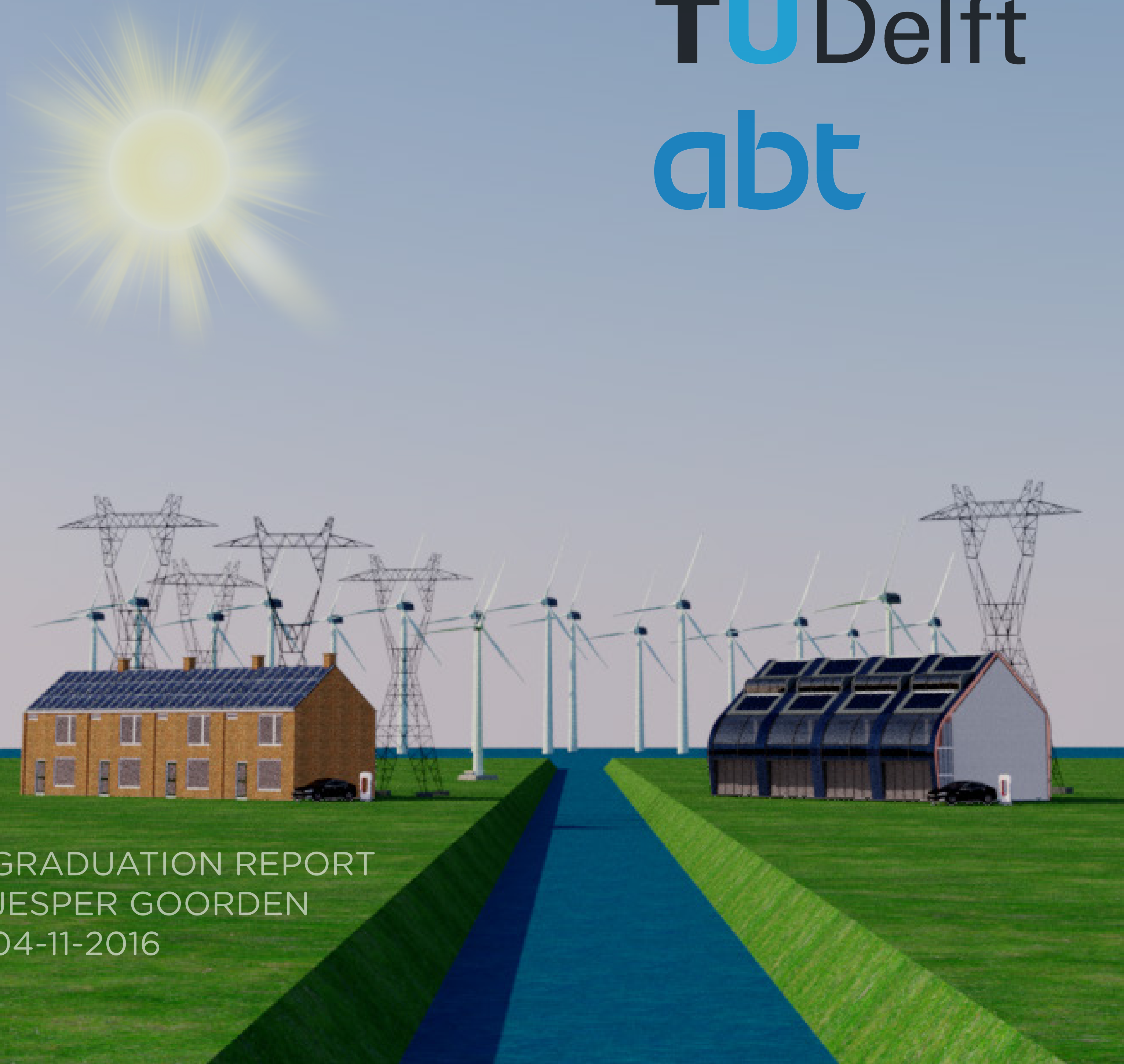
INTEGRATION OF SEASONAL THERMAL ENERGY STORAGE IN REFURBISHMENT PROJECTS

Development of an integrated thermal battery system towards renewable solar heat throughout the year

TU Delft

abt



GRADUATION REPORT

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04-11-2016

ABSTRACT

The world is on the verge of a new era where fossil fuels are no longer appropriate as is generally known. This so called "energy transition" is already going on and renewables such as solar and wind energy are emerging rapidly. Yet these renewable sources are not reliable in most regions due to their intermittent nature. An entire renewable future is only possible if energy in times of surplus can be stored for later use. Energy storage can therefore be seen as a last myriad towards a fossil fuel free future.

In the Netherlands, space heating of buildings already takes up 19% of total Dutch energy consumption. Sustainable interventions in the built environment therefore have significant impact and are less complex than renewable solutions for industrial processes. Given the fact that the whole Dutch building stock should be energy neutral by 2050, it makes sense to start here. Even in the Netherlands solar energy could potentially cover the total energy demand for space heating, as long as the mismatch between energy demand in winter and supply in summer is solved.

However, current refurbishment practice does not address this mismatch and is instead creating new problems. The excessive use of PV-panels and heat pumps in all-electric refurbishment concepts will result in high peak loads to the electricity grid. Due to net-metering surplus electricity is delivered back to the electricity grid on sunny days and during cold days heat pumps extract high peak-loads. Researchers state the grid capacity has to quadruple from 6GW in 2015 to 23GW in 2050. In other words: investments are done on a building scale now, but additional investments in the electricity grid in the near future are required to prevent power failures. Increasing popularity of electric cars will add even more peak loads to the grid.

Besides the double investment, PV-panels and heat pumps will not allow a fossil fuel free energy system because conventional energy resources will still be required during winter because of the mismatch. In fact, PV-panels can only be used 30% of the time. PV-panels are usually used to cover domestic electricity demand, while space heating demand takes up 58% more primary energy demand. Therefore, it would make more sense to focus on sustainable space heating rather than domestic electricity.

The aforementioned facts illustrate the need for a new refurbishment approach with a focus on renewable space heating. An approach built around solar thermal energy combined with decentralized seasonal thermal energy storage could allow for 100% renewable space heating throughout the year. Such a concept is likely to be more expensive compared to an all-electric concept, but when the additional investments in the energy infrastructure are taken into account it can be a more cost-effective and sustainable solution in the end. However, additional research is required on how this (seasonal) thermal energy storage can be integrated in a refurbishment concept.

Seasonal thermal energy storage can be realized with different technologies and methods. The most suitable option depends on several factors such as building typology and building density, but in this report a decentralized solution making use of thermochemical storage is selected because of the advantages over other technologies. The thermochemical energy storage principle will be used to develop a thermal battery system that can be integrated both technically and spatially in a refurbishment concept for row houses. Although thermochemical storage is still under development, it is a very promising technology and researchers expect the technology to be market ready within five years. It is therefore very relevant to already investigate how this technology could be implemented in existing buildings.

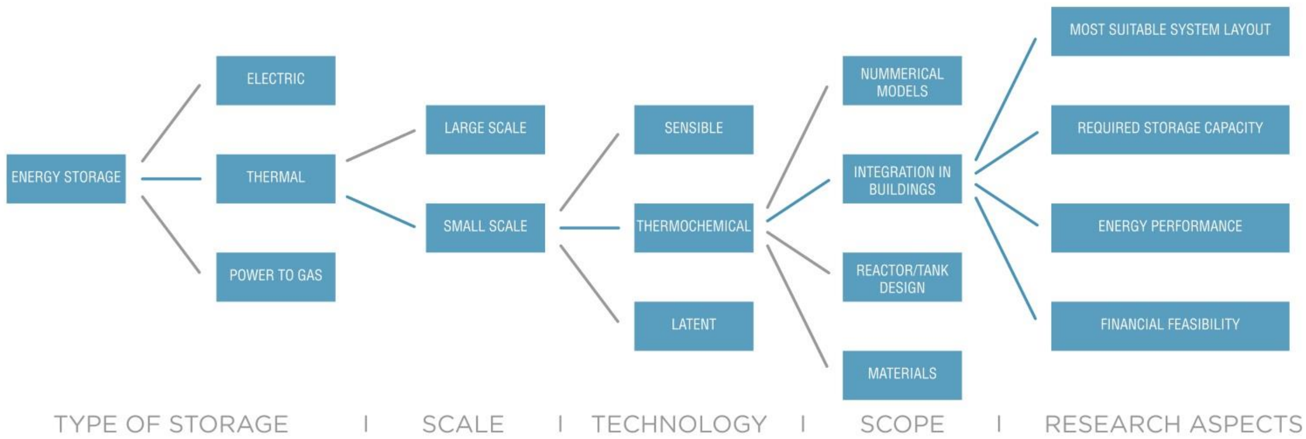
The report starts with a thorough background study, followed by extensive literature research in three main topics. These topics are: Row houses and (current) refurbishment practice, solar thermal systems and (seasonal) thermal energy storage. Relevant references will also be evaluated. The row house, which makes up 42% of Dutch building stock and 6/10 people living in there, is taken as case study for the design elaboration.

TRNSYS is used to accurately simulate thermal demands and solar yields for the case study dwelling. The results are analysed and used to determine the required storage capacity for different collector surfaces and deployment strategies. This will result in a number of boundary conditions and requirements the battery system should meet. Furthermore, all relevant performance parameters that affect system efficiency will be described and explained.

The actual design part of this report consists of a technical and a spatial design. The technical design is the system layout of a thermal battery system, which is based on the input of literature research, interviews with researchers and simulation results.

The spatial design part focusses on how the system layout can be integrated into a refurbishment concept for the case study. Different design directions will be explored to show the spatial impact of the implementation of energy storage. In contrast to the technical design, the spatial design is not meant as a final solution; it is meant to show the building industry what the possibilities are. It is up to architects and designers to actually design the eventual refurbishment concept, taking the boundary conditions and requirements from this report into account. The eventual battery system and its integration will be evaluated on both energy performance and financial feasibility, since this last factor is crucial for overall feasibility of the system.

Although the thermal battery system is used for seasonal storage in this report, it can also have very interesting applications for short-term storage. The battery system can also be charged electrically, for example with surplus energy of windmills. This would still allow sustainable heating, but required storage capacity can be reduced significantly because wind energy is still available during winter. The system can also be used for demand side management; low-tariff electricity could be used to charge the battery and provide cheap energy. Moreover, the battery could be part of a smart local network that prevents high peak loads to the electricity grid. The application for both long and short-term storage will increase the financial feasibility and make the system a potential game changer in sustainable refurbishment approaches and concepts.



Research aspects of energy storage in this report

PREFACE

This graduation report is the final part of the Building Technology master within the faculty of Architecture at TU Delft. The research covered a period of 1 year and was guided by three mentors:

Sabine Jansen (TU Delft, Climate design)

Thaleia Konstantinou (TU Delft, Façade design)

Jaap Wiedenhoff (ABT, Building physics and installations)

After my internship at ABT, I was very keen to have the opportunity to also graduate there. ABT is one of the leading engineering offices in the Netherlands with an extensive portfolio of cutting edge engineering. Nowadays, ABT is involved in all aspects of the building process and this makes it a very inspiring environment with lots of expertise. The mix between working on renowned architectural projects and graduating was extremely valuable and interesting, although the graduation process therefore took a little longer. However, I'm sure this working experience is a perfect start of my career.

When I started studying at the faculty of Architecture six years ago, my dream was to become an architect. I could not have imagined that my graduation would end up with the topic of seasonal energy storage, although I've always been interested in technical innovations that contribute towards a sustainable built environment. During my bachelor in architecture I found out that architectural design is probably not the expertise in which I can make such kind of contribution. During my master I have done many projects and papers on sustainability, and I got even more interested in the technology behind solutions. This technical fascination combined with my interest in societal issues has formed the basis for the graduation topic.

The topic of this research can be placed within the Energy transition the Netherlands and the world is facing. The Netherlands are facing a huge challenge towards 2050, when the built environment should be energy neutral. Current refurbishment practice and legislation does not lead to a fossil fuel free future and is even creating new threats for the energy infrastructure. This research will explain why a new refurbishment approach is needed and how this could take shape. Seasonal thermal energy storage plays a crucial role throughout the report.

Although my graduation topic is not directly related to current activities of ABT, I think it can be very relevant and interesting to look at the possibilities of thermal energy storage in the built environment since it is inevitable towards a sustainable future.

Now comes the moment of gratitude. First of all I would like to thank my parents for always supporting me and allowing me to focus things that really matter. Special thanks to my mentors Jaap, Sabine and Thaleia for the guidance and advice they have given me during the graduation process. I would also like to thank Rutger Callenbach, for the opportunity he gave me to do my internship and graduation at ABT. Furthermore I would like to thank several people who I consulted during the research phase, in particular Ruud Cuypers from TNO because he helped me a lot in understanding the technical principles.

The graduation has been very interesting for me and I would definitely like to bring my knowledge and expertise of the topic and into practice. I hope the reading of this report makes you as enthusiastic as I am about the potential of thermal energy storage in the built environment!

Jesper Goorden

Delft, November 2016

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1. INTRODUCTION

1.1 The energy transition

The world is on the verge of a new era where fossil fuels are no longer appropriate. Numerous environmental studies have been done in the last decades, and it is nowadays well known that humans are responsible for climate changes that have been observed now and in the future. World energy supply should shift from conventional and polluting fossil fuels to clean renewable energy. This process will take many years and therefore a transition period is necessary. This so called "energy transition" is already going on and renewables such as solar and wind energy are emerging rapidly. Especially offshore wind energy has become a major priority of Dutch government (fig. 1). Yet fossil fuels remain crucial during the transition period, and the challenge is to deploy them as efficient as possible.

Fig. 1. Offshore wind energy in the North Sea. (www.schevenningennieuws.com)

Besides the well-known effects of climate change due to use of fossil fuels and human lifestyles, there is a second important reason that will force the world to use renewable energy sources. It is the simple fact that conventional resources (mainly oil, coal and gas) are depleting and will run out at a certain point in the 21th century. Given the share of fossil fuels in current global energy consumption, global economy and prosperity are in serious danger if no alternatives can be found in the near future. To invigorate this threat; world population is expected to grow to 9.6 billion in 2050 (UN, 2013), where it is 7.3 billion in 2015. This means less fossil fuels for an increasing world population with increasing energy demands, illustrating the need for renewable energy technologies even more.

In case of the Netherlands the argument of depleting resources is more relevant than the argument of climate change, since the Netherlands has the knowledge and financial means to protect itself from rising sea levels and is thereby able to reduce the effects of climate change in its own country.

Yet, for decades the Dutch have been relying on the gas fields in Groningen, which not only supplied large amounts of natural gas but also contributed significantly to national wealth. These gas fields will eventually run out, but due to the earthquake problems in Groningen of the last years, this is accelerating and already less gas will be available on the short-term (Rijksoverheid, 2015).

To prevent becoming dependant on other countries for gas supply it is important that alternatives are developed and implemented in the energy system, especially since the majority of residential dwellings are heated with natural gas. The situation in Groningen should therefore be seen as a catalyst for this process. Besides dependency on natural gas, the share of fossil fuels in total energy consumption in the Netherlands looks even more dramatic. From figure 2 can be concluded that about 95% of primary energy consumption originated from fossil fuels in 2013 and this has not significantly changed since then.

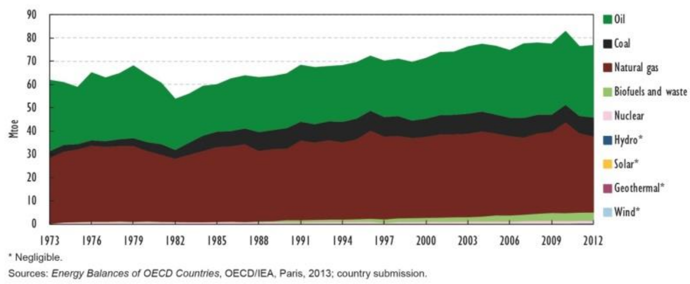


Fig. 2. Energy mix of the Netherlands in 2013. (IEA, 2014)

To turn the tide and to speed up the transition process a number of agreements have been made in the past years. In 2008 the European parliament agreed on a set of "climate goals" which have to be met by each member in 2020 to reduce the effects of climate change.

This has resulted in the European directive for renewable energy, also known as the 20-20-20 goals. Besides some common goals, this directive has been specified for each member state independently, according to their share in pollution.

For the Netherlands the main targets are:

- 20% reduction in energy consumption (taking economic growth in to account)
- 14% of final energy consumption is produced from renewable sources
- 15% reduction of emitted CO_2 compared to 1990 levels

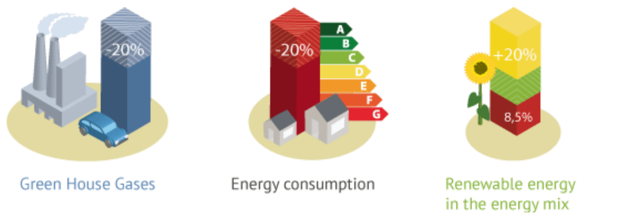


Fig. 3. The European 20-20-20 targets. (www.askjaenergy.com)

For most member states all these figures were 20%, and that's also where the name 20-20-20 goals comes from. In that perspective it seems a realistic and reachable target for the Netherlands. Besides the introduction of additional laws (EC, 2012) and policies such as the Energieakkoord (Energy Agreement), it turned out to be not that easy. The Netherlands are not the only country that has problems in reaching their targets, in fact most member states have.

Although it is expected the Netherlands will easily achieve their first target (ECN, 2015), they are performing particularly bad in terms of renewable energy production compared to other European countries, as figure 4 shows (OECD, 2015). Only Malta and Luxemburg are behind the Netherlands in this graph. In fact, in 2014 only 5,6% of total Dutch energy consumption was produced by renewable sources. If current efforts are extrapolated, this can increase up to 12% by 2020 (ECN, 2015), meaning the target is already out of reach. The report however states that a renewable share of 16% by 2023 is possible.

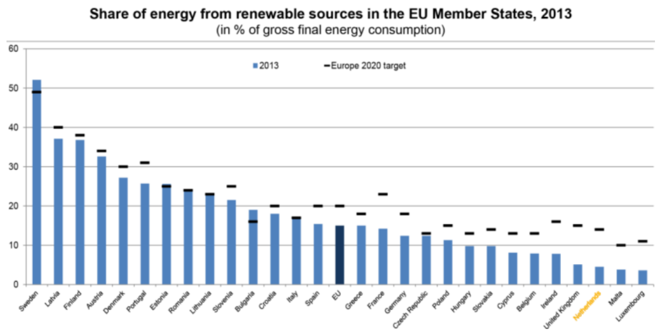


Fig. 4. Renewable energy production of EU member states. (Eurostat, 2015)

These poor statistics have even resulted in a lawsuit against Dutch government in June 2015 initiated by Urgenda, a foundation that wants to speed up the process of transition towards a more sustainable society and the use of renewable energy. Urgenda succeeded and the historic verdict of the court was that Dutch government has to sharpen their climate policy and reach a CO_2 reduction of 25 instead of 15 percent by 2020 compared to 1990 levels (NOS, 2015a).

Even if 14% of the energy would be produced by renewables in 2020, 86% would still originate from fossil fuels. This can again be illustrated by the opening of two brand new coal power plants in 2015 at the Maasvlakte and Eemshaven, requiring an investment of 3.1 billion euros (AD.nl, 2015).

Dutch government has put their visions and ideas regarding the energy transition in a policy report, called "Transitie naar Duurzaam". This report received a lot of critics because adequate solutions are missing. Furthermore, the report talks a lot about biomass, while this is only available in limited quantities and there is a geographical mismatch. It seems Dutch government is waiting for the industry to come up with and develop new technologies that increase the share of renewables.

Although strong efforts are made in the past years, it is not enough to reach the aforementioned climate goals, especially now even more strict agreements have been made to reduce carbon emissions at the global climate conference in Paris in November 2015 (NOS, 2015b). The energy transition obviously is a process of many years, but investing 3 billion in new coal power plants is hard to justify, even if they are meant to replace older power plants.

1.2 Renewable energy in the built environment

At this moment the built environment in the Netherlands is responsible for about 35% of total energy consumption (Topsector Energie, 2015). The appointments made in the climate agreements will therefore have profound consequences for the building industry. Besides agreements for 2020, agreements and legislation for the long term have also been made. Dutch government wants the built environment to be completely energy neutral by 2050 and a reduction of 50% in energy consumption compared to 1990 should already be reached by 2030.

A building is energy neutral when there is no nett use of fossil fuels or nuclear energy, measured over the whole year. Energy from renewable sources can compensate use of fossil fuels, as long as this energy is produced within the building context. Renewable wind energy produced at sea thus cannot contribute to an energy neutral dwelling (RVO, 2014).

Another reason for the importance of the built environment is the relative ease to implement energy saving measures. Where industrial process use a lot of energy, often with high temperatures, these processes are much more difficult to change and thus taking many years to have effect, it is relatively easy to save energy in the built environment with proven techniques that already exist. In order to effectively save energy and produce renewable energy it is important to have an idea of what the current energy use and production in the Netherlands looks like, especially for heating purposes.

The Netherlands uses 3493 PJ of primary energy* annually, which is largely generated by conventional sources such as oil, gas, coal and a small share of renewable sources. Energy used for heating in the Netherlands is 1324PJ, or 38% of the total primary energy use (Agentschap NL, 2013).

**Primary energy is defined as the raw energy as it can be found in nature before any conversion or transformation took place. To give an example of a conventional power plant using coal: to produce 1kWH of usable energy it takes on average 2.2 kWh of raw material due to conversion losses. In other words a power plant using coal has an efficiency of just 46% (Energiewijzer.nl)*

This 1324PJ can be further dissected into heat consumption in the built environment (646PJ/18,5% of total) and industry (579PJ/16,6% of total). The remaining heat consumption goes to agriculture. Primary energy used for space heating in the built environment can be split in residential use (388PJ/11,1% of total) and utility buildings (258PJ/7,4% of total).

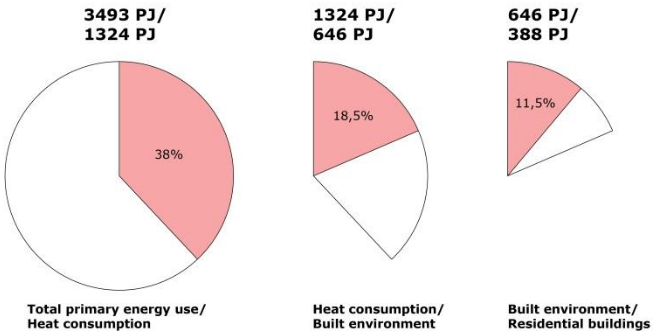


Fig. 5. Heat consumption in the Netherlands in 2013. (Own illustration)

In 2014 only 5,6% of total primary energy use was generated by renewables and about half of this figure consisted of renewable thermal energy as illustrated in figure 6. This comes down to about 54PJ, or 4%, hereby assumed that all produced renewable heat is consumed by the built environment. In other words; 96% of current heat consumption in buildings originates from fossil fuels.

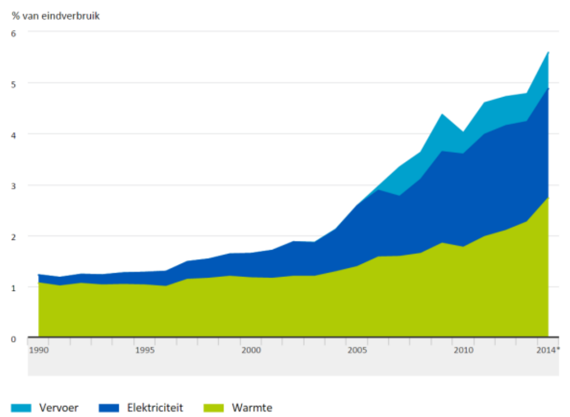


Fig. 6. Dutch share of renewables in final energy consumption in 2014. (CBS, 2015)

Figure 7 shows the different methods on how the renewable heat is generated. The majority of 54PJ is generated by biomass and bio gasses, where solar thermal energy only accounts for 1.1PJ, or 0,17%. Renewable energy for space heating, especially solar thermal energy therefore has enormous growth potential.

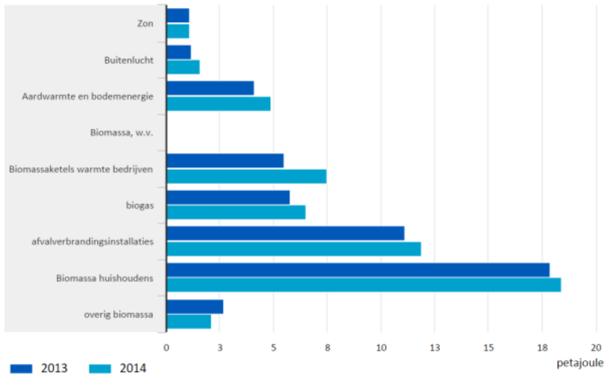


Fig. 7. Sources of renewable heat in the Netherlands. (CBS, 2015)

This potential for solar energy in the Netherlands has once been investigated by the company DNV-GL (DNV-GL, 2014). They have estimated that 60% of the 650km^2 roof area of all dwellings and utility buildings in the Netherlands is suitable for energy harvesting. The theoretical yield of this roof area exceeds both total thermal and electricity demand of the Netherlands on a yearly basis, but there is a problem.

Plenty of solar thermal energy is available during summer, but there is no space heating demand on sunny days. The reverse situation occurs during winter; high space heating demand but absence of sufficient solar radiation. There is a mismatch between thermal demand in winter and supply in

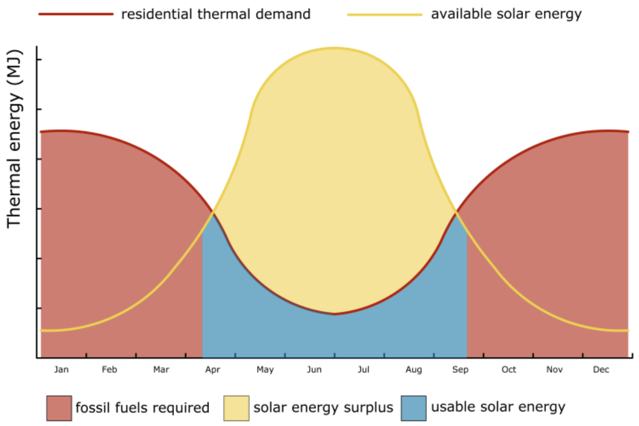


Fig. 8. The solar energy mismatch in the Netherlands. (Own illustration)

summer. As long as this mismatch is not solved, the solar potential cannot be exploited. Solving the mismatch is therefore crucial towards full utilization of the solar potential.

1.3 The refurbishment challenge

As mentioned in the previous paragraph, all buildings in the Netherlands should be energy neutral in 2050 (Ministerie van Economische Zaken, 2015). Energy neutrality can relatively easy be achieved in new buildings because relevant aspects such as orientation and technical installations can be taken into account during the design process. However, 90% of existing buildings will still be around in 2050. This means almost all existing buildings require an intervention that upgrades the energy performance towards an energy neutral built environment.

In this report the term refurbishment is used to describe these required interventions, because making buildings future proof involves more aspects than just an energy efficiency upgrade. In practice refurbishment covers a whole range of interventions on different scales. This is visualised in figure 9, where refurbishment is in between small and big interventions.

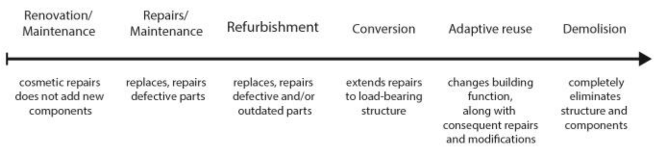


Fig. 9. How refurbishment relates to small and big interventions (Knaack, Konstantinou, 2012)

Refurbishment can also be explained by the following quote:

"Refurbishment does not include major changes in the load-bearing structure. In refurbishment not only defective building components are repaired or replaced, but also out-dated components or surfaces. Partial refurbishment includes only one component or part of the building, while the building is still in use. Normal refurbishment covers an entire building or a clearly separate, autonomous part of the building. In total refurbishment the building is stripped to its load-bearing frame" (Giebeler, 2009).

Although aspects like comfort, spatial quality and architectural appearance are also addressed in an adequate refurbishment, upgrading the energy performance is the crucial factor. Besides the reasons above, refurbishment is also more beneficial over demolition and rebuilding, since new dwellings use four to eight times more resources than an equivalent refurbishment (Itard, Klunder, 2007)

Roughly 2/3 of existing buildings are over 30 years old, and about 40% is over 50 years old (Knaack, Konstantinou, 2012). This is an important fact because insulation for the building envelope only became compulsory after legislation was made due to the energy crisis in the 1970's. Furthermore, in 2010 approximately 87% of Dutch dwellings were heated with a conventional boiler running on natural gas (Agenstchap NL, 2013). A Dutch study (Visser et al., 2012) has shown that in order to fulfil the desire of a completely energy neutral built environment by 2050, profound measures are required. All buildings should have an energy demand equal to a passive house which is 15kWh/m^2/year for new houses and 28kWh/m^2/year for existing buildings (Koene et al., 2010). This would mean a reduction of 70% in space heating demand between 2010 and 2050.

Because residential space heating plays a major role in total energy consumption, making this more renewable should be the focal point in refurbishment practise. The relevance of renewable space heating can also be explained by the building energy consumption. An average Dutch household consumes 3495kWh of electricity and 1320m^3 natural gas for space heating and domestic hot water (ECN, 2014), abbreviated as DHW.

It is interesting to see how much energy this 1320m^3 actually is. One cubic meter of natural gas contains roughly 35MJ of energy. 3.6MJ equals 1kWh, so 1m^3 gas equals 9,8kWh. 1320m^3 natural gas therefore equals 12.895kWh.

It is assumed that the electricity is produced with the average efficiency of 40%, and 5% transportation losses, so the primary energy of the electricity consumption would be 8135kWh. Basic mathematics show the primary energy use for space heating and DHW is 4760kWh (+58%) more than domestic electricity use. This shows that if the space heating demand is solved in a sustainable way, it can have a significant bigger impact on the residential primary energy use than renewable domestic electricity, although both eventually need to originate from renewables.

Current refurbishment can be explained with the Trias Energetica principle (see chapter 3.3). In practice, this leads to extreme insulation values, excessive use of PV-panels to produce renewable electricity and implementation of heat pumps as "sustainable" alternative for natural gas boilers. Although heat pumps allow decoupling of the natural gas network, they rely on electricity, which is not available during winter because of the mismatch. This mismatch is not addressed in current refurbishment, and fossil fuels are therefore still required during winter. The mismatch also makes PV-panels only usable when sufficient sunshine is available, which is the case in only 30% of the time.

Fig. 10. Example of current "Stroomversnelling" refurbishment in the Netherlands. (www.nul20.nl)

The excessive PV-use is a result of Dutch legislation, which allows unlimited net-metering ("salderen" in Dutch). Excess electricity produced during summer can be delivered back to the electricity grid for a financial compensation. If sufficient electricity is generated, the yearly energy bill can become zero due to this compensation. This principle is often used as business case for a refurbishment operation and a widely applied refurbishment concept is even named after it (Nul op de Meter). A dwelling refurbished according to these principles can be seen in figure 10, and more about this concept is explained in chapter 3.

Besides the financial benefits, the excess energy can compensate for use of fossil fuels during winter. This would make a dwelling energy neutral according to the previously mentioned definition, but fossil fuels will still be required. Current definition of energy neutral is therefore not adequate towards the future because it does not lead to a future free of fossil fuels.

The PV-panels will simultaneously deliver the electricity back to the electricity grid on sunny days, which causes high peak loads. The same happens with the heat pumps during winter; they are turned on simultaneously to provide space heating, extracting high peak loads. The current electricity grid is not designed to accommodate these peak loads and if this trend continues grid stability is in danger, resulting in power failures (ECN, 2014).

Researchers state the grid power has to quadruple from 6GW in 2015 to 23GW in 2050 to maintain grid stability (Ministerie van Economische Zaken, 2016). In other words: investments are done on a building scale now, but additional investments in the electricity grid in the near future are required to prevent power failures. Increasing popularity of electric cars will add even more peak loads to the grid.

Current refurbishment practice can be illustrated by the Nul op de Meter concept of which a characteristic example can be seen in figure 10. Large scale implementation of this refurbishment concept can eventually lead to aforementioned problems and the double investment. This relevant reference is further described in chapter 3.4.

However, there is another issue that might bring an end to current financial models for Nul-op-de-Meter concepts. Net metering will be limited and even completely set aside in the near future, just like happened in Germany (Energiebusiness.nl, 2013). Increased net-metering and decreased income from energy taxes makes the compensation too expensive for Dutch government. When net-metering will be limited, the business case for energy neutral refurbishments disappears, making the concept outdated. A future proof refurbishment concept should therefore not completely rely on uncertain governmental grants or subsidies.

A refurbishment of 90% of the existing dwellings would mean 6 million dwellings need to be addressed before 2050. Assuming a period of 30 years, this means 200.000 dwellings per year should be tackled. Besides this amount being a challenge in itself for the building industry, current refurbishment concepts will not successfully reach the goals and require additional investments later on as this paragraph explained.

Fig. 11. Besides the energy aspect, the spatial integration of "renewable technologies" also needs attention. This is illustrated by the Nathan Enery Module, which is a box full of equipment placed next to the entrance of the dwelling. Is this how the row-house of the future should look like?

1.4 An alternative approach

2050 seems far away, but the energy transition and correlating refurbishment challenge have already started. Future proof refurbishment concepts are needed that address the mismatch in order to allow 100% renewable energy throughout the year. At this moment the mismatch is solved by the use of fossil fuels in winter, and for the transition period this is a solution. In order to become independent of fossil fuels in the coming decades, the mismatch should be solved differently. Regarding renewable space heating, this could mean the surplus of solar thermal energy during summer should be used in winter. Therefore a new approach in which energy storage plays a crucial role is needed. This approach is described in more detail in chapter 3.3.

Such a concept will only have PV-panels to generate enough electricity for domestic energy use, and the excess panels are replaced by solar collectors. There will be less peak-loads to the electricity grid on sunny days and the thermal energy can be stored for use in winter. The storage could replace the heat pump, but storage can also be used to provide higher inlet temperatures for the heat pump, which reduces required power (Ecofys, 2015). The building energy demand of such a concept can be completely renewable and additional costs are prevented. A refurbishment approach with integrated thermal energy storage is likely to be more expensive compared to an all-electric concept, but when additional investments in the energy infrastructure are taken into account it can be a more cost-effective and sustainable solution in the end.

Besides necessary refurbishment, adequate governmental vision and policy also play a crucial role in accommodating the energy transition. The policy report "Transitie naar Duurzaam" (figure 12) lacks a holistic vision; it only describes boundary conditions and eventual targets. Municipalities are free to determine how the energy transition should take shape and which technologies / concepts are applied. This could eventually lead to a sprawl of different concepts and technologies making a decent coordination impossible. Although the report is about the period until 2050, only existing technologies are described, while researchers have clearly indicated that for example energy storage is crucial for full utilization of intermittent renewables. This illustrates Dutch government does not have an adequate vision on what is actually needed and they put the initiative entirely to other parties.

Fig. 12. Governmental report regarding the energy transition in the Netherlands. (Ministerie van Economische Zaken, 2016)

Furthermore, the report states the Dutch government will invest between 20 and 70 billion euros in the next decades to accomplish the energy transition (Ministerie van Economische Zaken, 2016). It is important that this money is spent wisely because it is a matter of societal relevance. The government should therefore evaluate whether their policy which is encouraging massive implementation of PV-panels and heat pumps is the right way towards 2050 because it may result in higher societal costs. PV-panels will nevertheless be important for future energy supply, showing the urge for a (diurnal) storage system (DNV GL, 2015). Therefore, installing large PV-power should be well considered if no storage is taken into account.

Although the Netherlands will not meet their 2020 targets, they can still reach an energy neutral built environment by 2050, but energy storing technologies are crucial for full utilization of intermittent renewables. (Seasonal) energy storage can therefore be seen a last myriad towards a sustainable future. This statement is also reinforced by numerical models that show long term energy storage is the most effective way of optimizing sustainable energy production and consumption (Blok et al., 2004). The question remains how energy storage can be implemented and integrated in the existing built environment. An alternative approach and integrating of seasonal thermal energy storage in refurbishment concepts is what this report is about.

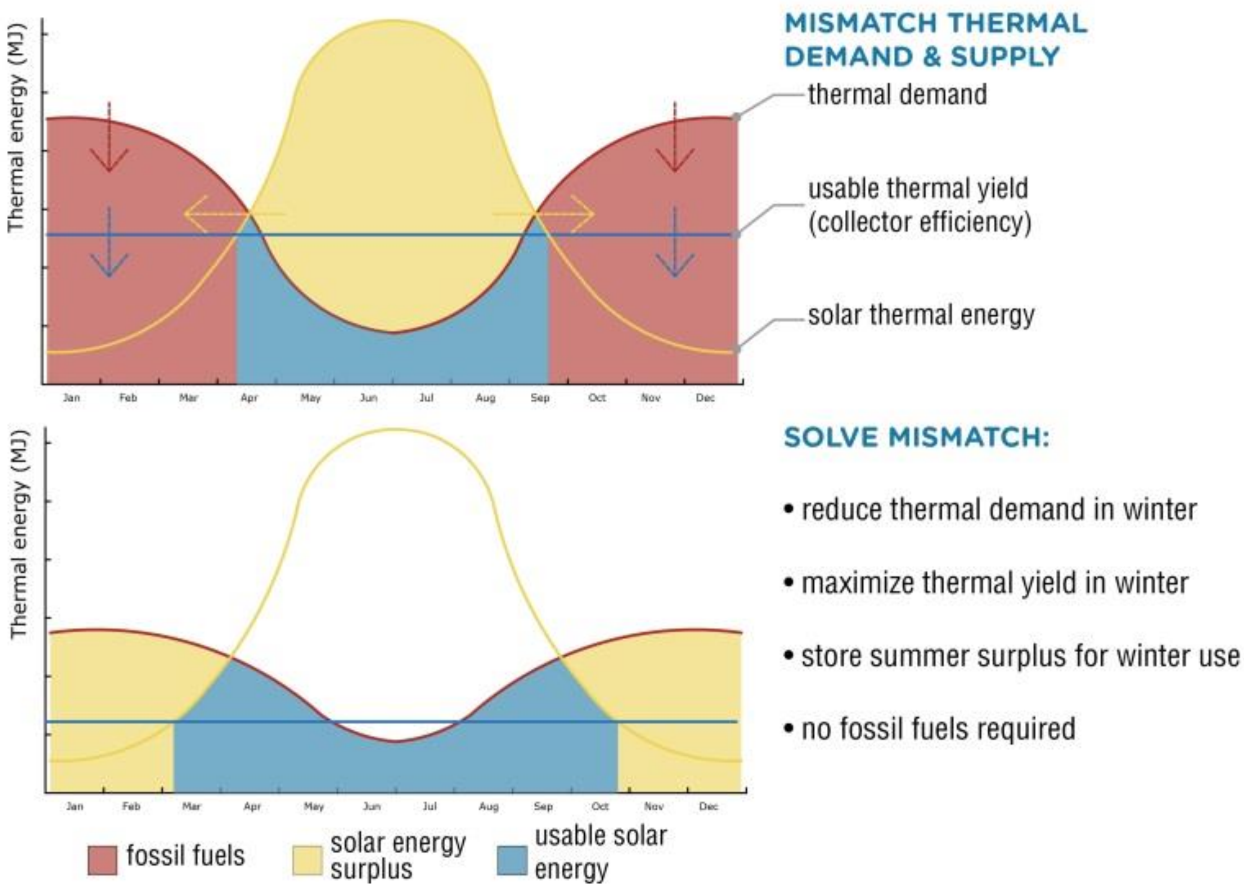


Figure 13. Solving the solar energy mismatch is the main challenge towards full utilization of renwables. (Own illustration)

2. RESEARCH OUTLINE

2.1 Problem statement

The problem statement follows directly from the background analysis. Several observations on multiple topics together form the problem statement, which is summarized below in seven crucial statements. The final statement will eventually result in the research question of this report.

1. Space heating demand of existing buildings is responsible for 18,5% of total primary energy consumption in the Netherlands.

2. Only a small fraction of this demand is generated by renewable sources, while the whole building stock needs to be energy neutral by 2050 and 90% of existing buildings will still exist by then.

3. Solar thermal energy could potentially fulfil this demand, but there is a mismatch between space heating demand during winter and solar energy supply during summer.

4. Current refurbishment practice does not address this mismatch and often ignores the potential of solar thermal energy. Instead oversized PV-roofs and heat pumps are implemented on a large scale.

5. Current refurbishment practice can therefore lead to undesirable peak loads to the electricity grid, causing an additional investment in the electricity grid on the long term to maintain grid stability.

6. Refurbishment concepts with an alternative approach in which energy storage plays a crucial role are desired to solve the thermal mismatch and provide 100% renewable thermal energy throughout the year. This will allow a fossil fuel free future and reduces additional investments in the electricity grid.

7. Additional research is required on how seasonal thermal energy storage can be integrated in existing dwellings.

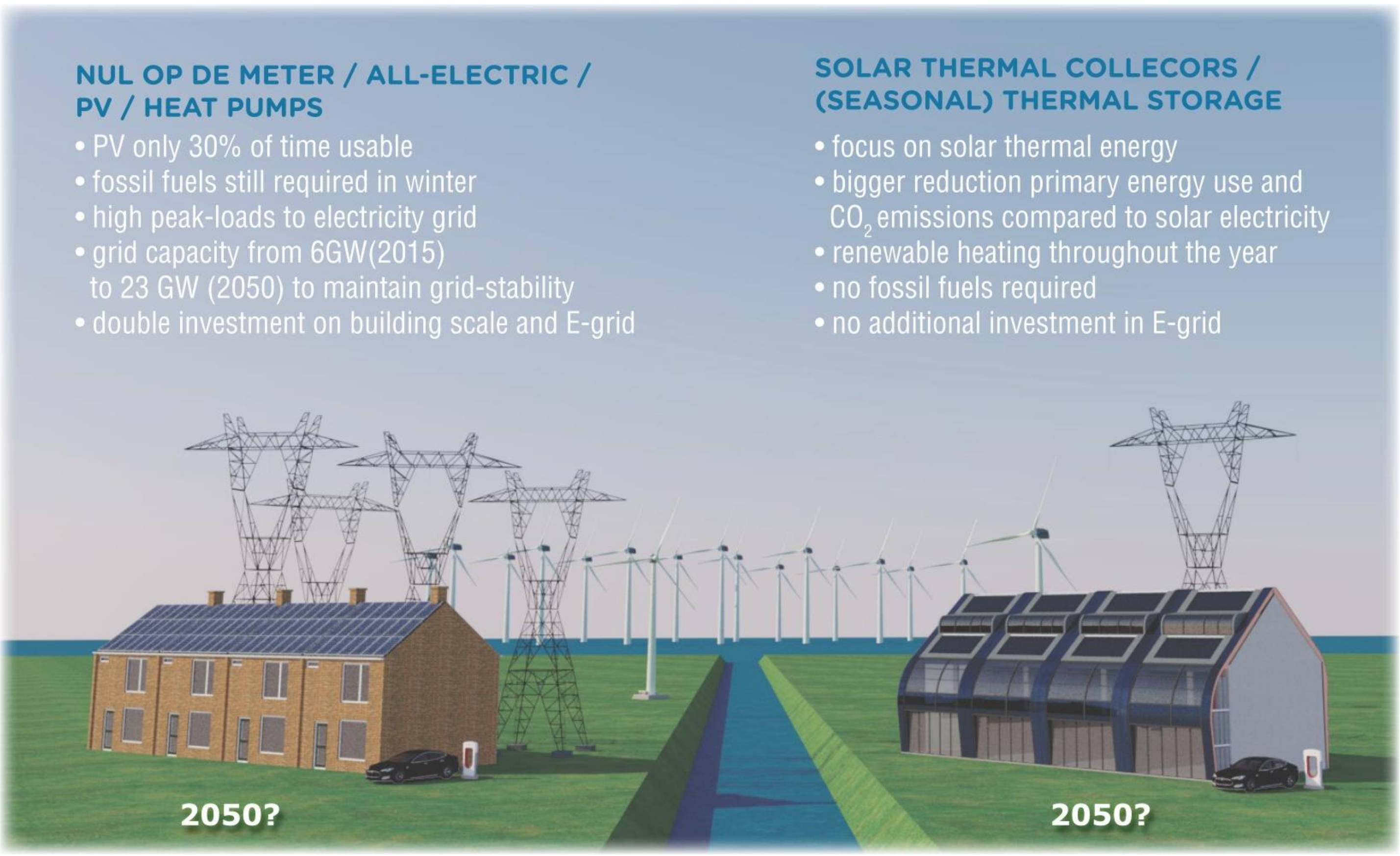


Fig. 14. The problem statement of this report. Continue with current refurbishment practice or a new approach? (Own illustration)

The last statement is what this report is about; a research on how seasonal thermal energy storage can be integrated into a refurbishment concept for row houses because current refurbishment practice does not lead to a true sustainable energy future. Besides refurbishment concepts such as Nul op de Meter remain dependant on fossil fuels during heating season, the large scale implementation of such concepts can lead to serious problems, resulting in an investment on both building scale and the electricity grid. Current approach versus the approach suggested in this report, is visualised in figure 14. Left of the river current row house refurbishment approach can be seen, on the right a concept with integrated storage. Notice the difference in electricity infrastructure; electricity grid needs to quadruple in capacity in order to maintain grid stability if the approach on the left continues…

2.2 Research focus & restrictions

This research is positioned within the context of the energy transition in the Netherlands. Because this is such a broad subject, some focus and restrictions regarding the research have to be made in order to define the actual scope of the research. This is done by a number of key issues.

Existing Row houses

The research focusses on existing row houses since this typology makes up 42% of Dutch residential building stock and 6/10 people live in here. All buildings in the Netherlands should be energy neutral by 2050 and 90% of the existing buildings is still standing by then. Most row houses have a poor energy performance, outdated appearance and do not meet current comfort standards. The challenge to upgrade this typology is therefore interesting from both a societal, engineering and architectural point of view.

Renewable (space) heating

The research focusses on an energy upgrade, in particular renewable space heating, because space heating in the built environment takes up 18,5% of primary energy consumption. Only a fraction is from a renewable source, while this has to be 100% renewable by 2050. Making space heating more renewable is crucial towards an energy neutral built environment. Thereby, renewable heating can save more primary energy than renewable electricity for a residential situation.

Solar thermal energy

The focus is on solar thermal energy because this could potentially cover total thermal demand of all existing buildings in the Netherlands, but in 2014 only 0,08% of heat consumption was generated by the sun. This energy potential should be exploited towards an energy neutral future and used in a refurbishment concept. Although solar energy potential is huge, the mismatch needs to be addressed in order to exploit this potential. A solution for the mismatch is the guiding theme in this report.

Seasonal thermal energy storage (STES)

Because this is needed to solve the mismatch between solar energy supply in summer and thermal demand in winter. Long-term energy storage is crucial towards 100% use of solar thermal energy throughout the year.

Decentralized STES

Although the most suitable storage scale is determined by local context, this research focusses on a decentralized solution. It is relevant to investigate whether a decentralized concept is feasible because this could prevent costly investments in energy infrastructure.

Thermochemical energy storage

Although other technologies will play a role in the energy transition as well, thermochemical storage is suitable for decentralized storage and has more benefits compared to other seasonal storage methods as will be explained in this report.

Technologies suitable for refurbishment

This excludes technologies that are only feasible in new buildings, for example underground (aquifer) thermal storage.

The following restrictions also have to be mentioned because of their importance, but they will not be directly addressed within the scope of this research.

A solution on the short-term

Although this research is about a problem the Netherlands is already facing, the solution in this report is not for direct implementation. Further research is required on thermochemical energy storage, but it is still relevant to already think and of future possibilities and define requirements for refurbishment concepts when this technology becomes available in the near future. The solution in this report will be market ready around 2020.

Storage tank design

An important restriction is storage tank design because of the complexity and it is not architectural or building technology related, but more related to mechanical or chemical engineering. Storage tank design will eventually become very important for technical feasibility of the system, but in this report reliable assumptions will be made that follow from interviews with researchers on that topic.

Sustainable material use

Although material use is crucial in a sustainable design, this will not be directly addressed in this report because it would result in a different research topic and would therefore make the research to broad.

2.3 Research objectives

Besides this report is part of the graduation, it is also meant to help building industry in gathering relevant knowledge towards integration of decentralized thermal energy storage solutions in the built environment. Although no tangible solution for direct implementation will be developed in this report, the aim is to define requirements for integration of such a storage solution and a method on how to calculate the required storage amount. Definition of relevant parameters and how they influence the performance of the design will be explained. This will be elaborated into a realistic technical design, which results in an exploration on how this can be spatially integrated in the case study context. The main and sub objectives are strongly related to both research questions and research methodology.

Main objective

Define requirements and elaborate a design direction for a thermal battery system which is integrated both technically and spatially into a refurbishment concept for a single family dwelling.

Sub objectives

Besides the main objective, a number of sub objectives can be defined that can be organized in four main research phases.

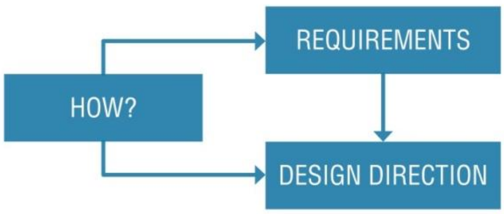
1. Literature study
    - Understand required backgrounds and consequences of current state of the art refurbishment practice.
    - Relevant knowledge on solar thermal energy properties, collectors and related system layouts
    - Relevant knowledge on STES-methods & technologies, in particular thermochemical STES
2. Development
    - Develop models to gather thermal demand and generation profiles/figures for a specific case study situation in order to determine required storage capacity
    - Development of a methodology on how to calculate required storage capacity with different parameters.
3. Design
    - Design of a suitable and realistic technical design for a thermal battery system layout
4. Elaboration
    - Realistic design direction for spatial integration of a thermal battery system in a refurbishment concept for the case study context.

2.4 Research (sub) question(s)

The main research question follows directly from the problem statement that is described in paragraph 2.1. The research focusses on the integration of seasonal heat storage in refurbishment concepts for single family dwellings. Integration refers to spatial integration and technical system integration because they are both important for a successful refurbishment concept.

Main research question

How can seasonal thermal energy storage be integrated both technically and spatially in a refurbishment concept for a single family house?



Sub research questions

The main research question can be answered by a number of sub questions that can again be organized in four main categories.

1. Literature study (chapter 3-5)

- *What is done and what are shortcomings in current refurbishment?*
- *What are the properties of and developments in solar thermal systems?*
- *What are the properties of and developments in (seasonal) thermal energy storage?*
- *What do the thermal demand and generation profiles look like for the case study dwelling?*

2. Development (chapter 6)

- *Which refurbishment strategy, solar collector type and storage method are most suitable for the case study context?*
- *Which parameters play a role in system performance?*
- *How much storage is required for the case study dwelling for different collector surfaces and deployment strategies?*

3. Design (chapter 7)

- *What are the technical and spatial requirements for the integration of a thermal battery system in a refurbishment concept?*
- *What is the most optimal system configuration in terms of energy performance and financial feasibility?*
- *What are possible design directions for integration of the storage volume in the case-study dwelling?*

4. Elaboration (chapter 7)

- *Which design direction for spatial integration is most suitable and what could this look like for the case study dwelling?*

Although the aim of this report is the development of a thermal battery system that can be integrated in a single family dwelling, this is formulated more abstract in the main research question. This done intentionally because the research involves more aspects than a technical design solution. Insight in relevant performance parameters, a methodology on how to calculate required storage amount and technical requirements are equally important from a theoretical point of view. Since this is a graduation report, theoretical knowledge about the topic is actually more important than a tangible design outcome.

The research question distinguishes both technical and spatial integration. Technical integration is explained by how the thermochemical STES interacts with other technical installation components in the dwelling. The combination of all different system components is referred to as the system layout. The aim is to develop the best possible system layout with integrated thermal energy storage for a case study dwelling. The technical outcome will be evaluated from both an energy and financial perspective.

The spatial integration of the system will not be translated into one specific design outcome, but has a more exploratory character on different design directions of how a thermal battery system could be integrated in the case study context. The eventual concept with integrated thermal storage will not be designed into detail in this report; this is up to architects and designers. This report is meant as guideline, providing boundary conditions and requirements for integration. The input for the spatial design follows from required storage capacity and corresponding dimensions of the technical system layout.

2.5 Research methodology

The research methodology (fig. 15) describes the method or process of how the research question(s) will be answered. It has been compiled prior to the actual research to help structure the process. However, the methodology has slightly changed throughout the process due to enhanced insights.

The methodology can be separated in four sequential research phases, which together form the graduation report.

1. Literature study

2. Development

3. Design

4. Elaboration

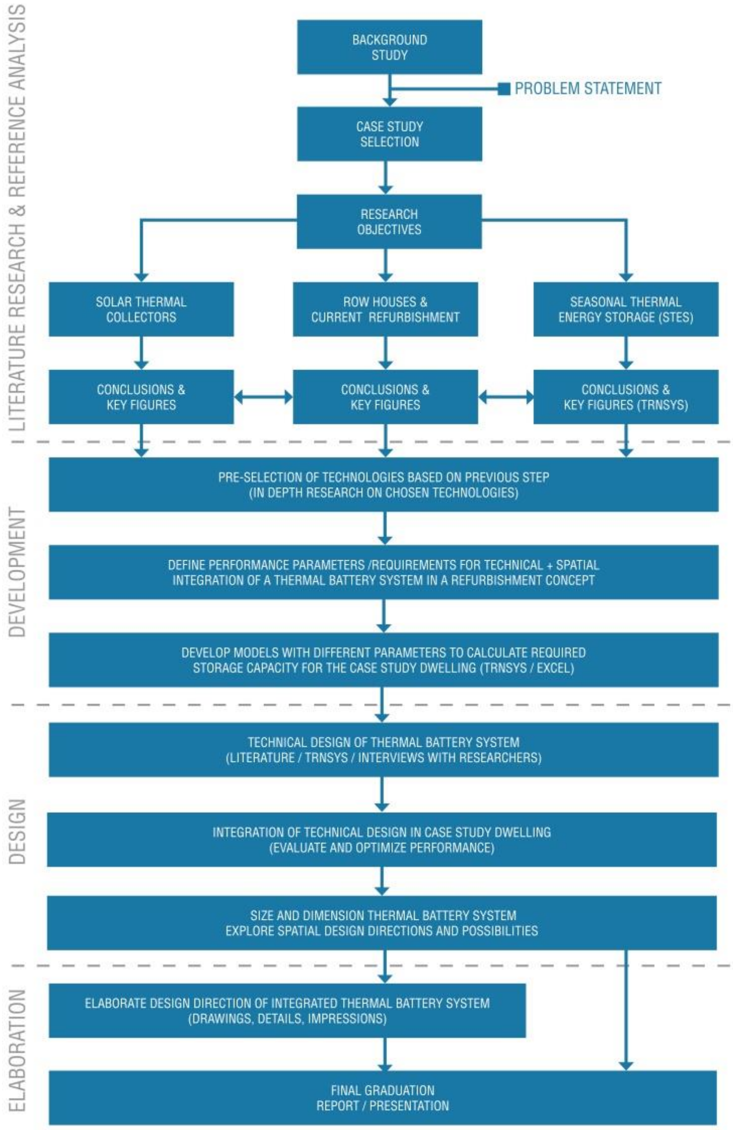


Fig. 15. Methodology scheme of this research. (Own illustration)

The graduation process in general can be described as a design by research approach (fig.16), because design decisions are based on technical input that follow from extensive research. More about the approach and an evaluation on the actual process can be found in the reflection at the back of this report.

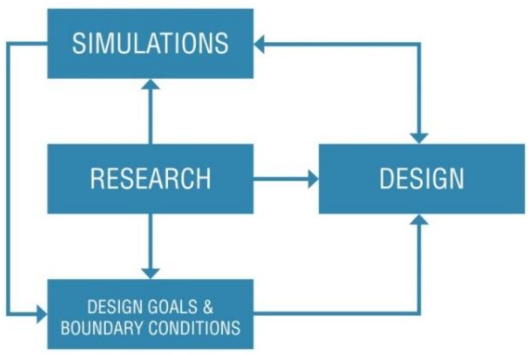


Fig. 16. Relation between research and design in this graduation. (Own illustration).

1. Literature research & reference analysis

The literature research is split into three main research topics, each representing a chapter in this report. Theoretical background of these topics form the foundation for the development of the thermal battery system in the next phase.

The first topic is about row houses and current refurbishment practice. It starts with an explanation of the relevance of the row house typology and energy demands. Methods on how to calculate and asses the this energy demand are discussed. Hereafter, the characteristics of current refurbishment and possible consequences will be elaborated in more detail.

The second topic is about properties of solar (thermal) energy and the potential in the Dutch context. Properties of solar thermal systems and collectors will be analysed and evaluated in order to gather relevant knowledge for system design in phase 3.

The third topic is the most relevant within the scope of this research, but is strongly related to the two aforementioned topics. Relevant information on methods and technologies for (seasonal) thermal energy storage will be discussed and evaluated. The most promising technology will be selected and described in more detail.

Besides the theoretical literature study, a number of relevant references will be analysed and described. These are meant to illustrate the literature study, but are also relevant regarding the design development in the next phase.

The last step of the first phase is to formulate a number preliminary conclusions for each research topic, which provide key figures and are combined to serve as starting point for the design process. This step also involves the first simulations for the case study using TRNSYS. Thermal heat demand profiles and solar energy potential are analysed in order to make design decisions in the next phase. More information about TRNSYS and a description of the model can be found in chapter 6. The results of literature research, organized per research topic can be found in chapter 3, 4 and 5.

2. Development

Prior to the actual design, the design goals and boundary conditions are defined, using output from the previous phase. Because the technical design will require specific knowledge, additional research in specific topics (mainly thermochemical storage) will be done. This also involves interviews with relevant experts from TNO and people from practice.

The theoretical input will result in a selection of technologies that will be used in the thermal battery system for the case study context. Besides the conceptual system layout, all relevant parameters that affect overall system performance will be described.

Another important aspect in this phase is to develop a methodology on how to determine the required storage capacity for the case study dwelling. This will done by processing the TRNSYS simulation results in Excel with a focus on the effect of collector surface area and system deployment strategy on the required storage capacity. A more detailed explanation of the development steps can be found in paragraph 6.3 and a detailed description of the simulation model and calculation method is explained in paragraph 6.4.

The simulations and calculations will eventually result in a number of graphs and tables that can be used for system design and determination of the most energy and financial optimal system layout. These graphs and tables can be found in paragraph 6.5 of this report, which ends by a description of the main characteristics of the most suitable basic system layout for the case study dwelling.

3. Design

In the third phase the final decisions regarding the deployment strategy and system layout are made. This starts with defining requirements for both the thermal battery system and the refurbishment concept. Although the refurbishment concept will not actually be designed into detail, requirements are necessary for the thermal battery system to work. These requirements follow from the TRNSYS simulations and additional literature research.

The conceptual system layout will be translated into a technical design of a thermal battery system, specific for the case study context. The technical design is elaborated using the input from the previous phases. The technical design and selected deployment strategy result in a required storage capacity. Once the storage capacity is determined, the system components can be sized. The resulting dimensions and sizes are used to explore several possible design directions for spatial integration of the system into the case study dwelling.

Besides the actual design, this phase also includes detailed information on how the system works during operation, what the energy performance is and what total system costs for different storage prices are. This is summarized in a matrix for different collector surfaces and deployment strategies (see paragraph 7.2.6). Such a matrix is relevant to determine the most optimal system layout since the eventual price of the storage is unknown and financial feasibility is crucial in refurbishment. The matrix source file could also be used in other projects to gather relevant information and to make design decisions regarding the best suitable system layout of a thermal battery system.

4. Elaboration

The elaboration phase is the final phase of the graduation process. It starts with the elaboration of the most promising design direction for spatial integration of the thermal battery system in the case study context. This will result in a conceptual elaboration of a refurbishment concept. The result is not meant to give a specific design solution, but indicates the consequences and potential of implementation of seasonal thermal energy storage in the built environment.

The elaboration phase ends with an evaluation of the system in terms of energy performance and financial feasibility compared to other systems. Consequences of large scale implementation of the system are also discussed. Furthermore, general conclusions, specific conclusions for the case study and conclusions for wider applicability of the thermal battery system will be discussed. The chapter ends with a number of recommendations for further research.

This phase is also used for the final graduation products such as technical schemes, drawings and renders. The report will be fine-tuned and the final presentation will be made.

3. ROW HOUSES & REFURBISHMENT

This chapter starts with an introduction on the row house typology, which is chosen as case study in this report. Thereafter the typical energy demand and methods on how to calculate and asses this are discussed. Characteristics and consequences of current refurbishment are discussed and illustrated by a reference project.

3.1 The row house typology

In the Netherlands there is one housing typology that can be found in virtually every village or city: the row house. This typology is known to be typically Dutch and makes up 42% of the building stock and 6/10 people are living in this typology (Eurostat, 2011). This comes down to about 4 million dwellings. Most of these dwellings need to be refurbished to some extend in the next coming years to make them future proof, and that’s what makes this typology a relevant case study.

Although the first modern row houses already date back to the first decades of 20th century, they became really popular in Post-war Netherlands to accommodate the shortage in single family dwellings. Especially in the 1960’s and 1970’s whole neighborhoods with row houses have been built rapidly (fig. 17) The construction process became standardized and often relatively cheap materials were used. However, in that time the row house was reckoned to be pretty luxurious since every dwelling had its own garden and plenty of space. The living space usually has two facades, resulting in plenty of daylight.

Fig. 17. Post-war residential neighbourhood with row-houses in Arnhem. (www.pbdoetmee.nl)

Row houses can be found in countless variations and formats, but they all share some basic characteristics. In fact, the Dutch government has specified a reference row house dwelling where all basic characteristics are mentioned, as well as energy performance. The row house case study dwelling, which is based on the reference dwelling is described in more detail in chapter 6.

Fig. 18. Typical Dutch row-house. (www.bouwwereld.nl)

In the Netherlands, insulation only became compulsory in the 1970’s as a result of the oil crisis. Consequently, nearly all buildings - and row houses - before that time do not have any insulation at all (fig. 19). Dwellings built after 1980 usually have some insulation, but this does not meet current standards.

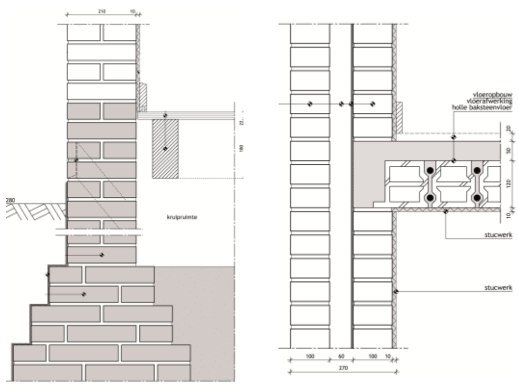


Fig. 19. Typical foundation and floor detail of uninsulated row-houses in the Netherlands. (Archidat, 2012)

The Dutch building stock is described as the least energy efficient of Northern Europe in literature (Archidat, 2012). Only from the 1990's the first row houses with sufficient insulation were built, and even those dwellings will not meet standards the Dutch government has set for 2030 and 2050.

By having a sustainable solution for row houses, a significant contribution to the climate goals can be made. Thereby, energy savings are easier to achieve in the built environment compared to industrial processes, which also have a big share in national energy consumption. A solution for the row house typology could also be adapted to (semi)-detached dwellings, thereby covering a major part of Dutch building stock.

Although energy performance is the most critical aspect, making the row house typology truly future proof is rather complex. Because so many people grew up and live in this typology, it is a matter of national social relevance. In the end the residents will determine what will happen to their dwellings, and if they do not directly benefit from any intervention, it is unlikely that a refurbishment will take place. To make the row house future proof, the appearance, indoor comfort and spatial quality should therefore also be addressed. This makes the row house particularly interesting from both an engineering and architectural perspective. The row house that once was a solution to the post war housing challenge now becomes an even bigger challenge itself!

3.2 The energy demand

Energy for space heating of buildings accounts for 18,5% of total primary energy use in the Netherlands, which makes it a crucial factor in achieving the climate ambitions earlier mentioned. Upgrading energy performance of buildings therefore has become a main priority of Dutch government.

3.2.1 Typical energy demand

An average Dutch household living in a row house with a conventional gas boiler consumes 3500kWh electricity for domestic appliances and about 1320m^3 natural gas for space heating and DHW on average (ECN, 2014). This volume of gas represents about 46GJ thermal demand, which would be roughly 13.000kWh (assuming 1kWh electric energy equals 1kWh thermal energy). These figures show that thermal energy demand makes up about 80% of domestic energy use.

Domestic energy use nowadays isn't increasing anymore, even though many new technologies have been adopted such as smartphones and other small electric equipment. Consumption of natural gas also shows a significant decline from 1900m^3 in 1995 to 1320m^3 in 2012 (ECN, 2014). This is mainly due to increasing number of insulated dwellings and implementation of high efficiency gas boilers.

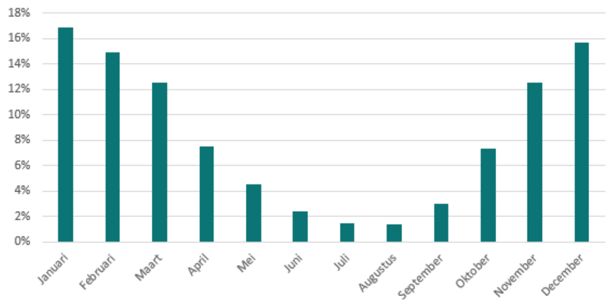


Fig. 20. Thermal demand profile of an average unrefurbished Dutch dwelling. (www.energievergelijken.nl)

Electricity consumption is quite independent from weather conditions (assuming no electric sources for heating are used), but consumption of natural gas used for space heating shows big deviations over the season, as shown in figure 20. 80% of annual consumption takes place between October and March and about 50% in December and January (energievergelijken.nl). This is an important observation because plenty of sun is available between April and September, illustrating the mismatch of heat demand and supply and the urge for a solution.

DHW demand is more or less constant over the year. An average single family dwelling has a DHW demand of about 9 GJ/year, but this is expected to become 8.1 GJ/year in the near future due to more efficient installations (Platform Nieuw Gas, 2008). DHW demand comes down to about 23MJ per day on average. If a dwelling has high quality thermal insulation, a situation can occur in which annual DHW demand is bigger than thermal demand for space heating.

The annual energy bill for Dutch households is on average €1790 (ECN, 2014). This figure energy for domestic electricity and thermal demand coverage (fig. 21).

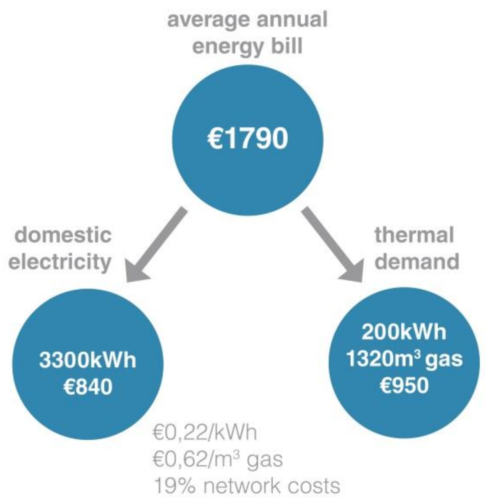


Fig. 21. Composition of the average Dutch residential energy bill. (Own illustration)

The Dutch weather institute KNMI is expecting a decline in energy consumption for space heating of 7% between 2005 and 2020 due to higher temperatures caused by climate change (ECN, 2010). This will further reduce gas consumption in the Netherlands. It is contradictive that climate change has a positive effect on the use of fossil fuels in this case.

3.2.2 Quantifying the (thermal) energy demand

The quantification or calculation of a building's energy demand is important to adequately size installation components and is a compulsory part of Dutch building regulations. This paragraph focusses on the calculation of building energy demand, which in the Netherlands largely consists of energy for space heating.

The energy demand of a building consists of energy used by building services to maintain a comfortable indoor climate and energy consumed by residents. In case of an existing building the energy consumption can be found on the energy-bill, but to predict energy consumption after refurbishment or a new building, calculations are required.

Key-figures play an important role in these calculations since its practically impossible to accurately predict electric energy used by residents. Moreover, residents also affect the building's energy use because in the end they determine the desired level of comfort. Therefore assumptions on the desired comfort level need to be made as well in order to determine the building's energy consumption. Usually an indoor temperature of 20ºC in winter with a deviation of 1 degree is genuine and used in calculations.

The actual building energy demand is affected the following parameters.

- Environmental parameters
  - solar gains
  - outdoor temperatures
  - wind (speed/direction)
- Building parameters
  - orientation
  - ratio volume/envelope
  - envelope insulation
  - draft proofing of envelope
  - efficiency of building services
- User parameters
  - desired level of comfort
  - DHW-use

To illustrate this in case of the row house typology, the difference in energy consumption between a corner and in between dwelling is about 28% (energievergelijken.nl). Lowering the indoor temperature by 1 degree can already contribute to a decrease of 7% on the energy bill (gaslicht.com), showing the importance of user related behaviour regarding energy demand.

If the peak load energy demand is required to size technical installation components, a couple of scenario's are calculated, usually for extreme hot or cold days. This could for example be done with comprehensive Excel sheets. The results give the maximum heat demand or cooling load for a given scenario and this information can be used to define maximum peak power or dimensions of installation components.

However, if accurate figures on energy demands of a building are required (for example to assess the energy demand), calculations for specific scenarios are not sufficient and dynamic simulation software is required. Several software applications can be used to do this, in this report TRNSYS will be used for the calculations since this is recommend by literature because of its flexibility in modelling new innovative systems. Thereby, TU Delft could provide a TRNSYS building file equal to the case study dwelling, which saved a lot of time.

3.2.3 Assessing the energy demand

In the Netherlands the EPC (Energy Performance Coefficient) is used to assess the energy performance of a building. An EPC-value refers to the building specific energy demand, which consists of energy for space heating, cooling, DHW, ventilation and lightning. The required EPC-value specifies the minimal energetic quality a dwelling should meet. These values are specified in Dutch building regulations and are different for several building types and functions. Besides a compulsory EPC, building regulations also specify minimum thermal resistance values of ground floor, facades and roof. These values are specified per building component since thermal losses are not equally distributed over the envelope. Usually, most energy gets lost through the roof, and therefore it is more important to have high quality roof insulation rather than ground floor or façade insulation.

The EPC is a qualitative indicator and is expressed in a certain value, where a value of 1,0 is defined as the average energy consumption of a dwelling in 1990 and 0 is an energy neutral dwelling. If a building produces more energy than it consumes, the value can be negative. At this moment all new buildings need to have an EPC of 0,4. Designers are free to determine how the required EPC is reached, allowing freedom in design. Extra PV-panels can for example compensate for less insulated windows.

An EPC-calculation involves a set of detailed building specific calculations that can be done with several software applications. The procedure to calculate an EPC-value has been specified in Dutch building regulations, NEN-7120. For energy calculations, a reference climate year is used. In case necessary values cannot be calculated, values from a reference dwelling, which is specified in Dutch building regulations, can be used.

For most people an EPC-value is hard to understand since it refers to relative energy use compared to energy consumption of a dwelling in 1990. Because building regulations will be more stringent in the coming years and energy performance becomes more important for society, a more accessible and tangible indicator is desired. Therefore a new indicator recently has been developed that will replace the EPC in anticipation of new Dutch building regulations, which state that new buildings need to be nearly energy neutral from 2020 on.

This new indicator is called BENG and stands for Bijna Energie Neutraal Gebouw, translated as nearly energy neutral building. The new regulations are derived from the European EPBD Recast and agreements in the Dutch Energieakkoord. In contrast to the EPC, the BENG-indicators provide quantitative values that refer to actual energy consumption of a building. The idea is that BENG is easy to understand, so people and investors are more likely to invest in energy saving measures, encouraging the energy transition. The following indicators are part of the BENG methodology (Guijt, 2015):

1. Energy demand in kWh/m²/year

The energy demand is split into energy for heating and cooling/comfort. Domestic lightning is not taken into account because this cannot be designed in advance. Lightning is however included in the calculation for utility buildings.

The energy demand for residential dwellings should be equal or less than 25kWh/m^2 (DGMR, 2015).

2. Primary energy use in kWh/m²/year

Primary energy use consists of heating, cooling/comfort, ventilation, DHW and PV-panels. Energy from PV-panels can be subtracted from total primary energy use. Primary energy from non-renewable sources has a standard conversion factor of 2,56. In case local PV contributes to building energy consumption, the same factor is applied. A single PV-panel accounts for 238kWh/year.

The primary energy use for residential dwellings should be equal or less than 25kWh/m^2 (DGMR, 2015).

3. Share of renewable energy in %

The share of renewable energy is calculated by the so called RER or Renewable Energy Ratio. This is defined as:

RER = gross renewable energy / (primary energy use + gross renewable energy) x 100%

The primary energy use follows from BENG-indicator 2. All produced renewable energy on the dwelling and its direct surroundings are involved in the determination of RER.

A residential dwelling should have a RER of at least 50% (DGMR, 2015).

The explanation on how to calculate aforementioned indicators is simplified. Just like in the EPC calculation, a lot of building specific input which require (complex) calculations is needed, but this will not be further elaborated in this report. Besides that, an EPC or BENG value will probably differ from actual energy consumption due to variations in residents' behaviour and changing climate conditions compared to the reference year.

3.2.4 Energy labels

Next to the compulsory EPC, the Dutch government has also introduced a so called "energy label" for existing buildings, similar to existing labels of electric equipment. The energy label is meant to indicate the energy efficiency of the dwelling and ranges from A to G, where A is the most energy efficient. The label refers to energy use per square meter, but is far less accurate compared to the EPC. An energy label just gives an indication on the energy efficiency of the dwelling, actual energy consumption again strongly depends on residents behaviour. An overview of different energy labels and corresponding thermal resistance values for foundation, roof, façade and windows can be found in appendix 1.

In the Netherlands, approximately 75% of residential building stock has energy label C or worse (fig. 22), which equals 5 million dwellings. Given the fact all buildings should be energy neutral by 2050 and 90% of current buildings still exists by then, shows the importance of upgrading energy efficiency of existing dwellings through refurbishment. If all these dwellings need a refurbishment to some extend in the next 30 years, this would come down to 160.000 dwellings a year, not even taking utility and industrial buildings into account. The Netherlands therefore face a major challenge to reach an energy neutral building stock by 2050.

Fig. 22. Division of energy labels in the Netherlands. (Archidat, 2012)

Energy labels, EPC or BENG do not take the energy of the construction and embodied energy of building materials into account, while this makes up a significant part of energy use spread over the lifetime of a building (Konstantinou, 2014). A true sustainable design or refurbishment strategy also addresses these aspects. More extended indicators such as LEED and BREEAM exist that also address these aspects. If these indicators are used to decide for new construction or refurbishment, the last one is often in favor. Refurbishment is therefore inevitable for reaching the climate ambitions.

3.3 Characteristics of current refurbishment practice

A successful refurbishment does not only address energy performance, but also addresses comfort, spatial quality and architectural appearance of the dwelling. Although more aspects are important in refurbishment, the energy performance upgrade usually is the main incentive and additional upgrades are optional. Yet, the feasibility is likely to increase if more aspects are addressed, because there is little benefit for residents if energy performance is improved at high cost since energy costs are only 3-4% of domestic expenses (Konstantinou, 2014). A holistic refurbishment will increase value of the dwelling and quality of living, giving residents tangible value for money.

3.3.1 General refurbishment strategies

In most refurbishment projects the upgrade of the building envelope is the most important feature of the refurbishment concept. The design outcome for upgrading the envelope usually follows from a chosen refurbishment strategy. Refurbishment projects can therefore be categorized on their refurbishment strategy, which is in general determined by the condition the building is found in and desired result.

Five main strategies (wrapping, replace, add-in, add-on, covering) are described in literature (Konstantinou, 2014) and are applied in current refurbishment practise. However, in case of row houses the cover strategy is excluded due to the shape of the buildings. A cover strategy is more applicable in larger building blocks without pitched roofs. The four remaining strategies are visualised in the diagram below, as well as possible combinations.

The first strategy is wrap it strategy. The existing building envelope is wrapped with a new construction layer which improves thermal resistance of the envelope, reduces thermal bridges and upgrades physical appearance. The wrap it can be placed directly on the existing façade (1A) or at a distance, making it a second skin façade (1B).

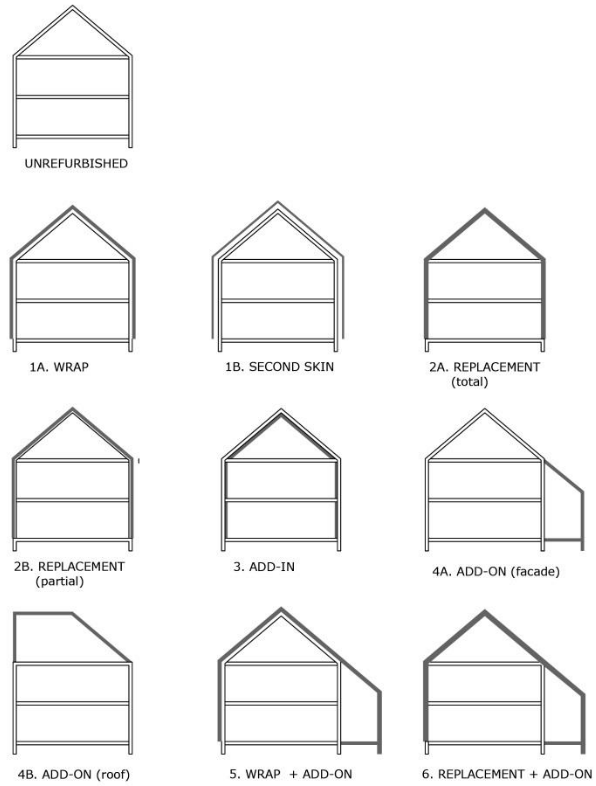


Fig. 23. General refurbishment strategies for row-houses. (Own illustration)

An important aspect in favour of this strategy is the little inconvenience for residents since they do not have to move out during construction.

The second strategy, replacement, can be divided in total (2A) and partial (2B) replacement of the building envelope. Both options are very common in the Netherlands. The choice for full or partly replacement of the façade is usually determined by the condition the façade is in or by possible restrictions, such as monumental facades. Replacement of the façade allows for optimal integration of technical installations combined with prefabricated solutions. Downside of this strategy is that residents have to move out during construction, causing inconveniences.

The third strategy, add-in, is often used in monumental buildings where the outer envelope is excluded from interventions. The only option to improve building envelope insulation in such buildings is placing insulation on the inside. This option is however not preferred since it reduces functional floor surface and requires decent calculations to prevent internal condensation.

Row houses are rarely listed as monumental building, and the add-in strategy is therefore very uncommon.

The last strategy, add-on, is the addition of a functional volume next to (4A) or on top (4B) of the existing building. This strategy is often found in more rigorously refurbishment projects where besides energy performance additional functional space is important. The add-on can be as small as a balcony up to a full extension of the building that also contributes to the energy performance of the building like the Prêt-à-Loger concept of TU Delft (figure 24).

Fig. 24. The Prêt-à-Loger refurbishment concept, developed by TU Delft. (TU Delta, 2014)

Although each strategy has its specific characteristics, they are often combined in practice for an optimum result. This is especially the case for add-on strategies since they often do not cover the entire building envelope. To improve energy performance the total façade needs to be addressed and the add-on is therefore often combined with a wrap-it (5) or replacement (6) strategy.

3.3.2 Energy performance upgrades

Besides the strategy, a refurbishment also involves a certain methodological approach for upgrading the energy performance of an existing dwelling. The most common and used approach is the Trias Energetica principle. This three-step guideline has been invented in 1979 by Dutch professor Kees Duijvestein at the TU Delft and can be used to make a building or design more energy efficient. It has been used in numerous projects ever since and has proven its value towards sustainable architecture. The steps are shortly explained below.

1. Reducing the energy demand

The first step is the most important one since thermal insulation measures can reduce energy demand significantly. In fact, researchers have estimated 2/3 of the potential carbon emission reduction can be achieved if all buildings in the Netherlands are provided with high quality insulation (Ecofys, 2015). Besides thermal insulation, draft proofing and efficient heat recovery are important as well. A reference refurbishment detail with thermal resistance value of 9,0 for roof and 7,0 for façade can be seen in the figure below.

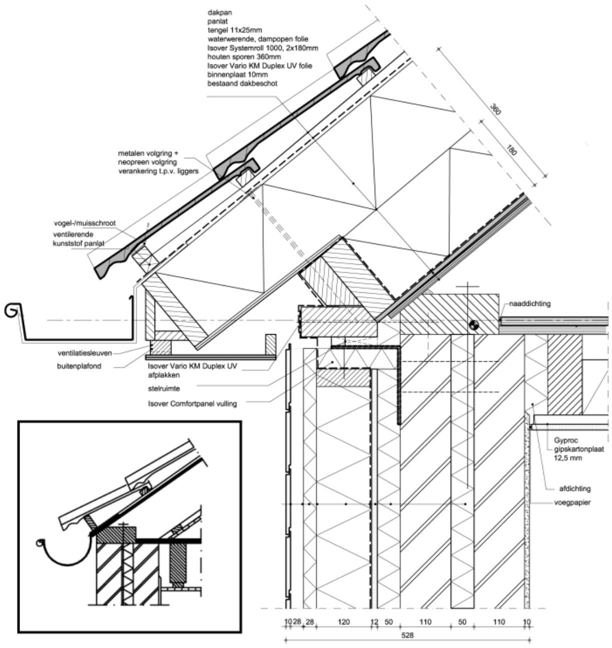


Fig. 25. Reference detail of current refurbishment with Rc 9,0 of roof and 7,0 of Façade. (Archidat, 2012)

2. Making use of renewable energy

The second step doesn't need explanation anno 2016 because renewable energy is all around us.

3. Efficient use of fossil fuels

The third step is efficient use of fossil fuels, which refers to efficient building installations, such as heat pumps. Heat pumps are very common in new buildings and are often implemented in refurbishment projects because of their efficiency.

This technology will become even more prevailing because prices drop and governmental grants are available. More information about heat pumps can be found in appendix 2. Although fossil fuels should eventually be replaced, they are inevitable during the transition period.

The Trias Energetica approach helps designers and engineers to effectively combine measures towards a sustainable design. When this methodologic approach is used correctly, a more energy efficient and cost-effective design is achieved compared to implementing measures without a clear approach (RVO, 2015a).

3.3.3 Limits of Trias Energetica

Although the Trias Energetica approach has worked for years, it has its limits towards a true sustainable energy future as already explained in the background of this report. In a future without fossil fuels the second step is of course obvious and the third step does not make sense. Therefore a new approach, based on the cradle to cradle principle was developed in the beginning of 21th century by TU Delft professor Andy van den Dobbelsteen (Huijbers, et al., 2013). The first step is the same, but the second step is about the reuse of waste-streams. In a domestic situation this can for example be the reuse thermal energy in shower water for space heating. The third step is about using renewable energy to cover remaining demand.

Unfortunately, the new stepped strategy isn’t addressing the actual problem of implementing renewable energy either. Although technology is mature enough to provide enough energy, a solution for the intermittence of wind and solar energy is the last hurdle towards full implementation. This intermittence, resulting in the mismatch between energy demand and supply should therefore be addressed in an approach for refurbishment projects.

Such an approach could have the following steps:

1. Reduce the energy demand

2a. Use energy efficient components

2b. Reuse waste streams

3a. Use renewable energy whenever possible

3b. Use energy storage to solve the remaining mismatch of renewable energy

The last step, the use of energy storage to solve the mismatch and allow a fossil-fuel free future, is the guiding theme in this report.

Besides the fact that the approach in current refurbishment will not lead to a sustainable energy future, the need for a new approach is illustrated even more by a number of negative side effects caused by current refurbishment practice. The most important ones are explained below. In the next paragraph a relevant reference regarding these side effects will be discussed.

Extreme insulation (step 1)

Although high Rc values and air-tight details will reduce thermal losses and save energy, it is at the cost of indoor comfort. Because outside air can hardly enter the building, additional measures are required to guarantee enough fresh air inside. Special attention to ventilation should therefore be given and often mechanical ventilation is needed. Cases have been reported where this does not function properly and residents are annoyed by the noise (Borsboom et al., 2015).

The extreme insulation can also have negative side effects during summer, because indoor spaces heat up and cannot get rid of the heat. Additional cooling is therefore often required. This means the energy demand is shifted from winter to summer (Bales, 2014). Cooling requires additional installations and there is little nett effect on the annual energy balance.

Excessive PV-use (step 2)

The second step, make use of renewable energy, manifests itself in the often excessive application of PV-panels (fig. 26), caused by several reasons. The first reason is described earlier: additional PV-panels are often used to reach required EPC-value. Secondly, the excess produced electricity during summer can be delivered back to the electricity grid. This is called net-metering, and at this moment residents get a compensation for the electricity that is given back to the grid. PV-panels could therefore potentially even generate money. The excess PV panels can make a dwelling energy neutral because there is no nett import of fossil fuels.

Moreover, PV-panels cannot be used during winter (when most energy is required) and cloudy days because of the absence of sufficient irradiance. This makes PV-technology unusable for roughly 70% of the year, thereby still relying on fossil fuels. This is 100% between November and February. In fact, without electricity storage only 13% of all Dutch electricity demand could be generated with PV technology (de Goederen, 2013). Without adequate storage, PV-panels will therefore only partially contribute to a renewable energy future.

Fig. 26. Example of excessive PV-use in current Dutch refurbishment practice. (www.installatie.nl)

Heat pumps (step 3)

In recent years, heat pump technology has been rapidly adopted by the building industry because it is able to replace conventional natural gas boilers for heating purposes. A heat pump makes use of a principle in which an energy carrier is evaporated, compressed, condensed an expanded again to generate thermal energy. A more detailed explanation of the working principle of heat pumps is given in appendix 2.

Fig. 27. Example of an air source heat pump applied in current refurbishment. (www.energievastgoed.nl)

If a whole street is equipped with heat pumps and they start heating simultaneously on a cold day, they will extract a huge peak power from the electricity grid. This can eventually cause grid instability, similar to the summer situation but in reverse direction.

The large scale implementation of PV-panels and heat pumps (fig. 26&27), known as electrification, will therefore threaten electricity grid stability. PV-panels for example, generate a surplus of up to a maximum of eight times the average grid load 30% of the time (de Goederen, 2013). Increasing share of electric cars will even enlarge the threat of grid instability.

The average domestic peak demand is expected to increase from 0,8kW in 2013 to 1,3-3,0kW in 2040 (Veldman, 2013).

Studies have shown the grid capacity needs to increase from 6GW in 2015 to 23 GW in 2050 to maintain grid stability if all dwellings in the Netherlands are refurbished according to the all-electric principle (Ministerie van Economische Zaken, 2016). Studies indicate that a 100% electric energy supply is 45% more expensive that a combination of natural gas and electricity (Veldman, 2013). Refurbishment according to current practice therefore involves a costly investment on a building scale and a second, additional investment in the energy infrastructure in the near future (see problem statement).

3.4 Relevant Reference: NoM

A wide range of refurbishment concepts and approaches are used in current Dutch refurbishment practise. Regarding the row house typology and aforementioned threats, there is one concept in particular that is of significant relevance due to its scale and social impact. This concept is called Nul-op-de-Meter (NoM) in Dutch, which can be translated as zero-energy bill dwelling. The concept is still under development, but plans for massive implementation are in an advanced stage.

Fig. 28. Example of a NoM refurbishment. (www.slimrenoveren.nl)

Nul-op-de-meter concept (NoM)

The NoM concept (fig. 28) is part of the Stroomversnelling project, in which six housing associations and four major building contractors cooperate, supported by Dutch government. The cooperation is meant to enhance the market for sustainable construction and refurbishment. All building contractors have their own NoM concept that slightly differs, but are very similar in approach and implemented technologies.

Concepts for both new buildings and refurbishments are used. Most of these concepts are all-electric, which means all building installations rely on electricity and a natural gas connection is needless. The name NoM is used because there are no costs for energy on an annual basis. The compensation for the excess produced electricity by the PV-panels during summer is used to purchase electricity from the grid during winter, resulting in a nett energy bill of €0,-

A NoM concept does not only improve energy performance, but also addresses indoor comfort, architectural appearance and spatial quality. The refurbishment usually involves a new kitchen, bathroom, toilet and an optional extension of the dwelling, but upgrading energy performance by a new building envelope is at the heart of the concept. After refurbishment the building energy demand is reduced to a maximum of 10kWh/m^2/year. Prefabricated elements for both roof and façade that have PV-panels and windows already integrated are used. This reduces building time and costs, but also minimizes building waste.

The main components/features of a NoM concept are listed below (RVO, 2015b). As explained, these characteristics can differ per NoM concept.

- Insulated façade elements (Rc 4,5)
- Triple glazing
- Insulated roof elements (Rc 6,0)
- Insulation flocks in crawlspace
- Exterior insulation of foundation
- Air-water heat pump
- Low temperature (floor) heating
- Balanced (mechanical) ventilation
- Heat recovery
- 24-30m^2 PV-panels
- New bathroom
- New kitchen
- New toilet

The consortium plans to refurbish 111.000 dwellings in the next coming years according to the following planning:

- Prototyping (2013-2014)
  1000 dwellings
- Industrialisation (2015-2016)
  10.000 dwellings
- Upscaling (2017-2020)
  100.000 dwellings

The average cost per dwelling now is about €60.000, but they expect this price can be lowered to 45.000 if the concept is applied on a large scale. The concept is meant for both social housing and privately owned dwellings, where the special attention is given to the financial feasibility. The focus on financial feasibility, especially in social housing, makes the NoM concept very promising.

In social housing, the required investment for refurbishment is paid with the energy bill of tenants. Although their energy bill is actually zero, the monthly bill remains equal to the bill prior to the intervention. This money is used to finance the concept. Tenants get a more energy efficient dwelling with improved comfort for the same monthly expenses. The building contractor guarantees the performance of the dwelling for 10 years, so the housing association will not have unforeseen maintenance. This approach is beneficial for all parties involved.

The implementation of a NoM concept in privately owned dwellings is more difficult to realise because residents need to invest with their own money. Yet, they can extend their mortgage by €25.000 if they choose for an energy neutral refurbishment. Again, the construction company gives a 10 year warranty for energy performance and maintenance on installations. In case of a privately owned dwelling, monthly expenses will slightly increase after a NoM refurbishment, but the value of the dwelling increases as well.

PV-panels applied in the NoM concepts generate about 5500kWh electricity per year on average, of which 30% is consumed directly by the dwelling itself (Energiesprong, 2014). The other 70% is given back to the electricity grid and taken back later. This means net-metering is crucial for the business case of this refurbishment concept.

Fig. 29. One of the first dwellings refurbished according to the NoM Concept. (RVO, 2015b)

Although the NoM concept is an excellent example of holistic refurbishment that can lead to energy efficient and affordable future proof dwellings, large scale implantation of the NoM concept will lead to aforementioned threats and additional investments. Moreover, the business case of the concept is in danger. Net-metering will be phased out in the next coming years because it is no longer financially feasible for Dutch Government. The concept will therefore become outdated in 2020 when net-metering will be more sober or completely abolished (Schootstra, 2015).

This shows the need for refurbishment concepts with integrated (thermal) energy storage, because only then it becomes possible to use renewable energy throughout the year, thereby avoiding the additional investment in energy infrastructure, dependency on fossil fuels and governmental subsidies. In the next two chapters more theoretical background is discussed on how this can be achieved.

4. SOLAR HEAT UTILIZATION

In this chapter the principles of solar heat utilization and solar thermal systems will be discussed, with a focus on Dutch context.

4.1 Introduction on solar energy

Solar energy is composed of electromagnetic waves. Approximately 40% of those waves is visible light, 50% is infrared radiation and another 10% is ultraviolet radiation. The rate of energy reaching a unit of surface area is called solar irradiance and is measured in W/m^2. The irradiance over a period of time, hour, day, month or year is called irradiation. This is often measured in kWh or MJ.

Solar irradiance consists of direct and diffuse radiation. Direct radiation is able to cast shadows and diffuse radiation is a result of reflection by clouds and atmospheric particles (fig. 30). The combined direct and diffuse radiation on a horizontal surface is called global irradiation. The actual received irradiance (on a tilted surface) also includes ground reflected radiation. In general the diffuse irradiation component is larger than direct irradiation, except for equatorial regions.

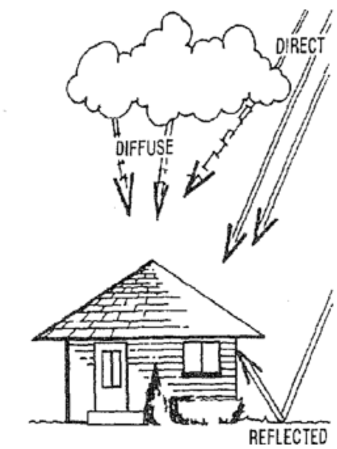


Fig. 30. Solar radiation components. (www.solarheating.org)

The irradiance at the top of the atmosphere is the same everywhere and is called the solar constant, which amounts 1368W/m^2 (Laughton, 2010). The actual received irradiance on a given surface depends on the solar height or elevation measured in degrees and the solar zenith, which is the direction relative to true North again measured in degrees (fig. 31). Both these variables are time and geographical specific. The amount of irradiance is obviously also affected by the amount of clouds. Maximum irradiance occurs when the sun is perpendicular to the surface and sunrays are not obstructed by clouds. Received irradiance on a cloudy day is approximately 75% less compared to a clear sky (Hermans, 2011). Nearer the poles the annual irradiation is bigger for a tilted surface which results in an annual optimal angle for each latitude. The optimum angle for summer is different from winter, respectively more horizontal and vertical.

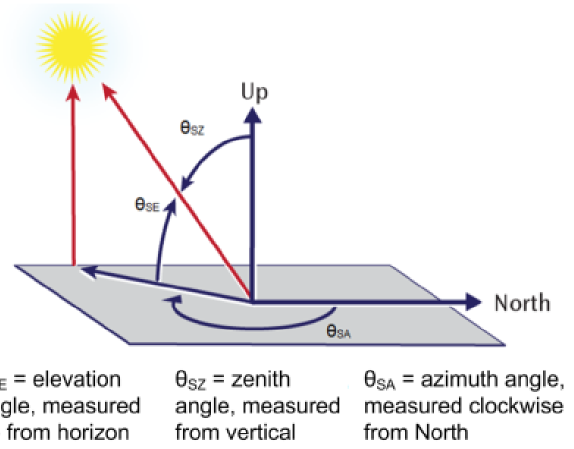


Fig. 31. Explanation of solar elevation, zenith and azimuth. (www.bxhorn.com)

4.2 Solar energy in the Netherlands

In the Netherlands an average of 110W/m^2 solar energy, which equals about 90m^3 of natural gas per year, hits the surface. This average is however strongly affected by the seasons. Where only 20W/m^2 is received during winter period, this can tenfold during summer months up to 200 W/m^2 (Hermans, 2011). In general solar irradiance is four times higher between April and August than the annual average. These differences can be explained by the angle of the sun; during winter the sunrays have to travel up to a four times longer distance through the atmosphere than during summer, thereby losing more energy. Besides, the long summer days obviously allow more irradiation compared to winter days, resulting in a much higher irradiation during summer months.

Besides season, geographic location also determines the amount of irradiance. Even in a small country as the Netherlands, differences in annual received irradiation are substantial as figure 32 is showing. In coastal regions an annual average of 1050kWh/m^2 is received where this is only about 950kWh/m^2 for the eastern part of the Netherlands. Furthermore, the vertical angle and orientation also affect receivable irradiation.

In the Netherlands the optimal orientation for solar collectors is 40-45º south facing, while the optimum angle for PV-panels is 36º. Even when the optimum orientation and angle are not feasible, it is often still profitable to install solar collectors because the efficiency losses are reasonable, especially for a deviation up to 40 degrees from a southern orientation. The efficiency losses for different orientations and optimal angles in the Netherlands can be found in the table below. (www.zonnepanelen.net)

Orientation	***Angle***	***Efficiency loss***
South	40-45º	Optimal
South West	30-40º	-5%
South East	30-40º	-5%
West	20-30º	-20%
East	20-30º	-20%

The average solar irradiance per month for different angles and a Dutch context is visualised in figure 33. On a vertical surface the deviations between summer and winter are considerably less compared to a horizontal surface. A surface that is constantly facing the ideal angle and orientation can have a 30% increase in efficiency compared the fixed ideal angle (de Goederen, 2013). However, this can only be done using mechanical equipment, and the extra costs do not compensate for the increased yield.

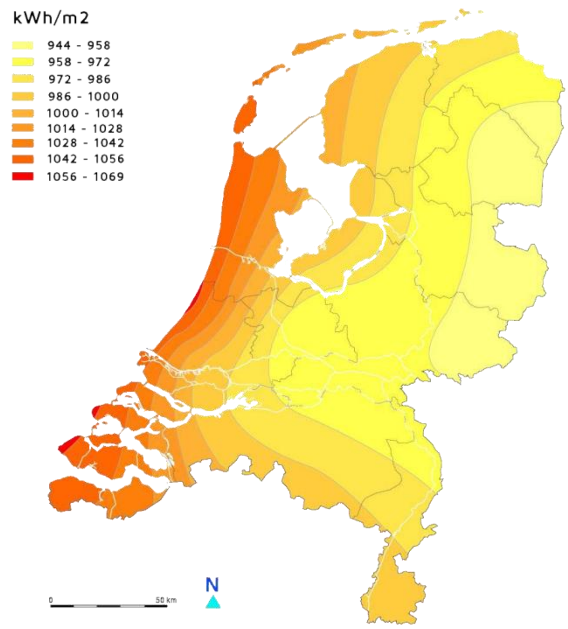


Fig. 32. Average annual solar irradiation in the Netherlands. (KNMI, 2012)

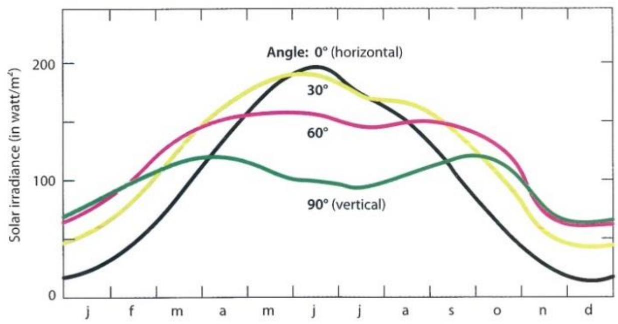


Fig. 33. Received irradiance on a Southern oriented surface in the Netherlands, for different angles. (Hermans, 2011)

4.2.1 Solar energy in the Netherlands anno 2015

Standard solar collectors are used for more than 30 years in the Netherlands. However, their market share is relatively small compared to PV-panels that are more common, even though solar thermal energy has far more energy potential; 475kWh/m^2/year compared to 122kWh/ m^2/year for PV-systems. This is very likely a consequence of the abundance of natural gas and the extensive gas network in the Netherlands. Due to low taxes on natural gas and net-metering it is more attractive for residents to invest in PV-panels. Yet from an energy point of view it would make more sense to use solar thermal energy instead of solar electricity. In southern European countries, solar thermal energy in CSP-plants is actually more cost-efficient than the use of PV technology.

At this moment only 0,17% of total space heating demand is generated by solar thermal collectors, showing the potential of solar thermal energy in the Netherlands. This potential for solar (thermal) energy has once been investigated by the company DNV-GL. They have estimated that 60% of the 650km^2 roof area of all dwellings and utility buildings are suitable for energy harvesting.

The theoretical yield of this roof area exceeds thermal demand on a yearly basis, but without adequate thermal storage this energy cannot be used. The report concluded that a collector area of about 80km^2 should be realistic in 2050, where it is about 2km^2 now. Although solar thermal energy is unlikely to cover all heat demand, the market for solar collectors has an immense growth potential of 4000% in the next decades.

4.3 Domestic solar thermal systems

Domestic solar thermal systems are usually used to cover DHW demand, but can also contribute to space heating. Such systems make use of short-term thermal energy storage in boiler or buffer filled with water. A solar thermal system differs from a conventional heating system because energy supply instead of energy demand is decisive.

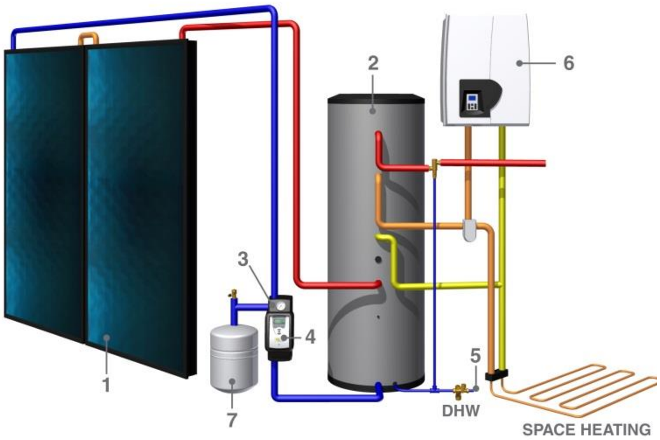


Fig. 34. Basic solar system layout for contribution to space heating. (www.hrsolar.nl)

A simplified example of a commonly used solar boiler system that can be used for DHW and space heating coverage is shown in figure 34. A domestic solar thermal system has several main components.

1. Solar collectors;
   provide solar thermal energy
2. Boiler/buffer;
   store thermal energy
3. Piping/pumps
   transfer thermal energy
4. Control unit;
   operate the system as efficient as possible
5. Water supply;
   provide water to be heated
6. Backup heating;
   Is used when not enough solar energy is available and is usually an electric element inside the boiler or a conventional gas boiler
7. Expansion tank;
   accommodate changes in volume of water due to temperature differences

4.3.1 Terminology

Before describing and comparing solar systems it is relevant to explain some specific terminology for better understanding of the topic.

Gross collector area

This is defined as the total dimensions of the collector, including frame.

Absorber area

As the name indicates, the absorber area is the surface on which received solar energy is collected and transferred to the heat transfer fluid.

Aperture area

The aperture area is the maximum projected area through which un-concentrated solar radiation enters the collector. In case of a FPC, the aperture area is smaller than the absorber area. In case of an ETC the aperture area equals the absorber area.

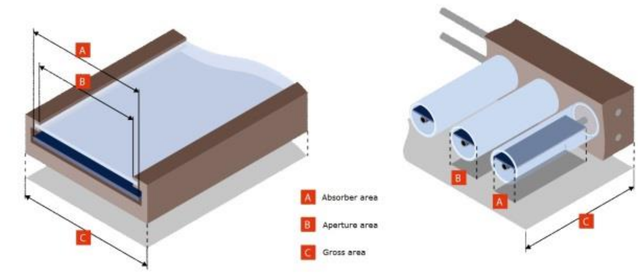


Fig. 35. Difference between gross, absorber and aperture area for a flat plate and an evacuated tube collector. (Viesmann, 2015)

Collector efficiency

The collector efficiency determines how much of the absorbed solar energy by the collectors is transferred to the HTF.
In a (simplified) formula:

$\eta = Q_{absorbed}/Q_{output}$

System efficiency

The system efficiency refers to efficiency of a total system. It is a combination of multiple parameters such as; collector efficiency, flowrate, thermal losses in piping and boiler, DHW-use, and pumping energy.
In a (simplified) formula:

$\eta = E_{input}/Q_{useful}$

E_{input} includes both thermal energy provided by collectors and electric energy used by equipment.

Solar fraction

Also known as "solar coverage" is defined as the amount of energy provided by the collectors divided by the required energy to heat up a volume of water. For example, if half the energy used to heat up a volume of water is provided by the collectors, the solar fraction is 0.5 or 50%.

In formula: $SF = Q_{collector}/Q_{demand}$

Heat transfer fluid (HTF)

This is a liquid (usually water or glycol) that is used to transfer thermal energy from collectors to boiler. In most systems the water or glycol runs through a closed circuit and exchanges heat by means of heat exchangers.

Flowrate

The flowrate plays an important role in the system efficiency. The optimum flowrate should be constantly monitored and react to the environment. A high flowrate results in a high collector efficiency because operation temperatures are lower, but the system efficiency drops because of increased pumping energy. Under normal circumstances the flowrate is about 0,02kg/s/m^2 collector surface or 30L/s. This depends on diameter of pipes and manifold, amount of junctions, viscosity and temperature of the fluid.

4.3.2 System types

A wide range of different solar thermal systems are available and they differ in system layout. System layouts can be categorized according to a few main characteristics.

Active or passive system

In an active system pumps are required to move the heat transfer fluid (HTF), and such systems therefore require electricity to operate the pump. In a passive system no pumping energy is required, but an active system is controllable and enables better solar heat management. This is illustrated in the figure below.

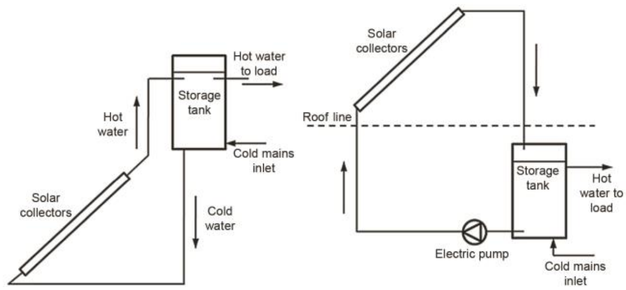


Fig. 36. Passive solar system (left) and active system (right). (Kalaiselvam et al., 2014)

Direct or indirect system

In a direct system, the water that needs to be heated flows through the collector before it is consumed. In an indirect system, a HTF is used to transfer the heat from the collectors to the water in the boiler by means of internal heat exchangers.

Fully filled or drainback system

In a fully filled system, the heat transfer fluid (water or glycol) is always present in the collectors, even when there is no useful irradiance. In a drainback system there is only HTF in the collectors when the pump is turned on. In order for a drainback system to work, the collectors must be placed higher than the tank. A drainback system doesn't require antifreeze or glycol and is therefore more sustainable and cheaper during operation.

Storage tank internal or external

In most cases the storage tank is placed inside the dwelling to minimize weather influences and resulting heat losses. Only in hot climates with mild winters, storage can be placed outside or on top of the collector. This last variant is called a thermosiphon system but will not be elaborated in this report.

The best system layout depends on the local context and design considerations that follow from the requirements. It must be noticed that not all system layouts can be applied in every climate region.

A solar thermal system has two main energy circuits. The primary circuit transfers thermal energy from the solar collectors to the storage tank. The secondary circuit transfers the water in the boiler to the tap (in case of DHW purpose), or in case of contribution to space heating, water from the buffer runs through the heating system.

4.3.3 Solar boilers

Besides the wide variety in system layouts, there are also several boiler types. The most common one is the monovalent-boiler (fig. 37a) in which water is heated up by an internal heat exchanger connected to solar collectors. Because solar energy is not always available, an (electric) heating element is placed inside the boiler for auxiliary heating. Another common type are bivalent boilers (fig. 37b) where besides solar collectors also an external heat source, for example a conventional gas boiler, is connected.

Another category are stratified boilers, which make use of the difference in density between hot and cold water. Different temperatures can exist in the boiler, with hot water on top and cold water at the bottom. This allows water of different temperatures inside the boiler, in contrast to a regular boiler where the whole contents has the same temperature. A stratified boiler can reach higher efficiencies because low return temperatures to the collectors are possible, allowing more energy uptake. Moreover, a stratified boiler heats up more quickly because it is not required to heat up the full volume in order to have useful temperatures as the scheme in figure 38 shows. This is especially beneficial during spring and autumn and will reduce required auxiliary heating.

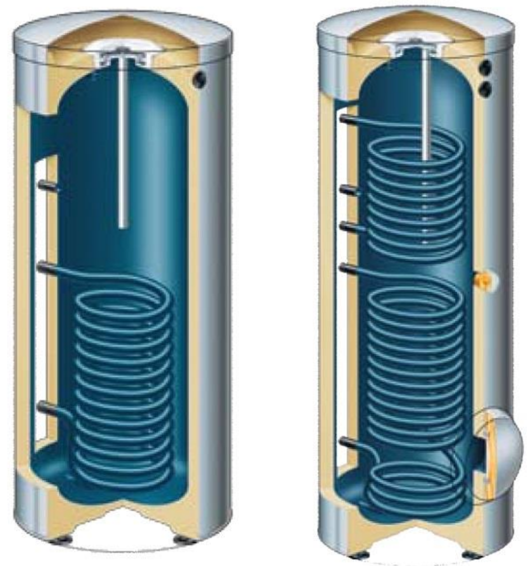


Fig. 37ab. Monovalent boiler (left) and bivalent boiler (right). (Viesmann, 2015)

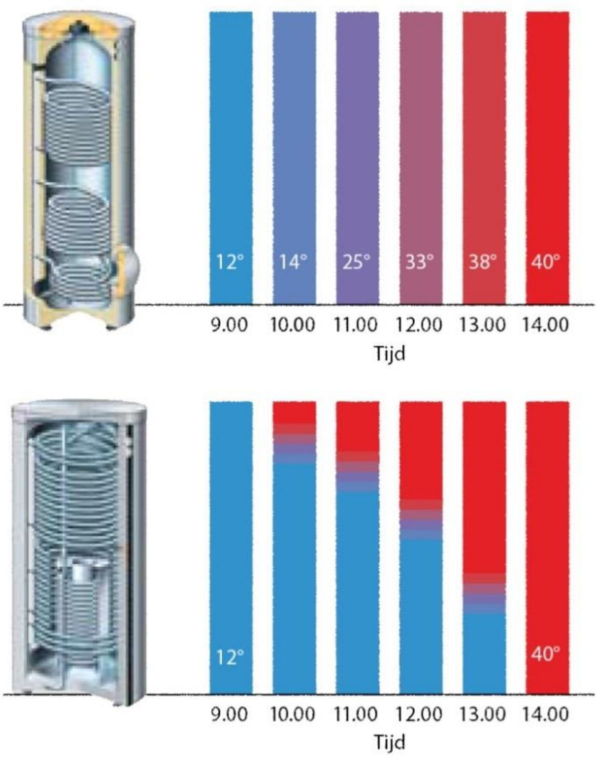


Fig. 38. Temperature of the boiler during the day of a conventional boiler (top) and stratified boiler (bottom). (Viesmann, 2015)

If solar energy also contributes to space heating the collector angle should be more towards 90º to make the best use of the low winter sun, and an additional buffer tank is usually part of the system layout. The principle difference between a boiler and a buffer is that water in the boiler leaves the system for DHW use, but the water in the buffer remains within the heating system. The buffer can control energy distribution and increase system efficiency. An integrated boiler and buffer combination is also available and is called a combi-boiler. This type has an additional spiral inside the tank through which cold water can be heated and used for DHW.

Boilers and buffers also cope with thermal losses. Two types of thermal losses occur: standby losses and radiation losses. Depending on the size, a boiler roughly loses 2,5kWh/day. In general a bigger boiler is more efficient because of the beneficial ratio of volume and surface area through which losses occur. Most boilers have about 70 to 100mm insulation around the tank.

During DHW demand, water from the boiler is mixed with cold water to achieve desired temperature. A boiler can therefore provide more consumable DHW than it actually contains. In a DHW solar thermal system, the temperature of the storage should be increased up to 65ºC twice a week to prevent legionella growth. Since it is uncertain whether this temperature can be reached by the solar collectors, a boiler always has an auxiliary heating element or a secondary energy source.

4.3.4 Sizing of system components

Literature describes several rules of thumb which can be used to determine the right boiler size and collector surface. Usually the amount of irradiation per square meter and DHW-use are indicative. The boiler size is related to the collector surface, which is usually 50 to 60L/m^2 collector surface. In the Netherlands the two-day method is often applied: the boiler should contain sufficient energy for 100% DHW coverage during 2 days.

In many cases suppliers and installers offer standard packages that can be chosen from.

Although rules of thumb provide a decent guideline for system sizing, calculations are needed to determine the optimal system size. Only computer simulations can accurately predict the optimum. Usually there are two kinds of optimum system sizes: the energy optimum and the economical or financial optimum. Unfortunately, these are never the same since the energy optimum will require an unprofitable investment.

A relatively big collector surface can yield a lot of thermal energy, resulting in a high solar fraction. The system efficiency will drop in this case because thermal losses in both piping and storage will increase due to higher temperatures. High system efficiency can be obtained if the average daily amount of DHW use per unit of area is greater. However, this will consequently lower the solar fraction.

A small boiler or buffer will heat up very quickly and reach its saturation point on a sunny day. Only a small part of the potential energy can be used resulting in a low solar fraction and system efficiency.

In the Netherlands a solar thermal system for DHW is usually dimensioned to cover 50 to 70% of demand. If the system gets closer to 100% coverage, the system efficiency drops. High performance goes at the cost of efficiency, as figure 39 is showing.

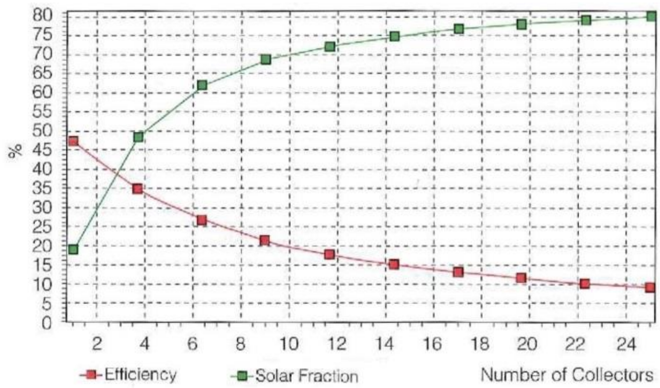


Fig. 39. Relation between system efficiency and solar fraction. (Laughton, 2010)

Systems with a relatively modest collector surface and a large buffer and/or boiler in respect to daily DHW use tend to have the best efficiencies. Yet, the decision between increased efficiency, best value for money and a high solar fraction is a fundamental design choice. Because systems with a high solar fraction require more collectors, they are often more expensive. If a system also contributes to space heating, the collector surface should be multiplied by a factor 2.2 (Viesmann, 2015).

4.3.5 Solar systems in the Netherlands

In the Netherlands solar systems are usually used for DHW appliances and examples of contribution to space heating can barely be found. Almost all systems are active (direct) systems with storage placed inside the dwelling to prevent thermal losses. The aforementioned system layout can be fully filled but in the Netherlands the drainback system is more common. A drainback system is an open system and needs about 8% expansion volume to accommodate changes in volume caused by temperature differences of the fluid. In closed system an expansion tank is used to accommodate these changes in volume.

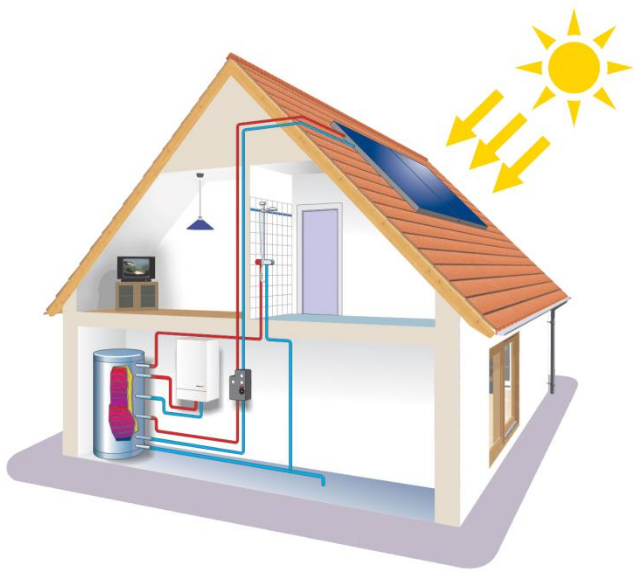


Fig. 40. Typical solar system layout in the Netherlands. (www.solarwatts.com)

A diagram of the most common system layout in the Netherlands is given in figure 40. The solar system only contributes to DHW demand and a natural gas boiler is still present.

As explained earlier, only 1.1PJ of Dutch annual thermal demand originated from solar thermal systems in 2015. With an average collector surface of 5m^2 and a yield of 1.4GJ/m^2 this comes down to roughly 160.000 systems. Most of these systems are installed in new dwellings that often have the optimal orientation and roof pitch, but due to governmental grants they are also becoming feasible in existing dwellings that are west or east orientated.

4.4 Solar thermal collector types

Nowadays, a wide range of solar heat harvesting technologies is available. A solar collector converts solar irradiance into usable heat. They can be classified into two categories: concentrating and non-concentrating. Non-concentrating solar collectors have the same area for intercepting and absorbing the solar energy, where concentrating solar collectors have a very large intercepting area and a small absorber area. This last technology is known as CSP (concentrated solar power) and is used in southern European countries and parts of the US as power plant. CSP usually requires large scale arrays or parabolic mirrors that cannot directly be integrated into existing dwellings. Therefore the scope of this chapter is narrowed down to non-concentrating solar collectors.

4.4.1 Flat Plate Collector (FPC)

The flat plate collector is the most common and used solar collector in the Netherlands and worldwide. The first FPC's already date back to the 1950's.

The FPC is a relatively low-tech system; it consists of a transparent cover, a black absorber plate, tubes and thermal insulation. Solar energy passes the cover and is absorbed by the absorber, where the cover creates a green-house effect. Tubes with water or glycol are located underneath this absorber plate to transfer the energy to the boiler (figure 41). Absorbers with integrated tubes are also familiar. The absorber and tubes are surrounded by insulation to prevent thermal losses.

Fig. 41. A typical flat-plate collector. (www.buderus.com)

The absorber and tubes are normally made of metal like copper, aluminium or stainless steel. A low absorber temperature reduces heat losses to the environment and increases efficiency. The cover is usually made from glass, but plastic covers are also known.

In a climate like the Netherlands, the output temperatures will vary between 40 and 80ºC degrees Celsius (Laughton, 2010). The measured thermal output is approximately 1,3GJ/m^2/year (Zegers, 2013).

A flat plate collector must be placed under an angle because the rain can otherwise not clean the surface. The FPC's come in fixed panel sizes, between 2 and 2,5m^2. FPC's are often connected in series, which reduces thermal losses and increases output temperatures because of reduced piping length.

In the past years some revolutionary FPC concepts have been developed such as the honeycomb panel, which has an improved efficiency. An evacuated FPC is also in development, which should have an even better theoretical efficiency.

4.4.2 Evacuated Tube Collector (ETC)

Fig. 42. Evacuated tube Collector. (www.enertech.co.uk)

Evacuated tube solar collectors (figure42) are available since the 1980s. Two types ETC's can be distinguished: direct flow and so called "heat pipes". In a direct flow-system water flows through the pipes and manifold, in a heat-pipe a secondary, closed system is used. Because the heat-pipe is the most common ETC, this type will be described in more detail.

The collector surface is an array of multiple tubes, each containing an absorber plate connected to a heat pipe with a liquid or gas inside. The tubes are about 30mm apart from each other in order to minimize shadows. The tubes are made of two glass layers with a vacuum in between, so one can speak of an outer and inner tube. The outside surface of the inner tube is covered in a coating that absorbs direct sunlight and reflects infrared light. When sun rays radiate on the tube the inner tube absorbs the direct heat and heats up. Because of the vacuum the heat cannot escape since it prevents thermal losses through both convection and conduction.

The inner tube contains an absorber plate fused to a heat pipe. This heat pipe is usually made of copper and filled with a liquid; for example methanol that undergoes an evaporating-condensing cycle. The hot liquid rises to the top of the heat pipe where the heat is transferred to the header that contains water or glycol. The liquid in the header exchanges heat with the storage tank, cooling down the liquid in the heat-pipe.

The cooled down liquid in the heat pipe will now return to the bottom of the pipe by means of gravity and the process is repeated again as visualised in figure 43. It is important to place the collector at an inclination of 15 to 75 degrees in order to allow the liquid to flow back to the bottom. The German company Viesmann has developed a set of collectors that can be applied on horizontal or vertical surfaces. Applying the heat pipes on a vertical surface will result in a 30% decrease in annual thermal yield compared to the ideal angle of 45°.

Evacuated tube collectors can produce high output temperatures ranging between 95 and 130ºC (Laughton, 2010). During strong sun each tube is able to provide 60W of thermal energy (Apricus, 2015). The average output in the Netherlands is measured at 1,8GJ/m^2/year (TNO, 2010).

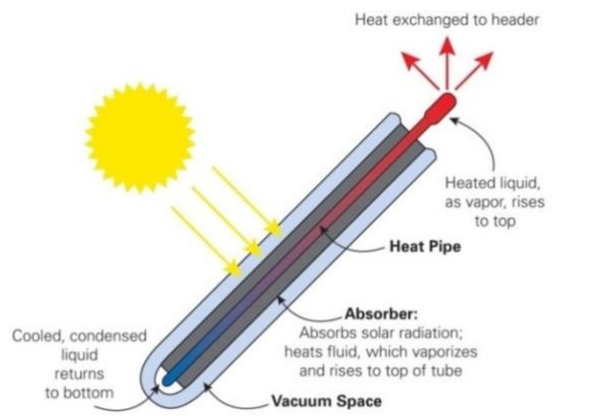


Fig. 43. Heat pipe principle. (www.homepower.com)

Another advantage of the ETC is its round shape. This shape allows the collector always to be perpendicular to the sun rays, meaning the amount of energy absorbed throughout the day remains constant.

Because ETC's operate on both direct and diffuse light, they are able to produce thermal energy during winter, even when the sky is covered in clouds. The life time of the collector is expected to be 15 - 20 years.

4.4.3 Photovoltaic Thermal Collector (PVT)

PVT-panels are capable of generating both electric and thermal energy. Although they can generate more energy per unit of area (if thermal and electric energy are added together) compared to FPC's and ETC's, the electrical and thermal yield is less compared to a regular PV-panel or solar collector.

It is important to notice there is a difference between a PVT-collector (which has a glazed cover) and the unglazed PVT-panels. Systems in the Netherlands usually do not have a cover and are therefore only capable of producing low temperatures. Thermal yield is in those cases used as low temperature feed for a heat pump.

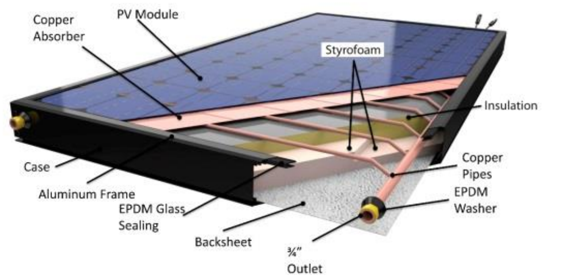


Fig. 44. Components of a Photovoltaic Thermal Collector. (www.innovatiecentrum.be)

At this moment PVT technology is still under development and prices are high compared to a PV-panels and aforementioned solar collectors. A PVT-panel in the Netherlands harvests around 1,2GJ/m^2 thermal energy per year and about 100kWh electric energy at a current price of €900/m^2 (Zegers, 2013).

If sufficient roof area is available, it is therefore cheaper to choose for separate PV-panels and solar collectors. Yet, if this technology becomes more efficient and cheaper it will definitely compete because of its combined yield.

4.4.4 Solar air-collectors

The previously described solar collectors all use a liquid to transfer thermal energy, but air may be used as well, although the specific heat capacity is about 4000 times less (0,9 kJ/m^3/K against 4180 kJ/m^3/K for water). This makes solar-air collectors unpractical for DHW and space heating contribution in a climate like the Netherlands, but in more warm climates they can be an appealing and especially cheap alternative.

Fig. 45. Example of a solar air collector. (www.nordluft.com)

Air collectors are usually used in the ventilation system to preheat incoming air in suitable climates. In a climate like the Netherlands solar air-collectors are usually used as source for heat pumps. The main advantage of solar-air collectors is the scalability; a bigger collector array does not reduce efficiency. The longer the air stays in the collector, the more energy it can absorb. Air-collectors do not necessarily have to be placed on the roof; they can also be placed on vertical surfaces such as walls.

Regular air-collectors can also be combined with PV cells, which is actually a PVT air-collector. In theory, the efficiency of the PV-cells can be increased because the air-flow cools down the cells increasing efficiency.

Solar-air collectors are a rarity in the Netherlands because of disadvantageous climate conditions. However, a reference technology which is described in chapter 5 makes use of solar air-collectors and is very promising, even for the Netherlands. Therefore it is worth to point out the air-collectors, but because of the scope of this report they will not be further elaborated.

4.5 Comparison of solar collectors

In the table below all relevant figures that are needed to determine the suitability of a collector type are visualized.

aspect	**FPC**	**ETC**	**PVT**
Efficiency (%)	20-50	30-80	20-40
Avg. annual thermal yield (GJ/m^2)	1,3	1,8	1,2
Avg. yield in winter (MJ/m^2)	90	180	60
Output temperatures (ºC)	40-80	60-130	30-50
Price/m^2 (€)	200	300	900

In the Netherlands, where solar collectors are predominantly used for DHW only, FPC's are more cost-effective. If collectors should also contribute to space heating it could me more interesting to choose for ETC's. Especially when energy has to be collected during winter or cloudy days, the ETC will always outperform the FPC due to the vacuum in the tubes, which significantly reduces thermal losses (Laughton, 2010).

Another advantage of the ETC is that their performance is only slightly affected by orientation due to its tubular shape, in contrast to FPC. This also accounts for low-angled winter irradiation which is mostly reflected by the FPC cover.

At this moment ETC's are more expensive compared to an FPC, but this price difference is getting smaller due to cheap Chinese products that flood the market, just like what happened with PV technology. This will make the ETC's a very interesting option for a solar system. Regarding life time, there are no big differences between collector types. An ETC is however more vulnerable because it is made of glass and leakages can occur, which affect efficiency.

PVT-collectors are very promising because of their combined yield, but their thermal performance is relatively poor compared to FPC's and ETC's. The expensive collectors exclude them for being feasible in a solar thermal energy system at this moment.

4.5.1 Best suitable collector type

The best suitable collector type depends on several factors and is strongly connected to the application of the collectors. Collectors that only have to provide DHW have different requirements than collectors that also have to contribute to space heating.

The choice of the best suitable collector type within the context of this report can be made by assessing how the three different collectors perform on the earlier mentioned aspects. Each aspect has a certain weight that relates to the importance regarding seasonal storage.

aspect	weight	**FPC**	**ETC**	**PVT**
efficiency	3	2	4	2
Annual thermal yield	2	2	3	2
Yield in winter	2	1	2	1
Output temperatures	2	2	3	1
Price/m^2	2	3	2	1
Maturity	1	3	3	1
Score		**25**	**35**	**17**

Efficiency, thermal yield during winter and output temperatures are the most critical aspects regarding the use of collectors for seasonal storage. This will all be explained in the next chapter of this report. The evacuated tube collector performs best on those aspects and also has the highest score compared to a FPC or PVT. The ETC will therefore be used in this report.

However, if the price for thermal energy storage becomes very low, thermal yield in winter becomes less important. In that case it would make more sense to yield all required energy during summer, which would be in favour of the FPC or even a PVT panel. The selection of the best possible collector type is therefore only possible if the whole system layout and deployment strategies are clear.

5. SEASONAL THERMAL ENERGY STORAGE (STES)

As indicated throughout this report, (seasonal) energy storage is the key element needed in order to achieve a renewable based energy future in the built environment. This accounts for both thermal and electric energy, but electric energy storage is only feasible for shorter periods. The Technology Roadmap Energy Storage, established by the International Energy Agency (IEA) also listed several reasons why energy storage technologies will play a crucial role in future sustainable energy systems. This accounts for both thermal and electric energy. The most important applications of thermal energy storage are:

- enable larger share of renewables
- system optimization
- demand side management

Especially demand side management will become crucial in the (near) future to effectively deal with energy surpluses and shortages, thereby reducing or preventing peak power and required investments in the electricity grid. Reduced peak power can also lead to optimized building installations since the systems can be smaller. TES in system optimization is also used to reduce the number of on and off cycles of the equipment, thereby saving energy and increasing the lifetime.

Conventional short-term energy storage systems such as solar boilers have proven their value for DHW applications, but seasonal thermal energy storage (STES) is a relatively new development. For years scientists and engineers have been searching for materials, methods and storage strategies to realize a solution. Today's research and development is mainly focussing on reducing the cost and improving the effectivity of high density storage methods (IAE, 2014).

The topic of seasonal heat storage covers a wide range of storage principles or methods and related technologies. In the first paragraph an introduction on thermal energy storage is given where the chapter focusses on seasonal storage later on.

Usually the scale of a thermal storage method is related to the scale of its purpose regarding financial feasibility. Because of the scope of this report, only decentralized small-scale storage technologies will be discussed, which excludes aquifer storage or other large-scale underground storage technologies.

5.1 Introduction on thermal energy storage

Thermal energy storage can be facilitated with different methods, materials and technologies. The three main storage principles (fig. 46) are:

- Sensible
- Latent (PCM)
- Thermochemical (TCM)

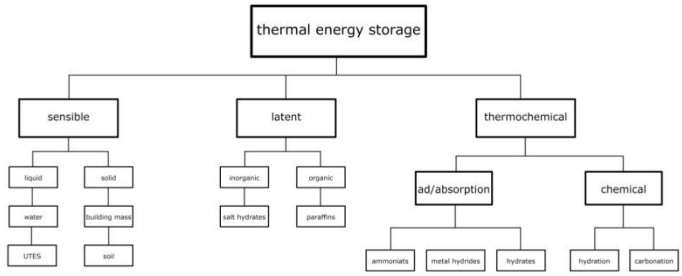


Fig. 46. Overview of thermal energy storage methods. (Own illustration)

Thermal energy storage or TES can be divided in short-term storage, which includes both peak shaving and diurnal storage, and long term (seasonal) energy storage.

Furthermore, a TES system or cycle involves 3 main processes:

- charging
- storing
- discharging

Most (seasonal) TES technologies are still in the early days of development and currently struggle to compete with other non-storage technologies due to high cost (IEA, 2014). However, STES will become very important for future renewable energy systems.

5.2 Thermal energy storage methods

This paragraph will describe the three main methods for thermal energy storage in order to make a pre selection for a suitable seasonal thermal energy storage system in the next paragraph. This paragraph will therefore not go in depth on actual storage solutions, since this will be done after a method is selected.

5.2.1 Sensible TES

Sensible heat storage is the most common form of thermal energy storage and is widely used in practice, as explained in chapter 4 of this report. Sensible heat can be stored in liquids (often water) or solid materials (usually the building structure). Solid storage includes all building materials such as brick and concrete, but also earth soil and rocks.

Although solid sensible storage is not relevant within the scope of this report, thermal energy storage in the building structure plays an important role in the building energy balance. A heavy structure can absorb more energy due to its large thermal mass. The advantage is that the indoor climate is less affected by outdoor temperature fluctuations. A disadvantage is that once this energy is absorbed it takes time to release, so additional (often cooling) energy is required to speed up this process and make the indoor climate comfortable. The ideal envelope should therefore have a variable thermal mass in order to be able to regulate its thermal gains and losses.

In sensible storage, the temperature of the storage material is increased by the amount of energy that is added to the material. The stored heat, or heat capacity can be directly related to the mass M, specific heat capacity of the material C_p and the difference in temperature T. The amount of energy stored in a certain amount of material can be calculated with the following formula:

$$Q = MC_p\,(T_1 - T_2)$$

Sensible thermal energy storage in water is a proven method and used in numerous applications. Especially short-term sensible storage in a buffer or boiler combined with solar collectors is widespread. These systems are described in the previous chapter.

Sensible heat storage is inevitably related to thermal losses because a temperature difference between storage and environment causes energy transport. A sensible storage tank therefore needs sufficient insulation. Performance of storage tanks is however still improving, for example the *Rikutherm* storage tank in which it takes 22 days for the water to cool down from 90°C to 40°C.

Large scale sensible storage concepts like the *Ecovat* (fig. 47) are another development that might be interesting for refurbishment of multiple dwellings. The concept consists of a large prefabricated concrete tank which contains water and is placed under ground. The system makes use of the power to heat principle, meaning excess PV electricity is converted to thermal energy and stored in the buffer. The water inside the tank is not pumped around like in a conventional boiler, but heat is exchanged at the sides of the tank. Multiple dwellings can be connected to the tank with a local district heating system and the storage capacity can vary between 1500 and 60.000m^3, depending on the amount of dwellings connected.

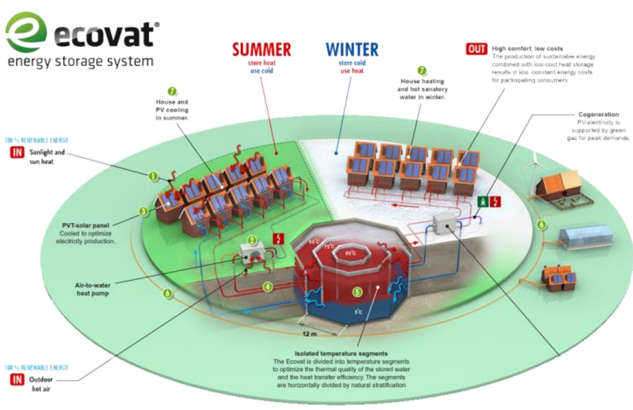


Fig. 47. Ecovat large scale sensible thermal energy storage. (www.ecovat.eu)

Conventional underground thermal energy storage (UTES) is another key application that uses sensible TES. UTES can be further specified in borehole (BTES), aquifer storage (ATES) and cavern or mine storage (CTES).

These techniques will not be further described because they cannot be used in small scale refurbishment.

Sensible underground heat storage is being used for single family dwellings in newly built buildings, but this method is often not suitable for refurbishment projects and is again not within the scope of this project.

5.2.2 Latent TES

Latent heat storage is achieved by heating up a material until it experiences a phase change. These materials are known as PCM's or Phase Changing Materials. The phase change can go from solid to liquid, solid to solid, or liquid to gas. PCM's can be dived in two groups: organic such as paraffin's and inorganic PCM's such as salt-hydrates. PCM's with one specific melting point are called eutectics, but by combining different PCM's a range of melting temperatures can be achieved. PCM's can also be integrated into a heat transfer fluid, so called slurry (Cabeza, Mehling, 2008).

When a PCM with a certain melting point is heated up above that point, it starts to melt by means of an endothermic process. The material absorbs and stores all excess heat until it is has reached its storage capacity. This heat is now stored latently. The amount of stored heat is equal to the increase in enthalpy or in formula:

$$\Delta H = U + pV$$

Where H is the enthalpy, U the internal energy, p he pressure and V volume.

Only when the temperature drops below the melting point, the heat is released again. This is a natural process and requires no additional energy. The process of charging and discharging is visualised in figure 48. Because of its natural energy absorbing and

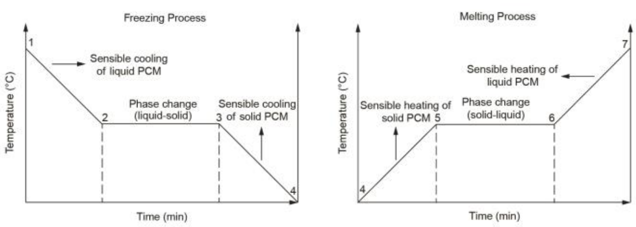


Fig. 48. (Dis)charging diagram of a PCM. (Kalaiselvam et al., 2014)

releasing properties, PCM's can be used to facilitate a variable thermal mass of the building envelope (Muntinga, 2013).

The natural ability to store and release energy makes PCM's particularly interesting for peak shaving of temperature differences in an indoor environment, thereby reducing cooling load and saving electricity.

During daytime when the space is heated up by the sun, the PCM's absorb the excess heat, preventing high indoor temperatures. Natural ventilation during night allows the PCM to discharge, releasing the stored heat.

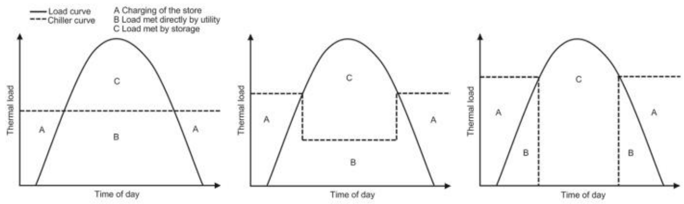


Fig. 49. Peak-shaving strategies for PCM's. (Kalaiselvam et al., 2014)

Peak shaving is a form of short-term energy storage and can be divided in three strategies as explained in figure 49. Peak shaving applications can be achieved with every storage method, but PCM's are particularly interesting since the process of absorbing and releasing heat does not require additional energy. PCM's are widely available and implemented in buildings. Different PCM integrated products exist, such as wallboards, ceilings (fig. 50) and even plasters with integrated PCM capsules. A comprehensive overview of PCM applications and methods for successful deployment can be found in appendix 3.

Fig. 50. Ceiling with integrated PCM's. (www.bine.info)

Where PCM´s are very suitable for the aforementioned appliances, they are most likely not suitable for seasonal storage due to a number of reasons. The PCM's that are now used in practise operate with a melting point around 20-26°C. For STES, much higher melting temperatures are required; at least 40°C is needed for low temperature space heating and 60°C to also provide DHW. This would mean a heat pump is still required.

PMC's operating with these temperatures are already available, but in order to prevent the material from releasing its heat the storage temperature should stay above the melting point (Cuypers et al., 2014). This means the PCM tank should be highly insulated and kept on a high temperature in order to prevent thermal losses, which is hard to reach inside a building because of shortage in space and costs of insulation.

Another major disadvantage is the low thermal conductivity of PCM's, causing the material to slowly charge and discharge. This can be improved by the storage tank design and often materials such as metals and graphite are added to improve conductivity. Another solution is to store the PCM liquid in a metal foam structure allowing for a high thermal conductivity. Downside of this method is that the total storage volume has to increase significantly and corrosion can take place, but moreover the costs will increase significantly.

PCM's are also rather expensive. Price of commercial PCM ranges from €0,5 and €10 for one kilogram of material. This makes seasonal storage using PCM´s far from economic at current prices of fossil fuels. To be competitive, the (dis)charging cycle should therefore be diurnal (Cabeza, Mehling, 2008).

5.2.3 Thermochemical TES

Thermochemical heat storage is a collective name for multiple chemical reaction types. This is clarified in figure 51, where the different types are visualised. Thermochemical storage and chemical storage are sometimes confused in literature. This is due to another term that is often used for thermochemical heat storage: compact thermal energy storage, because of the high material energy density these materials have. Material energy densities range from 1000 to 2900MJ/m^3 (Blok et al., 2004). Compact energy storage covers both thermochemical and chemical storage.

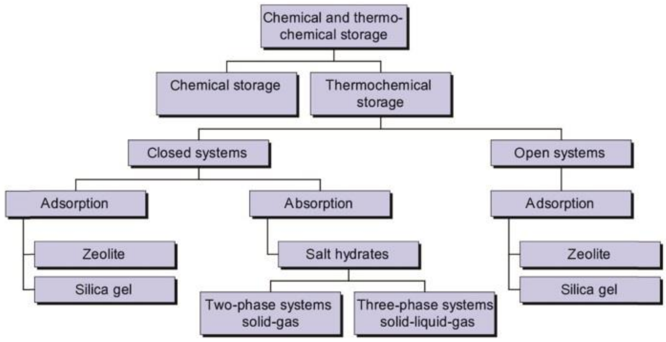


Fig. 51. Overview of (thermo)chemical storage. (Kalaiselvam et al., 2014)

Thermochemical reactions can take place in an open or closed system, where open implies contact with the environment. Closed systems are only suitable for adsorption reactions where open systems are suitable for both ad- and absorption reactions.

The main difference between chemical and thermochemical storage is the change in molecular bonds of the material. In sorption process these do not change, where molecular bonds are changed in chemical reactions. Sorption includes both ad- and absorption.

Adsorption can be defined as the adhesion of molecules on the surface of a solid substance. Absorption is a similar process, but involves adhesion of molecules to the whole volume of the substance. Desorption can be defined as the reverse reaction of both ad- and absorption.

Common TCM's are salt-hydrates and zeolites. The principle of storing energy in a TCM is visualised in figure 52. If a substance C (s) is heated up, it splits in substance A (s) and water vapor B (g) by means of an endothermic reaction. The energy for the endothermic reaction comes from an external heat source, usually solar collectors.

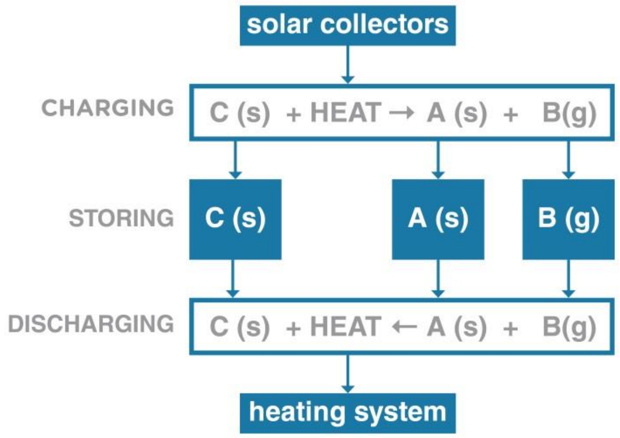


Fig. 52. Principle of thermochemical storage in a residential context. (Own illustration)

At this point the salt is dehydrated, which means the water is extracted from the salt and this process can be seen as the charging process (Kalaiselvam, et al., 2014). The charging process also requires a small amount of condensation energy to liquefy the water vapor.

Substance A and B can be stored separately at any temperature because no thermal losses are involved. If A and B are combined again the reverse hydration reaction occurs, recreating substance C plus an amount of heat. The discharging process occurs by means of an exothermic reaction, thereby releasing heat. The released heat can be guided along heat exchangers that transfer the heat to the heating system of a dwelling. During discharging, evaporation energy is required to turn the liquid water into vapor again.

An example of a thermochemical storage reaction using magnesiumsulphate-heptahydrate is given below:

$MgS0_4$ (s) + $7H_2O$ (g) ↔ $MgS0_4x7H_2O$ (s)+ Q

Magnesiumsulphate-heptahydrate is described in literature as one of the candidate materials for development of thermochemical storage (Blok et al., 2004).

In contrast to sensible and latent storage, thermochemical storage is still under development. Although thermochemical storage is more complex than sensible or latent storage, the technology is very promising for seasonal thermal energy storage. Several research institutes and companies are working on a feasible thermochemical storage solution, but a number of issues still need to be improved before technology becomes market ready.

Fig 53. Prototype of thermochemical storage modules used in the MERITS-project, see paragraph 5.6. (www.TNO.nl)

5.3 Seasonal thermal energy storage

This paragraph is about how three main TES methods can be used for seasonal storage and what their (dis) advantages are. The most suitable method will be selected at the end of this paragraph and elaborated in the next paragraph.

5.3.1 Design criteria for seasonal storage

Literature describes several design criteria and design factors that influence the suitability of a TES-method for seasonal or long-term storage (Tian, 2012). These general design criteria can be divided in technical and cost-effectiveness criteria.

- Technical criteria
  - high thermal storage capacity
  - low thermal losses during storage
  - efficient heat transfer between HTF and storage material
  - good stability of storage material
  - complete reversibility of large number of (dis)charging cycles
  - good controllability of (dis)charging process

- Cost-effectiveness criteria
  - cost of storage material
  - cost of heat exchanger(s)
  - cost of space/enclosure for storage container

Technical criteria are crucial for the system to become feasible anyway. However, if a system is not cost-effective it won't be financial feasible and will therefore never be implemented in real life practice. The importance of financial feasibility is illustrated by an example in paragraph 5.3.3. A good design also addresses environmental criteria, and these will also determine if a design is really sustainable.

5.3.2 Suitability of TES-methods for decentralized seasonal storage

Energy storage density is the most important factor to determine the suitability of storage method because of the shortage in space in the built environment. The figure below shows how much storage material is required to cover a space heating demand of 6,7GJ with a temperature difference of 50ºC. To determine the exact storage volume, accurate calculations have to be made, which is done for the case study in next chapter of this report. In reality, volume for heat exchangers and insulation will increase actual required volume, especially for storage in water.

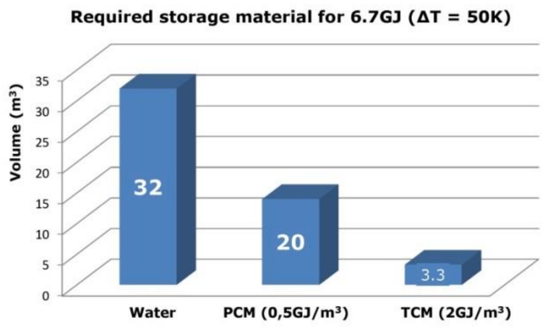


Fig. 54. Required material volume to store a thermal demand of 6,7GJ. (Own illustration)

Although Sensible TES systems are easier in design compared to latent or thermochemical systems, their energy density is too low to integrate in a single dwelling because a minimum of 32m^3 would be required (figure 27). Sensible STES can however be used in combination with underground storage methods, but this is not within the scope and boundary conditions of this report. In terms of energy density, TCM's are preferred over PCM's since their energy density is 4 times higher on average.

Another important aspect in favour of TCM's is the ability to store the heat without any thermal losses. Where sensible and latent heat storage tanks need to be kept on temperature requiring significant insulation and auxiliary heating, TCM storage tanks can operate at ambient temperature. Thermal losses will only occur during (dis)charging and these can be minimized by applying a thin layer of insulation.

Sensible heat storage in water is an already proven technique and PCM´s are already used in building materials for many different purposes, but TCM´s are still in their research and development phase. This is a disadvantage if a solution is desired that can be implemented on the short-term, but the scope of this report is aims on a realistic solution that is available in about 5 years from now.

The most important results of literature study regarding suitability of storage methods for seasonal TES are summarized in the scheme below. Each method is assessed on how it performs on a certain aspect. A 4 means the method performs very well and a 1 stands for a bad performance. Since not every aspect is equally important, each aspect has a specific weight that is used to multiply the score. The numbers at the bottom indicate the final score.

aspect	weight	**Sensible**	**Latent**	**Thermochemical**
Storage density	3	1	2	4
Thermal Losses during storage	2	1	1	4
Cost of Storage material	2	4	1	2
Number of Cycles	1	4	2	2
Complexity	1	3	2	1
Maturity	1	4	2	1
Score		**25**	**16**	**28**

The scheme shows that thermochemical storage performs best on the most relevant indicators for seasonal TES, although the difference with sensible storage is not significant. Yet, storage density and thermal losses are considered to be decisive and therefore thermochemical storage seems to have the most potential for further elaboration regarding the research objective in this report.

5.3.3 Importance of financial feasibility

To illustrate the importance of financial feasibility a storage concept from TNO, the COMPAS-project will be briefly discussed (without going into technical details). The concept makes use of the chemical looping combustion principle, which is normally used in carbon-capture. The concept is categorized under chemical storage and makes use of metal-metal oxide reaction using cupper combined with hydrogen electrolysis which is driven by PV-panels. The eventual storage density of the system is estimated at $6GJ/m^3$, but in current tests a density of $3GJ/m^3$ is achieved.

The storage element has a tubular shape of which the length indicates the storage capacity and the diameter the output power. Technical advantages compared to regular thermochemical storage are the absence of moving parts and pumping fluids in combination with a very high storage density. Modularity and flexibility make this concept seemingly promising.

Although this concept could be technically feasible, the price of the concept for a domestic context (5,3GJ thermal demand) is estimated to be €36.000 of which €22.000 for the cupper. Even though its high storage capacity, the costs makes the system unlikely to become feasibly in the future. Prices normally drop if a technology is scaled up, in the case of cupper the opposite may occur; a high cupper demand will increase prices even more. One should however note that cupper remains is value after use, but this doesn’t reduce the required investment.

5.4 Thermochemical STES

As explained in the previous paragraph, thermochemical storage has the most potential regarding decentralized seasonal thermal energy storage for a single family house. A thermochemical storage system can be explained as a sorption heat pump. The difference with a regular heat pump is that electric energy is only used for pumping, and not for compression.

5.4.1 Theoretical background

Accurate mathematical models of thermochemical storage reactions are still under development, but some relatively simple formulas can be used to calculate efficiencies of (dis) charging process. The efficiency relates to the energy flows between heat transfer fluid (from collectors and to heating system) and storage (dis)charging.

A dehydration reaction occurs in different steps, where each step requires a unique temperature and subsequent amount of energy. The energy that is stored in the material caused by dehydration (energy accumulation) is equivalent to the reaction enthalpy, ΔH. The nett energy input minus thermal energy losses is equal to the energy accumulation in the material. The efficiency of the charging process can be found when the energy accumulation in the TCM is divided by the energy input from the HTF. In formula, the charging process efficiency can be written as:

$$\eta_c = \Delta H_c / m_c C_p(T_2 - T_1)$$

In which m_c and C_p refer to the mass and specific heat capacity of the heat transfer fluid.

During discharging the efficiency can be calculated in a similar way, but the energy accumulation has a negative value because it equals the released energy of the exothermic reaction.

$$\eta_d = \Delta H_d / m_d C_p(T_4 - T_3)$$

Because the actual storage doesn't involve thermal losses, the overall efficiency of a storage reaction can be found if the released energy during discharging is divided by the energy input during charging. In formula:

$$\eta_o = m_d C_p(T_4 - T_3) / m_c C_p(T_2 - T_1)$$

Although thermochemical storage itself doesn't involve thermal losses, the overall efficiency of a storage reaction will never be 100% due to thermal losses during (dis)charging. The losses can be minimized if the reactor in which the reaction takes place is sufficiently insulated. The highest efficiency can be reached when the reactions take place inside a vacuum. An exergy evaluation of a thermochemical storage system plays an important role in system optimization since it can be used to identify and clarify thermal losses within a storage process (Abedin, 2015).

5.4.2 Candidate materials and reactions

After literature study and several interviews with researchers on Thermochemical STES (i.a. Wim van Helden and Ruud Cuypers), a pre-selection of the most promising materials can be made. This pre-selection is based on material performance, lab tests, reactor / storage design possibilities and costs of material.

Current research mainly focuses on zeolite storage and salt-hydrates. Salt-hydrates have the highest energy densities but they cope with corrosion issues when they are in contact with metals. Zeolites do not have these problems and their reaction is more reliable, but their energy density is significantly less. If corrosion problems are solved, salt-hydrates have the most potential for future use due to their high energy density. The focus in research is on the following salt-hydrates, where number 1 has the most potential and so on.

1. Na_2S x $7H_2O$
2. $MgSO_4$ x $7H_2O$
3. $CaCl_2$ x $6H_2O$
4. $MgCl_2$ x $6H_2O$
5. Na_2SO_4 x $10H_2O$

The choice for a material largely depends on available charging temperatures because each reaction step requires a specific temperature. The final dehydration reaction occurs at a relatively high temperature and results in the highest storage density. In general, high output temperatures from the collector will therefore result in a high storage density because of the better dehydration. In case the required temperature is not reached by the collectors, which is likely the case during winter, the storage can still be charged, but the storage density is less because the reaction is not complete. The choice for a material is therefore strongly related to the properties and performance of solar collectors.

Besides (de)hydration temperatures, other relevant requirements for material selection can be found in literature (Cabeza et al., 2015).

- Material storage density
- Specific heat capacity
- Thermal conductivity
- Chemical stability
- (dis)charging speed

Obviously, cost-effectiveness and environmental criteria also need to be considered (see 5.3.1).

5.4.3 Reactor concepts

A thermochemical reaction always takes place inside a reactor. Two basic reactor concepts exist (Drück et al., 2011).

- external reactor concept (pumping of substance between storage and reactor)
- integrated reactor concept (less pumping energy required)

The reactor concepts are visualised in fig. 55.

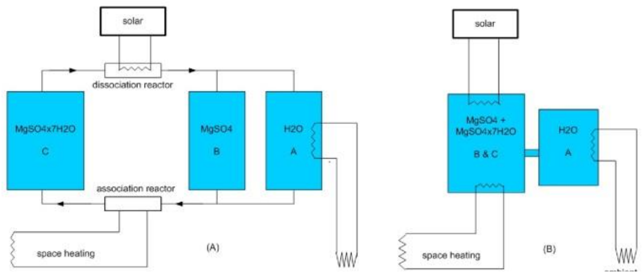


Fig. 55. External and integrated reactor concept for thermochemical storage. (Bleijendaal et al., 2008)

The choice between an external or integrated reactor is a fundamental design choice. Main advantage of the integrated reactor over the external reactor is that no pumping energy for material transport is needed. A disadvantage of the integrated reactor concept is that required heat exchange area is much larger than in an external reactor, resulting in a bigger reactor. In an external reactor only the required amount of TCM (Thermochemical material) is heated up, which makes this option more energy efficient and because of the smaller reactor the highest effective storage density can be reached.

Both systems in figure 55 are open storage systems. Open means the water in the gaseous state is released to the environment during charging, and water is extracted from humid ambient air during discharging. Local climate plays an important role in the performance of an open system and is therefore only suitable in climates with sufficient humidity (Bales et al., 2014). In Dutch context a closed system is preferred because of the low humidity in winter.

Closed reaction systems are able to reach higher output temperatures for heating application compared to open systems. A closed system can be designed to discharge thermal energy at different temperatures, making them an appealing option for medium temperatures TES (IAE, 2014). A closed system requires operation under vacuum for optimal vapor transport in the reactor.

5.4.4 System layouts for thermochemical STES

Besides research on storage materials, a lot has been done in system design for thermochemical storage as well. Simulation software (i.a. TRNSYS and INSEL) has been extensively used by researchers on thermochemical storage systems to adequately size thermal storage components for different applications. The simulations have not led to consistent rules of thumb that can be used for system design (Perfumo et al., 2014), but some interesting conclusions, derived from simulations are described in literature.

First of all, simulations have shown that the effect of the charging temperature of the TCM on the system performance depends on the type of collectors used and the system dimensions. ETC's are preferred for TCM charging, since relatively high charging temperatures have to be reached (Van Helden et al., 2008). As previously explained, higher feed temperatures result in the highest storage density and can lead to optimized storage sizes.

Simulations have also shown that adding a short-term buffer to the system layout (figure 56) has positive effects regarding the requirements for the TCM. In this system layout the solar collectors will always primarily charge the short-term buffer and only when this buffer is saturated the long-term TCM storage is charged. This will reduce required storage capacity but also reduces requirements on the cycleability of the material since less cycles are needed. In a system with short-term buffer the storage module delivers the energy to the buffer instead of directly to the heating system. This can reduce required peak power.

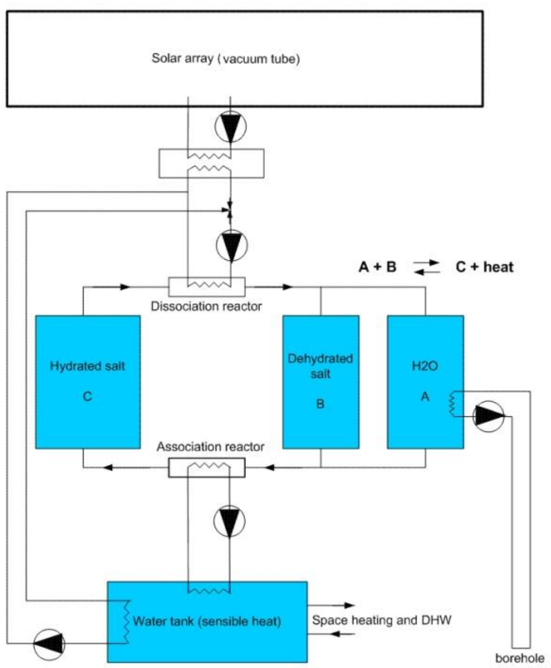


Fig. 56. Conceptual system layout for thermochemical storage in a residential context. (Bleijendaal et al., 2008)

Furthermore, simulations have shown that a thermochemical system works best for low or medium temperature applications. This means a thermochemical system that also needs to cover DHW demand, with a temperature of 60ºC is not desirable and reduces the performance of the salt-hydrate (Rindt et al., 2008). If no DHW coverage is required, the discharge power of the TCM storage can be reduced to about 1-2kW (Van Helden et al., 2008). Moreover, if ETC's are used as solar collectors and a short-term buffer is present, DHW demand can already be largely covered. It wouldn't make sense to set high output requirements for the TCM storage when the resulting DHW-demand can also be achieved by charging the short-term buffer efficiently at night or during low-tariff hours with a small auxiliary electric heater.

Some interesting conclusions for the collector surface are also found. An increased collector surface will only reduce the number of standstill hours and has little effect on the solar fraction. If the collector surface is dimensioned small, an increase in required TCM charging temperature implies that the storage capacity is not fully used. This result in a substantially smaller solar fraction than could be obtained when sufficient collector surface is used (Van Helden et al., 2008).

Reactor and tank design/geometry isn't within the scope of this thesis because of the complexity, but is eventually important in both technical and financial feasibility of thermochemical storage. Reactor and heat exchanger design is crucial for good vapor transport (also known as mass transport) out and into the TMC, because otherwise optimum storage densities cannot be reached. Fixed-bed reactors are described in literature as most appropriate for salt-hydrate (de)hydration reactions because of their simple design and working principle (Perfumo et al., 2014). Moving bed and fluidized bed reactors have a better heat and mass transfer (Abedien, 2015), but are far more complex and expensive.

5.5 The thermal battery

In this paragraph all relevant properties of a thermal battery will be discussed. This battery is currently being developed by TNO and is not a result of this research.

5.5.1 Storage material

After additional literature research and interviews with relevant researchers, the final storage material is selected. Given the current state of research on thermochemical storage, the Na_2S-hydrate storage reaction seems to have the most potential for future applications. The thermal battery in this report will therefore make use of Na_2S-hydrate reaction to store solar energy.

FIg. 57. Na_2S-hydrate flakes. (www.tbchemical.com)

Na_2S-hydrate is a hygroscopic salt and does not exist in nature, but its main compounds are widely available. The material is produced by a carbothermic reduction reaction and comes in yellowish flakes (fig. 57). Production mainly takes place in China and retail price is about €450/1000kg.

In practice the Na_2S-hydrate will not be used in its pure form; the particles are micro-encapsulated by polymers to enhance material stability. This guarantees a large number of storage cycles without degradation. The actual storage material is therefore a composite material, and its exact composition is patented by TNO
(patent nr: US 20150344763).

5.5.2 The battery

The battery has two main compartments separated by a valve; a top compartment with the active storage material in a fixed bed reactor, and a bottom compartment with a condenser and evaporator. There is a vacuum inside the battery and the whole battery is enclosed in 60mm insulation to minimize thermal losses during (dis)charging. The battery is schematized in figure 58.

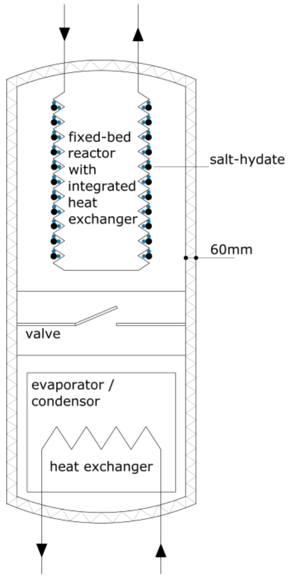


Fig. 58. Diagram of a thermal battery. (Own illustration)

The actual storage reaction takes place in the fixed bed reactor, of which an example can be seen in figure 59. This reactor type allows good vapor transport for optimal storage density. Pipes through the middle of the reactor transfer energy from and to the buffer during (dis)charging. In case the battery is charged or discharged the valve is closed to prevent vapor transport.

The bottom compartment houses an evaporation and condensation unit. This is used to liquefy the water vapor in order to store it and turn it into vapor again during discharging. The bottom part is connected to a low temperature source that provides energy for the condensation and evaporation process.

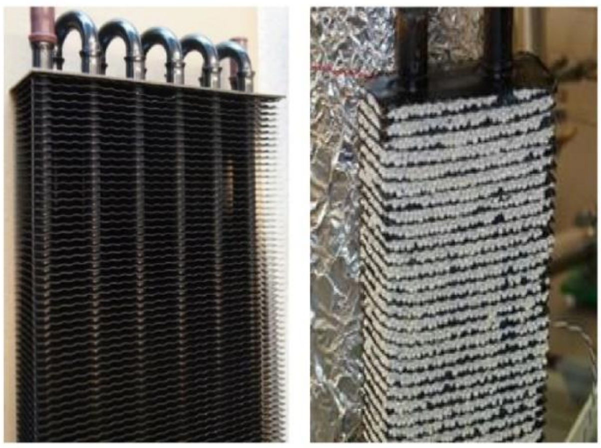


Fig. 59. Example of a fixed-bed reactor with salt-hydrate. (provided by Ruud Cuypers, TNO)

5.5.3 The storage reaction

The energy is stored in the material by means of a hydration reaction, which requires external energy. This energy comes from the solar collectors, but could also be generated electrically. The (de)hydration occurs in different steps, from the 5-hydrate to the half-hydrate. The 9-hydrate is not suitable due to its instability. Each step requires a certain temperature and increases enthalpy, or storage density (fig. 60).

Extrapolated onset temperatures, T_c, and enthalpies of reaction per mole of dry Na_2S for dehydration and rehydration reactions at $p_{H_2O} = 17$ mbar

Reaction	T_c (°C)	$\Delta_r H$ (kJ mol^{-1})
$Na_2S{\cdot}9H_2O\,(s) \rightarrow Na_2S{\cdot}5H_2O\,(s) + 4H_2O\,(g)$	32.5 ± 1.5	215 ± 20
$Na_2S{\cdot}5H_2O\,(s) \rightarrow Na_2S{\cdot}2H_2O\,(s) + 3H_2O\,(g)$	72.0 ± 1.0	176 ± 12
$Na_2S{\cdot}2H_2O\,(s) \rightarrow Na_2S{\cdot}\frac{1}{2}H_2O\,(s) + 1\frac{1}{2}H_2O\,(g)$	82.0 ± 0.5	94 ± 8
$Na_2S{\cdot}\frac{1}{2}H_2O\,(s) + 4\frac{1}{2}H_2O\,(g) \rightarrow Na_2S{\cdot}5H_2O\,(s)$	71 ± 1	−308 ± 20

Fig. 60. Reaction steps of Na_2S-hydrate. (de Boer et al., 2002).

The total storage reaction is written as:

$$Na_2Sx5H_2O + Q \leftrightarrow Na_2Sx\frac{1}{2}H_2O + 4\frac{1}{2}H_2O$$

A diagram of the storage reaction and required energy flows is shown below. The storage reaction only takes place during (dis)charging, so the actual storage does not involve any energy flows. The (dis)charging principles and required amounts of energy to store 1GJ of thermal energy are explained in the next paragraphs.

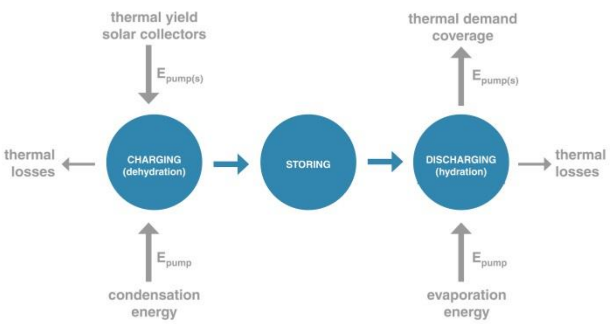


Fig. 61. Energy flows during (dis)charging. (Own illustration)

When the material is fully hydrated a theoretical material storage density of 2.9GJ/m^3 is possible. In practice, the reaction takes place inside a thermal battery, which consists of multiple parts that add volume. The effective storage density therefore has a theoretical maximum of about 1GJ/m^3, and this figure will also be used in this report. In current research, an effective storage density of 0.6GJ/m^3 is aimed for (CREATE-project), but this can be optimized.

5.5.4 The (dis)charging principles

The process of (dis)charging of a thermal battery can be explained by figure 62. The cycle starts with a discharged battery. At this moment the salt is fully hydrated, the valve is closed and the evaporation/ condensation compartment is empty.

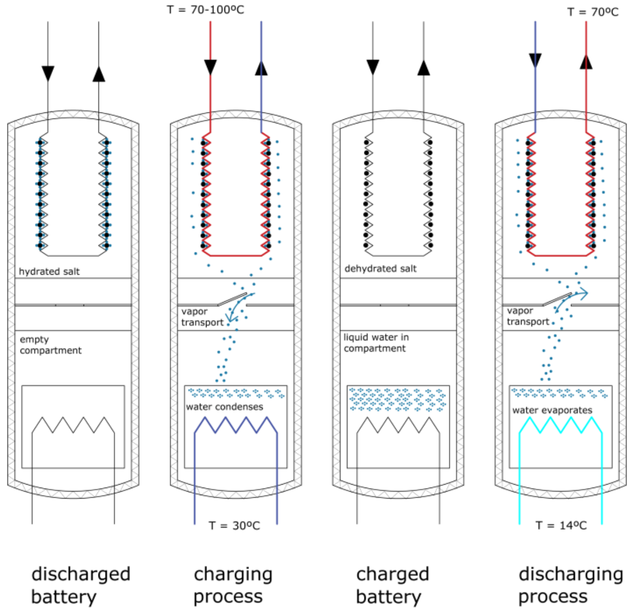


Fig. 62. Charging and discharging process of a thermal battery. (Own illustration)

During charging, water of a temperature between 70 to 100ºC from an external source, (solar collectors or electricity) runs through the heat exchangers in the salt-hydrate compartment. The dehydration process starts and water molecules are released from the salt. The valve is now opened and the water vapor enters the bottom compartment. Here the water is slightly heated up to force it to condensate. This is needed to turn the water into a liquid and requires a temperature of about 30ºC. This can be generated electrically, but the return water from the top compartment can also be used. This return water will be approximately 20 degrees, so only energy for a 10ºC temperature increase is required.

The battery can be charged in one time if sufficient energy is available, but can also be charged over multiple days. A battery can still be charged if the required temperatures for full hydration are not available, but this will lead to a lower storage density.

When the battery is charged, all the water is in the evaporation and condensation compartment. The salt is dehydrated and the valve is closed. The battery is now in a passive state; as long as the valve remains closed no energy gets lost and the thermal energy can theoretically be stored for eternity.

During discharging, the water in the bottom compartment is cooled down, forcing the liquid water molecules to evaporate. A temperature of about 14ºC is enough for the water to evaporate. This energy can be generated electrically and if the dwelling is situated in a watery environment, even outside water could theoretically be used.

When the valve is opened, the water vapor enters the storage material compartment, hydrating the salt. During the hydration process, the enthalpy energy is released again and this energy is absorbed by cold water flowing through the heat exchangers. The energy heats up the water and this can then be used for space heating or DHW purposes.

The battery can be discharged in once or in steps. The efficiency is the best when the battery is discharged at once, since almost all enthalpy energy can be transferred by the heat exchangers in that case. In case the battery is discharged in steps, some energy will get lost because the salt needs time to cool down, thereby still releasing heat without having water inside the heat exchangers. In current research the battery is discharged at once to accurately measure the thermal balance of charging and discharging energy. The discharging process will eventually be controllable, and this is also assumed within this report.

5.5.5 Energy use for (dis)charging

As explained in the previous paragraph, the charging and discharging process requires additional condensation and evaporation energy, as well as pumping energy for the energy to be transferred. This can be calculated per GJ of stored energy in the batteries. In this paragraph only the condensation and evaporation energy is calculated, since pumping energy depends on chosen system layout. The required pumping energy for (dis)charging is calculated in paragraph 7.2 of this report.

A material storage density of 2.9GJ/m^3 and a system storage density of 1GJ/m^3 means about 1/3 of the volume is salt-hydrate. Natriumsulfide-hydrate contains between 10 and 76% water (depending on the hydrate number), which is 40% on average. This means 0.13m^3 or 130L of water needs to be condensated during charging and evaporated during discharging to store 1GJ of thermal energy. During charging, a temperature of 30ºC is required, but this is partly covered by heat recovery, so the temperature increase is only 10ºC.

Thermal energy to charge 1GJ:

$$Q = MC_p(T_{out} - T_{in})$$

$$= 130*4186*(30-20) = 5,5MJ \pm 1,5kWh$$

Thermal energy to discharge 1GJ:

$$Q = MC_p(T_{out} - T_{in})$$

$$= 130*4186*(14-5) = 25MJ \pm 7kWh$$

Total condensation and evaporation energy to charge and discharge 1GJ of thermal is 8,5kWh.

It must be noticed that thermal losses during discharging are not taken into account since they are not known yet. In reality, that would mean more than 1GJ has to be stored to discharge 1GJ of thermal energy. This will consequently slightly increase required condensation and evaporation energy.

5.5.6 Battery storage capacity

Because thermal batteries are not fully developed and available yet, it is uncertain what the storage capacity of a single battery will be. From a cost-effectiveness perspective, the battery should be as big as possible because this means less heat exchanger surface and insulation per storage volume.

However, there are technical restrictions regarding battery size. The bigger the volume, the more complex the heat exchanger geometry should be because otherwise not all salt can be (de)hydrated. Additional research and computer simulations are required to determine the optimal size and correlating storage capacity.

TNO is currently testing thermal batteries of 60MJ, with an effective storage density of about 0,17GJ/m^3. It is however very unlikely for a battery of 60MJ to be feasible, since each battery requires a single evaporator, condenser and heat exchanger, making a single battery very costly. It is more likely that the eventual capacity of a thermal battery is somewhere between 200 and 300MJ each. In this report a storage capacity of 250MJ will be assumed, which equals a volume of 0,25m^3 at a storage density of 1GJ/m^3.

It is also imaginable that the eventual battery only has a salt-hydrate compartment. Multiple batteries could be connected to a single condenser/evaporator, which would reduce total system costs.

5.6 Relevant references

Because thermochemical energy storage is a new technology no actual references exist yet. However, there are some demonstration and test facilities that show the potential of this technology.

Icoonwoning Heerhugowaard

The Icoonwoning (fig. 63) is a residential dwelling in which new technologies and ideas are tested by ECN and TNO. The Icoonwoning is the first dwelling in the Netherlands equipped with a prototype of TCM heat storage and is located in Heerhugowaard.

The Icoonwoning is a newly built dwelling and in that perspective not directly a reference for a refurbishment project. However the dwelling is similar to a row house and has some interesting aspects that can actually be implemented in refurbishment concepts.

With an EPC of 0,04 the dwelling has an EPC of nearly zero. The dwelling does not make use of a heat pump, but has a whole range of energy saving and efficient technologies.

- 3300 Watt peak PV-panels (25m^2)
- 4,5m^2 flat plate solar collectors
- Compact heat storage (30kg of zeolites)
- Low temperature floor heating
- High efficiency balanced ventilation
- Preheating of ventilation air by sun
- Triple glazing

The Icoonwoning has a floor surface of 121m^2 and has a southern orientation for maximum use of solar energy. The average thermal resistance of closed façade parts is 5,45 m^{2}K/W

The applied compact heat storage, which uses zeolites as storage medium, is by far not capable of covering thermal demand of the dwelling in winter. It is purely used as demonstration as seen in figure 64.

Fig. 63. The Icoonwoning in Heerhugowaard. (www.icoonwoning.nl)

Fig. 64ab. The thermochemical storage demonstration set-up. (www.rvo.nl)

MERITS-project (2012-2016)

The MERITS-project, which stands for More Effective use of Renewables Including Thermochemical Storage, is a cooperation between several European research institutes (i.a. TNO), universities and companies. The project is funded by the European Commission and aims for the development of a compact rechargeable heat battery that provides solar energy throughout the year.

A 45ft sea container has been used to build a prototype of a seasonal heat storage system with solar collectors (12,4m^2 FPC), 300L short-term buffer, tanks with salt-hydrate and supporting system components such as pumps and valves. Eight storage vessels, each with a capacity of 60MJ and a volume of 326L have been tested. The effective storage density is 0.17GJ/m^3. The storage is charged at a temperature of 80ºC and discharges at 60ºC. The system is able to deliver 500W for a period of about 7 hours during discharging.

Because the set up was meant for testing, a lot of pipes and valves for controllability were required, resulting in a low system efficiency due to thermal losses.

The container has three compartments; one processing component, one system compartment and one empty compartment that resembles a small passive-house with underfloor heating. The container was assembled in Warsaw, Poland and shipped to Lleida in Spain for the first tests regarding solar heat harvesting and storing. In October 2015 the container was shipped back to Poland to test the discharging of the batteries in a cold climate.

In the MERTIS-project all key aspects of a heat battery system have been investigated and tested:

- Energy supply: solar collectors + storage integration
- Energy storage: materials, reactors, heat exchangers
- Energy delivery: system integration, control strategy

Fig. 65. The demonstration facility of MERITS. (www.merits.eu)

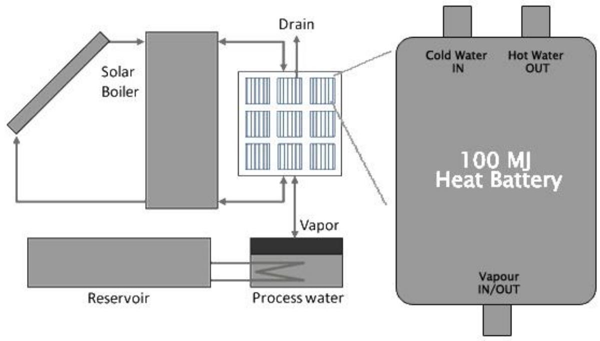


Fig. 66. System layout principle of the MERITS project. (www.mertis.eu)

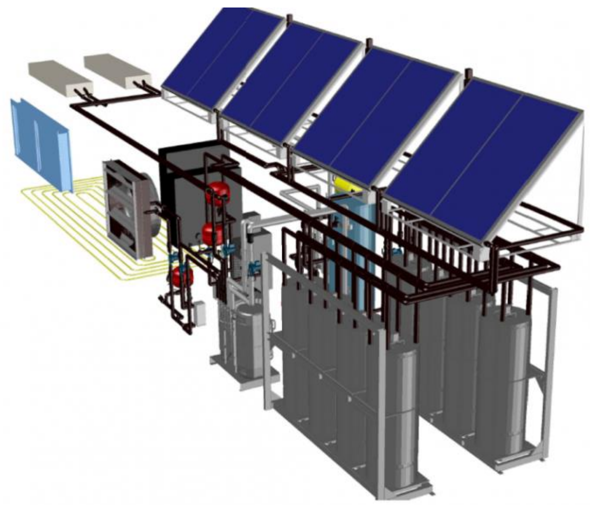


Fig. 67. Detailed system layout of the MERITS-project. (www.merits.eu)

The test results are used to develop a numerical model in order to optimize the system in a software environment since real-life testing is expensive.

More information can be found at www.merits.eu

CREATE-project (2015-2019)

The CREATE-project is the follow-up of the MERITS-project and is the abbreviation for Compact Retrofit Advanced Thermal Energy storage. The system components of the MERITS-project are installed in a single family house in Warsaw, Poland. Poland is chosen because of its cold winter and hot summers.

As the project title suggests, the aim is to develop a heat battery for existing buildings to make them more sustainable. In that sense, the aim of the project is very similar to this report. CREATE is funded by the European Commission and part of the Horizon 2020 project.

The selected dwelling (fig. 70) was built in 2009 according to modern standards, with 12cm wall insulation and 20cm roof insulation. In total 2.5m^3 salt-hydrate, which should cover about 1/3 of total thermal demand, is installed. The storage density aimed for is about 0.6GJ/m^3 system volume. Solar collectors will primarily charge the batteries, but surplus electricity can also be used to charge the battery.

The project aims for two main purposes:

- Decentral thermal energy storage to bridge the mismatch between solar energy supply and demand
- Decentralized grid connected storage

The focus within the project is on economic feasibility of the system in general and technical optimization of the compact storage modules. If everything goes according to plan, the experiences from both MERITS and CREATE are used to develop full-scale prototypes and eventually a commercial heat battery that can be a true game changer in sustainable refurbishment.

More information can be found at www.createproject.eu

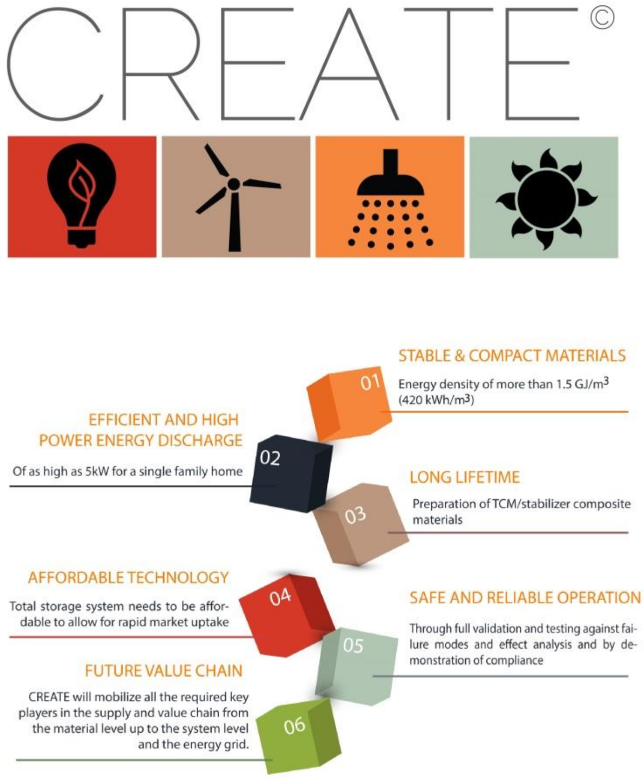


Fig. 68. Goals of the CREATE project. (wwww.createproject.eu)

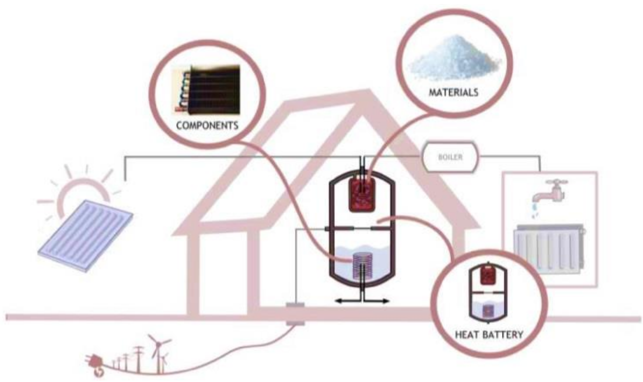


Fig. 69. Research topics of the Create project. (www.createproject.eu)

Fig. 70. Dwelling in Poland in which the thermochemical storage will be installed. (www.createproject.eu)

Ice storage (Eisheizung)

Another promising technology for seasonal thermal storage in large buildings is called ice storage or Eisheizung in German, where this technology has been implemented in numerous buildings. The biggest ice storage installation of Europe can also be found in Germany, at the Ecolab Academy in Monheim am Rhein.

Ice storage makes use the phase change energy (crystallization energy) that is released when ice turns into water. According to the law of conservation of energy, the melting of 1L ice equals the energy to heat up 1L water from 1 to 80ºC. An ice storage system consists of three main components: solar thermal air collectors, the ice storage (which is a tank with tubes containing water) and a heat pump.

During summer the air collectors deliver low temperature heat to the buffer, where the heat is stored until the heating season starts. The heat pump extracts energy from the buffer causing the buffer to cool down. During this process the water slowly turns into ice, releasing a lot of energy which is used for space heating. The ice is used for cooling during summer and simultaneously the collectors heat up the storage again.

In theory, an ice storage system can be operational for at least 80 years without any major replacements. A well working system can reach a COP of 7 and is able to save 50% in heating costs and 99% in cooling costs compared to conventional systems.

Although ice storage is relatively unknown in the Netherlands, the first projects are realized. The Dutch municipality Peel en Maas decided to build an energy neutral town hall. They planned to install a ground-source heat pump, but due to the poor quality of the soil three pumps would be required, making the system too expensive. ABT and Cofely, together with German company Viesmann designed an 600m^3 ice storage which is placed subterranean next to the town hall. 300m^2 air-collectors are placed on the roof of the town hall. The ice storage is a closed system and placed in a concrete encasing (fig. 71), preventing energy exchange with the soil and negative environmental impacts. The system annually saves 8.459m^3 of natural gas, which equals 15 tonnes CO_2 and €80.000. At current gas price, the system has a return on investment of just 8 years which makes this system very appealing for large utility buildings and perhaps even apartment buildings.

A Dutch company named Solar-freezer recently introduced an ice storage concept for single family dwellings. The actual storage isn't placed underground, but in the crawlspace of the dwelling. Although the system is an alternative for use of natural gas, the heat pump still requires significant electrical energy to operate, energy which won't be available when needed on cold days. The system therefore doesn't solve the mismatch between renewable energy demand and supply. Besides, most single family houses do not have a crawlspace at all, limiting the applicability of the system.

More information can be found at www.viessmann.de/de/wohngebaeude/waermepumpe/eis-energiespeicher.html and www.solareis.nl

Fig 71. Concrete container for ice storage (this is not the container used in the town hall). (www.maz-online.de)

Fig. 72. Solar air collectors on roof of town hall Peel en Maas. (provided by ABT)

6. DESIGN DEVELOPMENT

This chapter is the basis for the design which is elaborated in the next chapter. The objective is to gather all relevant data that is required to determine the most optimal thermal battery system layout for the case study dwelling in terms of energy performance and financial feasibility. The chapter ends with the most important results an conclusions.

6.1 Design context

6.1.1 the case study dwelling

The (fictional) case study dwelling is based on the row-house reference dwelling and is situated in a residential neighbourhood in a Dutch village with a low to medium building density. There are no waste heat resources in close proximity, so a decentralized heating solution is likely to be more feasible than a district heating network.

The dwelling is located in the middle of a block and has the optimal North-South orientation, allowing maximum irradiance. The dwelling is built in 1980 and has energy label E, indicating a very poor energy performance. Three people inhabit the dwelling and they have normal comfort behaviour.

The dwelling has 3 elevations with a gross floor surface of 120m^2. Both North and South façade can be seen in figure 74. Total roof surface amounts 60m^2, of which 30m^2 is southern orientated at an angle of 35º and usable for solar energy harvesting.

Fig 73. Urban context of case study dwelling. (Own illustration)

Fig. 74. Impression of the case study dwelling. (Own illustration)

Fig 75. Elevation/floorplan of case study dwelling. (RVO.nl - referentiewoning)

6.1.2 Case study refurbishment strategy

The refurbishment concept (and its strategy) are part of the design context and are therefore not actually designed in this report. However, the properties of the concept are very important in reaching a successful refurbishment, and the refurbishment strategy determines the options for integrating the thermal battery system.

In general, there is no "best" refurbishment strategy for any given context. Usually the context excludes some options, but the final decision will be based on the context conditions and boundary conditions, design principles of the architect, desired result and requirements, but above all available budget.

The aim of this graduation report is to develop a thermal battery system that can be integrated in a refurbishment concept, creating a feasible alternative to the NoM concept, thereby preventing additional investments in the electricity infrastructure and allowing a fossil fuel free future. The fundamental difference between a NoM-concept and the concept aimed for in this report is the use of solar thermal energy and a thermal battery system rather than excessive use of PV-panels and an electric heat pump. Other properties of the concept will be very similar to a NoM dwelling since they've been proven successful.

Most important criteria for strategy selection are the costs, consisting of both materials and construction. Prefabrication is therefore preferred and construction time should be minimized to save on labour costs. In this case scalability of the refurbishment is important as well, because a large number of dwellings need to be refurbished. Although these dwellings are similar, they are not completely identical. The strategy should therefore allow deviations and tolerances within the same concept.

As explained earlier in this report, a good refurbishment does not only upgrade energy performance, but also addresses spatial qualities, comfort and appearance. In that sense an add-on strategy combined with a wrap or replacement strategy for façade and roof are most suitable for a successful refurbishment. A wrap strategy is in favour because of the short construction time and minimized inconvenience for residents. This strategy also allows prefabrication and individual customizable elements, allowing residents to choose the appearance of their own dwelling and giving their dwelling identity. However, an add-on structure will significantly increase refurbishment costs and should therefore be an optional feature. The selected refurbishment strategy is visualised in figure 76 and a typical reference detail before and after refurbishment can be seen in figure 77.

In paragraph 7.3 several design directions are explored for spatial integration of the thermal battery system in the case study context. In paragraph 7.4 is explained how the thermal battery system can be integrated in a refurbishment concept with wrap it strategy and aforementioned properties.

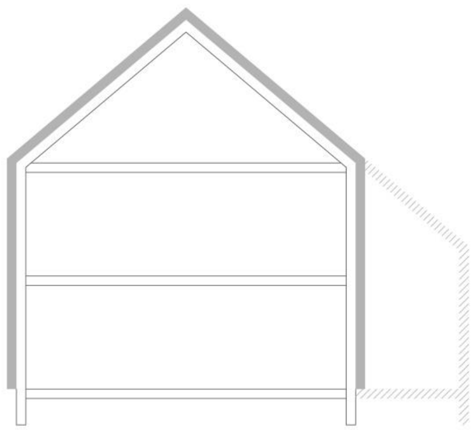


Fig 76. Selected refurbishment strategy for the case study dwelling. (Own illustration)

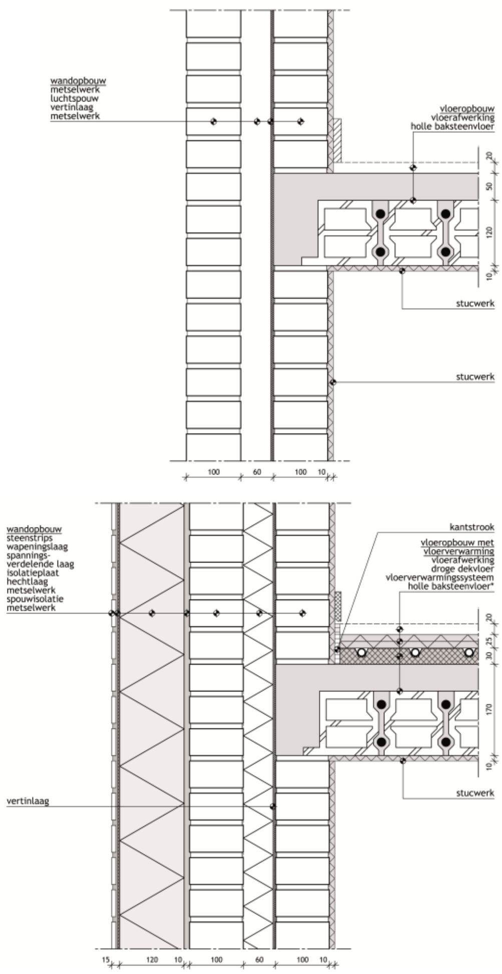


Fig. 77. Reference detail of a wrap refurbishment strategy for the case study dwelling. (Archidat, 2012)

6.2 Parameters affecting system performance

Before discussing the simulation model, it is relevant to explain which parameters affect the performance of the thermal battery system. Some of these parameters will be used as input in the eventual simulations. The parameters can be split in four main categories: demand parameters, yield parameters, storage parameters and system parameters.

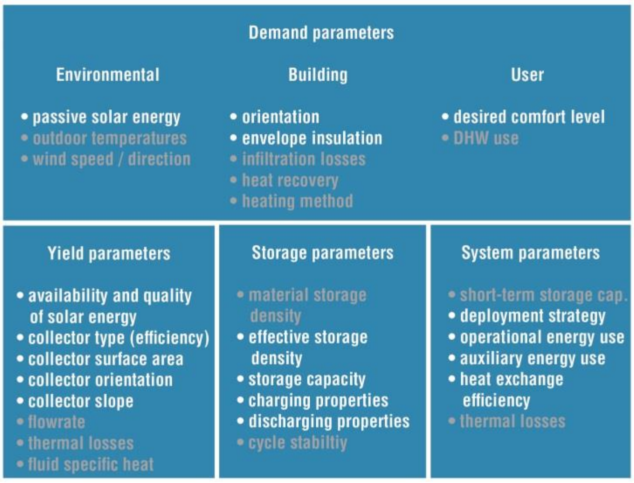


Fig. 78. Parameters that affect system performance. Parameters in white are the most influential. (Own illustration)

All described parameters will affect overall performance, but they are not equally influential. The importance of each parameter is indicated by its colour in the scheme, where the white parameters have a bigger impact on the performance.

6.2.1 Demand paramters

The demand parameters are subdivided in environmental, building and user parameters.

Environmental parameters

The environmental parameters follow from specific climate conditions and characteristics of a certain geographical location and local context.

Passive solar energy

Use of passive solar energy can significantly reduce building thermal demand. This parameter is strongly connected to building orientation.

Outdoor temperatures

These will largely determine space heating demand of the building. The outdoor temperature is also relevant for the collector efficiency because the larger the temperature difference between collector and environment the lower the efficiency is.

Wind

Wind speeds and directions have effect on both heat demand of the building and efficiency of solar collectors. Especially during winter, wind can blow cold air along the façade which cools down the building resulting in a higher heat demand. The same cold wind has a negative effect on the solar collectors causing higher thermal losses.

Building parameters

The building parameters refer to aspects that affect building energy demand. Unlike environmental and user parameters, building parameters are not dynamic.

Orientation

Building orientation directly affects thermal demands and solar yields. Buildings oriented southwards can benefit from passive solar energy thereby lowering the heat demand, where large windows on the north can result in a higher energy demand.

Envelope insulation

Thermal resistance values (Rc/U) directly affect thermal losses of the building and are therefore crucial in determination of the total heat demand.

Airtightness

Infiltration of cold outdoor air and escaping of hot indoor air caused by differential pressures across the building envelope will increase thermal demand. Air leakages are usually located around the window frames.

Heat recovery

Just like the thermal resistance values, heat recovery efficiency strongly affects thermal losses and subsequent heat demand. In this report a heat recovery system with an efficiency of 90% is assumed after refurbishment.

Heating method
The heating method plays a role in the energy and moreover exergy demand of the building. A low temperature heating system like floor or wall heating requires less energy than conventional radiators because supply temperature can be around 40 instead of 80ºC. Low temperature heating works best when the building envelope is sufficiently insulated to prevent heat losses.

User parameters
The user parameters are directly affected by the residents of the dwelling and are therefore unique for every situation. In practice representative key figures are often used in calculations.

DHW-use
This depends on the amount of people living in the dwelling and their behavior. DHW use is indicative for boiler size and collector surface. For an average single family dwelling this is about 8 to 8.5 GJ per year.

Desired comfort level
Every person has a different perception of comfort and this results in different energy consumption patterns. Lowering the indoor temperature by one degree Celsius can for example already make a difference of 7% in thermal demand, showing the impact of desired comfort on thermal demand.

6.2.2 Yield parameters
The yield parameters are related to the performance of the solar collectors.

Availability and quality of solar energy
The amount of receivable solar irradiation primarily determines thermal yield of collectors. Total global irradiation, direct and diffuse radiation, hours of sunshine or cloudiness, shadows, solar azimuths and zeniths are all influential.

Collector type (efficiency)
Each collector type has a certain efficiency that determines the percentage of absorbed solar energy converted into useful energy. Although a FPC and an ETC have comparable efficiencies during summer, the ETC performs way better during winter. Collector efficiency is strongly affected by outdoor temperatures and solar irradiance.

Collector surface area
The collector surface area determines the amount of solar energy that can be collected and turned into usable energy. The effect of collector area regarding a thermal battery system is described in paragraph 6.5.

Collector orientation
The orientation is already described under building parameters, because in most cases collectors are placed on the pitched roof which has a fixed orientation. More about effects of orientation in chapter 4.

Collector slope
This parameter affects the amount of receivable irradiance. The optimum angle throughout the year is about 40 to 45 degrees, but if energy harvesting is required during winter, a more vertical angle (60-70 degrees) is preferable. More about effects of collector slope can be found in chapter 4.

Control strategy
The control strategy is the "brain" of the system and determines how the solar collectors react to changes in environmental parameters, for example when clouds reduce irradiance. Temperature of water inside the boiler is constantly monitored to determine the optimal operation principle. The control strategy controls the pumps that determine when the system is operational and what the optimum flowrate is.

Flowrate
The flowrate plays an important role in system efficiency since it determines the amount of energy that is absorbed by the HTF. More about flowrate in paragraph 4.3.1.

Fluid specific heat
The fluid specific heat (heat capacity) is a material property which determines the amount of absorbable energy in the HTF. In case of pure water this is 4186 kJ/kg/K. If glycol or antifreeze is added it will be lower.

Thermal losses
The bigger the difference between outside temperature and liquid inside the collectors, the bigger the thermal losses will be. Performance of ETC is less affected because of the vacuum, but thermal losses play an important role in efficiency of FPC.

6.2.3 Storage paramters

The storage parameters only refer to the actual thermal batteries and are discussed in paragraph 5.5.

Material storage density

This parameter follows from the storage material (de)hydration reaction enthalpy. Once the material is fully dehydrated the storage density is at its maximum, so the higher the charging temperatures, the higher the storage density.

Effective storage density

The effective storage density is a combination of the storage material density and the volume of the material and components that are part of the battery (insulation, heat exchangers etc.). In this report an effective storage density of $1GJ/m^3$ is assumed, although current state of the art research aims at $0.6GJ/m^3$.

Charging properties

The charging properties follow from the hydration reaction characteristics and are specific for each TCM. Specific information about charging properties of the thermal battery system used in this report can be found in paragraph 5.5.

Discharging properties

These properties are specific for each TCM and are crucial for the usability of the stored energy. The most important properties are discharging temperatures, output power and required condensation energy.

Cycle stability

Just like an electric battery the efficiency of the thermal battery will slightly decrease over time. A good cycle stability will increase lifetime and financial feasibility of the system.

6.2.4 System parameters

The system parameters refer to the performance of the total system

Short-term storage capacity

This parameter refers to the size of the solar buffer and correlating amount of storable energy. The storage capacity is strongly related to collector area and DHW use as is explained in chapter 4.

Deployment strategy

The system can be used to cover the full thermal demand (space heating + DHW), but can also partially cover demand. The system can even be deployed for short-term storage. The deployment strategy will mainly determine how much storage capacity is required; this parameter is therefore explained in more detail in paragraph 6.4. and 6.5

Operational energy use

This refers to the (electric) energy that is required for the system to operate. In case of a thermal battery system this will be the energy used by pumps, control unit and required energy for the discharging process.

Auxiliary energy use

Auxiliary energy relates to energy that is required to provide thermal energy when not enough solar energy is available or batteries cannot be used. The auxiliary energy use says something about the effectiveness of the system and to what extend the system allows for decoupling of conventional energy infrastructure.

Heat exchange efficiency

Heat exchangers are crucial in system performance because they exchange energy between system components. Heat exchangers are made of metal and their geometry, flowrate, inlet and outlet temperatures will affect energy transfer efficiency. The greater the heat exchanger surface area, the easier it is to transfer heat to the system and lower return temperatures will improve system efficiency.

Thermal losses

These are inevitable and reduce overall system efficiency. The losses will mainly occur in boiler and buffer, despite applied insulation. Thermal losses through piping are also significant and pipes with hot water should therefore be well insulated and kept to a minimum length.

6.3 Development steps

This paragraph describes the steps that are required to find relevant data and results to develop the thermal battery system. As explained in the previous paragraph, the performance of a system is affected by many parameters. In this report the focus will be on the effect of collector surface area and deployment strategy (cover space heating + DHW demand or space heating demand only) on the required storage capacity.

1. Preselection of technologies

The first step is to select the technologies that will be used in the design. These have followed from the previous chapters and are explained in the conclusions of those chapters. The most important selections are:

- Refurbishment strategy (wrap it + add on)
- Collector type (ETC)
- Storage method (Thermal batteries, making use of thermochemical storage)

2. Determine the most optimal insulation value

The second step is to find out what the most optimal insulation value of the building envelope after refurbishment should be. Several options are simulated in TRNSYS ranging from a Rc value of 1,0 to 6,0. In each variant insulation values for roof and façade were assumed equal, but a more accurate result is possible if these are evaluated per building element as explained in paragraph 3.2.3.

3. Determine thermal demands

The third step is to calculate thermal demands of the case study dwelling after refurbishment, using the most optimal thermal resistance values calculated in the previous step. The thermal demand consists of both space heating and DHW. Space heating demand simulated in TRNSYS and is unique for each day.
DHW demand is based on literature sources (Platform Nieuw Gas, 2008) and is set at 8GJ/year or 666MJ/month (22MJ/day).

4. Determine thermal yields

The next step is to calculate thermal yields of the solar collectors, which is directly related to the weather data for a Southern orientated surface with a slope of 35º, which is equal to the slope of the case study roof. The actual collector yield is calculated in a simplified way by choosing a constant collector efficiency which is based on measured performance of evacuated tube collectors in the Netherlands (TNO, 2010). An average efficiency of 40% for the context of this report seems realistic.

The hourly irradiation values that follow from the TRNSYS simulations have been processed in excel to calculate thermal yields. For simplicity all radiation is taken into account, while in reality low irradiance is not usable. The available solar energy is multiplied by the efficiency of 0.4 (40%) and collector surfaces ranging from 6 to 30m^2, to calculate thermal yields. The efficiency factor can be replaced by more accurate values that follow from simulations, but in the reflection of this report is explained why this was not done in this report.

5. Determine required storage capacity

The final step is to calculate the required storage capacity, which is a combination of all previous mentioned steps. This will be done for the most important deployment strategies and different collector surfaces. The exact method on how the required storage capacity is calculated is explained in the next paragraph.

6. Select basic system layout

The previous steps result in a number of graphs that can be used in selecting the most optimal system layout in terms of energy performance or financial feasibility. The chapter will end with some design choices / considerations regarding the basic system layout that will be used for the design elaboration in the next chapter.

6.4 Simulation model & calculation of required storage capacity

This paragraph describes the steps from the previous paragraph more specifically. The simulation model, variants and method to calculate required storage capacity will be discussed.

6.4.1 Introduction on TRNSYS

In this report TRNSYS is used for simulations of building energy demand and solar collector yields for the case study Context. TRNSYS is a graphical software application that simulates the behavior of a transient system. The software has been around for more than 35 years and is used worldwide by researchers and designers. The main applications of TRNSYS are design, testing and optimizing of solar systems, low energy buildings, HVAC systems and renewable energy systems.

A TRNSYS model consists of 2 main parts: The building file (TRNBuild), in which a building can be programmed, and the calculation engine (simulation interface), in which components that represent a component of the building services are linked together. The calculation engine reads, processes and calculates desired values in a system for a given interval and number of time steps. Simulation results can also be plotted real time, making it easy to solve errors and optimize a system layout.

6.4.2 Model to determine thermal demand & yield (the building file)

The first part of TRNSYS, known as a type56, describes the case study dwelling, which is defined as a set of walls including window openings and a roof at a certain orientation (Fig. 79). The model is based on dimensions of the reference dwelling described in the previous paragraph. All elements have a specific orientation, surface area and thermal resistance value, which can be adapted to run different simulations. For simplicity, internal walls are not modelled.

Besides passive building parameters, the input file also describes desired comfort levels (set point temperature). This is used to determine when the heating system needs to be turned on and will be 20ºC in this case. A detailed overview of used building parameters can be found in appendix 4.

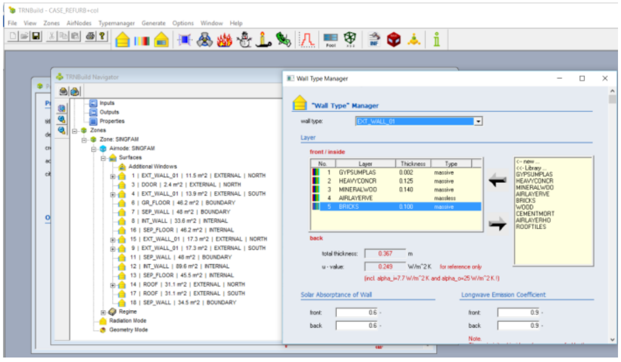


Fig. 79. TRNSYS building file interface (TRNBuild). (Own illustration)

The simulation interface

The second part is the calculation engine of TRNSYS, which consists of a number of mathematical defined components. Each component has several input and output parameters. By linking components and corresponding parameter values a, dynamic system can be set up. The radiation output from the weather file is for example linked to the collector radiation input. Because components can be manually adapted, the software can be used to test new climate concepts and components, offering a high degree of flexibility.

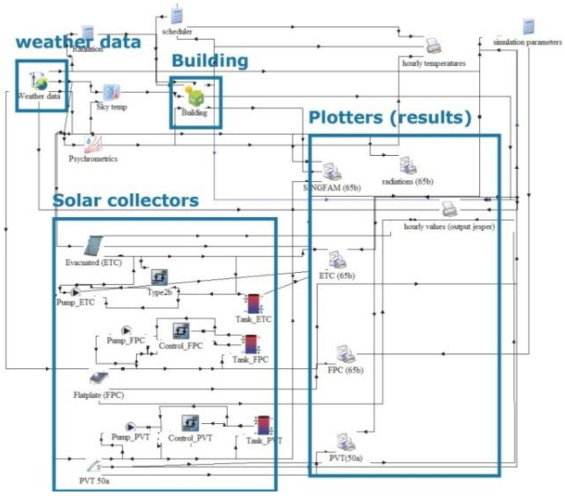


Fig. 80. Interface of the simulation model used in this report. (Own illustration)

The simulation interface used in this report can be seen in figure 80 and consists of the building component (that is programmed in the building file), the weather file, three different simplified solar collector systems and plotters that plot the result. The weather file in this case is the 10 year average weather data of Schiphol.

The simulations are runned with a time step of 0,5h during an entire year. The plotter converts this to 8766 hourly values, which are further processed in Microsoft Excel. In excel the simulation results are calculated per day and month.

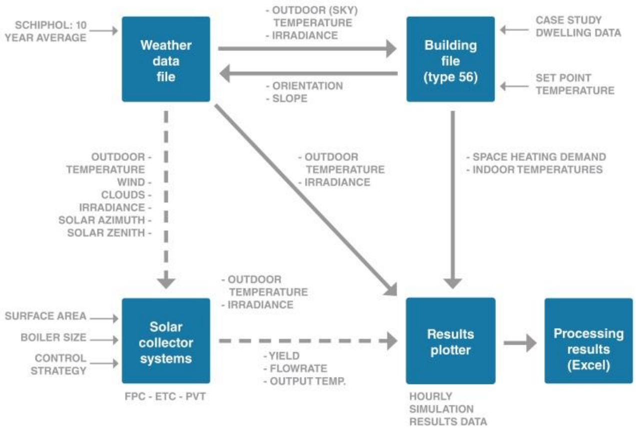


Fig. 81. Simulation diagram with main components, links, input and output parameters. (Own illustration)

A diagram of the simulation components, relevant input and output parameters and links between components is shown in fig. 81.

Input parameters used in the TRNSYS case study model and Excel sheet

- Outdoor temperatures
  (from Schiphol weather data file)
- Solar radiation
  (from Schiphol weather data file)
- Building envelope insulation
- Heat recovery rate
- Infiltration rate
- Collector orientation
- Collector slope
- Collector efficiency
- DHW use

6.4.3 Variants

Calculations on required storage capacity will be made for different system configurations (variants). Although all variants are able to meet the total thermal demand, the required storage capacity will be different.

The systems consist of the collectors, short-term buffer and thermal batteries. The required capacity depends on the performance of the total system, which in itself is affected by a range of parameters which are described in the previous paragraph. Because overall performance is so complex, the report only focusses on the most crucial parameters: collector area and deployment strategy.

Parameter 1: collector surface

To examine the effect of collector surface area on directly usable yield, in between surplus and resulting storage capacity, several variants have been calculated. The variants have a collector area ranging from 6 to 30m^2 with an increase of 3m^2 per variant.

Parameter 2: deployment strategy

The deployment strategy indicates how much of the energy shortage is covered by the thermal battery system and is a fundamental design choice. Variants within the same deployment strategy cover the same thermal demand, but required storage capacity depends on the system layout and amount of collectors. The thermal demand that is not covered by the batteries comes from an external (electric) source. The strategies that are looked after in this report are:

1. Full coverage strategy (SH + DHW_{total})
2. Space heating strategy (SH + $DHW_{Mar\text{-}Oct}$)
3. Partial coverage strategy (%SH)
4. Peak load preventing strategy
   (system as short-term storage)

Although the last strategy is not within the scope of this thesis, it is very relevant within the context of the energy transition in the Netherlands and current developments regarding wind energy.

Parameters that are not included in variants

A number of parameters that are relevant for system performance and resulting storage capacity have not been included in the variants. These are:

- Collector efficiency
- Collector orientation
- Collector slope
- Collector flowrate

- Thermal losses in system
- Short-term buffer size
- (dis)charging strategies
- Heating system
- Infiltration rate
- Heat recovery efficiency

Fig. 82. Simulation model variants. Collector surface from 6 to 30m^2, with steps of 3m^2. Each variant is calculated for the two main deployment strategies. (Own illustration)

By including the abovementioned parameters in the simulations, the system can be optimized for the optimal performance. The best result is achieved if all components and parameters are linked in the TRNSYS interface, allowing components to interact like in a real life situation. This is unfortunately not realistic within the timespan of this report.

6.4.4 Calculation method for required storage capacity

TRSYS produces an extensive file with hourly data of all relevant parameters. By further processing this data in excel, relevant graphs can be made and storage capacities for different deployment strategies can be calculated.

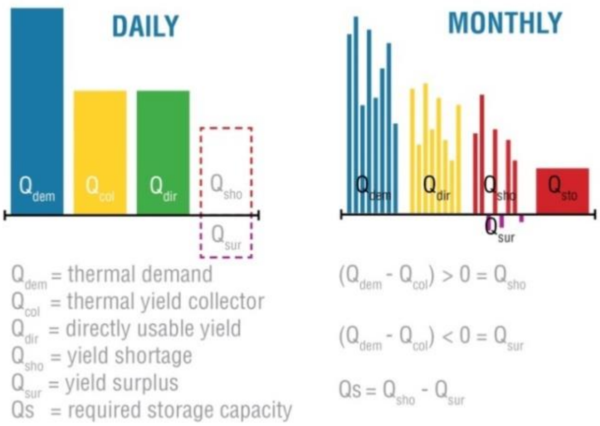


Fig 83. Important values regarding required storage capacity. (Own illustration)

The required storage capacity cannot simply be calculated by subtracting the total thermal yield from total heat demand within the shortage period. In order to accurately determine the storage capacity, thermal yields and demands have to be evaluated per day, or more accurately per hour. In this report daily values are evaluated, and required storage for a particular day is the result of thermal demand (Q_{dem}) minus directly usable thermal yield (Q_{dir}). If this result is a positive number there is a shortage (Q_{sho}) on that day, and if the number is negative there is an energy surplus (Q_{sur}) that can be stored. Such a surplus can also occur within the shortage period on a very sunny day for example. In that case Q_{col} is bigger than Q_{dir}.

Directly usable yield
Directly usable yield is defined as thermal energy that is used within the same day via the short-term buffer. Directly usable yield is affected by the solar collector's efficiency and surface area. A solar collector that performs well in winter and/or a big collector surface therefore reduces the time in which storage is required, consequently also reducing storage capacity. Directly usable yield is calculated per day in Excel and equals thermal yield as long as total yield is smaller than total thermal demand on that day.

In between surplus
An efficient collector with a big surface area that performs well during winter could have a yield that exceeds thermal demand on daily basis. In that case an in between surplus occurs. This surplus can be stored in the short-term buffer to use the next day or in the batteries for use later within the shortage period. The surplus is calculated per day by subtracting thermal yield from thermal demand. If the resulting value is negative, a surplus occurs. All negative values have been added together in excel to find total surplus per month.

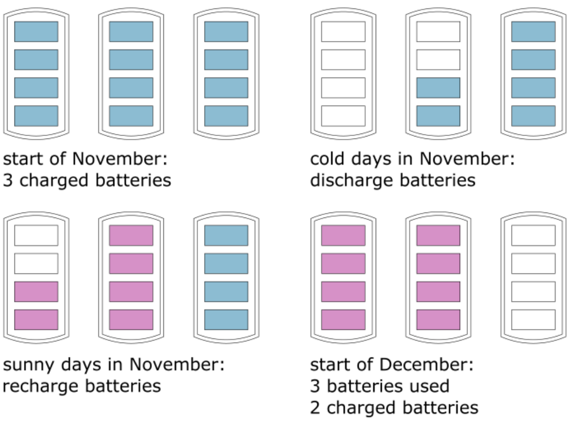


Fig. 84. Explanation of theoretical "in between" surplus. (Own illustration)

The in between surplus can be explained by the following example: In November a share of the storage capacity is used, leaving an empty storage volume. A few sunny days in November result in a small heat demand, leaving some extra "surplus" energy that can be used to recharge the empty storage volume. This thermal energy can be used later on within the shortage period.

However, the surplus in March cannot contribute to a decrease in required storage capacity since it can't compensate for thermal demands earlier in the shortage period.

Required storage capacity
The resulting storage capacity can be written in some simplified formulas. The possible surplus within the shortage period is hereby assumed to be used in the following month, but in reality a part will be used via the short-term buffer. This does not make any difference for the annual energy balance and required storage capacity. Q_{dir} and Q_{sur} are the sum of all daily values, and therefore have to be analysed first in order to calculate monthly values.

$$Qs_{nov} = Qdem_{nov} - Qdir_{nov}$$
$$Qs_{dec} = Qdem_{dec} - (Qdir_{dec} + Qsur_{nov})$$
$$Qs_{jan} = Qdem_{jan} - (Qdir_{jan} + Qsur_{dec})$$
$$Qs_{feb} = Qdem_{feb} - (Qdir_{feb} + Qsur_{jan})$$
$$Qs_{mar} = Qdem_{mar} - (Qdir_{mar} + Qsur_{feb})$$

Total required storage capacity:
$Qs_{nov} + Qs_{dec} + Qs_{jan} + Qs_{feb} + Qs_{mar}$

Since enough storage capacity needs to be left over to store possible surpluses within the storage period, there is a maximum for the November surplus, which is set at half the thermal demand of November.

$$Qsur_{nov} \leq 0.5 * Qdem_{nov}$$

Furthermore, a big surplus in February could result in a negative storage amount in March. Therefore:

$$Qsur_{feb} \leq Qdem_{mar}$$

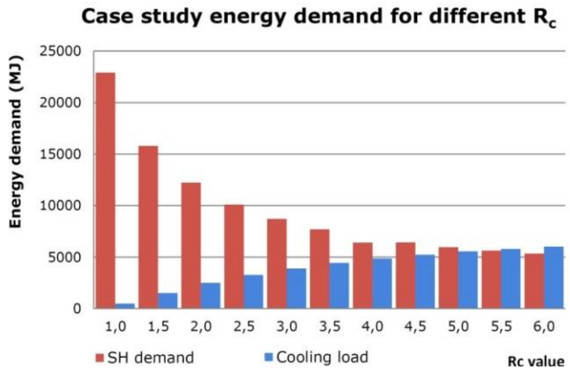
The required storage capacity is calculated from the simulation results and processed in Excel with the aforementioned boundary conditions. All daily simulation values and processed results can be found in appendix 5.

6.5 Results & conclusions

6.5.1 Optimal building envelope insulation

The effect of building envelope insulation on space heating demand and cooling load is visualised in graph 1. The results show that improving low Rc values has great impact on thermal demand. However, space heating demand only shows a minor decline with Rc values above 4,0. Higher values only seem to increase cooling load*.

*cooling demand will increase in reality, but not as significant as the graph indicates. The high cooling loads are a result of the heat recovery in the simulations, but this is turned off during summer in reality.



Graph 1. Optimal insulation value for the case study dwelling (Own illustration)

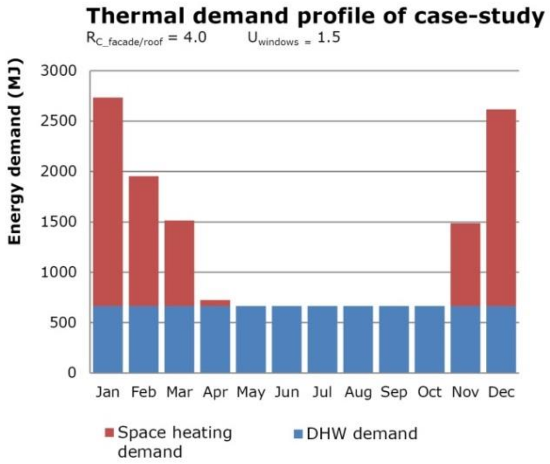
An Rc value of 4,0 is selected for building envelope insulation value. This value is used in the simulation of the space heating demand in TRNSYS. The DHW demand is added in excel, resulting in the thermal demand profile of the case study dwelling in graph 2.

6.5.2 Used input parameters for simulations

- Outdoor temperatures (from Schiphol weather data file)
- Solar radiation (from Schiphol weather data file)
- Building envelope insulation: Rc 4,0
- Heat recovery rate: 90%
- Infiltration rate: 0.19/h
- Collector orientation: South
- Collector slope: 35º
- Collector efficiency: 40%
- DHW use: 22MJ

6.5.3 Thermal demands

The space heating demand between November and March is 6973MJ, of which 4017MJ (58%) is required during December and January. The total thermal energy demand during winter is 10.303MJ.

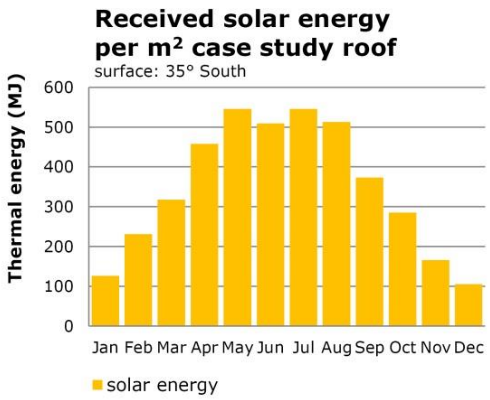


Graph 2. Thermal demand profile of case study dwelling after refurbishment. (Own illustration)

All thermal demand simulation results and relevant figures are evaluated per day and presented in appendix 5.

6.5.4 Thermal yields

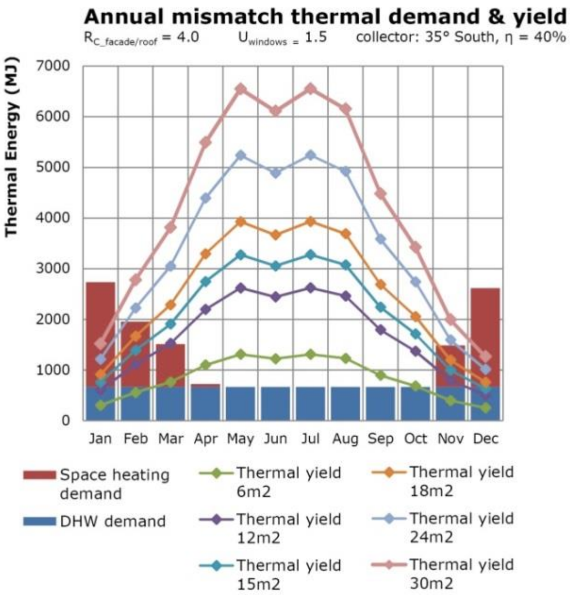
Before calculating thermal yields it is relevant to examine the solar potential for the case study situation. The received solar energy per m^2 case study roof can be found in graph 3. Total available energy is 4,177MJ/m^2/year, which equals 1160kWh. Available energy during winter months (Nov-Feb) is only 630MJ, or 15% of the annual total.



Graph 3. Received irradiation per m^2 case study roof per month. (Own illustration)

Thermal yield & mismatch

When thermal demands and yield are combined into a single graph, the mismatch can be visualized. The mismatch exists for all collector surfaces, and a bigger collector surface only makes the mismatch bigger. A bigger collector surface can however reduce required storage capacity since more energy can be directly used during winter.



Graph 4. The energy mismatch of the case study dwelling for different collector areas. (Own illustration)

After analysis of the simulation results, it is clear two main periods can be distinguished (fig. 85). The first one is the shortage or discharging period, lasting from approximately November to March in which storage is required. The second period is the surplus or charging period, lasting from approximately April to October.

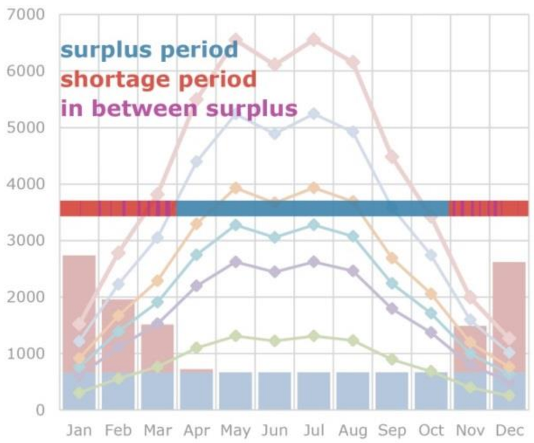
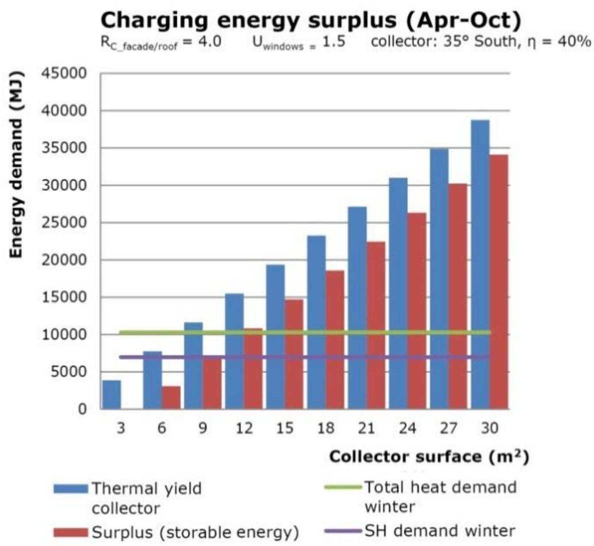


Fig. 85. The energy mismatch results in 2 main periods: surplus (charging) and shortage (discharging) period. (Own illustration)

Before calculating the actual required storage capacity, the amount of storable energy during charging season must be determined. The collectors will be used to cover DHW demand during the charging season, so the storable energy is the collector output minus DHW-demand.

Minimum required collector surface

A collector surface of 3m^2 cannot yield any storable energy and a surface of 6m^2 will not yield enough storable energy. A collector surface of at least 9m^2 is required to store all energy to cover the space heating demand, and this is 12m^2 if both space heating and DHW demand must be covered. Actual storable surplus is higher because of efficiency during summer is >40%, but this would not affect the conclusions. Collector areas smaller than 9m^2 will be excluded from further analysis since they are not usable in the case study context.



Graph 5. Mimimum required collector surface that can yield enough storable energy. (Own illustration)

6.5.5 Required storage capacities

In this paragraph the required storage capacities for different collector surfaces and deployment strategies will be discussed. Although partial and short-term coverage strategy are not specifically evaluated in this chapter, they are important from the bigger perspective of the energy transition.

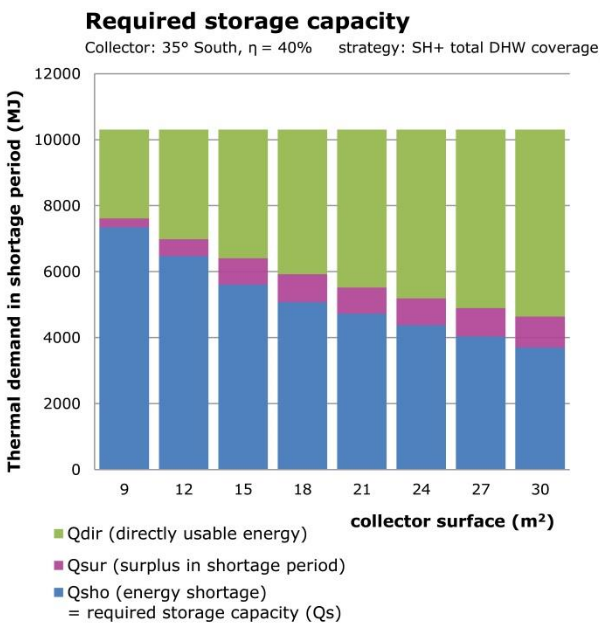
Full coverage strategy (SH+DHW)

This strategy is described before and covers both space heating and total DHW demand. The results regarding required storage capacity can be seen in graph 6. It is the best strategy from an energetic point of view, but has the worst financial feasibility. The question is whether cost for 2200MJ storage can compete against auxiliary (electric) heating of water during off-peak times. For example, the boiler could be heated up to a temperature of about 70 degrees at night with cheap electricity, providing a minimum temperature of 60 degrees the whole day. Time shifting is not possible for space heating since a constant energy demand is required.

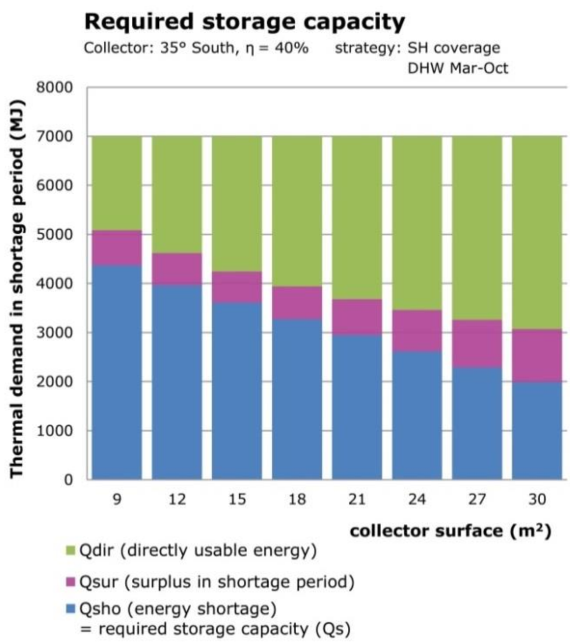
The graph shows three important values for each collector surface. The green bars indicate how much solar energy can be directly used. This increases as the collector area gets bigger. The purple part is the surplus that can be stored within the shortage period for later use and this will therefore reduce required storage capacity. The maximum storable surplus is reached at 18m^2. This is because a collector surface greater than 18m^2 will have more directly usable yield and a smaller storage capacity. The possible surplus can therefore not be stored anymore.

The blue bars represent the thermal energy shortage. This shortage has to be stored during the surplus period from April to October. For simplicity, it is assumed that the shortage equals required storage capacity, but in reality the shortage should be multiplied by an efficiency factor to take thermal losses during (dis)charging into account. It is impossible to exactly calculate these losses within the scope of this report since it requires extremely complex system simulations and some parameters are still unknown. If the eventual system works with an efficiency of about 90%, the shortage amount should be multiplied by a factor of 1.1 to find required storage capacity.

The graph shows that storage capacity decreases when collector area gets bigger, but gradually flattens out at a certain value because in the end storage is always required for thermal demands in December and January. A collector area of 18m^2 would require a storage capacity of about half the total thermal demand. A collector area of 30m^2 still requires a storage capacity of about 40% of thermal demand, which shows that the biggest possible collector surface will not result in the most optimal system layout. A big collector surface will only increase the mismatch and lowers the solar fraction since most of the energy yielded in summer cannot be used.



Graph 6: Required storage capacities for different collector surfaces within a space heating + total DHW coverage deployment strategy. (Own illustration)



Graph 7: Required storage capacities for different collector surfaces within a space heating + partial DHW coverage deployment strategy. (Own illustration)

Space heating (SH) coverage strategy
This strategy covers the full space heating demand and DHW demand between March and October. Batteries are not required to cover DHW demand during surplus season since this can be covered by the short-term buffer. In this strategy, the batteries need to cover a thermal demand of 7000MJ. DHW demand during winter is covered by electric auxiliary heating at night. The required storage capacity for different collector surfaces can be seen in graph 7.

Partial coverage strategy
The system is meant to be flexible in order for residents to determine their own level of self-sufficiency. This can be realized in a partial coverage strategy, in which a percentage of thermal demand is covered. The residents can choose this percentage and moments when demand is covered by thermal batteries or from another source. The system could be operated by a component that monitors energy prices to always have the most cost-effective operation.

Another option within this strategy is to only cover space heating demand in the most crucial months December and January. This would result in a space heating coverage of 60%.

Peak-load preventing strategy
This strategy follows from the previous strategy, but is actually a short-term storage strategy. Although the battery system is not used for short-term storage in this report, the short term application should be mentioned from a broader perspective of the energy transition and because of current developments in the Netherlands.

Fig. 86. Planned offshore windmill parks in the Netherlands. (www.noordzeeloket.nl)

Wind energy will play a crucial role in Dutch energy transition (fig. 86). The government recently approved plans to build massive windmill parks in the North Sea, providing electricity for nearly 5 million households (www.noordzeeloket.nl). Although windmills do not cope with a seasonal mismatch, they cannot provide a constant power due to fluctuating winds. Energy storage is therefore crucial in full utilisation of wind energy, but the energy does not have to be stored for long periods.

Although electric storage would be preferred, a thermal battery system can also be complementary next to windmills if they are used in a short-term storage strategy. Batteries will not be charged with solar collectors in that case, but use surplus windmill electricity for charging, which is still renewable.

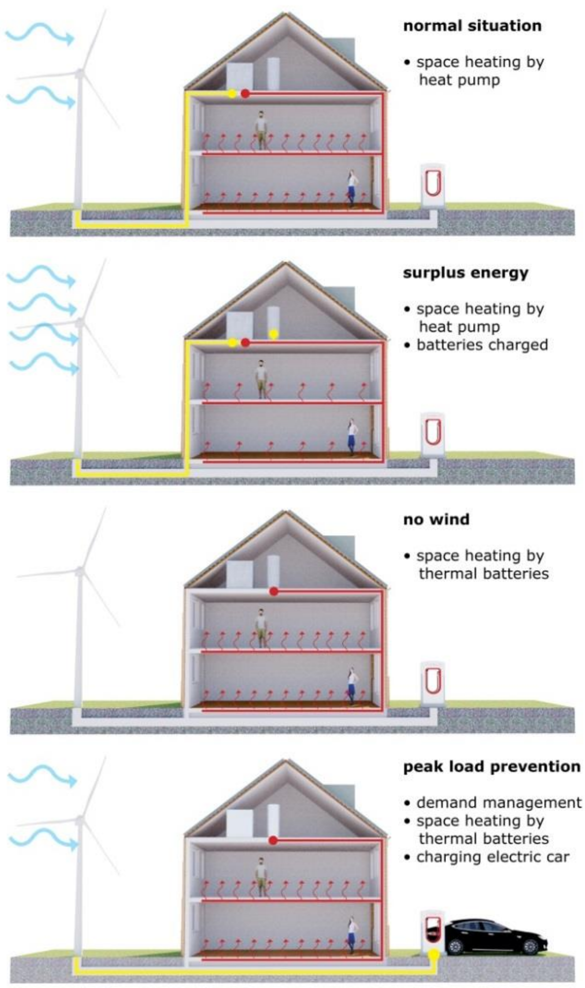


Fig. 87. A thermal battery system with short-term storage in a peak-load preventing strategy.
(Own illustration)

The batteries should be able to bridge roughly 3 days of absence of wind on a winter day. The highest daily space heating demand occurs in January and amounts 174MJ. In an extreme situation, the batteries should therefore cover 174+22 = 196MJ/day for space heating and DHW. This requires a storage capacity of about 600MJ for 3 day coverage, which could already be facilitated by 2 batteries of 300MJ each.

If the thermal battery system is used in a short-term storage strategy it should be connected to a local smart grid. The batteries can prevent local peak loads, improving grid stability and reducing required investments. The batteries can also be used for demand side management: they can be charged at low-tariff hours to provide cheap heating, just like in the partial coverage strategy.

In a short-term strategy, it does not make sense to connect the batteries to a solar collector since electric charging is required. Instead, a small array of PV-panels could be used. Required storage capacity will not depend on collector surface in this case, so required storage capacity always equals 3 days of most extreme thermal demand.

It must however be noticed that a 3 day storage could also be achieved with conventional sensible energy storage. About $3m^3$ of water (insulation excluded) would be required in that case, against a volume of $0.6m^3$ for batteries. The choice for a thermochemical battery system for short-term storage will mainly be determined by available space. A short-term electric storage would even be better in that case, because the electricity can be used for domestic appliances as well, increasing usability and allowing diurnal cycles, even during summer.

6.5.4 Conclusions

All described strategies have their (dis)advantages. Regarding seasonal storage, the coverage of space heating only is preferred over the full coverage strategy because this would require an additional storage capacity of around 2200MJ to cover 4 months of DHW, which is economically unfeasible compared to auxiliary heating at low-tariff hours. In case DHW demand does not have to be covered by the batteries, the system can work with lower temperatures. This reduces requirements of the discharging power, increasing technical feasibility.

The choice for a partial coverage strategy or even a short-term strategy will be a matter of ambition and available budget. Especially when huge investments are done in windmills, a short-term strategy would be more obvious.

A matrix of different system layouts and deployment strategies with corresponding savings and costs for different storage prices is given in paragraph 7.2. This matrix could eventually be used to determine the most suitable system layout and deployment strategy for a certain price of thermal batteries.

6.5.5 Starting point: basic system layout

The optimum system layout is a consideration between an energy and a financial optimum. From an energy perspective, the smallest possible collector surface is in favour, because it has the best solar fraction and smallest mismatch. The financial optimum will completely depend on the price of the storage as will be explained in paragraph 7.2.5, but this is unknown since the system is not fully developed yet. In this report, a collector surface of $12m^2$ is selected for the basic system layout because it yields enough storable energy. This would therefore be the most optimal configuration from an energy perspective.

Although flat-plate or PVT-panels can be used to store the energy during summer, they will not yield any energy during winter. This would increase required storage capacity significantly. Therefore, ETC will be used. In practice, the price of the storage will determine whether it is beneficial to reduce storage capacity by more expensive ETC's.

Because of aforementioned reasons, the system will be used in a deployment strategy in which only space heating is covered, meaning DHW demand between November and February will be covered electrically.

7. DESIGN ELABORATION

In this chapter the technical and spatial design of a thermal battery system will be elaborated. First design specifications are explained, where after the technical design is described. Different spatial design directions for integration of the system are explored, and one of them is elaborated into a possible refurbishment concept for the case study. The chapter ends with an evaluation of the system on both energy performance and financial feasibility.

7.1 Design specifications

This paragraph describes what the eventual system should be capable of and what the requirements of the integrated thermal battery system are. The basic system layout that is the starting point of the design elaboration has been discussed din the previous chapter.

7.1.1 Design goals

1. The thermal battery system allows for **100% coverage of space heating + DHW demand by solar thermal energy**, thereby addressing the current mismatch of solar energy.

2. The integration of a thermal battery **prevents** the refurbishment concept to deliver and extract **high peak loads to the electricity grid** as is happening in current refurbishment, thereby **avoiding grid instability and additional (long term) investments.**

3. The thermal battery system has a **modular set up**, allowing residents to determine their own **desired level of self-sufficiency** and possible extensions later on to increase financial feasibility.

4. The thermal battery system can be **technically and spatially integrated in a refurbishment concept** for the case study.

5. The eventual concept is a **feasible alternative to existing concepts** that cause aforementioned problems and are not adequate towards the future.

7.1.2 Requirements

The requirements are specified for the refurbishment concept (which is part of the design context), the solar collectors, thermal batteries and the whole system. Although the refurbishment concept will not be designed into detail, it must meet specific requirements (or boundary conditions in this case) in order to facilitate a successful refurbishment in which a thermal battery system can be integrated. Figure 88 shows how the refurbishment concept relates to the actual design part of this report. In this paragraph only basic requirements are specified; in paragraph 6.1 a more detailed description of the refurbishment concept is given.

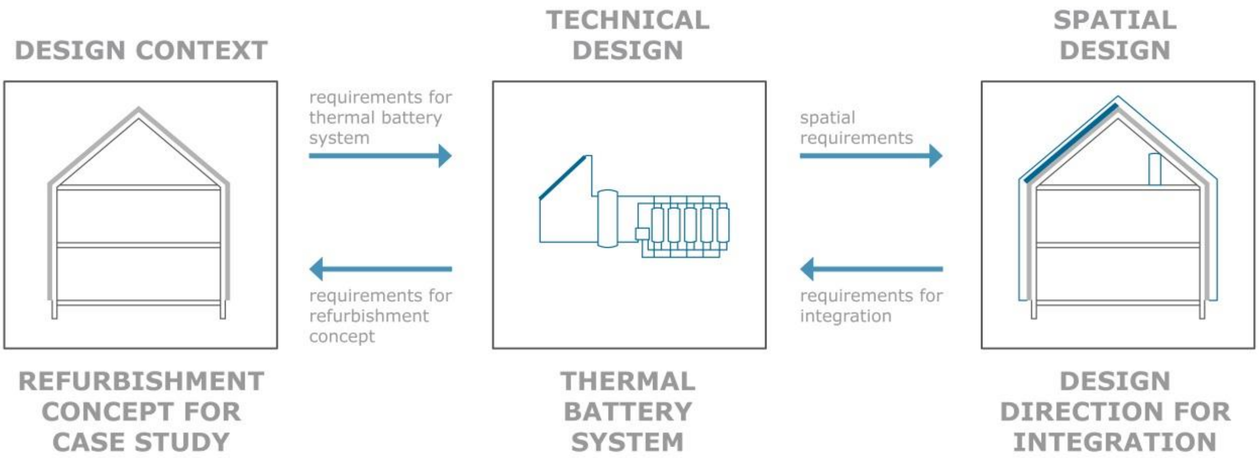


Fig. 88. Relation between design context, technical and spatial design. (Own illustration)

Refurbishment concept

- Thermal resistance of walls and roof is 4,0 $m^2/K/W$
- Windows have U-values of at least 1.5 W/m^2K
- Cooling load is prevented by adequate sun shading measures and mechanical exhaustion
- Envelope appearance is improved and customizable
- Prefab elements are used for reduction of cost and building time
- Heat recovery (90% efficiency) is used to reduce heat losses
- Floor heating is used for an efficient distribution of low temperature heat

Solar collectors

- Thermal yield is used to cover both DHW and space heating demand
- Evacuated tube collectors
- Minimum of $12m^2$ collector area
- Integrated in case study roof

Thermal batteries

- Extendable modular system
- Na_2S hydrate storage material
- effective storage density $1GJ/m^3$
- Charging temperature between 70 and 100℃
- 60mm insulation around battery
- non-corrosive and non-flammable
- Lifespan of at least 15 years.

Thermal battery system

- Is a combination of long- and short-term storage
- Uses both sensible and thermochemical storage
- Short-term buffer is primarily charged
- Short-term buffer primarily used for DHW from March to October
- Electric heating may be used for DHW from November to February
- Long-term (seasonal) storage charged in times of surplus solar energy
- Long-term storage primarily used for space heating
- Does not take up useful surface area in the dwelling
- Is accessible for maintenance

7.2 Technical design

The technical design refers to the thermal battery system and its components. The individual components will be discussed first, where after the selected system layout and operation principles are explained. The paragraph ends with an elaboration on optimum system sizes from both energy and economical perspective.

7.2.1 Specifications of system components

The basic thermal battery system layout is derived from simulation results, literature research and interviews with researchers from TNO. The system layout is based on the system layout of the CREATE-project, but some adaptations have been made to customize the system for the case study context. In figure 89, a conceptual scheme of the system layout with relations between components can be seen. The buffer is the central pivot that distributes the energy flows throughout the battery system.

Solar collectors (ETC)

Because the collectors also have to contribute to direct space heating, ETC's are selected since they give the best results in a Dutch context. The collectors will be integrated in the case study roof, which is oriented on the South with a slope of 35 degrees. An angle of 40º would be more beneficial, but the slope of the case study roof is decisive. In this report the collector surface area that gives the best system efficiency will be used, although the financial optimum system is more likely to be decisive in practice. A 12m^2 collector area is the best choice from an energy perspective and is therefore selected (see paragraph 6.5.4).

Buffer

The buffer tank plays a crucial role within the system since it distributes the energy throughout the system. The buffer increases short-term storage capacity, allowing a better system efficiency and a reduction in long-term storage.

The buffer is directly connected to the solar collectors and is always primarily charged. The buffer transfers the energy to either the solar boiler, thermal batteries or directly to the space heating system. The batteries will also discharge the energy into the buffer, which will distribute the energy to the space heating system.

Available buffer tanks are standard wrapped in 100mm thermal insulation. To further minimize thermal losses through piping, the buffer should be as close to the solar collectors as possible and is therefore placed in the attic.

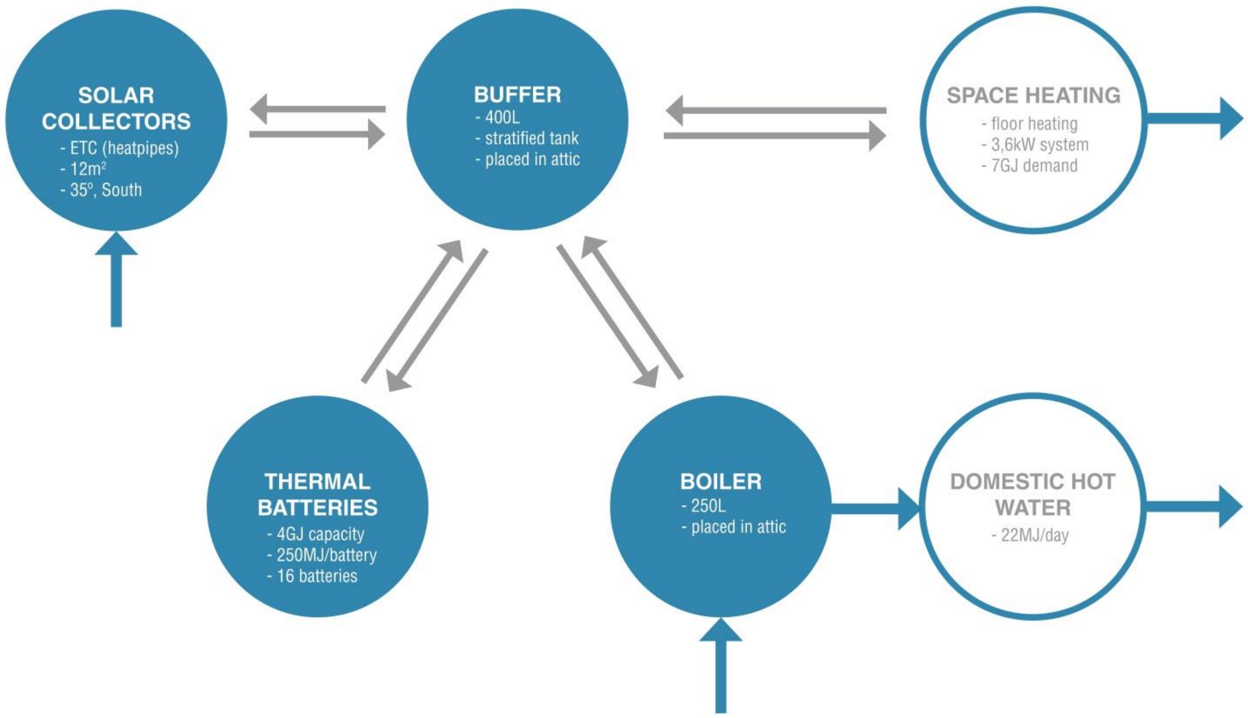


Fig. 89. Conceptual system layout with relations and requirements. (Own illustration)

The size of the buffer follows from the peak power it should deliver to the floor heating system. The floor heating system needs to deliver 3,6kW for 5 hours in a worst case scenario, resulting in an energy demand of 18kWh or 65MJ. This 65MJ must be delivered by the buffer to increase water temperature from 20 to 60ºC.

Q = MCp(Tout – Tin).

65*106 = M*4186*(60-20) M = 389kg

The buffer should contain roughly 390L of water to cover space heating demand in an extreme scenario. A buffer volume of 400L is therefore selected. This volume can be reduced if for example PCM's are added to the tank. This is not taken into account in this report, but if boiler size has spatial restriction this could be a design consideration.

The buffer is also equipped with an auxiliary heating element. This will only be used in extreme cases such as long periods without sunshine and extremely low temperatures.

Solar boiler

A DHW demand of 8GJ/year or 22MJ/day needs to be covered by the boiler. The required amount of water for DHW can be found with the formula for sensible heat:

Q = MCp(Tout – Tin).

22*106 = M*4186*(60-10) M = 105kg

Roughly 105L of water needs to be heated from 10 to 60ºC every day. Residential boilers are usually dimensioned according the 2-day principle (see paragraph 4.3), resulting in a boiler size of 210L. This is size is not on the market, and therefore a boiler of 250L is selected.

The solar collectors are not directly connected to the boiler like in a conventional system, but the buffer is placed in between. This allows a more efficient energy distribution and thermal energy is not used to heat up the whole volume; only incoming water is preheated.

The boiler is also wrapped in 100mm insulation and placed in the attic to minimize thermal losses. Furthermore, the solar boiler contains an internal auxiliary electric heating component which provides backup heating when necessary. The electric component is also used to raise temperature to 65 once a week to eliminate legionella growth. The efficiency of the heating element is assumed at 98%.

Thermal batteries

The thermal batteries are the real innovative part of the whole system. The exact properties of the batteries are already described in paragraph 5.5.

With the space heating coverage deployment strategy and a collector surface of 12m^2, a storage capacity of roughly 4000MJ is required (see paragraph 6.5), which comes down to 16 batteries. The batteries are connected in series, allowing multiple batteries to be charged simultaneously.

Low temperature source

The low temperature source provides energy to condense and evaporate the water during (dis)charging. In paragraph 5.5.5 is calculated that the (dis)charging process requires 5.5MJ of condensation energy and 25MJ of evaporation energy per GJ of stored energy.

Pumps

The thermal battery system has 4 pumps:

1: buffer – collectors
2: buffer – space heating/DHW
3: buffer – thermal batteries
4. low T source – thermal batteries

The pumps that are connected to the buffer have an output power of 50W, which is described in literature as sufficient (Laughton, 2010). The pump connected to the low temperature source is dimensioned at 25W since only a small peak power is required. For calculation of required pumping energy it is assumed that pumps always run on full capacity, although this will not be the case in practice. Actual pumping energy depends on piping lengths, section and flowrate, which requires more complex calculations. Values used in this report will therefore be less in practice.

Control strategy unit & thermostat
This is not a single component, but is a whole collection of sensors and valves that are controlled by the control unit and thermostat. The sensors give input and the control strategy unit reacts with a certain action. The thermostat regulates indoor climate and can be manually adjusted by residents. Both control unit and thermostat use 4W of energy and are always turned on.

Heating system
Although the heating system is not part of the thermal battery system, the performance of the system is strongly connected to it. Existing radiators could be used, but floor heating is preferred because it is more energy efficient compared to conventional radiators and it operates at lower temperatures, reducing required output power of the battery system. The floor heating system requires a feed temperature of 40ºC from the buffer, and return temperature is about 20ºC.

Fig 91. Uponor Minitec floor heating system. (www.uponor.nl)

Besides energetic benefits, floor heating will also increase comfort. Nowadays, floor heating can easily be implemented in existing dwellings. Systems like "Uponor Minitec" can be placed on top of the existing floors, only increasing total height by 15mm (fig 91).
No grooves have to be made in the existing floor, allowing the system to be installed in just one day (www.uponor.nl).

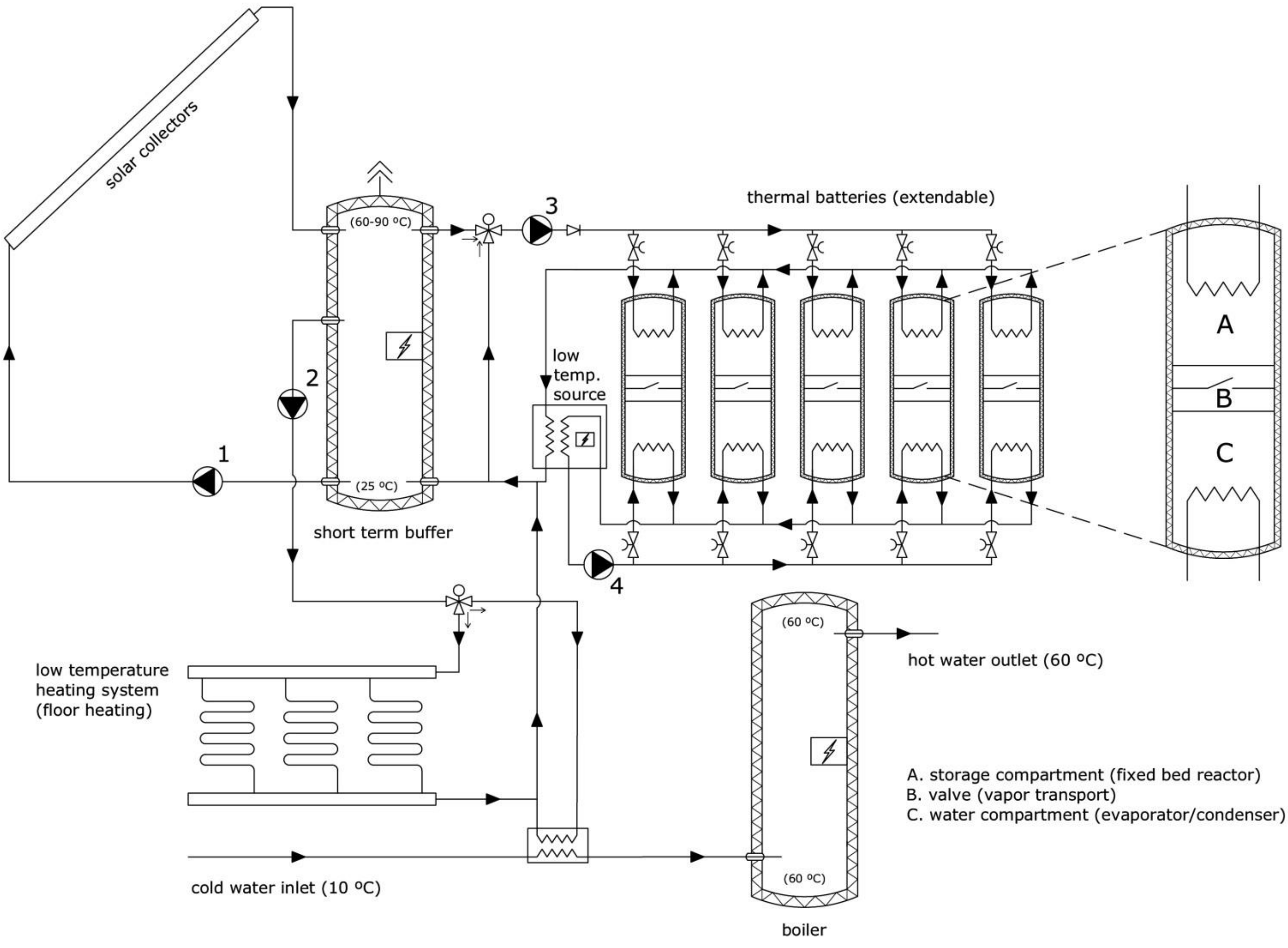


Fig. 90. (Simplified) technical installation scheme of the thermal battery system layout. (Own illustration)

Simulations are required to precisely calculate required output power of the system, but this doesn't fit within the scope of this report. Therefore an online calculator, found at www.wth.nl has been used to roughly estimate required power of the floor heating system. A value of 30W/m^2 has been calculated, so 3,6kW for a floor surface of 120m^2 is required.

7.2.2 System operation

The system layout with all its components can be seen in figure 91. The system is an open system where water is only present in the collectors if the pump is turned on, so no glycol is needed. The system has four main circuits, each operated by a pump. These circuits are strongly related to the operations modes of the system, which will be explained next.

Short-term charging

The buffer is always primarily charged by the collectors (fig. 92) and it can store thermal energy for several days.

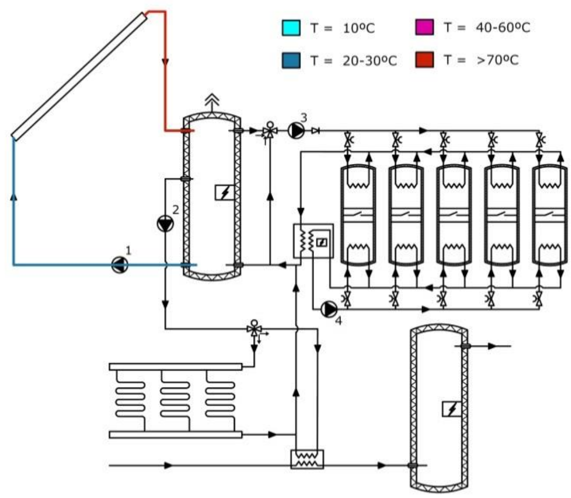


Fig. 92. Energy flows during charging of buffer by collectors. (Own illustration)

Direct solar energy utilization

In this mode, the solar thermal energy is directly (within the same day) used for space heating or DHW purposes. Heat from the collectors is exchanged in the buffer, and the buffer distributes it to the floor heating system or preheats incoming cold water for DHW consumption. These energy flows are visualised in figure 93.

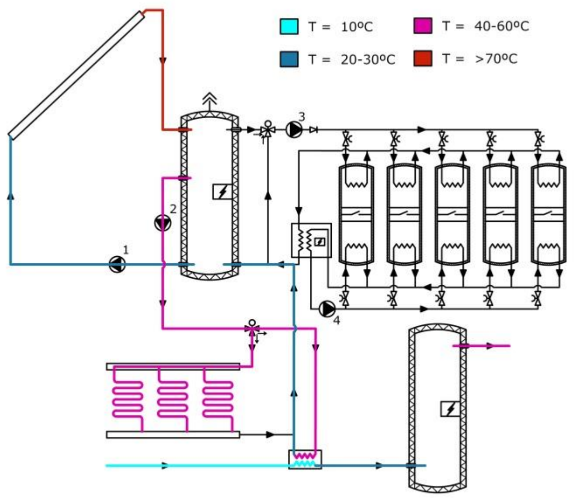


Fig. 93. Energy flows during direct solar energy utilization. (Own illustration)

During direct solar energy use, pump 1 and 2 are operational. The required pumping energy for 1GJ (278kWh) of directly used solar energy for space heating by the buffer can be calculated if the time it takes to yield 1GJ during winter is known. This can be calculated with the average monthly radiation during shortage period, which is 40kWh/m^2 (see appendix 5) and results in a yield of 16kWh/m^2 at a collector efficiency of 40%. This comes down to 192kWh for the total collector surface. The collectors are assumed to be operational for 6 hours a day for 30 days, resulting in an average thermal yield of 1,06kW/hour.

It now takes 278/1,06 = 260 hours to yield 1GJ of directly usable solar energy, requiring 13kWh of pumping energy.

The time it takes to discharge 1GJ of energy follows from the required output power of the floor heating system, which has been calculated in the previous paragraph and amounts 30W/m^2, or 3,6kW for the whole dwelling. It is assumed the system always delivers 3,6kW, although this might be less in reality. It now takes (278/3.6) = 77 hours to discharge 1 GJ, requiring 3,9kWh of electric energy.

Total pumping energy for direct solar energy use is 16,9kWh.

Thermal battery charging

The batteries are only charged when short-term buffer is saturated or high temperatures are available. Thermal energy is delivered to the buffer by the collectors, but because the pump of the batteries is turned on, the water will directly flow into the heat exchanger of a single battery. Multiple batteries could be simultaneously charged. A valve that is connected to both supply and return flow will regulate incoming temperatures, so batteries can be charged at desired temperature. During charging, the circuit that provides condensation energy is also active (fig. 94).

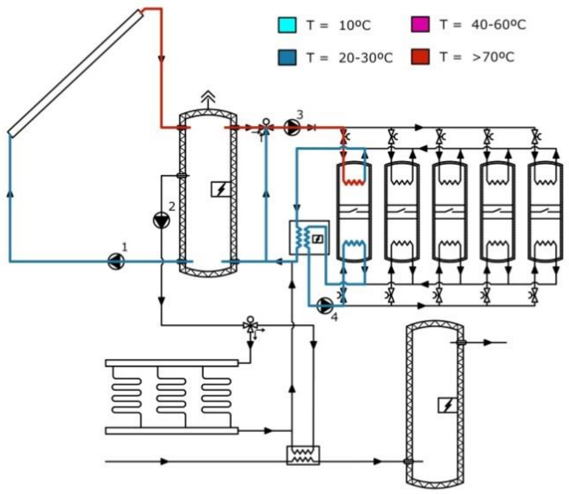


Fig. 94. Energy flows during charging of batteries. (Own illustration)

The time it takes to charge 1GJ (278kWh) can be calculated by the average irradiation in the charging period, which has been simulated for the case study context in TRNSYS. The average monthly irradiation on the collectors in the charging period is 130kWh/m^2 (see appendix 5). At a collector efficiency of 50% (which is realistic during summer), and an operation time of 10hours for 30 days, indicates a collector yields 0,22kW/m^2/hour. A collector surface of 12m^2 will yield approximately 2,65kW per hour.

To yield 1 GJ, the system needs to operate for: 278/2,65 = 105 hours. During charging pump 1, 3 and 4 are operational, resulting in an energy demand of 13kWh.

Thermal battery discharging

Discharging of batteries into the buffer to the heating system is the most fundamental and important operation mode within the thermal battery system (fig. 95). This mode can occur when the short-term buffer is fully charged, but usually goes along with discharging of the batteries to reach desired peak powers. The batteries replace the collectors in that case. During discharging, the circuit that provides evaporation energy is also active. The batteries will only be discharged for space heating purposes, so usually the space heating circuit is also active during discharging of a battery.

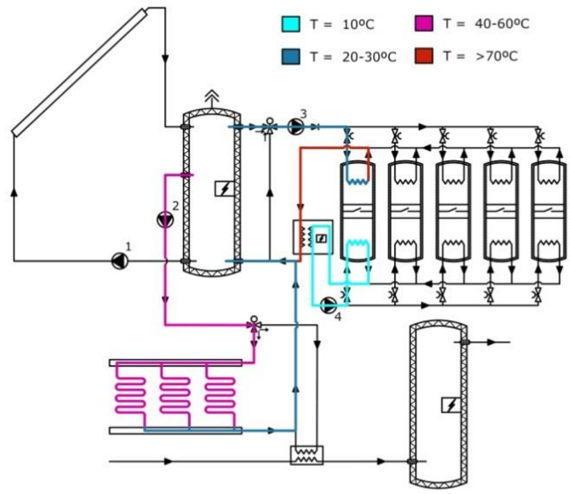


Fig. 95. Energy flows during discharging of batteries. (Own illustration)

The time it takes to discharge 1GJ of energy into the floor heating system is calculated under direct solar energy utilization and amounts 77 hours. During discharging pump 2, 3 and 4 are operational, resulting in an energy demand of 9,6kWh.

Discharging of buffer for DHW

The buffer can also discharge energy to preheat incoming DHW water (fig. 96), but this only occurs between March and October because of the chosen deployment strategy.

The system layout in figure 90 is a general layout, and says nothing about spatial integration. In the next paragraph several options for spatial integration of the system the case study dwelling will be discussed, and in 7.4 a design direction for integration in a refurbishment concept is explained.

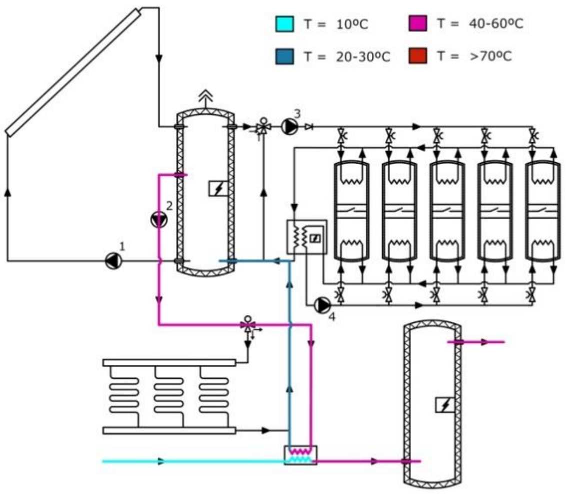


Fig. 96. Energy flows during discharging of buffer for DHW. (Own illustration)

7.2.3 Deployment strategy and required storage capacity

A strategy of full space heating coverage for deployment of thermal batteries is selected under design considerations. Within this strategy DHW demand between March and October is also covered directly by the collectors and buffer. The basic principles of the deployment strategy are described in more detail below.

- Thermal batteries are used to cover space heating demand only
- Short-term buffer is always charged and discharged primarily when possible
- Batteries are only charged when short-term buffer is saturated
- Batteries start to discharge if average buffer temperature drops below 40ºC
- Solar collectors and buffer cover DHW demand between March and October
- DHW demand covered by auxiliary heating element in boiler between November and February
- Auxiliary heating of boiler only takes place at night

7.2.4 Energy performance

The energy performance can be calculated if the energy use of the system and the energy savings are calculated. The system always covers total space heating and DHW demand, so the gross savings equal 7+8 = 15GJ of natural gas compared to coverage of the same thermal demand by a conventional boiler with an efficiency of 100%.

The annual system energy use consists of several components that are explained below. Although any system will have the same gross energy savings within a deployment strategy, operational energy use will vary because of system configuration and corresponding storage capacity, resulting in different nett energy savings. The system energy use in this paragraph is calculated for a thermal battery system with 12m^2 collectors and a space heating coverage deployment strategy.

Energy use for DHW

DHW demand is covered by the solar collectors and boiler for 8 months of the year, and covered by electric heating for 4 months during shortage period.

The energy it takes for DHW to be provided by the collectors only involves pumping energy of pump 1 and 2. These pumps are operational for 244 days for about 1 hour a day. This results in an electric energy use of 24,4kWh (assuming pumps always run on full power).

The thermal energy for 4 months of DHW coverage equals 2666MJ. If converted to electricity (assuming an efficiency of 98%) it requires 2720MJ electric energy, or 756kWh. This could be avoided if DHW demand from November to February would also be covered with the thermal battery system.

Besides electric energy for heating, coverage of DHW demand during shortage period involves 1 hour pumping energy of pump 2 for a period of 121 days. This results in an energy use of 6kWh.

Energy use for direct use of solar energy

The pumping energy required for direct use of solar energy is calculated in the previous paragraph and amounts 16,9kWh/GJ. This figure must be multiplied by the amount of GJ’s that are used directly to find total energy.

Energy use for thermal batteries

The energy use for the thermal batteries is calculated per GJ of stored energy and consist of pumping energy and energy during (dis)charging process to condensate and evaporate the water, as explained in chapter 5.5. The condensation energy was calculated at 1,5kWh/GJ and evaporation energy at 7kWh/GJ storage.

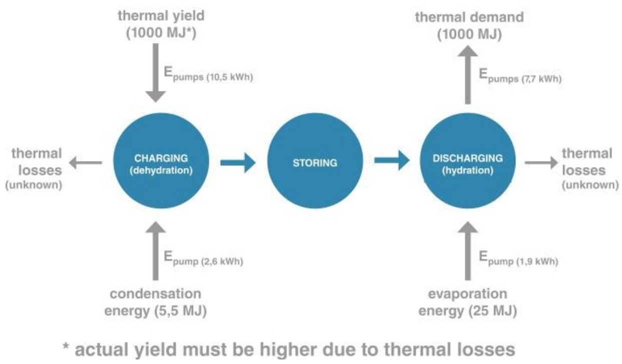


Fig. 97. Energy flows during (dis)charging. (Own illustration)

The pumping energy is calculated in the previous paragraph and amounts 13kWh during charging and 9,6kWh during discharging. Total energy for charging comes down to 16,6kWh and 14,5kWh for discharging 1GJ of thermal energy stored in the batteries. These figures must be multiplied by the amount of GJ's stored in the system to find total energy use for thermal batteries.

Energy use for control unit/thermostat

The energy for monitoring and adjusting the system is not affected by the amount of energy that is stored. A 4W control unit and thermostat are always operational, requiring 70kWh/year.

Combined system energy use

In the selected system layout, 4,6GJ is covered by the thermal battery system (Qsho + Qsur) and 2,4GJ is covered directly (Qdir).

The energy that is required for the system to cover total thermal demand (15GJ) is summarized in figure 98 and amounts 1050kWh electric energy and 12,3GJ thermal (solar) energy.

* If DHW demand is covered entirely by the thermal battery system, the system energy use would only be 306kWh.

PV-panels can however compensate system energy use. A PV-panel of 270Wp (1,65m^2) generates about 238kWh/year (Essent.nl, 2016). This means 5 panels (or 7,3m^2) are required to cover system energy use. If energy for DHW is not taken into account (787kWh), two panels are already sufficient. Due to the mismatch the additional PV-panels will still not harvest the energy when needed, so only when net-metering is allowed this is a viable solution.

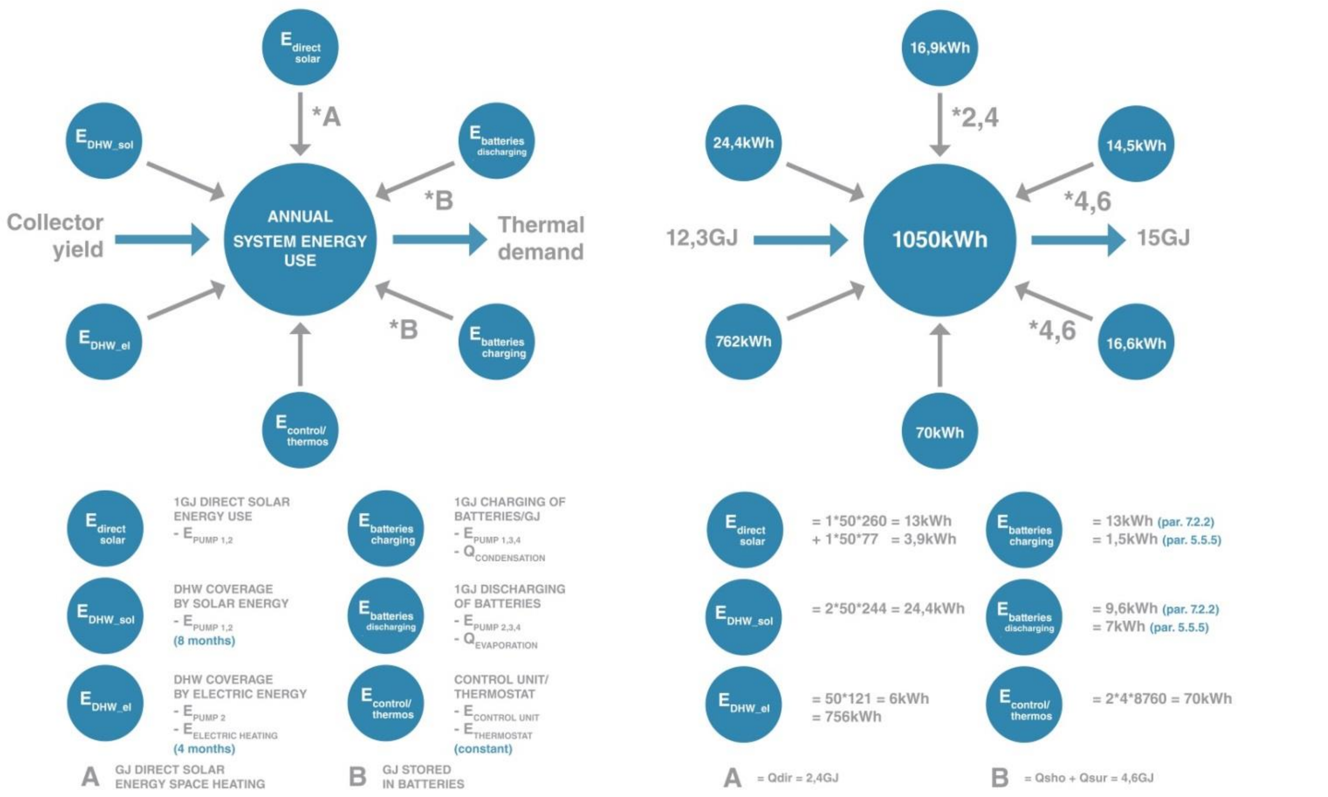


Fig. 98. Components of total system energy use (left) and calculated values (right). (Own illustration)

Energy savings

The gross energy savings are already discussed and amount 15GJ. The Nett energy savings are gross savings minus system energy use. This comes down to 15.000-3780 = 11.220MJ, or 11,2GJ. During the lifetime of the thermal batteries, a total of 11.2*15 = 168GJ is saved.

An evaluation of the energy performance and assessment on BENG-indicators is given in paragraph 7.5.

System efficiency

The overall system efficiency can be found by dividing the output energy by the input energy. The input energy equals the solar irradiance on the collectors, electrically generated DHW and electricity to operate the system.

$\eta = Q_{out}/Q_{in}$

15GJ/(12,3/0,4)+3,78 = 43%

Actual system efficiency will be lower, because thermal losses during (dis)charging are not taken into account.

The efficiency of the collectors has a big impact on the overall efficiency. If collector yield rather than solar radiation is taken as thermal input the efficiency would be:

15GJ/12,3+3,78 = 93%

The system efficiency, or performance can also be expressed in the COP. This indicates the required amount of electricity to cover the thermal demand. The COP is calculated by dividing thermal output by electrical input. For a system of 12m^2 and space heating coverage strategy only, this will be 15/3,78 = 4,0.

This figure however includes the inefficient four months auxiliary heating, and if this is not taken into account the COP becomes: (15-2,72)/(3,78-2,72)=11,2.

If a system with 30m^2 collectors would be used in the case study, more energy is covered by the short-term buffer and only 3000MJ would be covered by the batteries, resulting in a COP of 4,4. A system with more collectors will slightly increase COP, but actual system efficiency and solar fraction will be much lower because the extra surplus during charging season cannot be used, increasing the mismatch.

Natural gas and CO_2 savings

One of the three major climate goals is a CO_2 reduction of 50% compared to 1990 in 2030. It is therefore relevant to see to what extend the thermal battery system can contribute.

The nett savings are 11,2GJ/year. This equals 318m^3 of natural gas per year and 4780m^3 in 15 years. Burning one cubic metre of natural gas results in a CO_2 emission of 1,8kg, meaning 8604kg of CO_2 is saved.

The ratio between required material for storage and resulting savings is also interesting. About 1/3 of the required storage volume is salt-hydrate. The system has a storage capacity of 4GJ, which equals 4m^3, of which 1,3m^3 is salt-hydrate. The savings in this case equal the energy that is provided by the thermal batteries, which is 4,6GJ/year (the other part can also be covered by 12m^2 solar collectors without the use of storage). 1,3m^3 Na_2S-hydrate is able to save 1962m^3 natural gas during operational lifetime, thereby reducing CO_2-emissions by 3531kg. One cubic metre of Na_2S-hydrate will save 1510m^3 natural gas and 2717kg CO_2.

Fig. 99. Required volume of salt-hydrate compared to saved volume in natural gas during opereational lifetime. (Own illustration)

7.2.5 Optimal system size

A thermal battery system will have an energy and financial system optimum. These will both be discussed and will result in a matrix with different parameters and system sizes to determine the optimum.

Energy optimum

The energy optimum system size will save the most energy using the least additional (electric) energy. This can only be achieved in the full coverage strategy, where the batteries also cover total DHW demand, thereby completely solving the energy mismatch. This will equal the least electric energy since the thermal energy is mostly provided by the sun.

If additional energy use and correlating system COP is defined as energy optimum, the collector surface should be as big as possible (see conclusion matrix further on in this paragraph), because it will have the most direct energy use, which is more efficient than storing the energy. With this definition a collector surface of 30m^2 is the energy optimum.

However, in solar system design, the system efficiency is an important indicator for the energy optimum as explained in chapter 4. The energy optimum in that case is defined as the most beneficial ratio between collector surface, short term storage capacity, thermal battery storage capacity and additional energy use compared to energy savings. This ratio can only be found using complex simulations, that do not fit within the scope of this report.

Yet, it is obvious that a system with a collector surface of 12m^2 is in favor since this can already yield enough energy to cover annual thermal demand. Bigger collector surfaces yield more energy than can be used (throw away effect), resulting in a low system efficiency and increased mismatch.

Financial optimum

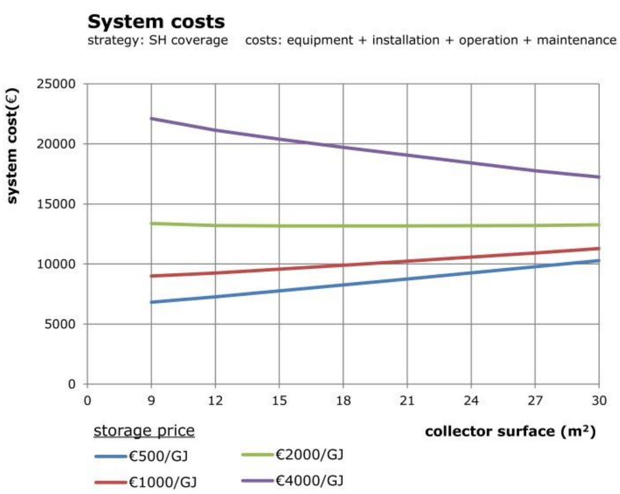
The financial system optimum does not equal energy optimum, especially regarding deployment strategy. Yet, the financial optimum system will always be in favor in practice. The financial optimum is defined as the system that covers total thermal demand at the least costs. Costs include equipment, installation, maintenance and (electric) energy use during the operational lifetime (15 years).

The exact costs of the system cannot yet be determined, since the costs the thermal batteries are unknown. However, all other factors are known or can be estimated, meaning a financial optimum for different system sizes and storage prices can be made. The following assumptions are made for this calculation.

- Solar collectors €300/m^2*
- Buffer + boiler €1500*
- Installation costs 10% of system, thermal batteries excluded
- Maintenance €100/year
- Electric energy €0,22/kWh
- Subsidy of €3000 for total system**

*prices are based on brief market research

** Subsidy for a heat pump is between €2000 and €3400 (milieucentraal.nl). Because a thermal battery system requires less electricity and is a more sustainable system, a subsidy of €3000 should be realistic. The collectors, boiler and buffer tank have a lifespan of 25 years. To compensate the longer lifetime, 65% of purchase costs are used. This will compensate for 10 years additional yield and some maintenance.



Graph 7. Total system costs during operational lifetime (15 years) for different prices per GJ of storage capacity. (Own illustration)

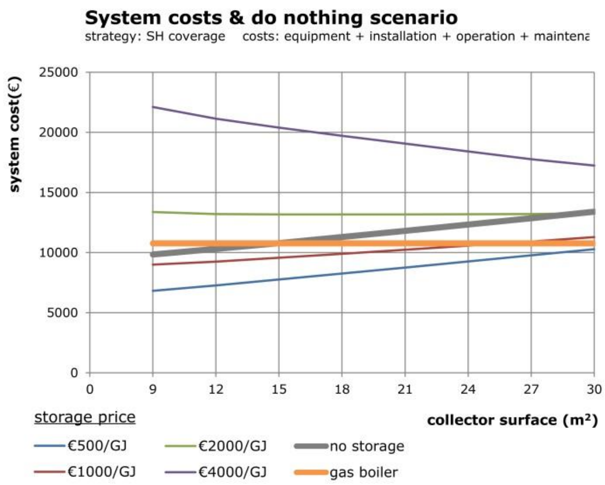
As the results in graph 7 are showing, the financial optimum strongly depends on the eventual storage price. If storage prices are below €1000/GJ, systems with small collector area are more feasible, but when price goes up it is better to have less storage capacity. If the price of storage is around €2000/GJ, collector area does not affect total price because additional collector costs equal costs of the reduced storage capacity. However, a small system is always favorable. In case storage price is €4000/GJ or more, a bigger collector surface is in favor since this is relatively cheap compared to the high costs for storage capacity.

The aforementioned system costs will remain abstract if they are not related to a system in which no storage is used. This can be seen as the “do nothing scenario”. Two scenarios are evaluated.

1. DHW + SH covered by a natural gas boiler over a period of 15 years. Solar energy does not contribute here.

2. DHW + SH covered by solar collectors (direct use) and a conventional gas boiler to cover the remaining shortage for different collector surfaces. In this scenario the cost for storage can directly be compared with the cost for a natural gas boiler covering the same demand.

The results are visualised in graph 8. The earlier calculated system costs for different storage prices are also included for comparison. The graph shows that a thermal battery system is cheaper compared to a conventional gas boiler if storage price is below €1000/GJ and a small collector surface is used. A system with collectors but without storage is more expensive compared to a thermal battery system with storage price below €1000/GJ. A thermal battery system with a storage price of €2000/GJ and a collector surface of 30m^2 is cheaper compared to the variant without storage. In case the storage will cost €4000/GJ, a thermal battery system will be significantly more expensive than a natural gas system.



Graph 8. Total system costs compared to a natural gas boiler and a solar collector system without storage, covering the same thermal demand. (Own illustration)

In practice, pay-back time is also crucial for financial feasibility because of the high investment costs involved. These would require a loan from the bank in most cases, resulting in additional expenses for interest. Actual pay-back time and resulting interest expenses will not be discussed in this report because eventual storage price is not known yet.

The graphs in this paragraph have indicated the most cost-effective system configurations for different storage prices and what the costs in the do nothing scenarios are. The eventual optimum completely depends on the price per GJ of storage and prices of natural gas.

However, even without knowing the price of the storage, a price for a reduction of storage capacity can be calculated. This is done in table 1, where a system with 9m^2 collector surface is taken as basis. The table shows additional costs of the system (storage excluded) and subsequent reduction in required storage capacity. For example: with a collector surface of 12m^2 it costs €1.65 to reduce storage capacity by one MJ compared to the basis layout, while this costs €1.95/MJ for a 27m^2 collector surface. A system with a collector surface of 9 or 12 m^2 is therefore more likely to approach the financial optimum, but this will strongly depend on price of the storage itself.

	Additional system costs (€)	Storage capacity reduction (MJ)	Additional cost per MJ reduction(€)
9m^2	0 = 4650	0 = 4368	0.94
12	+ 675	- 409	1.65
15	+ 1650	- 760	2.17
18	+ 2025	- 1095	1.85
21	+ 2700	- 1425	1.89
24	+ 3375	- 1735	1.95
27	+ 4050	- 2081	1.95
30	+ 4725	- 2380	1.99

Table 1. Additional costs per MJ of storage capacity reduction as a result of a bigger collector surface. A bigger collector surface will result in a higher costs per MJ reduced storage capacity, but this can be more cost-effective if storage prices are high.

In case one PV-panel is used to cover system energy use (4 months DHW demand excluded), 190kWh/year is saved. At a price of €0,22/kWh over a period of 15 years €627 is saved. This would be a very feasible investment at current prices of PV and net-metering possibilities.

7.2.6 Conclusion matrix for the case study dwelling

The optimum system size is a matter of definition and requires complex simulations with unknown parameters. Therefore a matrix with different system configurations and deployment strategies is given in fig. 100, which can be used to select optimum system size by certain indicators. The matrix has been made using excel and can therefore also be used in other contexts to determine the most suitable system configuration and deployment strategy.

A bigger collector area results in a smaller operational energy use because direct coverage of thermal demand by solar energy requires less energy. However, the difference is negligible as can be seen in the matrix. The same accounts for nett energy savings. From an energy perspective, a collector surface as small as possible is therefore preferred.

Regarding deployment strategy, a space heating coverage strategy (with DHW coverage from March to October) seems most applicable. The additional required storage capacity to cover the 4 months of DHW will not be cost-competitive compared to auxiliary low-tariff electric heating unless price per GJ storage is below €1000. System costs for different deployment strategies and collector areas are all visualized in the matrix.

The optimal system configuration strongly depends on eventual price per GJ storage. The total system costs, including operation for different storage prices are given in the matrix. The matrix could eventually be extended with other deployment strategies for better comparison.

collector surface (m2)	9	12	15	18	21	24	27	30
storage capacity / storage volume (GJ)/(m3)	7.35 4.37	6.47 3.96	5.61 3.61	5.08 3.27	4.72 2.94	4.38 2.61	4.04 2.29	3.70 1.99
operational energy use per year (kWh)	383.2 1047.5	374.2 1040.9	366.1 1035.5	359.2 1031.2	353.5 1027.6	348.8 1024.4	344.7 1021.6	341.0 1018.9
nett energy savings during operational lifetime (GJ)	204.3 168.4	204.8 168.8	205.2 169.1	205.6 169.3	205.9 169.5	206.2 169.7	206.4 169.8	206.6 170.0
system COP (annual average)	10.87 3.98	11.13 4.00	11.38 4.02	11.60 4.04	11.79 4.05	11.95 4.07	12.09 4.08	12.22 4.09
nett savings during operation, compared to gas boiler (€)	8877 8061	8888 8069	8898 8076	8907 8061	8914 8086	8920 8090	8925 8093	8929 8096
total system costs during operation (€500/GJ storage) (€)	6087 6791	6297 7239	6513 7722	6899 8215	7378 8713	7865 9213	8356 9714	8851 10231
total system costs during operation (€1000/GJ storage) (€)	9760 8975	9535 9219	9317 9526	9437 9851	9740 10185	10053 10520	10375 10858	10702 11225
total system costs during operation (€2000/GJ storage) (€)	17105 13343	16009 13178	14926 13135	14514 13125	14464 13128	14430 13135	14413 13144	14404 13213
total system costs during operation (€4000/GJ storage) (€)	31795 22079	28958 21096	26143 20353	24667 19672	23912 19016	23185 18365	22489 17718	21808 17188

Parameters

price buffer + boiler	1500 eu
governmental subsidy	3500 eu
maintenance battery system	1500 eu/15 years
collector price	300 eu/m2
lifetime correction boiler/buffer (65%)	525 eu
lifetime correction collectoren (65%)	0.35 factor
electricity price	0.22 eu/kWh
installation costs (10% boiler+collectors)	1.1 factor
energy use total DHW coverage	787 kWh
energy use storage (Qsho+Qsur)	31.1 kWh/GJ storage
energy use direct solar utilization	16.9 kWh/GJ Qdir
energy use control unit/thermostat	70 kWh/year
energy use DHW pump	31 kWh/year
total space heating demand	7 GJ/year
total DHW demand	8 GJ/year
operational lifetime	15 years
energy contents natural gas	35.17 MJ/m3
price natural gas	0.8 eu/m3
price gas boiler (incl maint.)	4230 eu

full coverage strategy   SH only strategy

Fig. 100. The conclusion matrix: relevant figures for different collector surface area's and deployment strategies. (Own illustration)

7.3 Spatial design directions

This paragraph is meant to explore the options for spatial integration of the thermal battery system in a refurbishment concept for the case study dwelling. This paragraph does not end with "a best" solution, but shows what the eventual considerations will be. The spatial integration includes 3 main components; solar collectors, short-term (sensible) storage and the thermal batteries.

The sensible storage will be placed in the attic to minimize thermal losses and the solar collectors are integrated in the southern roof for maximum yields. The actual integration is therefore mainly about the thermal batteries. The scheme in figure 101 shows how the design directions relate to the eventual refurbishment concept which is discussed in the next paragraph.

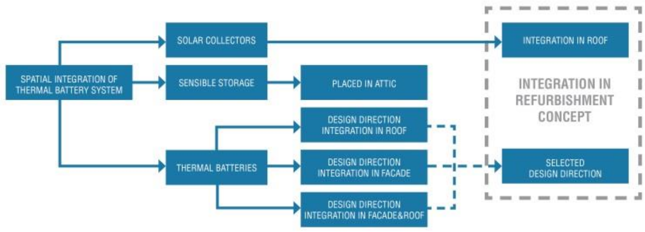


Fig. 101. Relation between design directions and the eventual refurbishment concept. (Own illustration)

7.3.1 Dimensions and spatial requirements of system components

To determine the dimensions of the system components the output from the conceptual technical design is used.

Solar collectors (12m^2)

The first step is to translate the required ETC surface into an amount of collectors. The length, diameter and height including frame of the tubes are always identical. The gross length is around 2000mm, nett 1800mm. Diameter of most tubes is 58mm and height including frame is 150-180mm. Collectors with 30 tubes are about 2400mm in width and have a gross area of 4.5m^2. Collectors with 20 tubes are about 1650mm in width with a gross area of about 3m^2.

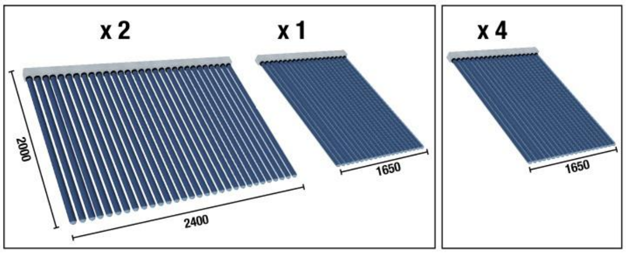


Fig. 102. Standard available collector dimensions to compose a surface area of 12m^2. (Own illustration)

A 12m^2 collector area can be made with two panels of 30 tubes (2x 4,5m^2) and one panel of 20 tubes (1 x 3m^2), or four panels of 20 tubes.

Short-term buffer (400L)

A short-term buffer with a capacity of 400L has been selected in the previous paragraph. This buffer has a height of 1700mm and a width of 700mm according to supplier data (fig. 103). This includes 100mm insulation on both sides, meaning the actual tank has a width of 500mm. The buffer is placed upright in the attic for a close distance to the collectors.

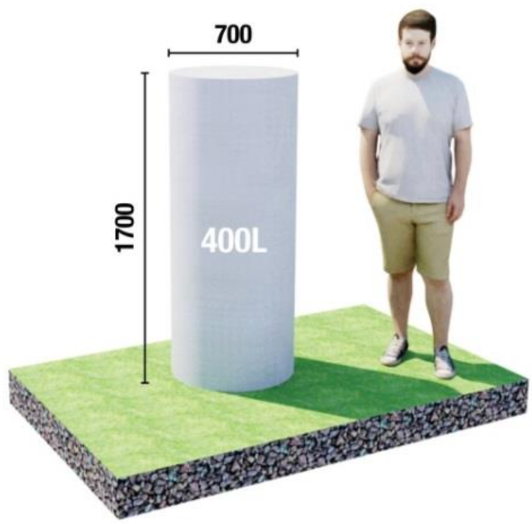


Fig. 103. Spatial impression of a 400L buffer tank. (Own illustration)

Solar boiler (DHW, 250L)
A boiler of 250L was calculated in the previous paragraph. According to supplier data, such a boiler has a height of 1590mm and a diameter of 600mm, 100mm insulation included (fig. 104). The boiler is placed upright in the attic.

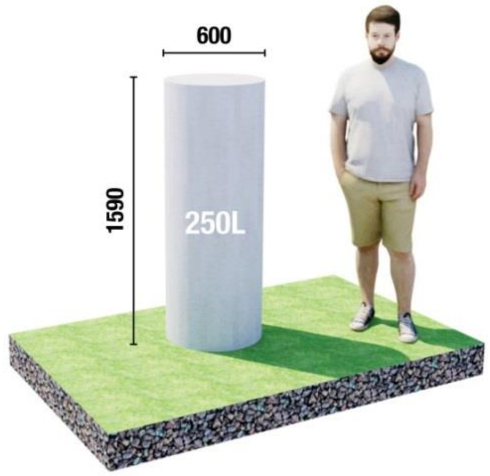


Fig. 104. Spatial impression of a 250L boiler tank. (Own illustration)

Thermal batteries (4000MJ in total)
Thermal batteries will have a tubular shape due to heat exchanger restrictions. It is more practical to place the batteries upright, but they can be placed at an angle. This will require extra attention

The actual storage capacity of a single battery and corresponding dimensions are unknown as explained earlier. A battery will eventually have a capacity between 200 and 300MJ each. The spatial optimum depends on the design direction for integration. If a battery needs to be integrated into for example the building envelope a thin and long battery is in favour, but if they are placed underground a small and thick one is preferred. Therefore 3 battery sizes are available, which are visualised in figure 105.

As explained in paragraph 5.5.6, the eventual batteries could also only consists of the fixed bed reactor with a common condensation/evaporation unit. This would be more economical, but is not assumed within this report.

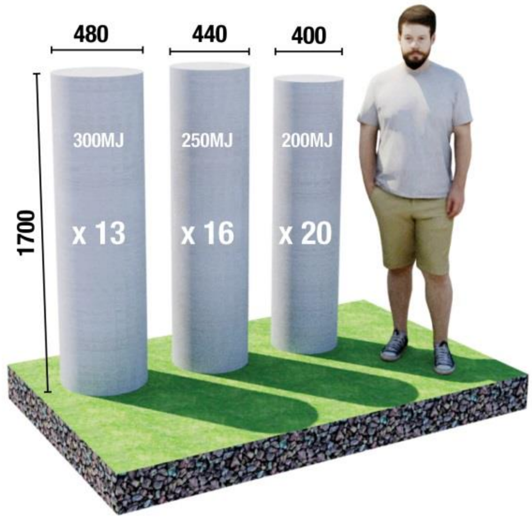


Fig. 105. Spatial impression of different thermal battery sizes. (Own illustration)

7.3.2 Integration of solar collectors

Solar collectors will be placed on the southern roof because the slope and orientation of the case study roof already approximate the optimum. Collectors are also less vulnerable on a roof than on a façade.

Before the collectors can be placed on the roof, additional insulation must be applied to achieve required Rc-values. Because of the wrap it refurbishment strategy and preference for prefabrication, it would be beneficial to combine collectors and insulation in a prefabricated roof element that is part of the refurbishment concept.

A conceptual design for such an element is visualized in figure 106.

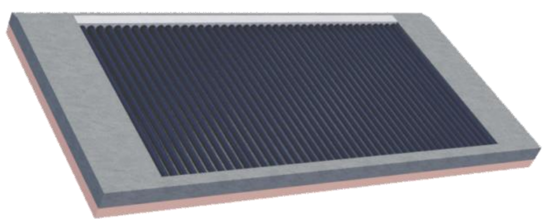


Fig. 106. Conceptual roof element with integrated evacuated tube solar collectors. A reflective coating could be placed behind the tubes to improve yield. (Own illustration)

7.3.3 Design directions

Several directions for integration of the thermal batteries in the case study dwelling are possible. A design direction does not specify a design outcome, but is meant to explore possibilities for integration and visualize spatial impact, thereby pointing out (dis)advantages. Different options are possible within a design direction. The most important design directions are schematized in fig. 107 and explained in this paragraph.

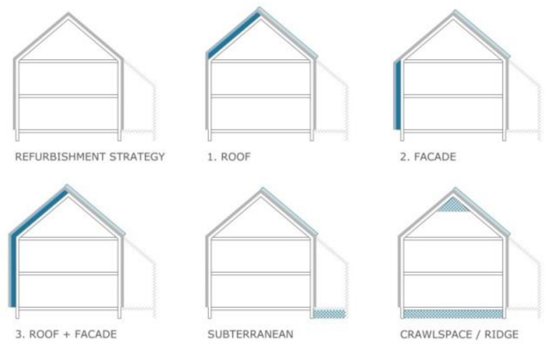


Fig. 107. Possible design directions for integration of the storage volume in the case study dwelling. (Own illustration)

* The exploration was made in an early design stage where a bigger storage volume was assumed. In the eventual design 4GJ storage capacity has to be integrated, which equals a volume of $4m^3$ or 16 batteries.

Direction 1: integration in roof

The first design direction is an exploration on integration in the roof of the case study dwelling. Because solar collectors are already integrated in the southern roof, less space is available on this side. Four options have been explored that are visualized in figure 108. An interesting direction would be to combine the storage elements with the solar collectors, into integrated heat harvesting and storage elements.

The most important pros and cons of this design direction are:

+ available surface area
+ integrated roof element
- visual impact
- structural reinforcements required
- poor accessibility

Direction 2: integration in façade

In this design direction the storage volume is integrated in the façade. Since daylight entering through windows is essential, no storage can be placed here. This will strongly reduce available surface. Placing the volume right next to window openings will cause undesirable shadows. Integrating the storage volume in the façade seems only possible if the volume is distributed over both facades, but this is not preferred due to increased piping lengths.

A direction in which prefabricated "building blocks" with integrated storage are used is also very unlikely. Each block should have its own (expensive) equipment and complicated piping networks are required to transfer the energy.

Fig. 108. Exploration of integrating the storage volume in the case study dwelling roof. (Own illustration)

Fig. 109. Exploration of integrating the storage volume in the façade(s). (Own illustration)

Direction 3: integration in roof and façade

A combination of integration in both roof and façade is explored in this design direction. By distributing the batteries along the roof and façade a more slender storage volume is possible. If this volume would be placed above the load bearing wall, no or less additional structure would be required. There's also a minimal effect on daylight entering, making this design direction the most promising.

+ slender volume possible
+ no structural reinforcements needed
+ architectural element
+/- visual impact
- safety issues

Fig. 110. Exploration of integrating the storage volume in both roof and façade. (Own illustration)

Fig. 111. Most obvious design direction: placing the batteries in a prefabricated container next to or near to the dwelling. (Own illustration)

Other design directions

The storage could also be integrated in the crawlspace of the dwelling, where plenty of unused space is available. The solar freezer system (paragraph 5.6) is also placed in the crawlspace. Apart from the fact that this solution would not be a design direction or way of integration, placing the storage in the crawlspace has some downsides. To begin with, many row-houses do not have a crawlspace at all, which would limit the applicability of the system. Furthermore, the crawlspace is hard to access for maintenance and pipes that connect the solar collectors need to go through the interior of the dwelling. The distance between collectors and thermal battery has a negative effect on system efficiency due to significant heat losses through piping.

In houses with a high pitched roof, the storage may be placed in the ridge. Yet this is only possible if sufficient height is available and most attics are not high enough. Besides spatial barriers, the roof structure needs to be strong enough to bear the weight of the storage, which could also be a problem.

Placing the storage subterranean (fig. 111) is the most obvious alternative. The batteries can be placed in a prefabricated concrete container which is placed under the ground next to or in close proximity to the dwelling. This is a simple solution and can be very cost-effective. There is no visual impact and because the batteries are clustered, piping lengths can be minimized.

Yet, this direction also has some downsides. Excavation of the soil also comes at a price and especially in the Netherland the subsurface is filled with all kinds of pipes and networks. It can be a very costly operation to rearrange these pipes.

7.3.4 Eventual consideration

The best design direction for any given context will always be a consideration of different design principles and costs. The chosen deployment strategy of the system will also play a crucial role; if for example a peak-load preventing strategy is chosen only 3 batteries are required, and this can easily be fitted in the existing dwelling. This is not possible when the whole space heating demand should be covered.

Although integration in the building envelope is strongly preferred for integration in an holistic refurbishment concept, it is probably not the most practical and cost effective design direction. In practice cost is always decisive, and therefore placing the storage underground seems the most obvious option. Placing the storage underground does also avoid spatial impact of the storage volume, which can be critical, especially in areas with a high building density.

In case of the row-house typology, a storage container that is shared with the whole block is also imaginable. This could again be placed subterranean, but can also be placed above ground, resulting in a new typology. This new typology offers new possibilities and might be combined with other functions.

It is clear a sustainable energy future for the built environment will have spatial impact. The question is where, how and on what scale it will take place. It is obvious integrated solutions are needed for a successful implementation. This can be illustrated by an example in current refurbishment: the Nathan energy module. This module is placed next to the entrance or placed in the attic, penetrating the roof. This is definitely not the way the row-house should be made future-proof.

Fig. 112abc. The Nathan energy module. Example of "integration" of renewable technologies in current refurbishment practice. (www.nathansystems.nl)

7.4 Integration in refurbishment concept

Although integration in the façade is not the most practical design direction, it offers the best possibilities towards a holistic refurbishment concept. In this paragraph is explained how such a refurbishment concept could look like. It should be seen as an initiative towards integration of energy storage in buildings, giving future designers guidelines and inspiration. It is up to architects and designers to eventually come up with an integrated refurbishment concept since development of a detailed solution would not be realistic within the scope and timeframe of this report.

7.4.1 The basic characteristics

The previous chapter concluded that integration of the storage in the building envelope is most suitable if the storage volume is placed around the load bearing walls. The heat harvesting elements with integrated solar collectors will be placed on the roof. A basic diagram of the refurbishment concept principle is visualised below.

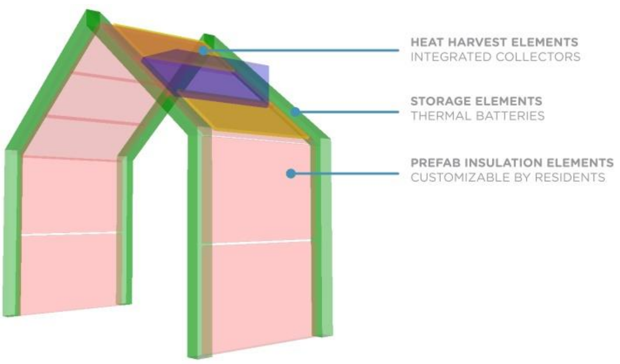


Fig. 113. Main elements of the basic refurbishment concept. (Own illustration)

7.4.2 The integrated refurbishment concept

As earlier explained, a future proof refurbishment will address more aspects than just energy performance. That's why the energy storage is combined with a spatial extension of the dwelling. This is visualized conceptually in figure 114.

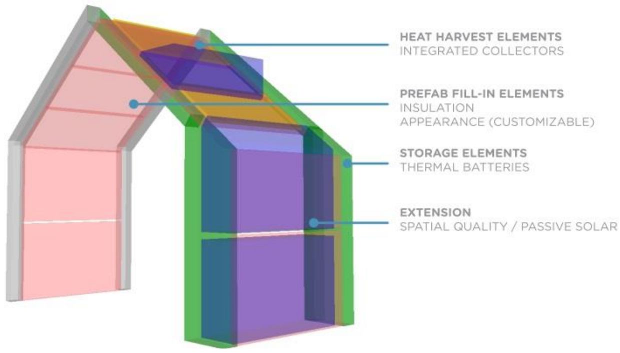


Fig. 114. Main elements of the refurbishment concept elaborated in this report. (Own illustration)

Heat harvest elements

These are prefabricated elements with integrated evacuated tube collectors (fig. 106). The amount of tubes can vary, depending on the most cost-effective system layout, which can be calculated by the matrix (fig. 100) for any given context. The elements also provide envelope insulation.

Prefab fill-in elements

These are placed between the storage elements. Their primary function is to improve envelope insulation, but they also play an important role in customizability. Residents should be able to determine the appearance of the elements. This gives the dwelling a personal identity and will also increase the willingness to pay for residents since they are actively involved in the design. This façade principle also fits in the upcoming "circular economy", which will also manifest itself in the built environment.

Extension

The extension adds more spatial quality to the dwelling on both ground and first floor. The façade on the ground level allows more daylight entering and can be opened completely to extend the living room into the garden.

The extension on the first floor is a semi-outdoor space that adds both spatial quality to the rooms adjacent, but also plays a role in passive solar energy contribution. The curved windows can be opened to create a private outdoor space. Curved glass innovations give the structure a futuristic appearance.

Storage elements

The storage elements, with the thermal batteries integrated, are the core of the refurbishment concept. Besides the function of thermal storage elements, they also bear the load of the fill-in elements. It now seems that the storage is divided over two elements, but when a whole row is refurbished the batteries of one dwelling are clustered in one element. The batteries are accessible from inside the dwelling by removing the side panels.

Other

Although the concept is focused around thermal energy, PV-electricity can still be useful and is even desired to compensate for thermal battery system energy use. PV-films are integrated in the finishing of the storage elements and roof, which together make a surface of 8m^2. In case residents don't choose for a dormer element, the middle roof panel can also be filled with PV-panels, allowing a total PV-surface of almost 15m2.

The eventual concept is visualized below.

Fig. 115. Roof elements.

Fig. 116. Storage elements.

Fig. 117. Fill-in elements (south façade curtain wall system).

Fig. 118. Impression of the eventual concept. (South façade)

Fig. 119. Impression with opened façade.

Fig. 120. Impression of North façade.

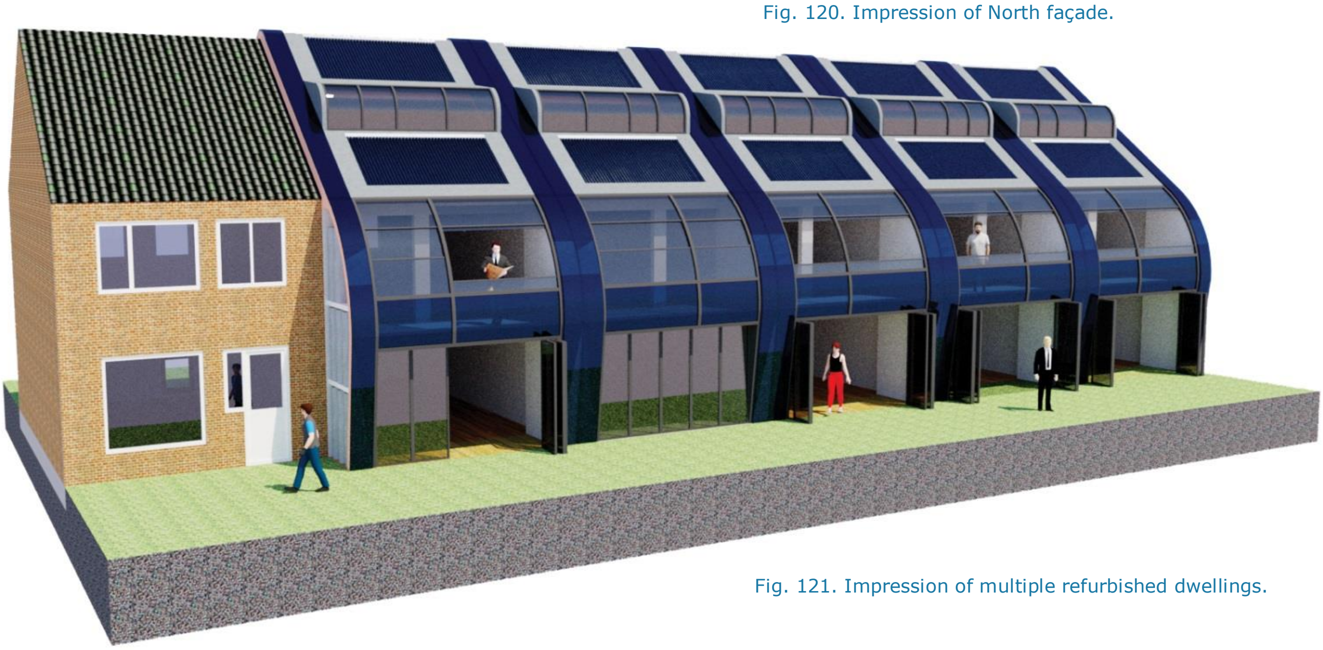


Fig. 121. Impression of multiple refurbished dwellings.

7.4.3 Towards True integration

In this report, the thermal batteries are integrated in the separation wall of the extension. This can be seen as integration 1.0 because the storage module is still composed of individual batteries. For this report it is a solution since it is about spatial impact of the required storage volume. However, the next step towards true integration is to develop a single, integrated element that has multiple functions, but this can only be done when the technology is fully developed and mature enough, which is unlikely to happen within the next decade. Yet, on the long term, some interesting developments are imaginable.

An integrated element that has multiple functions could for example be realized with the help of additive manufacturing such as metal printing. A complex metal structure that acts as both load bearing structure for the façade elements and fixed bed reactor for the salt-hydrate could be possible.

To develop truly integrated storage elements that have multiple functions, many different expertise's have to be combined. Scientists, system engineers, material experts, CFD-specialists, manufactures and designers all need to cooperate to develop such products. This will be one of the main challenges of the coming years, because the building industry by itself is rather conventional and not familiar with multidisciplinary cooperation's.

Even when (seasonal) energy storage is not implemented on a building scale, renewable technologies such as heat pumps require an integrated solution. The energy transition has a serious spatial impact on our built environment and this offers many new possibilities for designers, but also poses challenges due to shortage in space. Well integrated solutions, on every thinkable scale are required towards an energy neutral built environment by 2050.

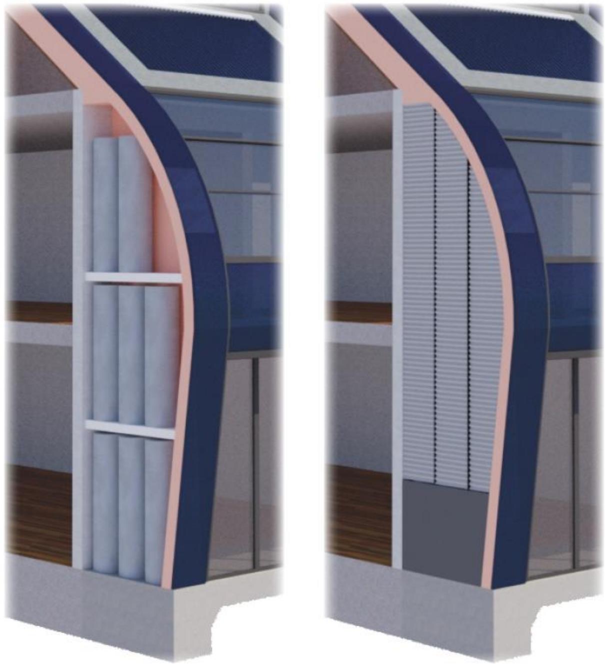


Fig. 122. From seperate batteries to one single integrated element. (Own illustration)

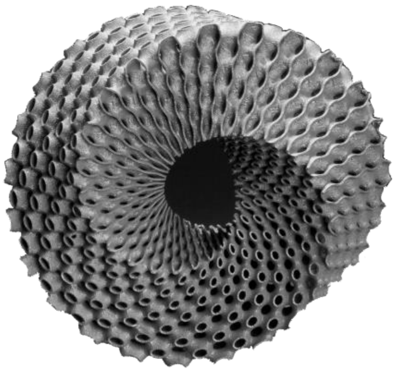


Fig. 123. Example of a complex 3d metal shape, produced with laser based additive manufacturing. (www.newsmaker.com.au)

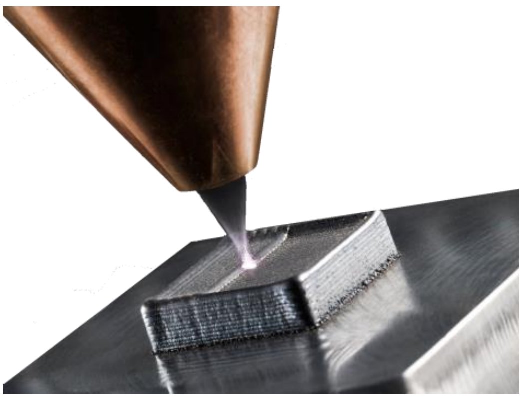


Fig. 124. Example of metal printing. (www.metalworkingnews.info)

7.5 Evaluation of the system

In this paragraph the implementation of a thermal battery system will be evaluated from both an energy and financial perspective. Because the thermal battery system is not fully developed yet, realistic assumptions will be made for unknown parameters. Both energy and financial feasibility are evaluated on the system layout described in paragraph 7.2, which is a system with 12m^2 collectors, 4GJ storage capacity, space heating coverage strategy and a lifetime of 15 years.

Although the thermal battery system is part of a whole refurbishment concept, only the performance and feasibility of the system itself will be evaluated. It would be too complex to also take cost for the refurbishment concept in to account within the scope of this thesis, but this is eventually very relevant. For comparison, only the thermal demand figures after refurbishment are used. The savings that are caused by building envelope upgrade and different heating method are used for financing of the refurbishment concept itself.

7.5.1 Energy performance

The system covers the full space heating and DHW demand after refurbishment, for a period of 15 years. Nett savings (see chapter 7.2) are 11,2GJ/year and 168 GJ during the operational lifetime.

Assessment on BENG-indicators

The BENG-indicators and calculation methods are described in paragraph 3.2.3.

1. Energy demand in kWh/m^2/year

The energy demand equals the space heating demand which is calculated in TRNSYS and amounts 7GJ thermal, which is assumed to be 1944kWh. The case study building has a floor surface of 120m^2, so the energy demand comes down to 16,2kWh/m^2

2. Primary energy use in kWh/m^2/year

The energy for heating and DHW demand is already calculated and amounts 1050kWh. For ventilation one heat recovery unit with a 50W fan, operating 2000h/year is assumed. A 5W control unit will monitor fresh air levels every 10 minutes. The energy this takes is 100kWh/year.

The primary energy use is calculated as:

(2,56*(1050+100) – 2,56*238) / 120 = 19,5kWh/m^2

This value is higher than the first indicator because only 1 PV-panel is applied on the case study roof, but is still below 25kWh/year. Theoretically there is space for a total of 10 PV-panels next to the 12m^2 collectors, which would result in a primary energy use of 4,7kWh/m^2/year

3. Share of renewable energy in %

Gross renewable energy in this case equals the full space heating, 8 months of DHW and energy of 1 PV-panel which comes down to 1944 + 1481 + 238 = 3663kWh.

3663 / (2335+3663)*100 = 61%.

In case 10 PV-panels are applied, the RER will be 87%.

If the case study is equipped with the selected system configuration, it will meet the new energy standards of the BENG indicators. Because DHW is generated electrically between November and February, the primary energy use is relatively high, resulting in an average RER. It would therefore make sense to apply additional PV panels to compensate this.

7.5.2 Financial feasibility compared to other heating solutions

The financial feasibility of the system is crucial for the overall feasibility of the system. It is hard to predict how much the eventual system will cost, but it is possible to calculate a maximum price. This can be done by comparing the system to a reference situation. The financial feasibility will be different for each deployment strategy, but in this case the strategy of covering space heating only (see paragraph 6.5) is used.

Some assumptions have to be made in order to perform financial feasibility calculations; these are listed below:

- Lifetime batteries 15years
- Lifetime collectors 25 years
- Lifetime boiler 25 years
- Average gas price €0,80/m^3.

The first step is to calculate what the costs would have been for a reference situation in which a conventional gas boiler is used. This will also be done for a situation in which a heat pump is applied. The costs are composed of a full year space heating and DHW demand for the case study dwelling.

Natural gas boiler (reference situation)
A thermal demand of 15GJ equals 429m^3 of natural gas. At a price of €0,80/m^3, this is €343/year. In 2015, network costs (vastrecht in Dutch) made up 19% of the energy bill on average (gaslicht.com), which would come down to €65/year. Total annual expenses on natural gas are therefore €408.

There is also some costs for thermostat (35kWh/year), and pumping energy for the floor heating system (80kWh/year). This will cost €25/year (Electricity price of €0,22/kWh).

A conventional natural gas boilers will cost around €2500, installation included (cv-ketel-weetjes.nl). Expenses for maintenance are €115/year on average, which results in a total cost of €4230. Total costs for thermal energy after refurbishment are €10725, which comes down to €59/month.

Heat pump.
A heat pump on average costs around €8000 including installation, but subsidies are available. This will make the purchase and installation costs roughly €6000. Again €115/year for maintenance costs are assumed after comparing prices of installation companies, making the total equipment costs for a heat pump €7725, or €515/year.

The heat pump operates with an average COP of 3,5 because the majority of thermal demand is generated during winter when the COP is at its lowest. The required electricity is 15GJ/3,5, which equals 4286MJ/3,6 = 1190kWh. Energy for thermostat is 35kWh year, pumping energy for floor heating system is around 80kWh, resulting in an annual energy demand of 1305kWh year. This costs €342/year and €5125 over a period of 15 years.

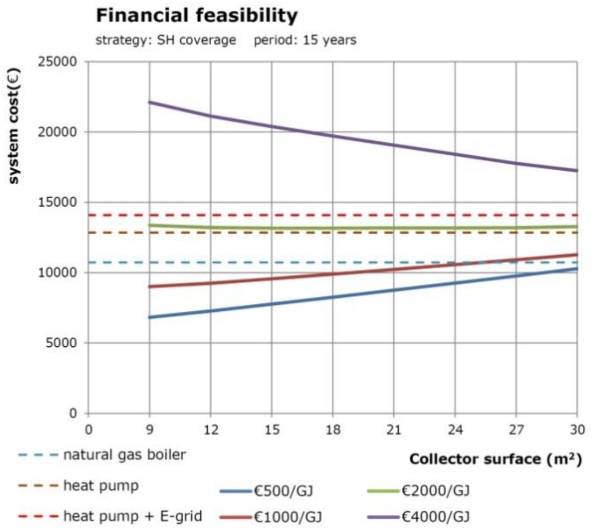
Total cost for thermal energy after refurbishment is €12850, or €69/month. It must be noticed that PV-panels could reduce this amount due to net-metering, but because this will be limited it is not taken into account now.

Heat pump & investment electricity grid.
As explained throughout this report, massive implementation of heat pumps will require an additional investment in the energy infrastructure. The exact amount of this investment is impossible to calculate and is therefore estimated. The eventual investment will be multiple billions and is not only caused by heat pumps. Besides, the write-off time is longer than the lifetime of the heat pump and battery system. Let’s assume 5 billion can be divided over 4 million heat pumps, which comes down to €1250 per installed heat pump. This is still an arbitrary value, but it can give an indication of societal costs.

Comparison of systems
The costs for covering thermal demand by a conventional natural gas boiler, a heat pump and thermal battery system with different storage prices and collector surfaces are visualised in graph 9.

The graph shows that, if storage price is below €1000/GJ, a thermal battery system is cheaper than a conventional gas boiler. A storage price of €2000/GJ will make it more expensive, but is still able to compete with a heat pump, especially when the additional investment is also taken into account.

The conclusion is again that price for storage will be crucial for its financial feasibility. If the thermal battery system competes with a regular heat pump, price of the storage should be around €2000/GJ or less. A lower price will always give the best financial feasibility for a thermal battery system, but a price of €4000/GJ would make the system nearly unfeasible, if no additional grants become available.



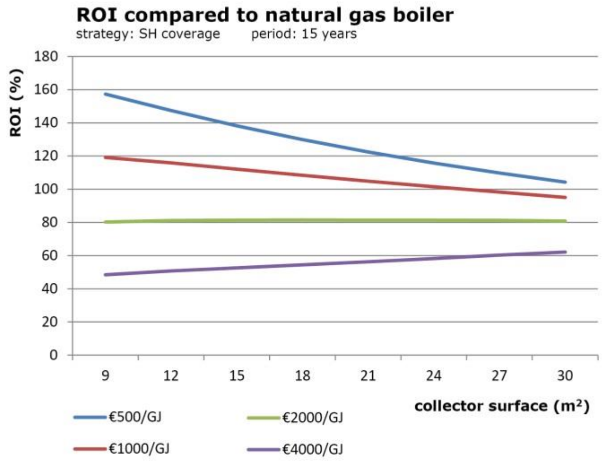
Graph 9. Costs of a thermal battery system for different storage prices compared to a natural gas boiler and heat pump. (Own illustration)

However, implementing a thermal battery system in a dwelling in combination with a refurbishment will also increase value of that dwelling. This added value will not be calculated in this report, but it is likely to allow a higher storage price than €2000/GJ. In the average NoM refurbishment an investment of €45.000 is done, of which 50 to 70% is added value of the dwelling (van de Groep, 2015).

Return on investment

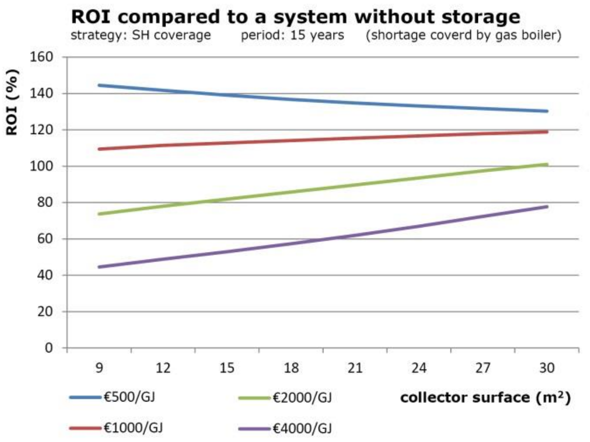
Financial feasibility can also be explained by the return on investment (ROI). This is very relevant in practice, since residents can actually see what their financial benefits will be by implementing a thermal battery system. The ROI can be found by dividing the financial benefits by costs and is calculated for two scenarios, similar to the do nothing scenarios discussed in paragraph 7.2.

In the first scenario, all system costs are related to the cost for a conventional gas boiler, which is €10.725 for the whole period. This amount is "saved" if a thermal battery system is applied. The savings are regarded as revenue. If a thermal battery system of for example €8000 is able to save €10.725, the ROI is 134%. The ROI for a thermal battery system with different storage prices compared to a natural gas boiler can be found in the graph 10



Graph 10. Return on investment of a thermal battery system for different storage prices compared to a natural gas boiler. (Own illustration)

The second scenario is in essence a comparison of system costs with and without thermal batteries. In the without situation the energy that cannot be covered by direct solar use is covered by a natural gas boiler.



Graph 11. Return on investment of a thermal battery system for different storage prices compared to a system in which no batteries are used (and the remaining demand is covered by a natural gas boiler). (Own illustration)

7.5.3 Large scale implementation

The feasibility can also be evaluated from a bigger perspective. In this report only a single dwelling is evaluated, but what happens if the thermal battery system is implemented on a similar scale as the NoM concept?

This would mean 110.000 dwellings will be equipped with a thermal battery system. Let's assume the same system layout will be applied as described in the report, meaning a storage capacity of 4GJ combined with 12m^2 collectors, which saves 168GJ during its lifetime. In total 18,48 million GJ will be saved, which equals 525.386.400 cubic meters of natural gas and 945.696 metric tonnes CO_2. Each system requires 57GJ energy to operate during the whole lifetime, making a total of 6.270.000GJ or 178.256.100m^3 natural gas that emits 320.861 tonnes CO_2.

These figures can be compared with the NoM concept, assuming a heat pump is used to cover the same thermal demand. A heat pump requires about 1190kWh electricity per year and 17850kWh in a period of 15 years. PV-panels compensate the energy use, but they will not generate electricity when most space heating is required. On those moments electricity is either produced in power plants relying on fossil fuels with a low efficiency or windmills. The figure of 1190kWh is therefore converted to 2000kWh (7.2GJ) primary energy. 110.000 dwellings will use:

110.000*7.2*15 = 11.880.000GJ or 337.748.400m^3 natural gas that emits 607.947 tonnes CO_2.

A dwelling equipped with a thermal battery system instead of a heat pump only uses 50% of the primary energy and emits 50% less CO_2. It can be concluded that large scale implementation of a thermal battery system is more sustainable and brings significant more savings than a dwellings with a heat pump, taken the mismatch into account. If the same calculation is made with net-metering taken into account, the heat pump might perform better, but it does not allow a fossil fuel free future.

However, applying a thermal battery system on such a scale requires a lot of resources. With the selected system layout a total 1,3km^2 solar collectors is required and 144.000m^3 Na_2S-hydrate should be produced, which will cause significant CO_2 emissions in itself. The required amount of salt-hydrate and natural gas savings, compared to the biggest building in the Netherlands (De Rotterdam) are visualized in figure 125. It would be interesting to see how much energy it takes to produce the collectors and Na_2S to calculate nett CO_2 savings.

Fig. 125. Required volume of Na2S-hydrate to refurbish 110.000 dwellings and the savings in natural gas, compared to the biggest building in the Netherlands. (Own illustration)

Another important aspect is the end of the life cycle. If the salt-hydrate can be regenerated at the end of its lifetime, it would allow a sustainable solution. If the salt cannot be used anymore the system causes a lot of waste, which isn't sustainable and can even threaten the environment. Further research is necessary to investigate environmental impact of large scale implementation.

8. CONCLUSIONS

In this chapter general conclusions regarding research questions will be discussed, followed by some case study specific conclusions, conclusions for wider applicability and recommendations for further research. The research question of this report was:

How can seasonal thermal energy storage be integrated both technically and spatially in a refurbishment concept for a single family house?

8.1 General conclusions

Current refurbishment is not adequate towards an energy neutral built environment by 2050 because it does not address the mismatch, still requires fossil fuels during winter and causes additional investments in the electricity infrastructure. Both electric and (seasonal) thermal storage are required to solve the mismatch, improve utilization of renewables, reduce the additional investment and become independent of fossil fuels towards 2050. Refurbishment concepts with integrated storage solutions are needed to make the built environment future proof.

Seasonal thermal energy storage can be realized with different methods, but regarding implementation on a building scale, thermochemical storage in salt-hydrates has the most potential because of the thermal loss free storage, high storage density, scalability and widely available and inexpensive storage material.

This report has shown that seasonal storage of solar energy in a residential context is technically feasible with a thermal battery system that uses salt-hydrates, but the storage technology is not commercially available yet. Eventual feasibility will strongly depend on actual price of the storage modules since economics are prevailing in residential refurbishments.

The most cost-effective system layout will strongly depend on price per GJ of storage. If the price is below €1500/GJ, a system with the smallest possible collector surface is in favour and is more cost-effective than a natural gas boiler.

If storage price is around €2000/GJ, the size of the collector surface has no effect on system costs, and total costs are equal to a heat pump. A thermal battery system will however save 50% more energy and CO_2 emissions and allows renewable heat throughout the year, making the system more sustainable than a heat pump.

In case storage price is above €3000/GJ a system with a big collector surface is in favour, but the system will not be cost-competitive with other solutions in that case if no governmental grants are available.

A thermal battery system could cover total thermal demand, but only when storage price is below €1000/GJ, it is financially feasible to also cover DHW demand between November and February because of the additional required storage capacity and involved costs.

A thermal battery system is not the final solution for the energy transition, but one of the options to achieve an energy neutral built environment by 2050. Local context and resources, will just like an architectural design, determine the best outcome. It is however clear that implementation of renewable technologies, on any scale, has spatial impact on the built environment, posing new challenges for designers.

The building industry has to choose whether it continues with the electrification, resulting in investments on both building scale and energy grid or focusing on refurbishment concepts with integrated energy storage.

8.2 Conclusions for case study

The implementation of a thermal battery system in the case study context can be seen as the answer to the main research question.

In chapter 7 is explained how the system can be integrated both technically and spatially in a refurbishment concept for a single family dwelling and what the requirements are. The elaborated design direction shows that thermal energy storage can be part of a holistic and flexible refurbishment concept that upgrades an existing row house in terms of energy performance but also adds architectural and spatial quality.

TRNSYS simulations and processing in excel have provided relevant thermal demand and yield figures after refurbishment, resulting in a thermal battery system with a required storage capacity of 4G to cover thermal demand.

Evacuated tube collectors were selected because of their yield during winter, which strongly reduces required storage capacity. If space is no issue, and storage is inexpensive, flat plate collectors can also be sufficient to yield total thermal demand during summer.

A collector surface of $12m^2$ was selected because this yields enough storable energy during summer for winter use. A deployment strategy of covering space heating only was selected because this has the best financial feasibility and strongly reduces required storage capacity and discharging requirements of the batteries

8.3 Conclusions for wider applicability

In this report the thermal battery system was used for decentralized seasonal thermal storage of solar energy in a row house dwelling because this is by far the most common typology in the Netherlands. A solution for this typology is a solution for about 35% of residential dwellings around in 2050. However, the system can be used on other typologies as well such as detached or semi-detached dwellings. A local, shared system with multiple dwellings connected is also possible.

A matrix (par. 7.2) was developed that can be used to select the best possible system layout of a thermal battery system for any given context. The matrix will provide all relevant savings and costs to determine energy performance and financial feasibility.

Besides applying the system on other building typologies, the system can also be charged differently and used for short-term storage as explained in paragraph 6.5. The system can be complementary next to the increasing amount of windmills and heat pumps in the Netherlands, preventing peak loads and making use of local energy surpluses.

A system connected to a smart-grid is beneficial for demand-side management, solving both mismatch and providing inexpensive space heating.

Additional applications for the thermal battery system will increase usability, thereby lowering the price of the system and increasing overall financial feasibility.

8.4 Recommendations

As explained throughout this report, the thermal battery system is still under development and will not be market ready within the next few years. According to Ruud Cuypers from TNO, the first systems are expected to be market ready in 5 years.

Before technology becomes market ready, additional research on (dis)charging properties is required, especially regarding controllability and cycle stability. Also storage density should be further increased to $1GJ/m^3$ (or even more), where it is aimed at $0.6GJ/m^3$ in the CREATE-project. This will require research on battery and heat exchanger geometry, but accurate simulation models are also needed. Simulation models can help optimizing the system and determination of the optimal system layout for any given context.

Moreover, a tool or matrix that shows the best storage solution in terms of technology and scale for any given context would be desired to effectively make choices in an early design stage. Such a tool could also help in making relevant decisions in current refurbishment practice, preventing additional investments in the coming years.

Furthermore, scientists, system engineers, material experts, CFD-specialists, manufactures and designers all need to cooperate to develop truly integrated storage solutions. Development of such products will be crucial for effective implementation of seasonal thermal energy storage, especially on a building scale.

9. REFLECTION

This graduation took place in the Building Technology master of TU Delft, where technology related to buildings and construction is at the heart. I chose to participate in this master because I have always been fascinated by sustainable technologies in the built environment. This sustainable technology is now at the heart of my graduation as well, because I think technology is indispensable towards a true sustainable future. Although I want to emphasize the technology, I should be aware of the fact that technology in buildings is only successful if it is properly integrated, respecting the architectural qualities and rules.

Besides the strong relation of the graduation topic with the building technology master, the graduation topic can be placed within the framework of the energy transition the Netherlands is facing. This is a very broad and complex topic, and this graduation tries to contribute to the integration of seasonal thermal energy storage technologies in existing buildings. Current refurbishment practice is not addressing this necessity, but is instead creating new problems of which most people are not aware of.

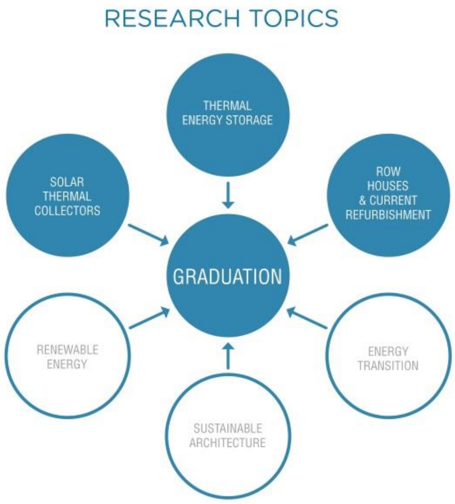


Fig. 126. Research topics and personal interests that formed this graduation. (Own illustration)

Increasing electrification of building installations and excessive use of PV will inevitably cause additional investments in the electricity infrastructure. This means an investment on a building scale now, but an additional investment later on that is at the cost of society. The graduation aims for a solution where this additional investment is prevented and is therefore again of social relevance. Besides, the graduation also focusses on existing buildings; which are a big challenge for the Netherlands towards complete an energy neutral building stock in 2050.

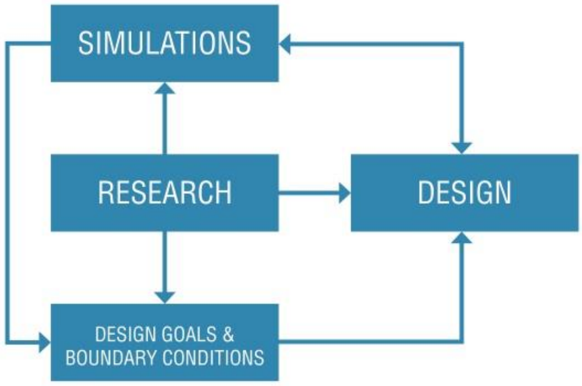


Fig. 127. Diagram of the "design by research" approach in this graduation report. (Own illustration)

The graduation process can be characterized as a "design by research" approach. Research plays a central role throughout the design phase since all boundary conditions and design goals result from literature study and interviews with researchers. This approach has worked quite well because the research helps in clarifying and supporting design decisions, but it also has some downsides. Three critical moments within the graduation process can be appointed which have led to a delay.

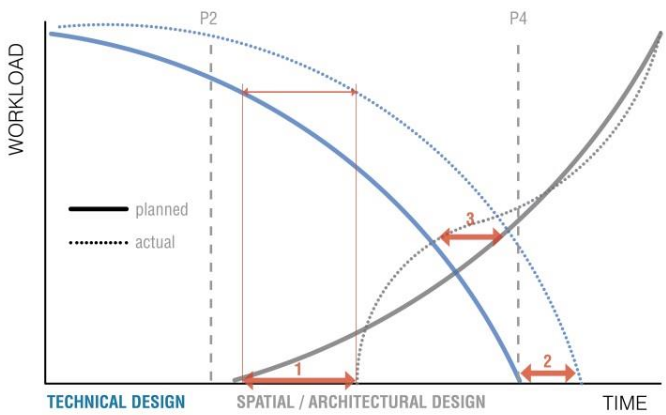


Fig. 128. Simplified visualisation of the graduation process. (Own illustration)

9.1.1 Start spatial design process

The start of the spatial design process was intentionally planned right after the P2 presentation. Since the spatial boundary conditions followed from the technical research, and this research took significantly more time than expected due to difficulties with the simulation model and complexity of the topic, the start of the spatial design was delayed.

9.1.2 Completion of technical design

The technical design was planned to be finished at the P4, but due to difficulties with simulations and necessary additional research on thermochemical storage, this was not feasible anymore. Eventually a decision was made to estimate thermal yields rather than extracting them from TRNSYS. The solar irradiation was derived from TNRSYS and yield declaration for TNO was used to determine an efficiency factor. Altough this is not as accurately as a simulation, the differences will not be very substantial. Besides, the estimated thermal yields can easily be replaced with simulation results or empircal thermal yield data. This will mainly affect the thermal yield in summer (where an efficiency of 40% is minimal) and to a small degree thermal yield in winter (where not all thermal energy can be stored because a minimum temperature of about 50ºC is required).

9.1.3. Intersection technical - spatial design

The intersection of technical and spatial design process can be defined as the actual integration of the thermal battery system in the refurbishment concept. This intersection was planned several weeks before the P4 in order to have sufficient time for architectural elaboration. Because the technical design also runs after P4 and the late start of the spatial design the integration process is not finished at the P5.

After all, the graduation topic might have been too complex for a graduation within the building technology master because especially the technical design has more affinity with mechanical engineering.

The technical research therefore took significant more time than expected, but this adds quality to the research.

9.2 Correctness of results

Although this report has indicated the principles of a thermal battery system and corresponding system dimensions, there is a margin of error regarding required storage capacity.

First of all, thermal losses during (dis)charging of the battery are unknown and are therefore not taken into account in this report. Especially thermal losses during discharging will affect required storage capacity. This means that to cover 1GJ of thermal demand, a bigger amount should be stored, for example 1.1GJ.

Secondly, the directly usable yield and in between usable surplus during the shortage period will probably be less positive in practice. In this report a constant efficiency of 40% is assumed, while this will be less in reality, resulting in a bigger shortage and required storage capacity.

Thereby, the calculation method for required long-term storage capacity is strongly simplified. In reality a bigger amount is covered by the short-term buffer. This is strongly connected to daily thermal demand profiles for DHW, which are not taken into account. This will not affect annual energy balance, but can have consequences for the amount long-term stored energy.

As explained earlier in this report, accurate figures on exact storage capacity can only be obtained by complex and extensive simulations, thereby knowing all values of relevant performance parameters. Besides these parameters are not exactly known yet due to the immaturity of thermochemical storage technology, these simulations are too complex for the timespan of this graduation.

10. LITERATURE

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Nomenclature

DHW	Domestic Hot Water
SH	Space Heating
TES	Thermal Energy Storage
STES	Seasonal Thermal Energy Storage
HTF	Heat Transfer Fluid
PCM	Phase Changing Material
TCM	ThermoChemical Material

APPENDICES

Appendix 1. Energy labels & thermal resistance values

In the scheme below an index of common thermal resistance values for different building parts and corresponding energy labels is shown.

Omschrijving	Origineel	C-label	B-label	A-label	A++-label
Rc-dak	0,22 m^2 K/W	1,3 m^2 K/W	2,5 m^2 K/W	3,5 m^2 K/W	5,0 m^2 K/W
Rc-gevel	0,36 m^2 K/W	1,3 m^2 K/W	2,5 m^2 K/W	3,5 m^2 K/W	5,0 m^2 K/W
Rc-vloer	0,15 m^2 K/W	1,3 m^2 K/W	2,5 m^2 K/W	3,5 m^2 K/W	5,0 m^2 K/W
U-raam	5,2 m^2 K/W	2,9 W/m^{2}K	2,3 W/m^{2}K	2,0 W/m^{2}K	1,6 W/m^{2}K
U-deur	5,2 m^2 K/W	2,9 W/m^{2}K	2,3 W/m^{2}K	2,0 W/m^{2}K	1,6 W/m^{2}K
Verwarming	Lokale gasverw.	VR-ketel	VR-ketel	HR-104-ketel	HR-107-ketel
Warmtapwater	Geiser	Combitoestel	Combitoestel	Combitoestel	Combitoestel
Ventilatie	NT,NA*	NT,NA*	NT,NA*	NT,MA*	NT,MA*
Gasverbruik	4100 m^3	2000 m^3	1550 m^3	950 m^3	550 m^3

2.4 – Verschillende energieconcepten ten behoeve van energetische verbetering van de referentiewoning.
*NT, NA = natuurlijke toevoer en natuurlijke afvoer, NT,MA = natuurlijke toevoer en mechanische afvoer

Appendix 2. Heat pumps

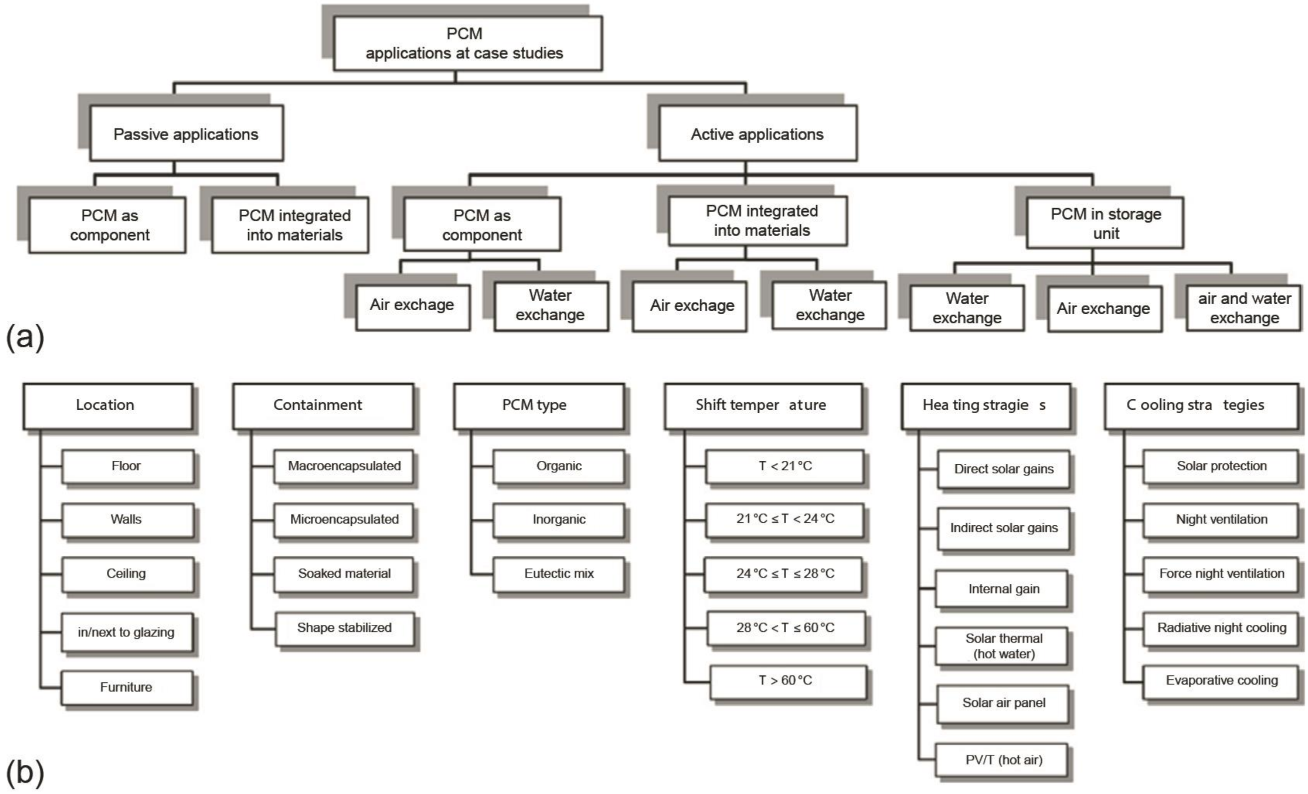
A heat pump is a reversible mechanical-compression refrigeration system that provides heating or cooling energy. The systems consist of two parts: an indoor unit called an air handler and an outdoor unit similar to a central air conditioner. A compressor circulates refrigerant that absorbs and releases heat as it travels between the indoor and outdoor units.

Different energy sources can be used in heat pump technology, for example ground, water and even outside air. Ground source heat pumps have the best performance, but in refurbishment projects usually water or outside air heat pumps are used.

Heat pumps do not convert energy like a regular boiler does, they only move energy. Therefore the term efficiency cannot be used to express the performance, instead this is expressed in COP (Coefficient of Performance). The COP can be calculated when delivered energy is divided by the used energy. The used energy is electricity for compression and pumping energy. A COP of 4 for example means 5kWh electricity is used to produce 20kWh thermal energy. A heat pump has the optimum COP when combined with low temperature heating because the temperature difference is smaller. Heat pump technology uses way less (primary) energy compared to conventional gas boilers and are therefore regarded as sustainable alternative by building and installation industry.

Appendix 3. Application overview of PCM's

A comprehensive overview of PCM applications (a) and methods for successful deployment (b) is given in the scheme below. The table is derived from

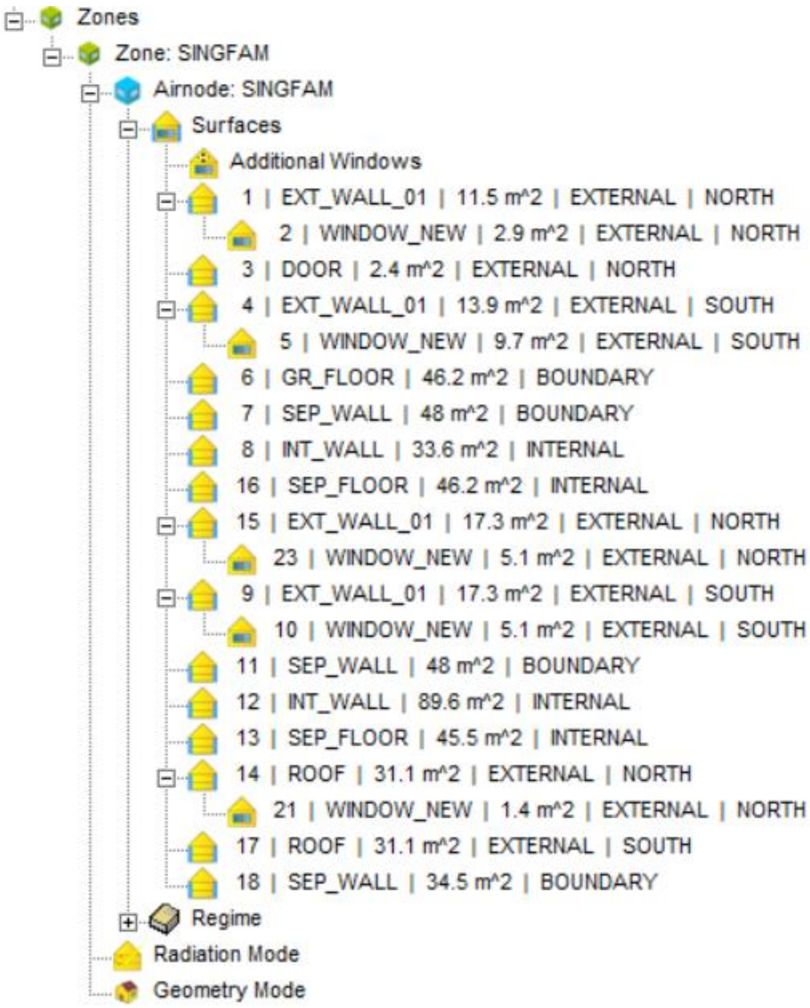


Appendix 4. TRNSYS model parameter values

Building parameters

- Air change rate:	0,07 1/h
- Temperature of airflow:	outside
- Humidity of airflow:	relative humidity
- Air change of infiltration:	0,19 1/h
- Set point temperature:	20ºC
- Humidification:	turned off
- Internal gains:	turned off
- Airnode volume:	305m^3
- Airnode capacitance:	366kJ/K

Building dimensions / surfaces / orientations



Building parts (part, layers, thickness, U-value)

- Exterior wall: bricks - air layer - mineral wool (0,14m) - heavy concrete (0,12m) - plaster, 0,367m, 0,249W/m^{2}K
- Roof: roof tiles - air layer - wood - mineral wool (0,13m) - wood - plaster, 0,185m, 0,251W/m^{2}K
- Doors: wood, 0,045m, 2,04W/m^{2}K
- Glass: double paned, 1,4W/m^{2}K

Appendix 5. Simulation results

The simulations have generated a lot of data since all relevant parameters are calculated per hour of the year. This data has been processed in Microsoft Excel to gather both daily and monthly values. The tables in this appendix are the source of all graphs in chapter 6 and 7.

Simulation results case study dwelling - monthly values Rc facade/roof = 4,0 Uwindows = 1,4 wtw 90% efficiency

	Toutisde	Tair	Tstar	Qdemand	cooling	Qsh+DHW	Solar irradiation on collectors		
	oC	oC	oC	(Qsh) MJ	MJ		MJ/m2	kWh/m2	
January	2.59	20.15	19.94	2,067	-	2,733.20	126.61	35.17	
February	2.66	20.53	20.36	1,287	-	1,953.36	231.59	64.33	
March	4.99	20.81	20.66	847	-	1,513.46	317.76	88.27	
April	7.77	22.03	21.91	58	-	723.93	457.62	127.12	
May	12.34	24.09	24.01	-	472	666.00	545.73	151.59	
June	14.73	24.66	24.61	-	848	666.00	509.10	141.42	
July	16.44	24.80	24.79	-	1,345	666.00	546.12	151.70	
August	16.85	24.74	24.75	-	1,505	666.00	512.69	142.41	
September	14.10	24.65	24.58	-	569	666.00	373.49	103.75	
Oktober	11.01	23.65	23.53	-	121	666.00	285.43	79.29	
November	6.43	20.62	20.45	821	-	1,486.81	166.09	46.14	
December	3.77	20.14	19.92	1,950	-	2,616.26	105.51	29.31	**629.80**
				6,973	**4,860**	**15,023**	**4,178**	**1,160**	**3,230**

The table above shows monthly totals of several parameters for the case study situation. Although a small thermal demand occurs in April, this is not taken into account in further processing. The green values represent the solar irradiation in the surplus period, the red values represent solar irradiation during shortage period. From this table can be concluded that the case study dwelling copes with a significant mismatch.

* It must be noticed that cooling demands are not representative and accurately calculated. The high cooling loads are a result of the heat recovery in the simulations, but this is turned off during summer in reality. For accurate cooling figures heat recovery needs to be turned off in an additional simulation. Yet, accurate cooling figures are not relevant for this report and are therefore not included.

The tables on the next page are more elaborated and show daily totals, derived from hourly values. The left columns show thermal demands and solar irradiation per day of the month. In the columns to the right, thermal collector yield (Qcol) is subtracted from both combined thermal demand (Qd) and space heating only demand (Qsh). The result is a negative (red) or positive (green) value for both Qd and Qsh, corresponding with the full coverage or space heating only deployment strategies. A red value means there is a thermal energy shortage on that particular day, and green indicates a thermal energy surplus. These values are added at the bottom in such way that a surplus cannot compensate for a thermal demand later on.

NOVEMBER	SH demand Qsh	Qsh+DHW Qd	Qsol/m2 Qsol		6M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	9M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	12M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	15M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	18M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	21M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	24M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	27M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	30M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol
1	1.12	23.32	2.08		5.00	18.32	-3.88	7.50	15.82	-6.38	10.00	13.32	-8.88	12.50	10.82	-11.38	15.00	8.32	-13.88	17.50	5.82	-16.38	20.00	3.31	-18.89	22.51	0.81	-21.39	25.01	-1.69	-23.89
2	50.63	72.83	3.88		9.30	63.53	41.33	13.96	58.87	36.67	18.61	54.22	32.02	23.26	49.57	27.37	27.91	44.92	22.72	32.57	40.26	18.06	37.22	35.61	13.41	41.87	30.96	8.76	46.52	26.31	4.11
3	66.66	88.86	3.32		7.97	80.89	58.69	11.96	76.90	54.70	15.94	72.92	50.72	19.93	68.93	46.73	23.92	64.95	42.75	27.90	60.96	38.76	31.89	56.97	34.77	35.87	52.99	30.79	39.86	49.00	26.80
4	75.50	97.70	0.91		2.18	95.51	73.31	3.28	94.42	72.22	4.37	93.33	71.13	5.46	92.23	70.03	6.55	91.14	68.94	7.65	90.05	67.85	8.74	88.96	66.76	9.83	87.87	65.67	10.92	86.77	64.57
5	74.89	97.09	1.30		3.12	93.98	71.78	4.67	92.42	70.22	6.23	90.86	68.66	7.79	89.30	67.10	9.35	87.74	65.54	10.91	86.19	63.99	12.47	84.63	62.43	14.02	83.07	60.87	15.58	81.51	59.31
6	51.37	73.57	10.11		24.26	49.31	27.11	36.40	37.18	14.98	48.53	25.05	2.85	60.66	12.91	-9.29	72.79	0.78	-21.42	84.92	-11.35	-33.55	97.06	-23.48	-45.68	109.19	-35.61	-57.81	121.32	-47.75	-69.95
7	18.46	40.66	6.11		14.67	25.99	3.79	22.00	18.66	-3.54	29.33	11.32	-10.88	36.67	3.99	-18.21	44.00	-3.34	-25.54	51.34	-10.68	-32.88	58.67	-18.01	-40.21	66.00	-25.34	-47.54	73.34	-32.68	-54.88
8	19.63	41.83	3.17		7.62	34.22	12.02	11.43	30.41	8.21	15.24	26.60	4.40	19.05	22.79	0.59	22.86	18.98	-3.22	26.66	15.17	-7.03	30.47	11.36	-10.84	34.28	7.55	-14.65	38.09	3.74	-18.46
9	20.04	42.24	5.19		12.46	29.78	7.58	18.69	23.55	1.35	24.92	17.32	-4.88	31.15	11.09	-11.11	37.37	4.86	-17.34	43.60	-1.36	-23.56	49.83	-7.59	-29.79	56.06	-13.82	-36.02	62.29	-20.05	-42.25
10	6.12	28.32	2.48		5.96	22.36	0.16	8.94	19.38	-2.82	11.92	16.40	-5.80	14.90	13.42	-8.78	17.88	10.44	-11.76	20.86	7.47	-14.73	23.83	4.49	-17.71	26.81	1.51	-20.69	29.79	-1.47	-23.67
11	15.64	37.84	6.95		16.68	21.16	-1.04	25.01	12.82	-9.38	33.35	4.49	-17.71	41.69	-3.85	-26.05	50.03	-12.19	-34.39	58.36	-20.53	-42.73	66.70	-28.86	-51.06	75.04	-37.20	-59.40	83.38	-45.54	-67.74
12	0.74	22.94	2.11		5.07	17.87	-4.33	7.60	15.34	-6.86	10.13	12.81	-9.39	12.66	10.28	-11.92	15.20	7.74	-14.46	17.73	5.21	-16.99	20.26	2.68	-19.52	22.79	0.14	-22.06	25.33	-2.39	-24.59
13	26.98	49.18	6.79		16.31	32.87	10.67	24.46	24.72	2.52	32.61	16.57	-5.63	40.77	8.41	-13.79	48.92	0.26	-21.94	57.07	-7.89	-30.09	65.23	-16.05	-38.25	73.38	-24.20	-46.40	81.54	-32.36	-54.56
14	23.04	45.24	2.56		6.14	39.10	16.90	9.22	36.03	13.83	12.29	32.95	10.75	15.36	29.88	7.68	18.43	26.81	4.61	21.51	23.74	1.54	24.58	20.66	-1.54	27.65	17.59	-4.61	30.72	14.52	-7.68
15	38.00	60.20	6.40		15.36	44.84	22.64	23.04	37.16	14.96	30.72	29.48	7.28	38.40	21.80	-0.40	46.08	14.12	-8.08	53.76	6.44	-15.76	61.44	-1.24	-23.44	69.12	-8.93	-31.13	76.80	-16.61	-38.81
16	29.01	51.21	12.65		30.37	20.84	-1.36	45.55	5.66	-16.54	60.74	-9.53	-31.73	75.92	-24.71	-46.91	91.10	-39.89	-62.09	106.29	-55.08	-77.28	121.47	-70.26	-92.46	136.66	-85.45	-107.65	151.84	-100.63	-122.83
17	0.00	22.20	9.77		23.44	-1.24	-23.44	35.16	-12.96	-35.16	46.87	-24.67	-46.87	58.59	-36.39	-58.59	70.31	-48.11	-70.31	82.03	-59.83	-82.03	93.75	-71.55	-93.75	105.47	-83.27	-105.47	117.19	-94.99	-117.19
18	0.00	22.20	3.81		9.13	13.07	-9.13	13.70	8.50	-13.70	18.26	3.94	-18.26	22.83	-0.63	-22.83	27.40	-5.20	-27.40	31.96	-9.76	-31.96	36.53	-14.33	-36.53	41.10	-18.90	-41.10	45.66	-23.46	-45.66
19	4.31	26.51	13.34		32.01	-5.50	-27.70	48.02	-21.51	-43.71	64.02	-37.51	-59.71	80.03	-53.52	-75.72	96.04	-69.53	-91.73	112.04	-85.53	-107.73	128.05	-101.54	-123.74	144.05	-117.54	-139.74	160.06	-133.55	-155.75
20	0.00	22.20	11.24		26.97	-4.77	-26.97	40.45	-18.25	-40.45	53.94	-31.74	-53.94	67.42	-45.22	-67.42	80.91	-58.71	-80.91	94.39	-72.19	-94.39	107.88	-85.68	-107.88	121.36	-99.16	-121.36	134.85	-112.65	-134.85
21	0.00	22.20	11.13		26.70	-4.50	-26.70	40.06	-17.86	-40.06	53.41	-31.21	-53.41	66.76	-44.56	-66.76	80.11	-57.91	-80.11	93.46	-71.26	-93.46	106.81	-84.61	-106.81	120.17	-97.97	-120.17	133.52	-111.32	-133.52
22	0.00	22.20	6.27		15.04	7.16	-15.04	22.56	-0.36	-22.56	30.08	-7.88	-30.08	37.60	-15.40	-37.60	45.12	-22.92	-45.12	52.64	-30.44	-52.64	60.16	-37.96	-60.16	67.68	-45.48	-67.68	75.20	-53.00	-75.20
23	0.00	22.20	4.89		11.73	10.47	-11.73	17.59	4.61	-17.59	23.46	-1.26	-23.46	29.32	-7.12	-29.32	35.19	-12.99	-35.19	41.05	-18.85	-41.05	46.92	-24.72	-46.92	52.78	-30.58	-52.78	58.65	-36.45	-58.65
24	0.00	22.20	9.49		22.77	-0.57	-22.77	34.16	-11.96	-34.16	45.54	-23.34	-45.54	56.93	-34.73	-56.93	68.31	-46.11	-68.31	79.70	-57.50	-79.70	91.08	-68.88	-91.08	102.47	-80.27	-102.47	113.85	-91.65	-113.85
25	0.00	22.20	1.88		4.51	17.69	-4.51	6.76	15.44	-6.76	9.01	13.19	-9.01	11.27	10.93	-11.27	13.52	8.68	-13.52	15.78	6.42	-15.78	18.03	4.17	-18.03	20.28	1.92	-20.28	22.54	-0.34	-22.54
26	9.10	31.30	1.90		4.56	26.74	4.54	6.85	24.46	2.26	9.13	22.18	-0.02	11.41	19.89	-2.31	13.69	17.61	-4.59	15.97	15.33	-6.87	18.25	13.05	-9.15	20.54	10.77	-11.43	22.82	8.49	-13.71
27	56.10	78.30	0.68		1.64	76.66	54.46	2.46	75.84	53.64	3.28	75.02	52.82	4.09	74.20	52.00	4.91	73.38	51.18	5.73	72.57	50.37	6.55	71.75	49.55	7.37	70.93	48.73	8.19	70.11	47.91
28	71.63	93.83	2.90		6.97	86.86	64.66	10.45	83.38	61.18	13.94	79.90	57.70	17.42	76.41	54.21	20.90	72.93	50.73	24.39	69.44	47.24	27.87	65.96	43.76	31.36	62.48	40.28	34.84	58.99	36.79
29	91.38	113.58	2.93		7.02	106.56	84.36	10.53	103.05	80.85	14.04	99.53	77.33	17.55	96.02	73.82	21.07	92.51	70.31	24.58	89.00	66.80	28.09	85.49	63.29	31.60	81.98	59.78	35.11	78.47	56.27
30	69.49	91.69	9.86		23.67	68.03	45.83	35.50	56.19	33.99	47.33	44.36	22.16	59.16	32.53	10.33	71.00	20.69	-1.51	82.83	8.86	-13.34	94.66	-2.97	-25.17	106.50	-14.80	-37.00	118.33	-26.64	-48.84
31																															
total	819.85	1485.85	166.09	Qcol Novemb	398.63		421.22	597.94		221.91	797.25		22.60	996.56		-176.72	1195.88		-376.03	1395.19		-575.34	1594.50		-774.65	1793.81		-973.97	1993.13		-1173.28
				Qsho November		1103.80	599.82		970.80	521.57		855.74	457.81		755.42	409.87		666.87	376.78		602.92	354.61		549.09	333.97		510.56	314.86		477.91	295.76
* all values in MJ				Qsur November		16.58	178.60		82.89	299.66		167.14	435.21		266.14	586.59		376.90	752.81		512.26	929.95		657.74	1108.62		818.52	1288.83		985.19	1469.04

DECEMBER	SH demand Qsh	Qsh+DHW Qd	Qsol/m2 Qsol		6M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	9M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	12M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	15M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	18M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	21M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	24M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	27M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol	30M2 Qcol	n = 0.4 Qd_nett Qd-Qcol	Qsh_nett Qsh-Qcol
1	38.52	60.72	3.59		8.61	52.11	29.91	12.92	47.80	25.60	17.23	43.49	21.29	21.53	39.19	16.99	25.84	34.88	12.68	30.15	30.57	8.37	34.46	26.27	4.07	38.76	21.96	-0.24	43.07	17.65	-4.55
2	54.54	76.74	5.15		12.36	64.38	42.18	18.55	58.20	36.00	24.73	52.02	29.82	30.91	45.84	23.64	37.09	39.65	17.45	43.27	33.47	11.27	49.45	27.29	5.09	55.64	21.11	-1.09	61.82	14.93	-7.27
3	53.08	75.28	1.02		2.45	72.82	50.62	3.68	71.60	49.40	4.91	70.37	48.17	6.13	69.14	46.94	7.36	67.92	45.72	8.59	66.69	44.49	9.81	65.46	43.26	11.04	64.24	42.04	12.27	63.01	40.81
4	48.11	70.31	0.63		1.50	68.81	46.61	2.25	68.06	45.86	3.00	67.31	45.11	3.76	66.56	44.36	4.51	65.81	43.61	5.26	65.05	42.85	6.01	64.30	42.10	6.76	63.55	41.35	7.51	62.80	40.60
5	55.58	77.78	3.88		9.30	68.48	46.28	13.95	63.83	41.63	18.60	59.18	36.98	23.25	54.53	32.33	27.91	49.88	27.68	32.56	45.23	23.03	37.21	40.57	18.37	41.86	35.92	13.72	46.51	31.27	9.07
6	69.81	92.01	1.21		2.91	89.10	66.90	4.36	87.65	65.45	5.81	86.20	64.00	7.26	84.75	62.55	8.72	83.29	61.09	10.17	81.84	59.64	11.62	80.39	58.19	13.07	78.93	56.73	14.53	77.48	55.28
7	61.59	83.79	10.26		24.62	59.17	36.97	36.93	46.86	24.66	49.24	34.55	12.35	61.55	22.24	0.04	73.86	9.93	-12.27	86.17	-2.38	-24.58	98.48	-14.69	-36.89	110.79	-27.00	-49.20	123.10	-39.31	-61.51
8	14.93	37.13	9.14		21.93	15.20	-7.00	32.90	4.23	-17.97	43.87	-6.73	-28.93	54.84	-17.70	-39.90	65.80	-28.67	-50.87	76.77	-39.64	-61.84	87.74	-50.60	-72.80	98.70	-61.57	-83.77	109.67	-72.54	-94.74
9	14.58	36.78	5.98		14.34	22.43	0.23	21.51	15.26	-6.94	28.68	8.09	-14.11	35.86	0.92	-21.28	43.03	-6.25	-28.45	50.20	-13.42	-35.62	57.37	-20.59	-42.79	64.54	-27.76	-49.96	71.71	-34.93	-57.13
10	47.49	69.69	2.81		6.76	62.93	40.73	10.13	59.56	37.36	13.51	56.18	33.98	16.89	52.80	30.60	20.27	49.42	27.22	23.64	46.05	23.85	27.02	42.67	20.47	30.40	39.29	17.09	33.78	35.91	13.71
11	65.86	88.06	5.24		12.57	75.50	53.30	18.85	69.21	47.01	25.13	62.93	40.73	31.41	56.65	34.45	37.70	50.36	28.16	43.98	44.08	21.88	50.26	37.80	15.60	56.55	31.52	9.32	62.83	25.23	3.03
12	65.99	88.19	2.58		6.20	82.00	59.80	9.29	78.90	56.70	12.39	75.80	53.60	15.49	72.70	50.50	18.59	69.60	47.40	21.69	66.51	44.31	24.78	63.41	41.21	27.88	60.31	38.11	30.98	57.21	35.01
13	78.53	100.73	1.03		2.47	98.26	76.06	3.71	97.02	74.82	4.94	95.79	73.59	6.18	94.55	72.35	7.41	93.31	71.11	8.65	92.08	69.88	9.89	90.84	68.64	11.12	89.61	67.41	12.36	88.37	66.17
14	73.14	95.34	0.33		0.78	94.55	72.35	1.18	94.16	71.96	1.57	93.77	71.57	1.96	93.37	71.17	2.35	92.98	70.78	2.75	92.59	70.39	3.14	92.20	70.00	3.53	91.81	69.61	3.92	91.41	69.21
15	57.04	79.24	0.65		1.55	77.68	55.48	2.33	76.91	54.71	3.11	76.13	53.93	3.89	75.35	53.15	4.66	74.57	52.37	5.44	73.80	51.60	6.22	73.02	50.82	7.00	72.24	50.04	7.77	71.46	49.26
16	38.02	60.22	0.17		0.41	59.81	37.61	0.61	59.61	37.41	0.82	59.40	37.20	1.02	59.20	37.00	1.23	58.99	36.79	1.43	58.79	36.59	1.64	58.58	36.38	1.84	58.38	36.18	2.05	58.17	35.97
17	48.30	70.50	0.73		1.75	68.75	46.55	2.63	67.87	45.67	3.51	66.99	44.79	4.38	66.12	43.92	5.26	65.24	43.04	6.13	64.36	42.16	7.01	63.49	41.29	7.89	62.61	40.41	8.76	61.73	39.53
18	37.50	59.70	2.84		6.82	52.88	30.68	10.23	49.47	27.27	13.64	46.06	23.86	17.05	42.65	20.45	20.46	39.24	17.04	23.87	35.83	13.63	27.28	32.42	10.22	30.69	29.01	6.81	34.10	25.60	3.40
19	19.22	41.42	4.98		11.96	29.46	7.26	17.94	23.48	1.28	23.92	17.50	-4.70	29.90	11.52	-10.68	35.88	5.54	-16.66	41.86	-0.44	-22.64	47.84	-6.42	-28.62	53.81	-12.40	-34.60	59.79	-18.38	-40.58
20	14.33	36.53	4.62		11.09	25.44	3.24	16.64	19.89	-2.31	22.19	14.35	-7.85	27.73	8.80	-13.40	33.28	3.25	-18.95	38.83	-2.29	-24.49	44.37	-7.84	-30.04	49.92	-13.39	-35.59	55.47	-18.93	-41.13
21	54.91	77.11	3.60		8.65	68.46	46.26	12.97	64.14	41.94	17.29	59.82	37.62	21.62	55.49	33.29	25.94	51.17	28.97	30.26	46.85	24.65	34.59	42.52	20.32	38.91	38.20	16.00	43.24	33.88	11.68
22	70.33	92.53	1.41		3.38	89.15	66.95	5.07	87.46	65.26	6.76	85.77	63.57	8.45	84.08	61.88	10.15	82.39	60.19	11.84	80.69	58.49	13.53	79.00	56.80	15.22	77.31	55.11	16.91	75.62	53.42
23	55.23	77.43	1.41		3.38	74.05	51.85	5.07	72.36	50.16	6.76	70.67	48.47	8.45	68.98	46.78	10.15	67.29	45.09	11.84	65.59	43.39	13.53	63.90	41.70	15.22	62.21	40.01	16.91	60.52	38.32
24	73.19	95.39	4.38		10.52	84.87	62.67	15.78	79.61	57.41	21.04	74.34	52.14	26.31	69.08	46.88	31.57	63.82	41.62	36.83	58.56	36.36	42.09	53.30	31.10	47.35	48.04	25.84	52.61	42.78	20.58
25	127.48	149.68	2.40		5.77	143.91	121.71	8.65	141.02	118.82	11.54	138.14	115.94	14.42	135.25	113.05	17.31	132.37	110.17	20.19	129.48	107.28	23.08	126.60	104.40	25.96	123.71	101.51	28.85	120.83	98.63
26	125.87	148.07	3.05		7.33	140.74	118.54	10.99	137.08	114.88	14.66	133.42	111.22	18.32	129.75	107.55	21.99	126.09	103.89	25.65	122.42	100.22	29.32	118.76	96.56	32.98	115.09	92.89	36.64	111.43	89.23
27	125.79	147.99	0.76		1.82	146.16	123.96	2.74	145.25	123.05	3.65	144.34	122.14	4.56	143.43	121.23	5.47	142.51	120.31	6.38	141.60	119.40	7.29	140.69	118.49	8.21	139.78	117.58	9.12	138.87	116.67
28	116.83	139.03	1.83		4.39	134.64	112.44	6.59	132.45	110.25	8.78	130.25	108.05	10.98	128.06	105.86	13.17	125.86	103.66	15.37	123.67	101.47	17.56	121.47	99.27	19.76	119.28	97.08	21.95	117.08	94.88
29	116.83	139.03	0.47		1.12	137.91	115.71	1.68	137.35	115.15	2.24	136.79	114.59	2.80	136.23	114.03	3.36	135.67	113.47	3.92	135.11	112.91	4.48	134.55	112.35	5.04	133.99	111.79	5.60	133.44	111.24
30	78.29	100.49	3.97		9.53	90.96	68.76	14.30	86.19	63.99	19.06	81.43	59.23	23.83	76.66	54.46	28.59	71.89	49.69	33.36	67.13	44.93	38.12	62.36	40.16	42.89	57.60	35.40	47.65	52.83	30.63
31	63.06	85.26	8.20		19.68	65.58	43.38	29.52	55.74	33.54	39.36	45.90	23.70	49.20	36.06	13.86	59.04	26.22	4.02	68.88	16.38	-5.82	78.72	6.54	-15.66	88.56	-3.30	-25.50	98.40	-13.14	-35.34
total	1963.97	2652.17	98.32	Qcol Decemb	235.98		1727.99	353.96		1610.01	471.95		1492.02	589.94		1374.03	707.93		1256.04	825.91		1138.06	943.90		1020.07	1061.89		902.08	1179.88		784.09
				Qsho December		2416.19	1734.99		2298.21	1637.22		2186.95	1547.62		2079.93	1459.29		1979.16	1383.24		1884.43	1313.05		1808.42	1246.88		1735.70	1182.04		1669.53	1126.35
* all values in MJ				Qsur December		0.00	7.00		0.00	27.21		6.73	55.60		17.70	85.26		34.92	127.20		58.18	174.99		100.15	226.81		145.42	279.96		197.24	342.26

JANUARY	SH demand Qsh	Qsh+DHW Qd	Qsol/m2 Qsol		6M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	9M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	12M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	15M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol
1	11.97	34.17	4.17		10.01	24.16	1.96	15.01	19.16	-3.04	20.01	14.16	-8.04	25.02	9.15	-13.05
2	33.11	55.31	0.96		2.31	53.00	30.80	3.47	51.84	29.64	4.63	50.68	28.48	5.79	49.53	27.33
3	34.98	57.18	5.67		13.61	43.57	21.37	20.42	36.76	14.56	27.23	29.95	7.75	34.03	23.15	0.95
4	24.52	46.72	9.63		23.11	23.61	1.41	34.67	12.05	-10.15	46.23	0.50	-21.70	57.78	-11.06	-33.26
5	29.72	51.92	0.86		2.07	49.85	27.65	3.10	48.82	26.62	4.13	47.78	25.58	5.16	46.75	24.55
6	64.80	87.00	5.54		13.29	73.71	51.51	19.94	67.06	44.86	26.58	60.42	38.22	33.23	53.77	31.57
7	62.43	84.63	3.20		7.68	76.94	54.74	11.53	73.10	50.90	15.37	69.26	47.06	19.21	65.42	43.22
8	89.61	111.81	1.02		2.44	109.37	87.17	3.66	108.14	85.94	4.89	106.92	84.72	6.11	105.70	83.50
9	114.16	136.36	1.35		3.24	133.13	110.93	4.85	131.51	109.31	6.47	129.89	107.69	8.09	128.27	106.07
10	96.07	118.27	2.86		6.87	111.40	89.20	10.31	107.96	85.76	13.75	104.52	82.32	17.18	101.09	78.89
11	68.61	90.81	7.75		18.61	72.20	50.00	27.91	62.90	40.70	37.22	53.59	31.39	46.52	44.29	22.09
12	72.48	94.68	9.79		23.50	71.18	48.98	35.25	59.43	37.23	47.00	47.68	25.48	58.75	35.94	13.74
13	96.44	118.64	6.50		15.60	103.04	80.84	23.40	95.25	73.05	31.19	87.45	65.25	38.99	79.65	57.45
14	119.67	141.87	0.47		1.12	140.75	118.55	1.68	140.19	117.99	2.24	139.63	117.43	2.80	139.07	116.87
15	155.78	177.98	0.74		1.78	176.20	154.00	2.67	175.31	153.11	3.56	174.42	152.22	4.45	173.53	151.33
16	136.04	158.24	0.46		1.12	157.12	134.92	1.67	156.56	134.36	2.23	156.01	133.81	2.79	155.45	133.25
17	79.15	101.35	8.16		19.58	81.77	59.57	29.37	71.98	49.78	39.15	62.19	39.99	48.94	52.40	30.20
18	49.41	71.61	6.82		16.37	55.24	33.04	24.55	47.06	24.86	32.74	38.87	16.67	40.92	30.69	8.49
19	43.87	66.07	2.89		6.94	59.13	36.93	10.41	55.66	33.46	13.88	52.19	29.99	17.35	48.72	26.52
20	65.67	87.87	0.24		0.58	87.28	65.08	0.87	86.99	64.79	1.16	86.70	64.50	1.45	86.41	64.21
21	70.83	93.03	1.26		3.03	90.00	67.80	4.55	88.48	66.28	6.07	86.96	64.76	7.58	85.45	63.25
22	64.07	86.27	0.30		0.71	85.56	63.36	1.06	85.20	63.00	1.42	84.85	62.65	1.77	84.50	62.30
23	72.56	94.76	1.45		3.49	91.28	69.08	5.23	89.53	67.33	6.97	87.79	65.59	8.71	86.05	63.85
24	72.26	94.46	9.25		22.20	72.27	50.07	33.30	61.17	38.97	44.40	50.07	27.87	55.50	38.97	16.77
25	77.01	99.21	4.64		11.15	88.07	65.87	16.72	82.50	60.30	22.29	76.92	54.72	27.86	71.35	49.15
26	51.73	73.93	10.66		25.59	48.35	26.15	38.38	35.55	13.35	51.17	22.76	0.56	63.96	9.97	-12.23
27	16.23	38.43	0.93		2.23	36.20	14.00	3.34	35.09	12.89	4.45	33.98	11.78	5.56	32.86	10.66
28	52.82	75.02	13.17		31.61	43.41	21.21	47.41	27.61	5.41	63.22	11.81	-10.39	79.02	-4.00	-26.20
29	18.58	40.78	2.11		5.07	35.71	13.51	7.60	33.18	10.98	10.14	30.64	8.44	12.67	28.11	5.91
30	61.43	83.63	1.83		4.40	79.23	57.03	6.60	77.03	54.83	8.80	74.83	52.63	10.99	72.63	50.43
31	57.62	79.82	1.91		4.58	75.24	53.04	6.87	72.96	50.76	9.16	70.67	48.47	11.45	68.38	46.18
total	**2063.65**	**2751.85**	**126.61**	**Qcol January**	303.87			455.80			607.73			759.66		
				Qsho January		**2447.98**	**1759.78**		**2296.05**	**1621.03**		**2144.12**	**1496.06**		**2007.24**	**1388.72**
				Qsur January			**0**		*0*	**13.19**		**0**	**40.14**		**15.06**	**84.74**

JANUARY	18M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	21M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	24M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	27M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	30M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol
1	30.02	4.15	-18.05	35.02	-0.85	-23.05	40.03	-5.86	-28.06	45.03	-10.86	-33.06	50.04	-15.86	-38.06
2	6.94	48.37	26.17	8.10	47.21	25.01	9.26	46.06	23.86	10.42	44.90	22.70	11.57	43.74	21.54
3	40.84	16.34	-5.86	47.65	9.53	-12.67	54.45	2.73	-19.47	61.26	-4.08	-26.28	68.07	-10.89	-33.09
4	69.34	-22.62	-44.82	80.90	-34.17	-56.37	92.45	-45.73	-67.93	104.01	-57.29	-79.49	115.57	-68.84	-91.04
5	6.20	45.72	23.52	7.23	44.69	22.49	8.26	43.65	21.45	9.30	42.62	20.42	10.33	41.59	19.39
6	39.87	47.12	24.92	46.52	40.48	18.28	53.16	33.83	11.63	59.81	27.19	4.99	66.45	20.54	-1.66
7	23.05	61.57	39.37	26.90	57.73	35.53	30.74	53.89	31.69	34.58	50.05	27.85	38.42	46.21	24.01
8	7.33	104.48	82.28	8.55	103.26	81.06	9.77	102.04	79.84	10.99	100.81	78.61	12.22	99.59	77.39
9	9.71	126.66	104.46	11.32	125.04	102.84	12.94	123.42	101.22	14.56	121.80	99.60	16.18	120.19	97.99
10	20.62	97.65	75.45	24.06	94.21	72.01	27.49	90.78	68.58	30.93	87.34	65.14	34.37	83.90	61.70
11	55.83	34.98	12.78	65.13	25.68	3.48	74.44	16.37	-5.83	83.74	7.07	-15.13	93.05	-2.24	-24.44
12	70.50	24.19	1.99	82.24	12.44	-9.76	93.99	0.69	-21.51	105.74	-11.06	-33.26	117.49	-22.81	-45.01
13	46.79	71.85	49.65	54.59	64.05	41.85	62.39	56.25	34.05	70.19	48.45	26.25	77.99	40.66	18.46
14	3.36	138.51	116.31	3.92	137.95	115.75	4.48	137.39	115.19	5.04	136.83	114.63	5.60	136.27	114.07
15	5.34	172.64	150.44	6.23	171.75	149.55	7.12	170.86	148.66	8.02	169.97	147.77	8.91	169.08	146.88
16	3.35	154.89	132.69	3.90	154.33	132.13	4.46	153.78	131.58	5.02	153.22	131.02	5.58	152.66	130.46
17	58.73	42.62	20.42	68.52	32.83	10.63	78.31	23.04	0.84	88.10	13.25	-8.95	97.89	3.46	-18.74
18	49.11	22.50	0.30	57.29	14.32	-7.88	65.48	6.14	-16.06	73.66	-2.05	-24.25	81.85	-10.23	-32.43
19	20.82	45.25	23.05	24.29	41.78	19.58	27.76	38.31	16.11	31.23	34.84	12.64	34.70	31.37	9.17
20	1.74	86.12	63.92	2.03	85.83	63.63	2.33	85.54	63.34	2.62	85.25	63.05	2.91	84.96	62.76
21	9.10	83.93	61.73	10.61	82.41	60.21	12.13	80.90	58.70	13.65	79.38	57.18	15.16	77.87	55.67
22	2.13	84.14	61.94	2.48	83.79	61.59	2.84	83.43	61.23	3.19	83.08	60.88	3.54	82.72	60.52
23	10.46	84.31	62.11	12.20	82.56	60.36	13.94	80.82	58.62	15.68	79.08	56.88	17.43	77.34	55.14
24	66.60	27.87	5.67	77.70	16.77	-5.43	88.79	5.67	-16.53	99.89	-5.43	-27.63	110.99	-16.53	-38.73
25	33.44	65.78	43.58	39.01	60.21	38.01	44.58	54.63	32.43	50.15	49.06	26.86	55.73	43.49	21.29
26	76.76	-2.82	-25.02	89.55	-15.62	-37.82	102.34	-28.41	-50.61	115.13	-41.20	-63.40	127.93	-53.99	-76.19
27	6.68	31.75	9.55	7.79	30.64	8.44	8.90	29.53	7.33	10.01	28.41	6.21	11.13	27.30	5.10
28	94.83	-19.80	-42.00	110.63	-35.61	-57.81	126.43	-51.41	-73.61	142.24	-67.22	-89.42	158.04	-83.02	-105.22
29	15.21	25.58	3.38	17.74	23.04	0.84	20.28	20.51	-1.69	22.81	17.97	-4.23	25.35	15.44	-6.76
30	13.19	70.44	48.24	15.39	68.24	46.04	17.59	66.04	43.84	19.79	63.84	41.64	21.99	61.64	39.44
31	13.73	66.09	43.89	16.02	63.80	41.60	18.31	61.51	39.31	20.60	59.22	37.02	22.89	56.93	34.73
total (Qcol January)	911.60		1152.05	1063.53		1000.12	1215.46		848.18	1367.40		696.25	1519.33		544.32
Qsho January		**1885.49**	**1287.80**		**1774.57**	**1210.91**		**1667.79**	**1149.49**		**1583.64**	**1101.35**		**1516.94**	**1055.70**
Qsur January		**45.24**	**135.75**		**86.25**	**210.79**		**131.41**	**301.31**		**199.19**	**405.10**		**284.42**	**511.38**

*** all values in MJ**

FEBRUARY	SH demand Qsh	Qsh+DHW Qd	Qsol/m2 Qsol		6M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	9M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	12M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	15M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol
1	57.08	79.28	1.54		3.70	75.58	53.38	5.55	73.73	51.53	7.40	71.88	49.68	9.25	70.03	47.83
2	59.60	81.80	2.00		4.80	77.00	54.80	7.21	74.60	52.40	9.61	72.20	50.00	12.01	69.79	47.59
3	74.06	96.26	1.19		2.85	93.41	71.21	4.27	91.99	69.79	5.70	90.57	68.37	7.12	89.14	66.94
4	90.79	112.99	5.81		13.94	99.05	76.85	20.91	92.09	69.89	27.88	85.12	62.92	34.85	78.15	55.95
5	76.25	98.45	4.68		11.23	87.22	65.02	16.85	81.60	59.40	22.46	75.99	53.79	28.08	70.37	48.17
6	91.61	113.81	0.79		1.89	111.92	89.72	2.83	110.98	88.78	3.77	110.04	87.84	4.72	109.09	86.89
7	87.76	109.96	3.14		7.53	102.43	80.23	11.30	98.66	76.46	15.06	94.90	72.70	18.83	91.13	68.93
8	107.76	129.96	1.41		3.37	126.58	104.38	5.06	124.90	102.70	6.75	123.21	101.01	8.44	121.52	99.32
9	106.09	128.29	5.29		12.70	115.58	93.38	19.06	109.23	87.03	25.41	102.88	80.68	31.76	96.53	74.33
10	87.75	109.95	6.02		14.46	95.49	73.29	21.69	88.26	66.06	28.91	81.03	58.83	36.14	73.81	51.61
11	66.49	88.69	12.21		29.29	59.40	37.20	43.94	44.75	22.55	58.59	30.10	7.90	73.24	15.46	-6.74
12	57.92	80.12	4.31		10.34	69.78	47.58	15.51	64.61	42.41	20.68	59.44	37.24	25.85	54.27	32.07
13	72.27	94.47	4.39		10.53	83.95	61.75	15.79	78.68	56.48	21.06	73.42	51.22	26.32	68.15	45.95
14	68.56	90.76	16.52		39.64	51.13	28.93	59.46	31.31	9.11	79.27	11.49	-10.71	99.09	-8.33	-30.53
15	63.78	85.98	14.63		35.11	50.87	28.67	52.67	33.31	11.11	70.23	15.75	-6.45	87.78	-1.80	-24.00
16	32.92	55.12	14.77		35.45	19.67	-2.53	53.18	1.94	-20.26	70.90	-15.79	-37.99	88.63	-33.51	-55.71
17	5.64	27.84	10.41		24.98	2.86	-19.34	37.47	-9.63	-31.83	49.96	-22.12	-44.32	62.45	-34.61	-56.81
18	17.57	39.77	7.21		17.30	22.47	0.27	25.95	13.82	-8.38	34.60	5.17	-17.03	43.25	-3.48	-25.68
19	46.20	68.40	11.53		27.68	40.73	18.53	41.52	26.89	4.69	55.36	13.05	-9.15	69.20	-0.79	-22.99
20	19.43	41.63	19.19		46.05	-4.43	-26.63	69.08	-27.46	-49.66	92.11	-50.48	-72.68	115.14	-73.51	-95.71
21	0.00	22.20	17.31		41.54	-19.34	-41.54	62.31	-40.11	-62.31	83.07	-60.87	-83.07	103.84	-81.64	-103.84
22	0.00	22.20	1.06		2.55	19.65	-2.55	3.83	18.37	-3.83	5.11	17.09	-5.11	6.38	15.82	-6.38
23	0.00	22.20	13.44		32.27	-10.07	-32.27	48.40	-26.20	-48.40	64.53	-42.33	-64.53	80.66	-58.46	-80.66
24	0.00	22.20	17.52		42.05	-19.85	-42.05	63.08	-40.88	-63.08	84.10	-61.90	-84.10	105.13	-82.93	-105.13
25	0.00	22.20	11.75		28.20	-6.00	-28.20	42.30	-20.10	-42.30	56.40	-34.20	-56.40	70.50	-48.30	-70.50
26	0.00	22.20	11.77		28.24	-6.04	-28.24	42.36	-20.16	-42.36	56.48	-34.28	-56.48	70.60	-48.40	-70.60
27	0.00	22.20	5.43		13.03	9.17	-13.03	19.54	2.66	-19.54	26.06	-3.86	-26.06	32.57	-10.37	-32.57
28	1.36	23.56	6.28		15.08	8.49	-13.71	22.62	0.95	-21.25	30.16	-6.59	-28.79	37.69	-14.13	-36.33
total	**1290.91**	**1912.51**	**231.59**	**Qcol February**	555.81		735.10	833.72		457.19	1111.62		179.28	1389.53		-98.62
				Qsho February		**1422.42**	**985.19**		**1263.32**	**870.39**		**1133.31**	**782.16**		**1023.26**	**725.58**
				Qsur Febraury		**65.72**	**250.09**		**184.53**	**413.20**		**332.43**	**602.88**		**500.28**	**824.21**

FEBRUARY	18M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	21M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	24M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	27M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	30M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol
1	11.10	68.18	45.98	12.96	66.33	44.13	14.81	64.48	42.28	16.66	62.63	40.43	18.51	60.78	38.58
2	14.41	67.39	45.19	16.81	64.99	42.79	19.22	62.59	40.39	21.62	60.19	37.99	24.02	57.78	35.58
3	8.55	87.72	65.52	9.97	86.29	64.09	11.40	84.87	62.67	12.82	83.44	61.24	14.25	82.02	59.82
4	41.82	71.18	48.98	48.79	64.21	42.01	55.75	57.24	35.04	62.72	50.27	28.07	69.69	43.30	21.10
5	33.70	64.75	42.55	39.31	59.14	36.94	44.93	53.52	31.32	50.55	47.91	25.71	56.16	42.29	20.09
6	5.66	108.15	85.95	6.60	107.21	85.01	7.55	106.26	84.06	8.49	105.32	83.12	9.43	104.38	82.18
7	22.59	87.37	65.17	26.36	83.60	61.40	30.12	79.84	57.64	33.89	76.07	53.87	37.65	72.31	50.11
8	10.12	119.84	97.64	11.81	118.15	95.95	13.50	116.46	94.26	15.18	114.77	92.57	16.87	113.09	90.89
9	38.11	90.17	67.97	44.47	83.82	61.62	50.82	77.47	55.27	57.17	71.12	48.92	63.52	64.76	42.56
10	43.37	66.58	44.38	50.60	59.35	37.15	57.83	52.12	29.92	65.06	44.89	22.69	72.28	37.66	15.46
11	87.88	0.81	-21.39	102.53	-13.84	-36.04	117.18	-28.49	-50.69	131.83	-43.13	-65.33	146.47	-57.78	-79.98
12	31.02	49.10	26.90	36.19	43.93	21.73	41.36	38.76	16.56	46.53	33.59	11.39	51.69	28.42	6.22
13	31.59	62.89	40.69	36.85	57.62	35.42	42.12	52.36	30.16	47.38	47.09	24.89	52.65	41.83	19.63
14	118.91	-28.15	-50.35	138.73	-47.97	-70.17	158.55	-67.78	-89.98	178.37	-87.60	-109.80	198.19	-107.42	-129.62
15	105.34	-19.36	-41.56	122.90	-36.92	-59.12	140.45	-54.47	-76.67	158.01	-72.03	-94.23	175.56	-89.58	-111.78
16	106.36	-51.24	-73.44	124.08	-68.96	-91.16	141.81	-86.69	-108.89	159.54	-104.42	-126.62	177.26	-122.14	-144.34
17	74.94	-47.11	-69.31	87.43	-59.60	-81.80	99.93	-72.09	-94.29	112.42	-84.58	-106.78	124.91	-97.07	-119.27
18	51.90	-12.13	-34.33	60.55	-20.78	-42.98	69.20	-29.43	-51.63	77.85	-38.08	-60.28	86.50	-46.73	-68.93
19	83.04	-14.63	-36.83	96.88	-28.47	-50.67	110.72	-42.31	-64.51	124.56	-56.15	-78.35	138.40	-69.99	-92.19
20	138.16	-96.54	-118.74	161.19	-119.57	-141.77	184.22	-142.59	-164.79	207.25	-165.62	-187.82	230.27	-188.65	-210.85
21	124.61	-102.41	-124.61	145.38	-123.18	-145.38	166.15	-143.95	-166.15	186.92	-164.72	-186.92	207.68	-185.48	-207.68
22	7.66	14.54	-7.66	8.93	13.27	-8.93	10.21	11.99	-10.21	11.49	10.71	-11.49	12.76	9.44	-12.76
23	96.80	-74.60	-96.80	112.93	-90.73	-112.93	129.06	-106.86	-129.06	145.19	-122.99	-145.19	161.33	-139.13	-161.33
24	126.15	-103.95	-126.15	147.18	-124.98	-147.18	168.20	-146.00	-168.20	189.23	-167.03	-189.23	210.25	-188.05	-210.25
25	84.60	-62.40	-84.60	98.70	-76.50	-98.70	112.80	-90.60	-112.80	126.90	-104.70	-126.90	141.00	-118.80	-141.00
26	84.73	-62.53	-84.73	98.85	-76.65	-98.85	112.97	-90.77	-112.97	127.09	-104.89	-127.09	141.21	-119.01	-141.21
27	39.09	-16.89	-39.09	45.60	-23.40	-45.60	52.12	-29.92	-52.12	58.63	-36.43	-58.63	65.15	-42.95	-65.15
28	45.23	-21.67	-43.87	52.77	-29.21	-51.41	60.31	-36.75	-58.95	67.85	-44.28	-66.48	75.39	-51.82	-74.02
total (Qcol February)	1667.43		-376.53	1945.34		-654.43	2223.25		-932.34	2501.15	-588.64	-1210.24	2779.06	-866.55	-1488.15
Qsho February		**958.66**	**676.91**		**907.90**	**628.24**		**857.95**	**579.57**		**808.00**	**530.89**		**758.06**	**482.22**
Qsur Febraury		**713.59**	**1053.44**		**940.74**	**1282.67**		**1168.69**	**1511.90**		**1396.65**	**1741.14**		**1624.60**	**1970.37**

*** all values in MJ**

MARCH	SH demand Qsh	Qsh+DHW Qd	Qsol/m2 Qsol		6M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	9M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol
1	14.62	36.82	12.48		29.96	6.86	-15.34	44.93	-8.12	-30.32
2	17.49	39.69	5.53		13.27	26.42	4.22	19.91	19.79	-2.41
3	49.36	71.56	5.59		13.41	58.16	35.96	20.11	51.45	29.25
4	64.61	86.81	7.43		17.83	68.99	46.79	26.74	60.07	37.87
5	45.98	68.18	9.07		21.78	46.40	24.20	32.67	35.51	13.31
6	45.36	67.56	8.07		19.37	48.19	25.99	29.06	38.50	16.30
7	43.13	65.33	7.92		19.01	46.32	24.12	28.52	36.81	14.61
8	76.66	98.86	2.59		6.22	92.64	70.44	9.33	89.54	67.34
9	103.69	125.89	3.13		7.52	118.37	96.17	11.28	114.61	92.41
10	77.14	99.34	6.60		15.83	83.51	61.31	23.75	75.59	53.39
11	77.14	99.34	12.76		30.62	68.72	46.52	45.94	53.41	31.21
12	32.42	54.62	6.39		15.34	39.28	17.08	23.01	31.61	9.41
13	50.30	72.50	5.75		13.80	58.70	36.50	20.70	51.80	29.60
14	45.66	67.86	21.47		51.53	16.33	-5.87	77.30	-9.43	-31.63
15	0.00	22.20	20.23		48.55	-26.35	-48.55	72.82	-50.62	-72.82
16	0.00	22.20	20.77		49.84	-27.64	-49.84	74.76	-52.56	-74.76
17	0.00	22.20	11.44		27.45	-5.25	-27.45	41.18	-18.98	-41.18
18	0.00	22.20	6.11		14.66	7.54	-14.66	22.00	0.20	-22.00
19	0.00	22.20	3.58		8.58	13.62	-8.58	12.87	9.33	-12.87
20	0.00	22.20	13.63		32.72	-10.52	-32.72	49.08	-26.88	-49.08
21	0.00	22.20	11.14		26.73	-4.53	-26.73	40.09	-17.89	-40.09
22	0.00	22.20	3.94		9.46	12.74	-9.46	14.19	8.01	-14.19
23	16.87	39.07	2.39		5.73	33.34	11.14	8.59	30.48	8.28
24	41.65	63.85	3.43		8.23	55.62	33.42	12.35	51.50	29.30
25	38.60	60.80	23.91		57.38	3.42	-18.78	86.07	-25.27	-47.47
26	0.00	22.20	24.09		57.82	-35.62	-57.82	86.73	-64.53	-86.73
27	0.00	22.20	20.20		48.48	-26.28	-48.48	72.73	-50.53	-72.73
28	0.00	22.20	3.23		7.75	14.45	-7.75	11.63	10.57	-11.63
29	0.00	22.20	2.75		6.59	15.61	-6.59	9.89	12.31	-9.89
30	9.30	31.50	7.87		18.90	12.61	-9.59	28.34	3.16	-19.04
31	22.85	45.05	24.27		58.25	-13.20	-35.40	87.37	-42.32	-64.52
total	872.84	1561.04	317.76	Qcol March	762.62	798.43	110.23	1143.92		
				Qsho March		947.82	533.85		784.25	432.28
* all values in MJ				Qsur March		149.39	423.62		367.13	703.36

MARCH	12M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	15M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	18M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	21M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol
1	59.91	-23.09	-45.29	74.89	-38.07	-60.27	89.87	-53.05	-75.25	104.84	-68.03	-90.23
2	26.54	13.15	-9.05	33.18	6.51	-15.69	39.82	-0.12	-22.32	46.45	-6.76	-28.96
3	26.81	44.75	22.55	33.51	38.05	15.85	40.22	31.35	9.15	46.92	24.64	2.44
4	35.66	51.16	28.96	44.57	42.24	20.04	53.48	33.33	11.13	62.40	24.42	2.22
5	43.56	24.62	2.42	54.45	13.73	-8.47	65.33	2.84	-19.36	76.22	-8.04	-30.24
6	38.75	28.81	6.61	48.43	19.13	-3.07	58.12	9.44	-12.76	67.81	-0.25	-22.45
7	38.02	27.31	5.11	47.53	17.80	-4.40	57.03	8.29	-13.91	66.54	-1.21	-23.41
8	12.44	86.43	64.23	15.55	83.32	61.12	18.65	80.21	58.01	21.76	77.10	54.90
9	15.04	110.85	88.65	18.80	107.09	84.89	22.56	103.33	81.13	26.32	99.56	77.36
10	31.67	67.67	45.47	39.58	59.76	37.56	47.50	51.84	29.64	55.42	43.92	21.72
11	61.25	38.10	15.90	76.56	22.78	0.58	91.87	7.47	-14.73	107.18	-7.84	-30.04
12	30.67	23.94	1.74	38.34	16.28	-5.92	46.01	8.61	-13.59	53.68	0.94	-21.26
13	27.60	44.90	22.70	34.50	38.00	15.80	41.40	31.10	8.90	48.30	24.20	2.00
14	103.07	-35.20	-57.40	128.83	-60.97	-83.17	154.60	-86.73	-108.93	180.36	-112.50	-134.70
15	97.09	-74.89	-97.09	121.36	-99.16	-121.36	145.64	-123.44	-145.64	169.91	-147.71	-169.91
16	99.68	-77.48	-99.68	124.61	-102.41	-124.61	149.53	-127.33	-149.53	174.45	-152.25	-174.45
17	54.90	-32.70	-54.90	68.63	-46.43	-68.63	82.36	-60.16	-82.36	96.08	-73.88	-96.08
18	29.33	-7.13	-29.33	36.66	-14.46	-36.66	43.99	-21.79	-43.99	51.32	-29.12	-51.32
19	17.16	5.04	-17.16	21.46	0.74	-21.46	25.75	-3.55	-25.75	30.04	-7.84	-30.04
20	65.45	-43.25	-65.45	81.81	-59.61	-81.81	98.17	-75.97	-98.17	114.53	-92.33	-114.53
21	53.45	-31.25	-53.45	66.82	-44.62	-66.82	80.18	-57.98	-80.18	93.54	-71.34	-93.54
22	18.92	3.28	-18.92	23.65	-1.45	-23.65	28.38	-6.18	-28.38	33.11	-10.91	-33.11
23	11.45	27.62	5.42	14.32	24.75	2.55	17.18	21.89	-0.31	20.04	19.03	-3.17
24	16.46	47.39	25.19	20.58	43.27	21.07	24.69	39.15	16.95	28.81	35.04	12.84
25	114.76	-53.95	-76.15	143.45	-82.64	-104.84	172.14	-111.33	-133.53	200.83	-140.02	-162.22
26	115.64	-93.44	-115.64	144.55	-122.35	-144.55	173.46	-151.26	-173.46	202.37	-180.17	-202.37
27	96.97	-74.77	-96.97	121.21	-99.01	-121.21	145.45	-123.25	-145.45	169.70	-147.50	-169.70
28	15.50	6.70	-15.50	19.38	2.82	-19.38	23.26	-1.06	-23.26	27.13	-4.93	-27.13
29	13.19	9.01	-13.19	16.49	5.71	-16.49	19.78	2.42	-19.78	23.08	-0.88	-23.08
30	37.79	-6.29	-28.49	47.24	-15.74	-37.94	56.69	-25.18	-47.38	66.13	-34.63	-56.83
31	116.49	-71.44	-93.64	145.61	-100.57	-122.77	174.74	-129.69	-151.89	203.86	-158.81	-181.01
total	1525.23			1906.54			2287.85			2669.16		
Qsho March		660.71	334.94		541.99	259.46		431.27	214.90		348.85	173.48
Qsur March		624.90	987.33		887.48	1293.15		1158.07	1629.91		1456.96	1969.80

MARCH	24M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	27M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol	30M2 Qcol	n = 0.4 Qd_nett | Qd-Qcol	Qsh_nett | Qsh-Qcol
1	119.82	-83.00	-105.20	134.80	-97.98	-120.18	149.78	-112.96	-135.16
2	53.09	-13.40	-35.60	59.73	-20.03	-42.23	66.36	-26.67	-48.87
3	53.62	17.94	-4.26	60.32	11.24	-10.96	67.03	4.53	-17.67
4	71.31	15.50	-6.70	80.23	6.59	-15.61	89.14	-2.33	-24.53
5	87.11	-18.93	-41.13	98.00	-29.82	-52.02	108.89	-40.71	-62.91
6	77.49	-9.93	-32.13	87.18	-19.62	-41.82	96.87	-29.31	-51.51
7	76.05	-10.72	-32.92	85.55	-20.22	-42.42	95.06	-29.73	-51.93
8	24.87	73.99	51.79	27.98	70.88	48.68	31.09	67.77	45.57
9	30.08	95.80	73.60	33.85	92.04	69.84	37.61	88.28	66.08
10	63.33	36.01	13.81	71.25	28.09	5.89	79.17	20.17	-2.03
11	122.49	-23.15	-45.35	137.81	-38.46	-60.66	153.12	-53.77	-75.97
12	61.35	-6.73	-28.93	69.02	-14.40	-36.60	76.68	-22.07	-44.27
13	55.20	17.30	-4.90	62.10	10.40	-11.80	69.00	3.50	-18.70
14	206.13	-138.27	-160.47	231.90	-164.03	-186.23	257.66	-189.80	-212.00
15	194.18	-171.98	-194.18	218.46	-196.26	-218.46	242.73	-220.53	-242.73
16	199.37	-177.17	-199.37	224.29	-202.09	-224.29	249.21	-227.01	-249.21
17	109.81	-87.61	-109.81	123.53	-101.33	-123.53	137.26	-115.06	-137.26
18	58.66	-36.46	-58.66	65.99	-43.79	-65.99	73.32	-51.12	-73.32
19	34.33	-12.13	-34.33	38.62	-16.42	-38.62	42.91	-20.71	-42.91
20	130.89	-108.69	-130.89	147.25	-125.05	-147.25	163.61	-141.41	-163.61
21	106.90	-84.70	-106.90	120.27	-98.07	-120.27	133.63	-111.43	-133.63
22	37.84	-15.64	-37.84	42.58	-20.38	-42.58	47.31	-25.11	-47.31
23	22.90	16.16	-6.04	25.77	13.30	-8.90	28.63	10.44	-11.76
24	32.92	30.92	8.72	37.04	26.81	4.61	41.16	22.69	0.49
25	229.52	-168.71	-190.91	258.21	-197.40	-219.60	286.90	-226.09	-248.29
26	231.28	-209.08	-231.28	260.19	-237.99	-260.19	289.10	-266.90	-289.10
27	193.94	-171.74	-193.94	218.18	-195.98	-218.18	242.42	-220.22	-242.42
28	31.01	-8.81	-31.01	34.88	-12.68	-34.88	38.76	-16.56	-38.76
29	26.38	-4.18	-26.38	29.67	-7.47	-29.67	32.97	-10.77	-32.97
30	75.58	-44.08	-66.28	85.03	-53.53	-75.73	94.48	-62.98	-85.18
31	232.98	-187.93	-210.13	262.11	-217.06	-239.26	291.23	-246.18	-268.38
total	3050.46	-1489.42	-2177.62	3431.77			3813.08		
Qsho March		303.63	147.92		259.35	129.02		217.39	112.15
Qsur March		1793.05	2325.54		2130.07	2687.95		2469.43	3052.38

The daily values are added and converted back to monthly values that are visualised in the tables below, again for both full coverage and space heating only strategy. The $6m^2$ collector surface is not included anymore since simulations have shown that it cannot yield enough thermal energy for storage. The values in the tables are calculated according to the calculation rules described in paragraph 6.3.

The first column shows the nett thermal energy demand, which means resulting thermal demand after subtraction of directly usable energy, also referred to as Qdir in this report. The second column shows the in between surplus within the storage period. The eventual value is subtracted from the first column to find the required storage capacity in the last column. The third column gives the output from the collectors. These Qcol (or Qdir) values directly follow from the solar irradiation per square metre, collector surface and efficiency factor (0,4 in these simulations).

Full coverage 9m2

	Qd-Qcol	Qsur	Qcol	Qs
NOV	970.8	82.9	597.9	970.8
DEC	2298.2	0.0	354.0	2215.3
JAN	2296.0	0.0	455.8	2296.0
FEB	1263.3	184.5	833.7	1263.3
MAR	784.2		1143.9	599.7
totals	7612.6	267.4	3385.3	**7345.2**

Space heating only 9m2

	Qsh-Qcol	Qsur	Qcol	Qs
NOV	521.6	260.8	597.9	521.6
DEC	1637.2	27.2	354.0	1376.4
JAN	1621.0	13.2	455.8	1593.8
FEB	870.4	413.2	833.7	857.2
MAR	432.3		1143.9	19.1
totals	5082.5	714.4	3385.3	**4368.1**

Full coverage 12m2

	Qd-Qcol	Qsur	Qcol	Qs
NOV	855.7	167.1	797.3	855.7
DEC	2187.0	6.7	472.0	2019.8
JAN	2144.1	0.0	607.7	2137.4
FEB	1133.3	332.4	1111.6	1133.3
MAR	660.7		1525.2	328.3
totals	6980.8	506.3	4513.8	**6474.5**

Space heating only 12m2

	Qsh-Qcol	Qsur	Qcol	Qs
NOV	457.8	228.9	797.3	457.8
DEC	1547.6	55.6	472.0	1318.7
JAN	1496.1	40.1	607.7	1440.5
FEB	782.2	334.9	1111.6	742.0
MAR	334.9		1525.2	0.0
totals	4618.6	659.6	4513.8	**3959.0**

Full coverage 15m2

	Qd-Qcol	Qsur	Qcol	Qs
NOV	755.4	266.1	996.6	755.4
DEC	2079.9	17.7	589.9	1813.8
JAN	2007.2	15.1	759.7	1989.5
FEB	1023.3	500.3	1389.5	1008.2
MAR	542.0		1906.5	41.7
totals	6407.8	799.2	5642.2	**5608.7**

Space heating only 15m2

	Qsh-Qcol	Qsur	Qcol	Qs
NOV	409.9	205.0	996.6	409.9
DEC	1459.3	85.3	589.9	1254.3
JAN	1388.7	84.7	759.7	1303.5
FEB	725.6	259.0	1389.5	640.8
MAR	259.5		1906.5	0.5
totals	4242.9	634.0	5642.2	**3608.9**

Full coverage 18m2

	Qd-Qcol	Qsur	Qcol	Qs
NOV	666.9	333.4	1195.9	666.9
DEC	1979.2	34.9	707.9	1645.7
JAN	1885.5	45.2	911.6	1850.6
FEB	958.7	431.3	1667.4	913.4
MAR	431.3		2287.8	0.0
totals	5921.5	844.9	6770.7	**5076.6**

Space heating only 18m2

	Qsh-Qcol	Qsur	Qcol	Qs
NOV	376.8	188.4	1195.9	376.8
DEC	1383.2	127.2	707.9	1194.9
JAN	1287.8	135.8	911.6	1160.6
FEB	676.9	214.9	1667.4	541.2
MAR	214.9		2287.8	0.0
totals	3939.6	666.2	6770.7	**3273.4**

Full coverage 21m2

	Qd-Qcol	Qsur	Qcol	Qs
NOV	602.9	301.5	1395.2	602.9
DEC	1884.4	58.2	825.9	1583.0
JAN	1774.6	86.3	1063.5	1716.4
FEB	907.9	348.9	1945.3	821.7
MAR	348.9		2669.2	0.0
totals	5518.7	794.7	7899.1	**4723.9**

Space heating only 21m2

	Qsh-Qcol	Qsur	Qcol	Qs
NOV	354.6	177.3	1395.2	354.6
DEC	1313.0	175.0	825.9	1135.7
JAN	1210.9	210.8	1063.5	1035.9
FEB	628.2	173.5	1945.3	417.4
MAR	173.5		2669.2	0.0
totals	3680.3	736.6	7899.1	**2943.7**

Full coverage 24m2

	Qd-Qcol	Qsur	Qcol	Qs
NOV	549.1	274.5	1594.5	549.1
DEC	1808.4	100.1	943.9	1533.9
JAN	1667.8	131.4	1215.5	1567.6
FEB	858.0	303.6	2223.2	726.5
MAR	303.6		3050.5	0.0
totals	5186.9	809.7	9027.6	**4377.2**

Space heating only 24m2

	Qsh-Qcol	Qsur	Qcol	Qs
NOV	334.0	167.0	1594.5	334.0
DEC	1246.9	226.8	943.9	1079.9
JAN	1149.5	301.3	1215.5	922.7
FEB	579.6	147.9	2223.2	278.3
MAR	147.9		3050.5	0.0
totals	3457.8	843.0	9027.6	**2614.8**

Full coverage 27m2

	Qd-Qcol	Qsur	Qcol	Qs
NOV	510.6	255.3	1793.8	510.6
DEC	1735.7	145.4	1061.9	1480.4
JAN	1583.6	199.2	1367.4	1438.2
FEB	808.0	259.3	2501.2	608.8
MAR	259.3		3431.8	0.0
totals	3258.2	859.2	10156.0	**4038.0**

Space heating only 27m2

	Qsh-Qcol	Qsur	Qcol	Qs
NOV	314.9	157.4	1793.8	314.9
DEC	1182.0	280.0	1061.9	1024.6
JAN	1101.3	405.1	1367.4	821.4
FEB	530.9	129.0	2501.2	125.8
MAR	129.0		3431.8	0.0
totals	3258.2	971.5	10156.0	**2286.7**

Full coverage 30m2

	Qd-Qcol	Qsur	Qcol	Qs
NOV	477.9	239.0	1993.1	477.9
DEC	1669.5	197.2	1179.9	1430.6
JAN	1516.9	284.4	1519.3	1319.7
FEB	758.1	217.4	2779.1	473.6
MAR	217.4		3813.1	0.0
totals	4639.8	938.0	11284.5	**3701.8**

Space heating only 30m2

	Qsh-Qcol	Qsur	Qcol	Qs
NOV	295.8	147.9	1993.1	295.8
DEC	1126.4	342.3	1179.9	978.5
JAN	1055.7	482.2	1519.3	713.4
FEB	482.2	112.1	2779.1	0.0
MAR	112.1		3813.1	0.0
totals	3072.2	1084.5	11284.5	**1987.7**