Demand response with building related energy storage solutions

Modeling and simulation of storage solutions in dwellings

J. van Laarhoven (Jordi)

Unit Building Physics and Services,
Department of the Built Environment,
University of Technology Eindhoven,

11 July 2014

Supervisors: prof.dr.ir. J.L.M. Hensen (Jan)
ir. P. Hoes (Pieter-Jan)
PD. J.I. Torrens Galdiz (Ignacio)

Abstract

The demand of energy in Dutch houses does not align with the energy production that is generated by renewable sources such as wind and solar power. Backup generators have to stay in service to compensate this mismatch. When during the day a surplus of energy occurs, this energy should be used ore stored to reduce the load on the electricity network during peak hours. This way, the energy from renewable sources could be used when it is generated.

Storing energy has proven to be a difficult and expensive on a large scale and because of this, the focus of this research is on small scale building related thermal energy storage. In this project the influence from different demand response strategies on different systems and occupation profiles were investigated using computational modeling with TRNSYS.

The results show that it is indeed possible to shift the energy demand to a more convenient moment. Using a financial incentive, the energy bill can be reduced by over 13% in the best case scenario without loss of comfort.

Key words: Demand response, TABS, thermal storage, load shifting, computational modeling

1 Introduction

European environmental policies impose national governments to reduce the energy production from conventional power plants and shift to the renewable energy sources by the year 2020 (United Nations, 1998; PBL, 2011). This forces the contributing partners, such as energy companies and policy makers to investigate alternative options to produce a balanced energy network with economical, secure and reliable options.

1.1 Demand side management and demand response

Including renewable energy sources, such as wind power and solar power, into the distribution grids complicates the balancing of demand and supply due to the fluctuating character of these sources. Predicting the net output has proven to be a challenge and therefore, backup generators have to stay in service to compensate this energy shortage.

These problems can be solved by increasing demand elasticity or decoupling generation and consumption; for the first, an advanced metering infrastructure and, for the second, decentralized electricity storage are considered core enablers (Römer et al, 2012). Because of this, smart grids are being recognized as one of the necessities to provide this reliable metered energy supply in the future (IEA, 2012; Orecchini, 2011). The next-generation grid uses information technology in the existing grid to communicate information in real-time between power suppliers and consumers, to balance and optimize the level of energy efficiency (DNV, 2011).

The information communicated between supplier and end user must be used adequately to manage the energy flow optimal. Therefore, numerous research topics are dedicated to the management of the energy systems. Medina *et al.* (2012) conclude that the demand side management (DSM) is the most promising method to efficiently use the available energy and therefor reduce the energy demand. The main goal of demand response (DR) is more economic and these programs are designed to encourage end-users to make short-term reductions in their energy demand as a response to a price signal from the suppliers. By making use of energy storage solutions, generated electricity from intermittent sources can be stored in case of a surplus and the stored energy can be discharged later during peak demand hours. Two major categories can be distinguished here; time-based demand response and incentive-based demand response (Zhang, 2012). The goal of DR is to encourage the consumer to use less energy during peak hours by moving the energy demand to off-peak times, for instance during the night or in the weekend. This does not necessarily result in lower energy consumption but could reduce the peak power demand of the overall network. Therefore, new investments in generators are superfluous and less fossil fuel has to be used to provide electricity during peak hours and will results in a lower electricity bill for the user.

1.2 System and storage

In the build environment the current focus is on energy reduction by implementation of energy efficient systems such as low temperature heating, high temperature cooling and heat recovery units. Unfortunately not all existing residential buildings can be fitted with such a system and the heating system predominantly utilized in urban settlements is high temperature water heating with local fossil fuel powered boilers as a heat source. For renovation of these buildings other factors need to be considered compared to building a brand new house.

Low temperature heat emissions from, for instance, floor heating or thermally activated building systems (TABS) are well suited to combine with a heat pump system. The large heat exchange area allows for low supply water temperatures and especially with TABS, the high thermal capacity has an important part in reducing thermal peaks inside the building. The thermal inertia makes it however difficult to guarantee thermal comfort. Changes in the thermal load of the room cannot be compensated quickly by the system (Gwerder et al, 2008). Therefore, control is currently based on a weather dependent heating curve which determines the desired supply or return water temperature to the floor. In this type of control, the water temperature set point relates to the mean ambient temperature of the past three days. (Verhelst et al, 2011)

High temperature heating, for instance with radiators, uses water temperature up to 80 degrees Celsius. This type of system is capable of reacting fast to demand changes in the room and therefor the control is based on the room temperature directly using a thermostat. The disadvantage of the system is the high energy demand compared to low temperature heating and the lack of thermal storage. Also, only heating is possible with the use of radiators which means that there is a risk of overheating.

This paper focusses on building related solutions to make optimum use of renewable energy sources with these different systems. The emphasis is on energy storage methods that are related to the design process and type of heating system. As mentioned, the thermal inertia of low temperature systems delays the influence of the system on the operative temperature in the room. When the occupancy of the room is known, this inertia can be used to shift the energy demand to a more convenient moment. This and other techniques are mentioned in literature and provide options to locally store energy, e.g. electric batteries, thermal storage tanks, phase changing materials, etc. (Bassam et al, 2013)

1.3 Research questions

The goal of this project is to investigate building related solutions that enable shifting the energy demand of Dutch dwellings, to the energy supply from renewable sources. In this paper the potential of different concepts is being explored using the following research questions:

- *Which building related storage methods could contribute in shifting the energy supply and demand for heating a dwelling?*
- *Which of the storage methods are most promising for shifting the energy supply and demand?*
- *How should the different storage options be compared to each other?*
- *What are the best operational strategies for each storage method?*

This study uses a computational performance prediction to assess the impact of additional energy storage capacity. The model describes an energy concept consisting of a dwelling with a thermally activated building system and a radiator system combined with thermal energy storage.

2 Research methodology

The method used consists of two parts, first a literature review has been conducted to investigate the current systems and the storage possibilities that are available on the market. The second part of the research investigates the influence of different demand response strategies on three systems concepts taking into account external influences for instance; climate, occupancy and temperature set points.

Figure 2.1 presents a schematic representation of the method. It shows the electricity input form the smart grid which communicates the hourly electricity rates to the buildings thermal system. A chosen DR strategy allows or restricts the system to use energy at a certain moment in time. The system is influenced by different factors as can be seen in de scheme. A simulation is performed for each of the considered DR strategies, generating results that provide an overall economic score. This method was used to investigate all three systems and a detailed description of each section is given in the corresponding paragraph.

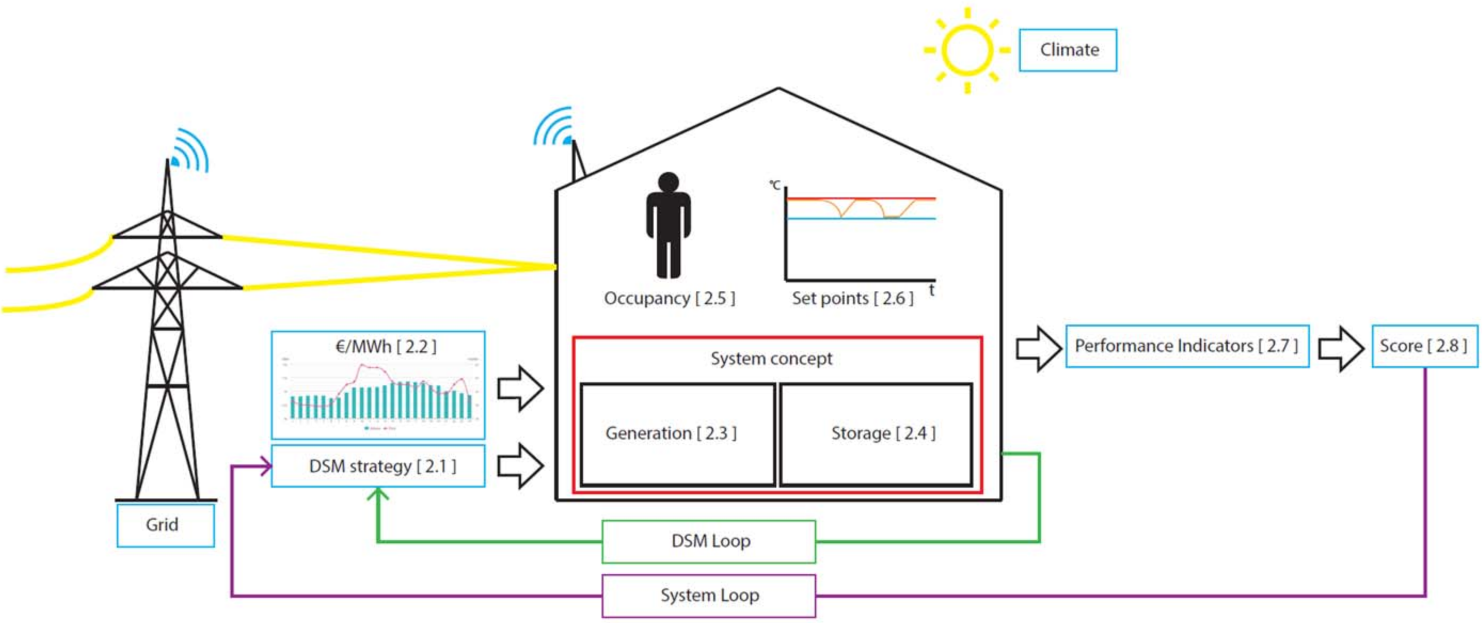

Figure 2.1: Schematic representation of the used method

2.1 Demand response strategies

Generally, the load shapes which indicate the electricity demands during peak and off peak times can be altered using one of six main techniques: peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape (Logenthiran, 2012). This research investigates the influence of the load shifting technique using the following strategies, (i) 24 hour strategy, (ii) nighttime load shift and (iii) off-peak load shift using smart pricing.

DR i The 24 hour strategy operation does not restrict the system in terms of time of use and can provide the desired energy demand at any point in time.

DR ii The nighttime load shift strategy restricts the systems to only operate during the hours of 8:00pm to 8:00am.

DR iii Off-peak load shift uses energy during off-peak hours when the price per kilo watt is lowest, taking the day-ahead electricity rates into account (fig 5). Since these are not jet available for the consumer marked, a day-ahead auction from APX Power NL is used as a reference for the hourly electricity prices. Paragraph 2.2 discusses this more in depth.

2.2 Day-ahead auction

On the Day-Ahead auction, trading takes place one day for the delivery of electricity for the next day. Members submit their orders electronically, after which supply and demand are compared and the market price is calculated for each hour of the following day. Hourly contracts and flexible block contracts can be traded (APX Group, 2014). During this project the results of the day-ahead auction are used to calculate the energy cost as demanded by the building. Figure 2.2 provides an example of an electricity price profile for one of the seven days that were used during this research, taking into account the different price profiles of workdays and weekends.

Figure 2.2: Hourly day-ahead electricity rates (April 1st 2014)

DR iii determines the 12 economical advantageous hours a day from the profiles and restricts the system to heat up the building and any additional storage during these hours only.

2.3 Systems

For this research two heating systems were chosen to represent the average Dutch dwelling. The first is an upcoming system that uses low temperature heating by activation of thermal mass. The second is more common radiator heating which is installed in most houses in the Netherlands.

TABS – By integrating the building structure as thermal energy storage into the building services concept, thermally activated building systems (TABS) have proven to be economically viable for the heating and cooling of buildings. Control of this system is usually based on the outside temperature and determines the water temperature set point for the inlet flow according to a heating curve, without considering heat gains (Gwerder et al, 2008).

Radiators – This type of system uses hot water of 65 to 80 degrees Celsius to heat the radiators in the occupied room. The heat is mainly distributed convective and the system can react fast on changes in the room which makes is easy to control. This has proven to be of great influence on the accurate use of the system by the residents. The system is monitored by a thermostat, controlling the hot water flow from the boiler to the radiators.

2.4 Storage methods

From the literature it was concluded that there are two main categories of energy storage, namely; electrical and thermal. During this research the focus is on building related solutions and therefore only thermal storage was included. This category includes a number of options that are used in practice, i.a. thermal mass, (water) storage tanks, phase changing materials (PCM), compressed air, ice, isolated concrete, thermal battery and seasonal storage (Bassam, Maegaard, 2013). Today, only a few are available for small scale implementation and can supply at least heating to the building, the more dominant thermal demand in the Netherlands. For this study the thermal mass and a hot water storage tank were selected.

Thermal mass – It has been shown that the use of the structural storage capacity in buildings is able to significantly decrease the energy demand use during peak hours (Reynders, 2013). The floor heating system shows better potential for shifting demand since it is able to directly activate the thermal mass. Radiators tend to mostly heat the air inside de room and as a result, temperature fluctuations will be faster. Also, the potential of DR is higher for massive buildings compared to light-weight buildings.

Water storage tank – Hot and cold water storage tanks have been widely studied for use in building applications and a substantial increase has been observed. For this research a stratified storage tank is used since the energy delivered by a stratified tank is between 6% and 20% higher than in comparison with a fully mixed tank (Ghaddar, 1994). The water's thermal stratification is affected by several aspects, such as the size and shape of the tank, the location and geometry of the in- and outlets, the temperatures and flow rates when the tank is charged or discharged (Arteconi, 2013).

2.5 Occupancy

Households come in a variety of different compositions, each having their own occupancy profile which influences the energy demand for heating. When people are more at home the demand increases as will the internal gains. D. Aerts et al. (2014) investigated realistic domestic occupancy sequences for building energy demand simulations. Seven main patterns were found using survey data from 6400 respondents from which three were chosen as a reference to use in this research.

Occupancy 1 *Couple no children*	A full-time employed couple without children results in a daytime absence. The study shows that the average of employed people in the age of 25 to 55 are at home for a few hours in the morning and couple of hours in the evening, resulting in the following occupied hours: 6am – 8am and 6pm – 11pm.
Occupancy 2 *Couple retired*	This pattern represents a situation where the owners are mostly at home; this sequence is predominantly applicable toe retired people. The pattern indicates occupation between the hours of 8am and 11pm.
Occupancy 3 *Couple with children*	In the situation with school going children and young parents, the night-time absence pattern is implemented where the occupancy is reduced over the day. It starts at 8am and increases to a peak at 1pm after which it reduces until 10pm.

2.6 Temperature set points

The operative temperature should be comfortable at all time when the room is in use. Therefore a temperature set point is determined where comfort is ensured. Peeters et al. (2008) concluded that the range of thermal comfort temperatures is much larger for residential buildings as compared to office buildings. They found that the neutral set point for the operative temperature, T_n, is calculated according to equation 1 where $T_{e,ref}$ is the reference outdoor temperature which can be calculated from the average outdoor temperature of the past three days using equation 2. A dead band of 2 degrees is introduced to provide storage potential for the systems. Therefor thermal comfort is assumed when the operative temperature is between T_n-1 and T_n+1 degree Celsius.

$$\begin{aligned} T_n &= 20.4 + 0.06 \cdot T_{e,ref} \quad \text{for} \quad T_{e,ref} < 12.5\ ^\circ\text{C} \\ T_n &= 16.63 + 0.36 \cdot T_{e,ref} \quad \text{for} \quad T_{e,ref} \geqslant 12.5\ ^\circ\text{C} \end{aligned} \tag{1}$$

$$T_{e,ref} = \frac{(T_{today} + 0.8T_{today\text{-}1} + 0.4T_{today\text{-}2} + 0.2T_{today\text{-}3})}{2.4} \tag{2}$$

To make comparing the different strategies with each other possible, the comfort inside the room must be the equal during occupied hours. Otherwise, an average of 20°C could be compared with an average of 21°C, both comfortable but the latter often would require more energy to get to the higher temperature. The electricity demand of DR i is not restricted and therefore does not need energy storage to ensure thermal comfort. The indoor temperature for system control is set at T_n with the bandwidth of T_n + 1°C and T_n – 1°C to guarantee thermal comfort at all occupied hours.

DR ii and DR iii on the other hand are restricted in their time of use and by simulating every hour of the investigated week, the ideal temperature set point for each hour was determined manually. This with the insurance that comfortable operative temperatures between T_n-1 and T_n+1, during occupied hours are guaranteed. In some situations this results in high temperatures during unoccupied hours to heat up the thermal mass of the building. Since these hours are unoccupied, this was considered acceptable. Figure 2.6 shows an example of the temperature set points for the radiator system with occupancy 1 and DR iii.

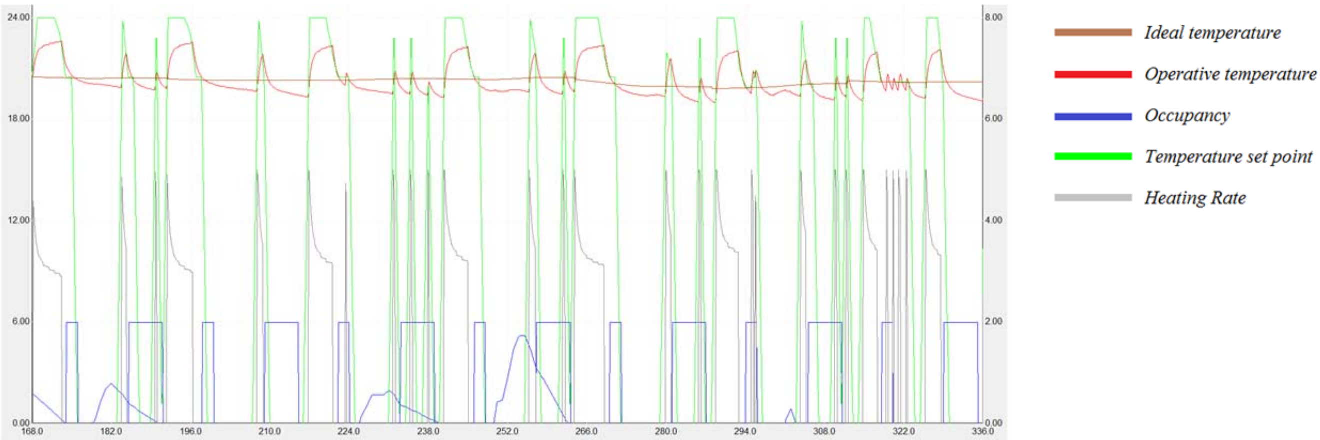

Figure 2.6: Example of simulation output showing temperature set points to guarantee a comfortable operative temperature.

The third system investigated includes a water tank for thermal energy storage. In this case the temperature set point for the operative room temperature was set to T_n and the demand for energy was controlled by the average tank temperature which was set to 75^{o}C with a dead band of 5^{o}C. During the allowable hours, depending on the applied DR, the tank was heated up and water can be drawn from it when the room temperature drops below T_n-1.

2.7 Performance indicators

To compare the storage methods with the different DSM strategies to each other a number of performance indicators were selected, total energy demand, the energy cost and the thermal comfort was monitored using the over- and under heating hours during occupancy.

The total energy demand is the demand used for heating the building, this consist of the energy used by the systems heating components, heat pump and boiler. The goal of the research is not to reduce de demand but to shift the demand.

The overheating hours are defined as the number of occupied hours when the indoor temperature is higher than T_n+1°C, while the under heating hours represent the number of occupied hours when the indoor temperature is lower than T_n+1°C. As mentioned in the previous paragraph, this was done to make a reliable comparison between the different systems, the thermal comfort inside the room has to be equal at all times, therefor all concepts are controlled to obtain an average temperature of T_n.

The energy cost can be calculated by multiplying the energy demand with the day-ahead electricity rates from the APX group website. Seven different profiles, one for each day of the week, were selected from the website to present a price profile that takes into account the different parts of the week. This makes it possible to compare the influence of the different time of use control that is provided by the DR strategies and compare them.

2.8 Economic score

Since the focus of this study is on the energy cost, this was the main indicator for comparing the different DR strategies. The other indicators discussed in de previous paragraph were used to make sure that the comparison was reliable and not influenced by comfort.

2.9 Case study

For investigating the influence that the different DR strategies have on the operational cost of the selected systems, the transient simulation of the system was performed with TRNSYS 17. It is a well-known simulation environment for dynamic evaluations. It consists of different 'types' which represent buildings and plant equipment, including control strategies, occupant behavior, alternative energy systems and storage solutions. The building model was generated with the type 56 which is provided in the program. From Cruijs (2009) it was concluded that the active layer within the type 56 would fulfill the needs of the project without over complicating the model.

The building model in the type 56 represents the living room of an average Dutch dwelling. The building is located in 'de Bilt' (Netherlands) and the total ground floor surface is $50m^2$. The building is well insulated (external walls U-value 0.21 W/m^2K) and has two triple glazed windows of $5.25m^2$ each (U-value of 0.7 W/m^2K and G-value of 0.501 W/m^2K). One is facing north and the other is facing south. The concrete floor is 200mm thick and thermally activated using water carrying pipes with an outside diameter of 20mm and pipe spacing (center to center) of 200mm. Sizing of the system was carried out on the basis of ISSO publication 85 'Thermally active floors'. The TABS is connected to a heat pump system with a ground heat exchanger and the mechanical ventilation is equipped with a heat recovery system with 80% efficiency (J. Jokisalo et al 2003). It supplies $0.9dm^3/s$ per square meter floor surface when unoccupied and when occupied, the ventilation is higher, $1.2dm^3/s$ per square meter which is in line with the Dutch building code. The internal load is calculated and consists of the number of people inside the building, seated and at rest. The gains per person are calculated by the type 56 using ISO 7730 values.

3 Results

This chapter shows the results that were generated using the TRNSYS simulation studio; they represent the total amount of energy (kWh) and cost (€) required for space heating during one week in January. Each paragraph focusses on one of the systems and displays the effect that different DR strategies have on different occupancy patterns.

3.1 Thermally active building system

The energy demands shown in figure 3.1a-b-c indicate that the energy used by occupancy profile 1 is higher in the reference strategy DR i than with DR ii and iii. A slight increase in demand can be found when DR ii and DR iii are imposed on the thermally active building system effecting occupancy 2 and 3 more when the night load shift is used and occupancy 1 when the smart pricing strategy is implemented.

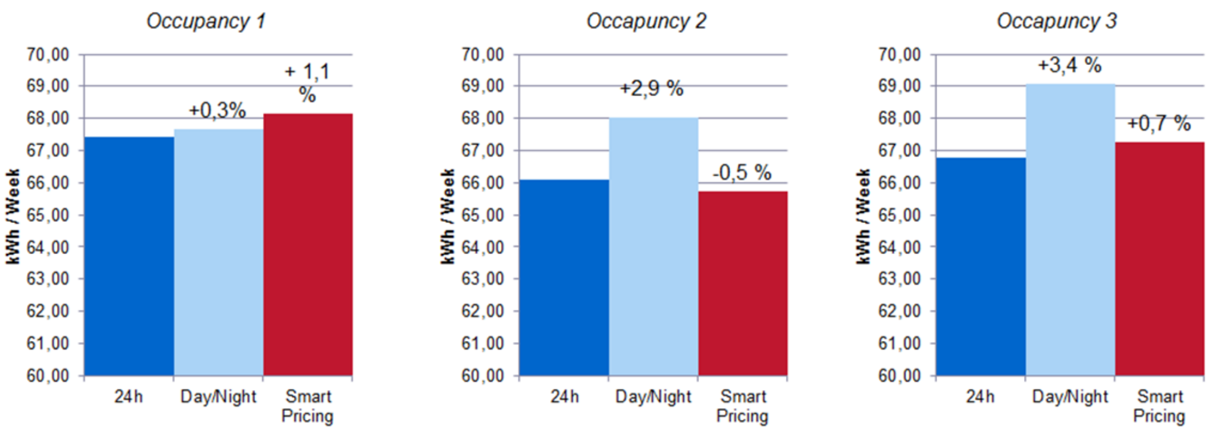

Figure 3.1.a-b-c: Energy demand for space heating using TABS, one week in winter

Focusing on the energy costs that belong to the previously mentioned demands, a different pattern emerges. It can be seen in figure 3.1d-e-f that in all cases the cost are reduced significantly when DR iii is used and the influence is best for occupancy profile 1 which had the highest increase in demand with this strategy (figure 3.1a). Using DR ii seems to have a negative effect on both energy demand and energy cost. This result can be explained by the long storage period that is used in strategy ii where transmission through the buildings construction elements have a larger influence due to the higher temperature of these parts to and the longer storage period to ensure enough heat supply during all occupied hours. The internal gains are lowest during the day with occupation 1, resulting in the highest increase in demand for night load shift.

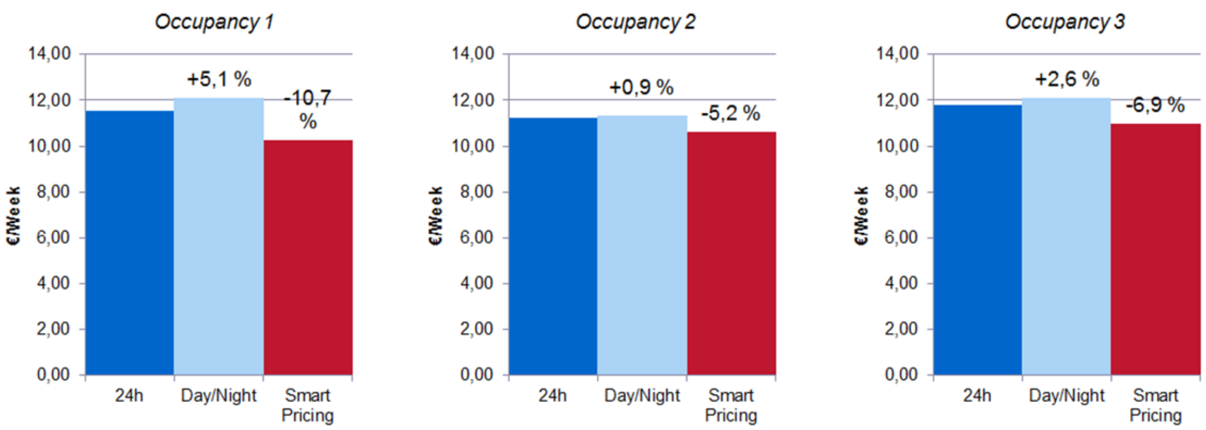

Figure 3.1.d-e-f: Energy cost for space heating using TABS, one week in winter

3.2 Radiator heating system

When considering energy reduction as the main motivator for selecting the best fit demand response strategy for a radiator system, the results in Figure 3.2.a-b-c show that the most commonly strategy of heating when needed is preferred regardless which occupancy profile applies to the building. A massive increase can be seen in 3.2.a where energy demand increases over 15% with DR ii and over 10% with DR iii. In the other situations, the rise in energy use is less concerning but remains higher than the currently used control in Dutch dwellings. Again we see that the influence of internal gains by the user plays a part since occupancy 2 and 3 are in the same order of magnitude and occupancy 1 deviates from it.

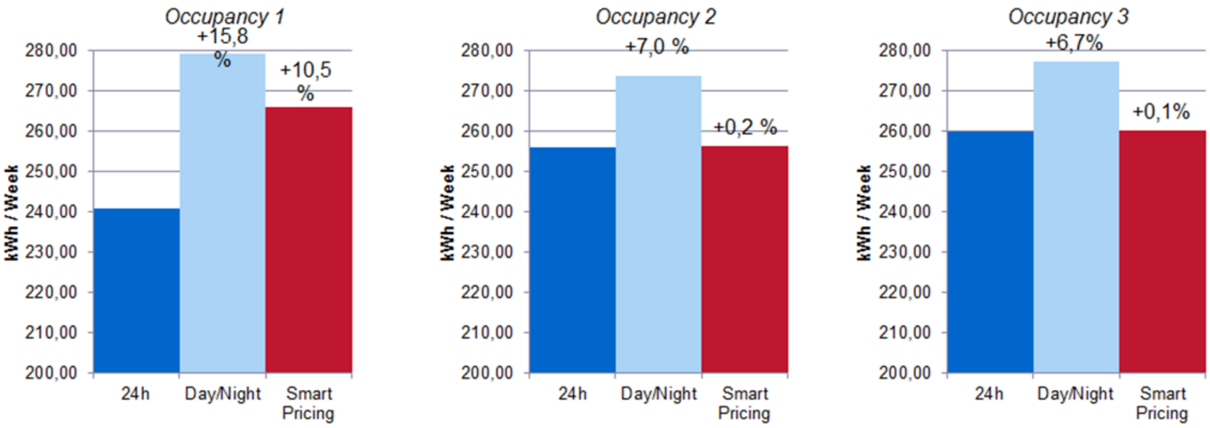

Figure 3.2.a-b-c: Energy demand for space heating using radiators, one week in winter

On the other hand, figure 3.2.d-e-f, reveals the corresponding energy cost for the radiator systems demand which, overall, decrease compared to the reference strategy. DR ii with occupancy profile 1 is the exception in this case with an increase of 7.7% corresponding with an increase in demand of 15.8% and the increase of 10.5% in demand results in a cost reduction of 2.4%. As could be seen in figure 3.2.b and c, the increase in energy demand is minimal for DR iii whereas the cost drops significantly. Also DR ii results in a higher demand and lower cost for occupancy 2 and 3, respectively -4.5% and -5.4%.

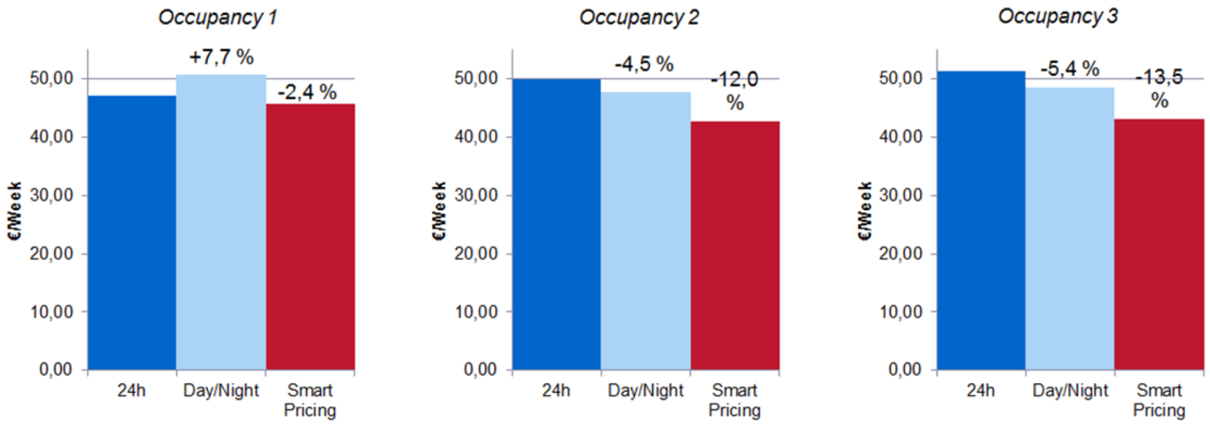

Figure 3.2.d-e-f: Energy cost for space heating using radiators, one week in winter

3.3 Radiator heating equipped with thermal storage tank

The overall energy demand of this system has increased compared to the system without any storage tank. This is probably due to the fact that the boiler has to increase the output temperature to the boiler to reach an average of 75°C. The significant difference in energy demand between the different occupancies can be explained by the size of the tank. Since profile 1 is occupied only eight hours a day whereas the occupancy of the room for profile 2 and 3 is 15 hours, the storage tank of occupancy 1 in set to 1m^3 and the other systems were fitted with a 1.5m^3 tank, resulting in higher heating demand. As was found in the case without storage, occupancy 2 and 3 show an increase in energy demand compared to their reference control, this does not apply to occupancy 1 where a decrease in demand can be observed (Figure 3.3a).

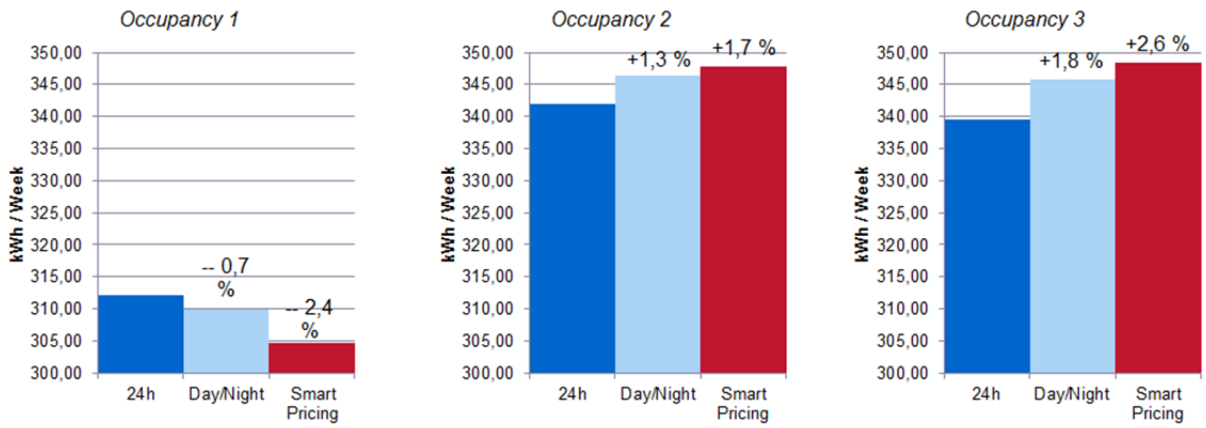

Figure 3.3.a-b-c =: Energy demand for space heating using radiators and storage tank, one week in winter

Figure 3.3.d-e-f presents the energy cost for one week in winter with the radiator and storage tank system. Again it can be seen that DR ii and DR iii both result in a higher energy demand (figure 3.3.e-f) but also in a lower energy bill for the user. With an average reduction of 7.5% DR iii is slightly better than DR ii.

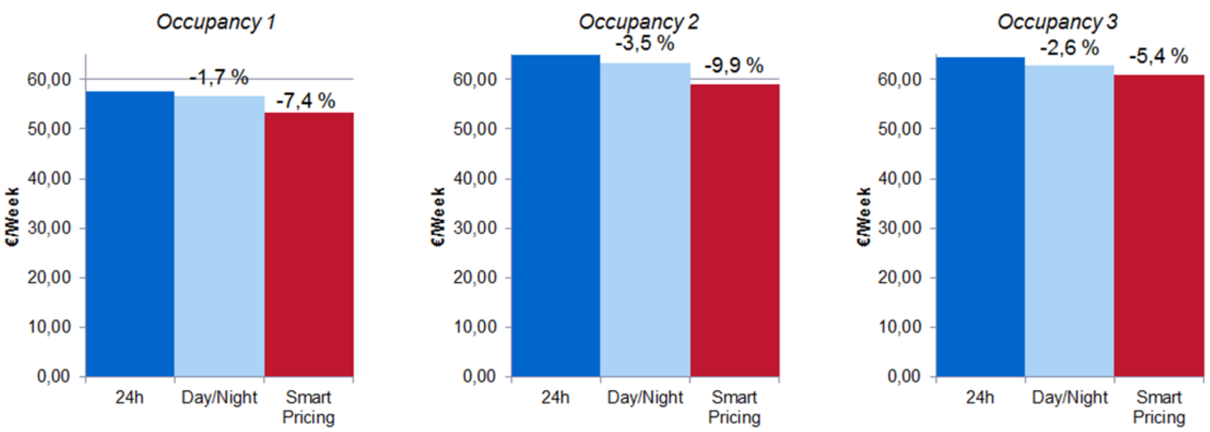

Figure 3.3.d-e-f: Energy cost for space heating using radiators and storage tank, one week in winter

Because the goal of the research was to investigate the advantages for home owners, table 1 presents the results based on the cost motive. It can be seen that DR iii is the economically preferable choice since it reduces cost in all investigated situations. Night load shift with tabs should be avoided when the system is restricted to use energy only during the night. Situations with pre heating during the night and final control during the day were not investigated in this research.

Matrix	TABS		Radiator		Radiator + Tank	
Occupancy 1 Couple (no children)	*DR i - 24 hour*	o	*DR i - 24 hour*	o	*DR i - 24 hour*	-
	DR ii - Day/Night	-	*DR ii - Day/Night*	-	*DR ii - Day/Night*	o
	DR iii - Smart pricing	+	*DR iii - Smart pricing*	+	*DR iii - Smart pricing*	+
Occupancy 2 Couple retired	*DR i - 24 hour*	o	*DR i - 24 hour*	-	*DR i - 24 hour*	-
	DR ii - Day/Night	-	*DR ii - Day/Night*	o	*DR ii - Day/Night*	o
	DR iii - Smart pricing	+	*DR iii - Smart pricing*	+	*DR iii - Smart pricing*	+
Occupancy 3 Couple with children	*DR i - 24 hour*	o	*DR i - 24 hour*	-	*DR i - 24 hour*	-
	DR ii - Day/Night	-	*DR ii - Day/Night*	o	*DR ii - Day/Night*	o
	DR iii - Smart pricing	+	*DR iii - Smart pricing*	+	*DR iii - Smart pricing*	+

Table 1: comparison matrix

4 Discussion

In retrospect the control of the system should be improved. During this research the temperature settings were adjusted manually by re-simulating the same hours numerous times to determine the ideal set points. This proved to be very time consuming and as a result, the influence of building and system parameters could not be investigated properly. Using model predictive control would help with this and at the same time would create the opportunity to simulate the total heating season or perhaps the whole year. The investigated period now was limited to a cold winter's week while the transitioning between seasons could influence the results significantly.

The case study that was used for this project was based on a living room only. Therefor the influence of cooking or the comfort of bath- and bedrooms are not considered during this investigation. Problems might occur with the users wellbeing when bathrooms are under heated or bedrooms get to warm to sleep comfortably.

Since there was no reference case of a dwelling with concrete core conditioning (TABS), assumptions had to be made using the ISSO 85 guideline which is meant for utility buildings. The results from the simulation therefore could not be compared with verified data and were only compared mutually to determine the influence of the different demand response strategies.

The systems' power was determined by a heat loss calculation from the building. The impact of different system sizes was not included in the research. A smaller system would need a longer time to heat up the surroundings influencing the time of use necessary to maintain a comfortable operative temperature. On the other hand, a large system would heat up quickly reducing the time of use.

The definition of thermal comfort for this project does not include all influencing factors like temperature distribution, humidity, air speed or CO_2 concentration.

5 Conclusion

The goal of the project was to investigate building related energy storage solutions to shift the energy demand for heating in Dutch households. This has proven to be possible with the investigated systems without loss of thermal comfort. TABS are dependent on the inertia of the system and the influence of the users is therefore less than with the radiator system. The thermally active building system would not benefit from additional storage since the response time is already multiple hours. On the other hand, a high temperature radiator system which has a shorter reaction time would also not benefit from additional storage when heated by a boiler since this has to heat up the a larger volume of water, resulting in a higher output temperature. The water tank principle does however provide energy storage which can be used later, this combined with a thermal solar panel would enable the user to heat up the tank during the day and use the energy in the evening.

The influence from the occupancy profiles is relatively large in terms of energy demand but for the energy cost, it is much smaller. Using demand responds strategies increases the energy demand for space heating in most situations but from the house owner's point of view, the smart pricing strategy would result in lower energy bills regardless the system or occupancy profile of the building. By only using energy while the price is below a certain set point, the results showed that a decrease of 13.5% in energy cost is possible. When all houses are implementing this strategy, the price difference between peak and off peak hours might become smaller, reducing the effect in the long-term.

Based on the reviewed results and methodology, some recommendations can be made for future work concerning identification of the energy reduction potential by use of demand response strategies in dwellings.

- A higher accuracy can be obtained by performing year round simulations using model predictive control in combination with the TRNSYS model.
- Using model predictive control, the influence of system parameters as thermal capacity or storage tank size can be investigated more in depth.
- Other systems and storage methods should be analyzed to expand the matrix so it can be used by a wider audience, for instance; low temperature radiators and PCM storage could be considered.
- The influence from small scale renewable energy sources connected to the building could be investigated to determine the usefulness of these private investments.

References

1 Agentschap NL, 2011, ‘voorbeeldwoningen 2011 – bestaande bouw’, Chapter 6.4, Rijwoningen – gebouwd in de periode 1975-1991, 43p

2 Aerts, D. Et al, 2014, A method for the identification and modeling of realistic domestic occupancy sequences for building energy demand simulations and peer comparison, Building and environment, volume 75, 67-78 p.

3 APX Group, 2014, http://www.apxgroup.com/market-results/apx-power-nl/dashboard/, visited March 31, 2014.

4 Khudhair, A.M., Farid, M.M., 2004, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, Energy conversion an management, volume 45, 263-275 p.

5 ASHRAE, 2001, Handbook: Fundamentals 2001. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA

6 Arteconi, A. et al, 2013, Analysis of control strategies for thermally activated building systems under demand side management mechanisms.

7 Arteconi, A. et al, 2013, Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems, Applied thermal engineering, Volume 51, 155-165 p.

8 DNV, 2011, *The smart grid – what is it and what is it not*, Norway, 5 p.

9 Bassam, El (Nasir), 2013, distributed renewable energies for off-grid communities, United Kingdom, 194-195 p.

10 Bassam, el, (Nasir), 2013, Strategies and Technologies toward Achieving Sustainability in Energy Generation and Supply - Distributed renewable energies for off grid communities, 194-195 p.

11 European commission, 2011, *Energy roadmap 2050*, Brussels, 19-20 p.

12 Ghaddar, N.K. 1994, Stratisfied storage tank influence on performance of solar water heating system tested in Beirut, Renewable energy, volume 4, 911-925 p.

13 Gwerder, (Markus), et al. "Control of thermally-activated building systems (TABS)." *Applied energy* 85.7 (2008): 565-581.IEA, 2012, *Energy technology perspectives (ETP) – pathway to a clean energy system*, France, 62 p.

14 ISSO-publicatie 51, warmteverliesberekening voor woningen en woongebouwen

15 ISSO-publicatie 85, Thermisch actieve vloeren

16 Jokisalo, J. et al, 2003, Performance of balanced ventilation with heat recovery in residential buildings in a cold climate, The international journal of ventilation volume 2, December 2003.

17 Logenthiran, T, 2012. Demand side management in smart grid using heuristic optimization, Smart Grid, IEEE Transactions, sept. 2012

18 Medina (Jose), 2010, Demand response and distribution grid operations: opportunities and challenges, IEEE, p.

19 Muralidharan, Krishna, Pierre A. Deymier, and G. Frantziskonis. "Compressed-Air Energy Storage Systems for Stand-Alone Off-Grid Photovoltaic Modules."

20 Orecchini (Fabio), 2011, *Beyond smart grids – The need of intelligent energy networks for a higher global efficiency through energy vectors integration*, Italy, 7 p.

21 PBL - Planbureau voor de leefomgeving, 2011, *Beleid voor klimaat en hernieuwbare energie: opweg naar 2050*, Netherlands, 15 p.

22 Peeters, L. Et al, 2008, Thermal comfort in residential buildings: Comfort values and scales for building energy simulation, Applied Energy

23 Porritt, S.M. et al, 2010, ‘Building orientation and occupancy patterns and their effect on interventions to reduce overheating in dwellings during heat waves’, United Kingdom, 3p.

24 Reynders, G. et al, 2013, Potential of structural thermal mass for demand-side management in dwellings, Building and Environment, Volume 64, 187-199 p.
25 Römer (Benedikt), 2012, *The role of smart metering and decentralized electricity storage for smart grids: The importance of positive externalities*, Germany, 1 p.
26 United Nations, 1998, *Kyoto protocol to the united nations framework convention on climate change*, Japan, 3 p.
27 Verhelst, (Clara), et al. "Study of the optimal control problem formulation for modulating air-to-water heat pumps connected to a residential floor heating system." *Energy and Buildings* 45 (2012): 43-53.
28 Waqar, A. et al, 2011, Impact of energy storage in buildings on electrictity demand side management, Energy conversion and management, volume 52, 2110-2120 p.
29 Zhang (Junwei), 2012, *The impact of renewable energy resources on demand response management in a smart grid*, California, 1-2 p.