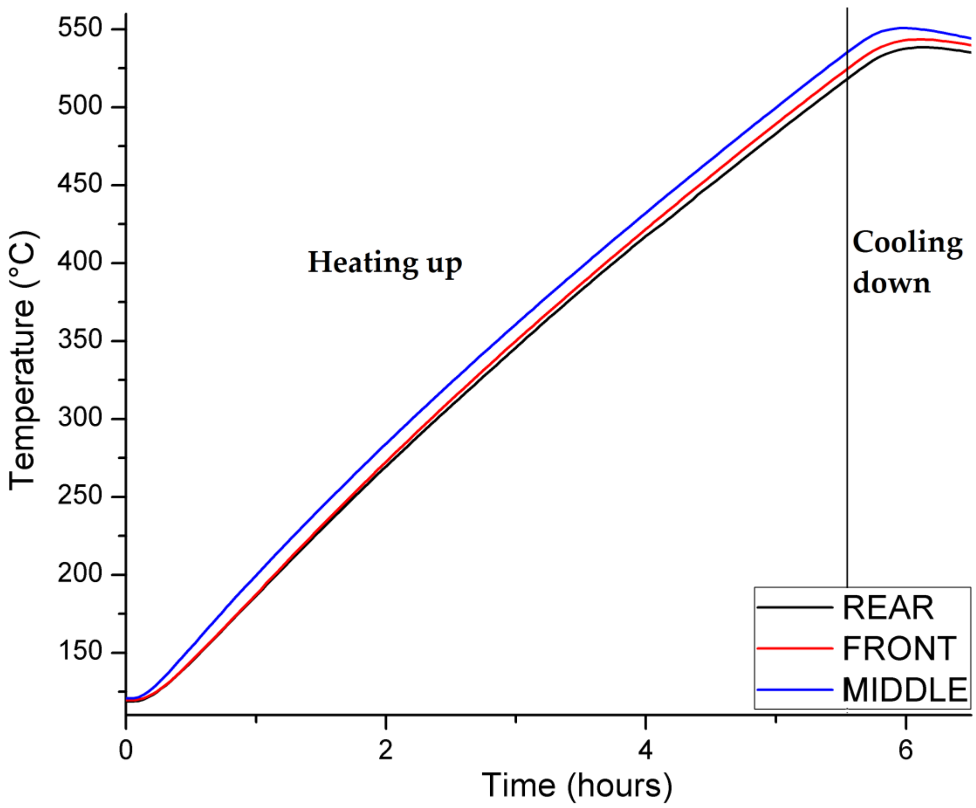


Figure 36 - 3D effect experiment. TC location

The results obtained in this last experiment are shown in the graph below:



Graph 15 - 3D effect experiment. Top of brick 19

Although a slight temperature difference is present between the three thermocouples, it is evident that it is too small to account for the overestimation of the heat stored in the core of the heater. The difference between the middle and the rear thermocouples oscillated between 6.5% and 1.5 % with a 4% average. Compared to the 31% gap between the energy input and the energy stored, this difference is insignificant.

It is important to notice that only two surfaces out of the six (plus the internal surfaces of the air circulation holes) available in the bricks have been monitored throughout this project. This was due to the very reduced number of thermocouples available for this project. Therefore, further experiments to monitor the temperature of the bricks in every surface are needed to address this issue. Unfortunately, they will have to be carried out in following projects.

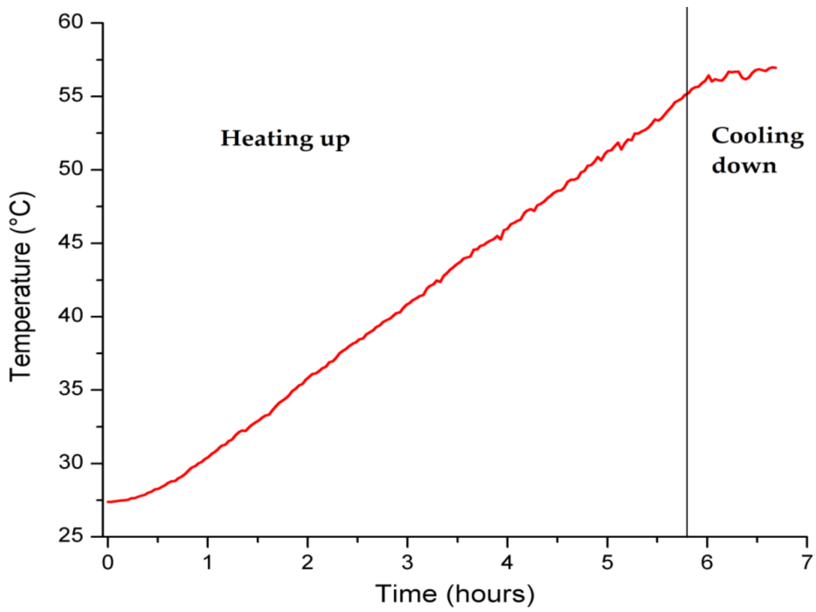
Another possible cause for the excessive value obtained of the energy stored inside the heater could be an overestimation of C_P. It has been shown in section 4.2.2 that the average value obtained for C_P is near a 70% higher than that of TAO-35 feolite.

This topic is further discussed in section 4.4.4.

Finally, since the results of the energy stored in the heater have been largely overestimated using the brick-by-brick approach, a detailed study of the heat losses using a comparison between the energy input and the energy stored is not possible.

4.3.4 Outer surface temperature

This section briefly presents the results obtained from a thermocouple placed at the centre of the front panel of the heater. The following graph corresponds to the last-minute experiment performed to assess the possible 3D effects in the heater and, thus, it only covers 7 hours.



Graph 16 - Outer surface temperature

The graph above shows that the surface temperature increases steadily as the core of the heater heats up. It reaches a maximum value of 57°C. As explained in section 4.3.1, the controls were bypassed so it is not possible to know when the heater is at its maximum rated capacity. Nevertheless, the experiments were designed to attain levels of charge close to those in normal operation conditions. Therefore, the surface temperature is not likely to be much hotter than 60°C at the heater's rated storage capacity.

NSH (2013) states that exposed surfaces should not be hotter than 43°C to prevent burns. Low surface temperature (LTS) heaters are designed to comply with that indication. The SM heater is not an LTS heater and, therefore, needs to be used with caution to avoid burning hazards. Nevertheless, its temperature is lower than that of standard wall radiators. These usually reach temperatures of around 75°C and can produce partial thickness burns in one second and full thickness burns in less than 10 seconds (Jaga, 2013; Ciphe, 2005).

4.4 Discussion

4.4.1 Remark about the validity of the experimental results

The experiments have shown that the brick-by-brick approach used to study the temperature distribution in the core of the SM heater overestimates the average temperature of the bricks. However, it still is a very reasonable and visual way of monitoring the temperature distribution.

Likewise, it should be noted that this method was not designed to give accurate values and was only adopted due to the limited number of thermocouples and overall resources available for the experiments in this project.

Thus, in the following discussion, the reader should always bear in mind that the approach is only valid to provide comparative values of the temperatures of the bricks and not their real magnitude.

4.4.2 SM heater as a 'night storage heater'

In this section, it is discussed how the performance of a storage heater may be affected by its temperature distribution and heat losses when used as a night storage heater. Some of the results from the experiments are used in the discussion.

Temperature distribution

As expected from the properties of ceramic magnetite, the temperature distribution has been shown to be very inhomogeneous in all the tests performed on the heater. However, if the SM heater is used simply as a night storage heater, i.e. charging it solely during the night at off-peak time, the degree of inhomogeneity exhibited in the experiments is not likely to affect the performance of the heater.

The SM heater automatically sets and controls the temperature of the core to meet the energy requirements of the following day. Typically, the time necessary to charge the heater, i.e. to achieve the set temperature, is significantly lower than the duration of the off-peak charging period. Due to the standing heat losses of the heater, the heating elements need to be switched on intermittently to maintain a constant temperature in the core until the off-peak charging period finishes.

All the results obtained in the different experiments, especially those of Graph 14, show that the temperature tends to homogenise rather fast just after the heating elements are switched off due to the elevated temperature difference between different parts of the heater. Thus, maintaining the temperature of the core at its maximum value during the end of the charging period will tend to make the temperature distribution more homogeneous.

This way, it is ensured that even if the local temperature around the thermosensor that controls the charging process becomes eventually too high and the heating elements are switched off too early, the inhomogeneities in the temperature distribution will tend to be smoothed out. The heating elements will be turned on again and the rated level of storage will probably be attained by the end of the charging period.

Therefore, the temperature distribution is likely to be less important if the SM heater is used as a night storage heater. Probably, this is the reason why this topic cannot be easily found in the literature. However, as it will be explained later on, the situation is totally different when the heater is used as DSM.

Likewise, blowing air through the core of the heater to release the stored heat is also likely to affect the temperature distribution of the core.

Since the internal controls of the heater had to be bypassed for the realisation of this project, there were no automatic controls to regulate and maintain the temperature of the core at a constant level nor the internal fan was working so these matters could not be investigated in this project.

Heat losses

Heating up

Graph 16 gives a very approximate idea of how the temperature of the outer surface of the heater changes during the heating up. It is clear that the larger the outside temperature, the more radiative and convective losses from the heater to the room.

The convective losses have an approximately linear dependence with the surface temperature while radiative losses typically increase with T^4 so the latter will be the dominant heat loss process.

Thus, the only idea that can be extracted from Graph 16 is that, logically, the heat losses will increase during the charging up as the temperature of the core increases.

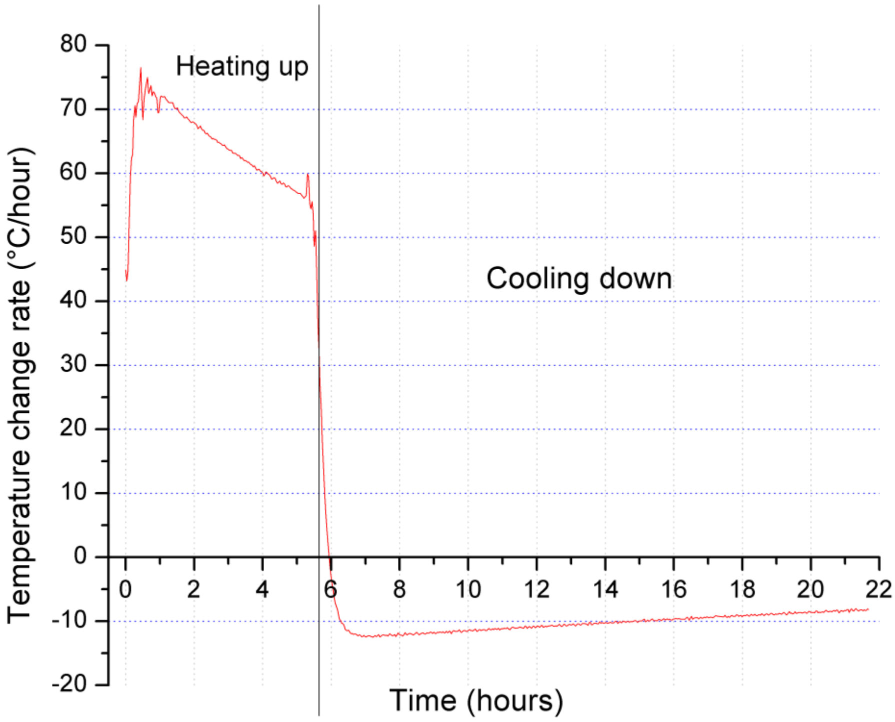
The standing losses that occur during the charging up of the heater are released to the room during the night while the outside temperature is low and the dwelling is fully occupied. Therefore, these heat losses are not wasted. They can be considered useful heat since they help to maintain the temperature inside the house during night. This results in less of the energy stored in the heater having to be released during the first heating period in the morning (see Figure 21).

In addition, the losses will be greater with higher set core temperatures and these, in turn, will set to higher values when the weather is colder so overheating problems are not likely to happen.

Therefore, heat losses during the charging up of the heater should not be an important concern in the SM heater if used as a night storage heater.

Cooling down

Graph 13 illustrates a good representation of the average loss of temperature in the core of the heater during the cooling down. It shows that the temperature decreases very steadily with time. The rate of temperature loss can be better analysed by working out the derivative of the temperature with respect to time:



Graph 17 - Average temperature change rate

The graph above shows that the rate of temperature loss decreases slightly during the cooling down from around 12°C/hour to 8°C/hour in roughly 15 hours. These losses are the highest that can occur in the heater since they take place when the core and surface temperature are at their highest value.

However, normally a storage heater is not charged and left unused during such a long time. It is very likely that the heater will be used just after the end of the charging period to provide the so-called 'morning rise' (see Figure 21). Thus, the temperature of the core of the heater will be lower after this heating period and, in consequence, the standing losses will be lower too.

In conclusion, the rate of temperature loss of the heater does not seem an important concern in terms of heat losses when the SM heater is used as a night storage heater. This is especially true in highly insulated houses with a high occupation during the day in which, the passive losses of the heater can fulfil a large portion of the heating requirements. On the contrary, in houses with poor insulation and a low occupation during the day in which the heater is left unused during long periods, the passive output of the heater would be translated into lots of heat being wasted.

4.4.3 SM heater as demand side management

In this section, it is discussed how the performance of a storage heater may be affected by its temperature distribution and heat losses when used as DSM. It is also explained why the results from the experiments are not useful in this case and what type of experiments should be done to address these issues.

Temperature distribution

Possible scenarios that may affect the performance of the SM heater

As explained above, the temperature distribution should not pose a problem if the heater is used as a night storage heater because of the long charging period.

However, if used as demand side management the situation is totally different. Instead of one long charging period overnight, there are several partial charges throughout the day. Each charge has a set temperature associated and, therefore, a maximum allowable core temperature.

If the heater is used as DSM to accommodate wind generation as discussed in section 3.2.2, the charging periods are usually in the scale from several minutes to a couple of hours typical for the diurnal variation of the wind speed (Bentek Energy, 2010).

These kind of charging patterns were not studied in this project. Nevertheless, for the results obtained for a full charging cycle, a very inhomogeneous temperature distribution can be expected in short charging periods, with temperatures much higher near the heating elements and in the centre of the heater (see Graph 7 and Graph 11).

In addition, the utility providers can programme one, two or the three heating elements to turn on depending on the expected conditions of the grid. Only one or two heating elements charging the heater may make the temperature much more unevenly distributed than in the experiments performed during this project. Taking all this into consideration, the following scenarios could occur:

If the local temperature near the thermosensor that controls the level of charge of the heater increases faster than in other parts of the core, the heating elements may be turned off too early. Since this sensor is located at the bottom of the SM heater, this situation is more likely to occur when only the bottom heating element is used to charge the heater. Contrarily to night storage heaters, there may not be enough time for this local temperature to smooth out before the heating period ends. Thus, the heater would not attain the expected level of charge.

This can lead to an early depletion of the heat stored and, consequently, to the activation of the heating elements out of the predetermined heating periods, to avoid the core temperature going below the minimum allowable.

On the other hand, if the local temperature near the sensor remains lower than in other parts of the core, the opposite situation may take place resulting in too much energy being charged. Furthermore, if during a heat output period the temperature near the sensor is lower than it should be, the heating elements may need to be activated although there may be enough energy stored in the heater to provide heating.

Finally, a very inhomogeneous temperature distribution during the release of heat may cause the air to heat up at some points of the core and cool down at others decreasing its effectiveness carrying the heat out of the heater.

Heat losses

The standing losses may be more significant for the performance of the heater as DSM than they were for night storage heaters.

With partial charging cycles spread throughout the day, the temperature of the heater is likely to be maintained at higher levels on average. Thus, the heat losses are potentially greater.

If the heat losses occur in a highly insulated dwelling with a high level of occupancy during the day, they will help to maintain the temperature of the house and contribute to the fulfilment of the heating requirements. Nevertheless, if the heater is maintained at a rather high temperature during a warm day it could lead to overheating.

On the other hand, in poorly insulated houses with long periods of no occupancy and no usage of the heater, a higher average temperature means that more heat will be wasted.

Therefore, heat losses appear as a more important concern for DSM partial charging cycles.

4.4.4 Energy stored and heat losses

The results of the brick-by-brick approach used to monitor the temperature of the core of the heater during a charging cycle showed a value of 17.8 kWh for the energy stored in the bricks (see section 4.3.3). This is an overestimation since the energy input to the heater during the charging period was estimated to be a 31% lower.

According to the technical specifications of the SM heater, its storage capacity is rated at 14.9 kWh (see Table 5). Unfortunately, the conditions under which this capacity was estimated are not given.

However, the following assumption can be made: since the SM heater is designed to be used mainly as a night storage heater using an off-peak tariff, it is likely that the rated storage capacity corresponds to a full 7 hours overnight charging period. Thus, using the rated charging power of the heater, it can be obtained that

$$2.4 \text{ kW} \cdot 7 \text{ h} = 16.8 \text{ kWh}$$

are delivered to the heater during the charging period. Using the method proposed in section 4.3.3, it is possible to obtain a very rough approximation of the expected heat losses that take place during the charging process of the heater as

$$16.8 \text{ kWh} - 14.9 \text{ kWh} = 1.9 \text{ kWh}$$

Therefore, it can be concluded that the expected heat losses during the charging up of the heater are in the range of 13% in normal operation conditions.

This result can be applied to the outcomes of the present project to provide a very crude idea of the actual energy stored after the charging up period. Since the power input to the heater has been estimated to be 13.4 kWh, the total energy would be around

$$13.4 \text{ kWh} \cdot 0.87 = 11.7 \text{ kWh}.$$

This is a 21.5% less that the rated capacity of the SM heater. It is possible to estimate the average C_P that the storage medium should have in order to store 11.7 kWh with the temperature difference obtained from the brick-by-brick approximation (see Table 8):

$$C_P = \frac{E_{stored}}{m_{bricks} \cdot \Delta T} = \frac{11.7\ kWh}{24 \cdot 4.9\ kg \cdot (480°C - 118°C)} = 0.99\ J/g \cdot K$$

Interestingly, this value is very similar to the specific heat of TAO-35 feolite (Samot, n.d.) and the results by Gronvold and Sveen (1974). LFA is an accurate method and three different samples were analysed giving similar results. In addition, the density and thermal diffusivity obtained from the analysis of the samples present values within the expected range. Conductivity, in contrast, exhibits improved characteristics but, as explained in section 4.2.3, it is probably due to the presence of MgO in the storage medium. Therefore, it is scarcely possible that a systematic error was committed during the analysis that led to an overestimation of C_P only without affecting other thermal properties. The following discussion indicates that an overestimation of the temperature of the core is a more probable cause.

In addition to the duration of the charging period, the initial conditions for the estimation of the rated capacity are also unknown. Graph 5 and Graph 7 show, however, that with heating times of 5-6 hours, very high local temperatures (more than 600°C) are reached within the core. The manufacturer claims that, at full charge, the temperature of the core should be around 600°C. It also needs to be taken into account, that the manufacturer is likely to provide the value of the maximum storage capacity achievable with the heater. Thus, for a 7 hour charging period, it seems reasonable that the storage capacity has been worked out with heater starting the charging up at room temperature. This way, local temperatures higher than 600°C are avoided and the value represents the highest storage capacity.

Using these assumptions and the average heat capacity of the storage medium obtained in section 4.2.2 (see Graph 3), it is possible to perform a rough investigation of the maximum average core temperature expected at the rated heat capacity level:

$$E_{rated} = m_{bricks} \cdot C_P \cdot (T_{max} - 25℃) \rightarrow T_{max} = \frac{E_{rated}}{m_{bricks} \cdot C_P} + 25℃$$

$$= \frac{14.9kWh}{24 \cdot 5kg \cdot 1.58\ J/gK} + 25℃ \approx 305℃$$

In contrast to this temperature, the average core temperature obtained from the experimental data is 480°C. This is a 57% higher value than the one just obtained above. The level of charge after the experiments carried out in this thesis is near the rated storage capacity. Thus, it can be concluded that the overestimation of the core temperature is approximately 50%.

As explained above, this overestimation arises from approximating the heater to a 2D system. In addition, only the temperatures in the upper and lower surface of the bricks were monitored. It is clear now that the temperature at these surfaces is much higher than the average temperature of the bricks. Since the front and rear surfaces of the bricks are in contact with the insulation panels their temperature is likely to be much lower than in the upper and lower surfaces that are in contact with other hot bricks.

Therefore, the 3D characteristics of the temperature distribution need to be studied to obtain a good approximation of the energy stored in the heater and the heat losses. Sensors should be located in every external and internal surface of every brick to obtain a 3D mapping of the temperature distribution. Unfortunately, this was not possible during the project due to the limited time and equipment as mentioned before.

4.5 Conclusions and further work

4.5.1 Temperature distribution

The experimental results show clearly that the temperature distribution is very inhomogeneous during the cycle studied. Since there are no data in the literature about this topic, the information provided by this project is very valuable to understand the internal behaviour of the SM heater.

In addition, the brick-by-brick approach introduced in this project appears as a useful methodology to monitor the temperature distribution in high-detail using a small number of sensors. However, as discussed above, the values that it provides are only valid for temperature comparison between different parts of the bricks and do not correspond the actual values of the average temperature of the bricks.

It should be noted that the heater needs to cool down completely to allow the redistribution of the thermocouples between consecutive experiments and that one or more reference temperatures are needed to gather the outcomes from the different experiments together coherently. This evidently is very challenging and time-consuming and, therefore, it is not an effective way of monitoring the temperature distribution of the heater. It took more than eight experiments and around 25 days to analyse a single charging cycle using this method. In addition, the temperature distribution during discharging periods could not be studied either since the bypassing of the controls made the internal fan to stop working.

In order to obtain a detailed study of the performance of the heater as DSM from its temperature distribution, many different partial charging and discharging situations have to be evaluated. This cannot be performed as several experiments are needed to obtain a complete picture of the temperature distribution due to the difficulty of replicating the exact same conditions in every partial experiment.

In addition, the performance of the heater as DSM will only be properly analysed if the internal charging controls are employed. This was a very important limitation as well for the possible outcomes of this project.

Therefore, the data provided by the experiments are obviously insufficient to evaluate how the temperature distribution affects the performance of the heater as DSM. Thus, the original aim of this project has been shown to be unreachable with the available equipment and will need to be addressed in further studies. The results from the experiments done in this project suggest that the temperature distribution is likely to affect the performance of the heater as DSM as discussed above. Therefore, it is vital to study this topic in detail.

For further work, the temperature distribution of the core should be monitored completely and continuously using a very elevated number of sensors in a fixed position. Using the internal control, different charging and discharging corresponding to real life conditions should be simulated. Thus, dynamic information about the internal state of the heater would be provided and would give results to better understand how the SM heater behaves. From these data, it would be possible to optimise the charging and discharging patterns and controls.

4.5.2 Energy stored and heat losses

Heat losses are usually monitored using a calorimeter room. This provides very accurate results but they are only valid for the standard conditions of the experiment that do not correspond to real-life conditions.

The method proposed in this project, i.e. to evaluate the heat losses from the amount of energy stored in the heater at every moment, is a less accurate but very flexible method that can be easily applied to monitor real-life standing losses. However, it has been shown that it is necessary to have a detailed 3D map of the temperature distribution in the core to provide a more or less accurate value of the energy stored and, thus, of the losses.

Overall, heat losses are a very complex topic and depend on many different factors like the location of the heater in the room, insulation of the building, usage patterns, open doors and windows or occupancy. Thus, it very difficult to make generalisations about it and could better be studied in further projects using computer modelling simulations. The model proposed would provide simple experimental data that could be introduced into the model.

4.5.3 Summary

In the early stages of the project, it seemed rather simple to monitor the temperatures inside the core of the heater but soon after obtaining and analysing the first results it came out that a very detailed study would be needed to obtain useful outcomes from the experiments. The difficulty and technical complexity of the experimental part of this project was highly underestimated.

Unfortunately, due to innumerable technical problems, by the time the author of this thesis arrived to those conclusions, it was already too late to change the direction of the experimental research to more achievable objectives. That is why the temperature distribution was studied in detail although it was insufficient for evaluating the performance of the heater as DSM.

However, the project has useful outputs like the methodology used for the study of the temperature distribution using a limited number of thermocouples and the heat losses evaluation from the amount of energy stored.

The concepts behind this project are of vital importance for the understanding of the performance of storage heaters as DSM and highly advisable for further studies.

For future investigations it would be recommend to pay a great amount of attention from the very early stages of the experiment to the high technical complexity associated to the monitoring a very inhomogeneous temperature distribution, analyse in detail the available resources and set achievable goals.

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