Methods and Potentials to Reduce Peaks in Heating Power Demand

- in Residential Buildings

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

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ABSTRACT

The demand for heating power in buildings varies a lot over the day. Peaks in the heating power demand occurs during times when the outdoor temperature is low and the activities of the inhabitants create peaks in the hot tap water power demand.

To compensate for the energy peaks which occur when the heating power demand is at its highest, the district heating suppliers have to keep alternative energy sources, such as fossil fuel or energy storages, ready.

The aim of this thesis was to investigate if these peaks could be removed, and thereby the need to keep alternative energy sources. To achieve this, two methods of peak reduction were defined and simulated. The first method investigates the benefits of having daily change of the control curves, with different target indoor temperatures, over the day. The second method investigated the use of solar energy to help reduce the power demand peaks.

A number of building types were studied in the Göteborg area and the two methods of peak reduction were applied to them using a simulation tool.

The main conclusion of this work is that all methods show some potential but none is perfect. By altering the control curves a peak reduction can be achieved but at the expense of indoor comfort. The time constant plays a large role to help reduce the negative effects of this method. This is because the time constant is a measurement of how fast buildings react to a temperature change and thereby how large the temperature fluctuations will be. Subsequently, the building with the largest thermal mass gave the most positive response to this method.

The method which utilizes solar energy for peak reduction was analyzed in two ways: firstly, by adding the energy directly into the building and secondly, by storing the energy temporary in a local energy storage and use it when desired. The first approach gave similar results as the method with variable control curves. The second approach, to store the energy until the peak occurs, was equally successful in all building types and showed good results. Though, the problem with keeping a system for energy storage remained.

All methods would require further development and optimization before an implementation would be possible, but their potentials have been established in this thesis.

Key words: Peak reduction, control curves, solar energy, energy storage.

Metoder och deras potential att minska toppar i energiförbrukning
- i flerbostadshus
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SAMMANFATTNING

Energianvändningen i byggnader variarar kraftigt över dagen. Variationen i utomhustemperaturen skapar toppar i behovet av uppvärmningsenergi och en ojämn förbrukning av tappvarmvatten skapar toppar i energibehovet för varmvattenproduktion. Kombinerar man dessa två varierande effektbehov får man ett väldigt ojämnt energibehov.

För att kompenseraför dessa energitoppar måste fjärrvärmeproducenterna ha alternativa energikällor i beredskap, t.ex. fossila bränslen eller stora energilager.

Om energitopparna kunde kapas skulle behovet av dessa alternativa energikällor minska då energin skulle tillföras byggnaderna under mer jämna förhållanden. Utifrån denna problemformulering har två stycken metoder för att åstadkomma detta analyserats och utvärderats. Första metoden undersöker fördelarna med att använda varierande kontrollkurvor för att nå olika inomhus temperaturer över dagen. Den andra metoden undersöker ifall man kan använda solenergi för att kompensera för energitopparna.

Ett antal byggnader i Göteborgsområdet undersöktes och på dessa byggnader applicerades de två metoderna genom att simulera byggnaderna i ett simuleringsprogram.

Slutsatserna i arbetet är att alla metoder visar potential men att inga är felfria. Genom att förändra reglerkurvorna så kunde man åstadkomma förminskning av effekttopparna men på bekostnad av inomhusklimatet. Byggnadernas tidskonstant har stor betydelse för hur stora dessa negativa effekter blir eftersom den avgör hur mycket energi en byggnad kan lagra och hur stora temperaturfluktuationerna blir. Alltså funkar hus med stor tidskonstant bäst med den här metoden.Metoden som använder solenergi för att ta bort energitopparna genomfördes i två versioner. Först att köra in energin direkt i byggnaderna och sen att mellanlagra det i något slags energilagringssystem, t.ex. i enackumulatortank. Då man tillför energin direkt i byggnaden fick vi liknande resutlat som i metoden med olika kontrollkurvor. Tidskonstanten spelar an avgörande roll i hur bra husen svarar på metoden. Den andra versionen av den här metoden, att mellanlagra energin tills då energitoppen inträffar, visade samma goda potential i samtliga hustyper. Dock kvarstår problemet med att ha ett temporär energilager.

Samtliga metoder kräver vidare utveckling och optimering innan de kan implementeras i verkligenheten. Dock har deras potential fastställts i denna rapport.

Nyckelord: Energitopp reducering, Reglerkurvor, Solenergi, Energilagring.

Contents

Preface

In this thesis, possible methods to reduce peaks in the heating power demand of buildings have been simulated, evaluated, and their potentials have been compared with each other.

The work was initiated by Ernströmsgruppen and has been carried out during the spring of 2012 at the division of Building Technology, Chalmers University of Technology, Sweden. The work has been supervised by Angela Sasic, Docent and Göran Johansson from Armatec.

We would like to give a special thanks to Göran Johanson, Armatec, and Angela Sasic for supervising and providing valuable input throughout the project. Finally we would like to thank Joris van Rooij at Göteborg Energi who provided the energy data for the different building types and Annika Malm at Göteborg Vatten for providing tap water usage data.

Göteborg June 2012

Carl Molander
Måns Olofsson

Notations

Roman upper case letters

A	Area	[m^2]
A_{tot}	Building envelope area	[m^2]
A_w	Window area	[m^2]
C_{tb}	Thermal bridge coefficient	[-]
C_{door}	Blow door test	[l/s,m^2]
C_p	Outdoor pressure coefficient	[-]
C_{pi}	Indoor pressure coefficient	[-]
F	Power of heater from function	[W/K]
G	Global radiation	[W/m^2]
P	Power of heater from fixed value	[W/K]
P_w	Pressure difference between indoor and outdoor	[Pa]
Q	Power	[W]
T	Temperature	[K]
T_s	Window transmittance, 0-1	[-]
U	U-value	[W/m2,K]
V	Airflow through building envelope	[m^3/s]
W_c	Window shade coefficient, 0-1	[-]
W_f	Window frame coefficient, 0-1	[-]

Roman lower case letters

c_p	Heat capacity	[J/kg,K]
c_{pa}	Heat capacity of air	[J/kg,K]
d	Thickness	[m]
t	Time of the day	[-]
v	Wind speed	[m/s]

Greek lower case letters

ρ	Density	[kg/m^3]
ρ_a	Density of air	[kg/m^3]

Translations of names of institutes

Stadsbyggnadskontoret	Board of City Building
Boverket	National Board of Housing, Building and Planning
Statistiska Centralbyrån	Statistics Sweden
Energimyndigheten	Swedish Energy Agency

1 Introduction

The energy used by the heating system in buildings today follows the outdoor temperature very closely. This means that during periods of cold temperature there will also be a peak load in the district heating system. The energy from the district heating is also used to heat the hot tap water. Since the usage of tap water varies over the day with peaks in the morning and the evening this will also contribute to the creation of peaks in the district heating system.

The result of this behaviour is that the district heating suppliers will have to compensate by adding extra energy during these peak periods. This can be done by burning fossil fuel or to keep large amounts of energy stock piled in energy storage systems, for example in accumulator tanks.

1.1 Purpose

If the energy consumption can be reduced during peak hours and, to compensate, be increased during periods with lower energy consumption the overall energy usage will be more even throughout the day and the need for extra sources of energy will be reduced.

This thesis aims to evaluate and compare different methods used to achieve this goal. These methods will also be applied to different buildings in order to evaluate which methods works best for which type of buildings.

1.2 Methodology

In order to evaluate what kind of impact different peak reducing methods would have on different kind of buildings a work method had to be established.

The first step is to acquire data for a number of buildings which represents the building stock in Göteborg; these buildings will be called Archetype buildings. This will be done both through field studies as well as through the BETSI study, which is a large database based on a Swedish study on the Swedish building stock.

The next step is to create a simulation model which will be used to describe the performance of each archetype building. In order to verify the simulation results real energy data must be gathered for each building type.

The final step is to introduce the proposed methods for peak reduction into the simulation model. The resulting changes in energy consumption and performance of each archetype building will be compared and evaluated.

1.2.1 Archetype Buildings

To be able to perform energy simulations on a district of multi-family residential buildings all buildings in that districts need to be analysed and all their thermal properties must be known.

It would be very time-consuming to investigate and analyse all these parameters and the results from one district would not be very useful when simulating another or to compare two districts. If several districts were to be simulated the data collection from the included buildings would take even more time and probably contain several errors. This creates a very time-inefficient and not very correct result.

To solve this and to still achieve reasonable results the simulations in this thesis was decided to be based on the use of archetype buildings.

The archetype building is a representative for a certain type of buildings that can be found throughout the building stock. The archetype building does not correspond totally with the parameters and properties of each one of the buildings it represents, but is very close. It is sort of a mean building of all the represented buildings.

This means that the total building stock is represented by a number of different archetype buildings where a larger amount of archetype buildings gives more detailed results in the energy simulations.

The number of archetype buildings can be set depending on how time-efficient and comprehensive the desired results are, but also on how easily the results can be understood and compared.

In this thesis the time-limit is rather short and the aim is to achieve a simulation model that can easily be modified to suit different residential buildings and to produce results that can easily be compared. This means that the identification of building types and thereby also archetypes building has to be rather rough to be able to, with only a few archetype buildings, represent a significant part of the Göteborg multi-family residential building stock.

1.2.2 Simulation

A very effective way of evaluating the effects of changes and modifications done to a building is by simulating the building in a computer program. There are several programs which can be used for this and the choice for this thesis was Matlab and Simulink. This simulation tool works well with the rather rough data that is gathered in the archetype building study.

The first step in the simulation process is to create a model that represents all the different archetype buildings. It must be able to produce reasonable results for all archetype buildings with just a change in the indata. This model and its performance can then be compared to real energy data from the different archetype buildings to verify its accuracy. When the results from the model correspond to the real energy data the model is verified as working correctly.

The next step in the simulation phase is to apply the changes, proposed by the different methods, to the simulation model and evaluate them through further simulations. Since the model was first verified against real energy data the results from the modified simulation model will also be verified.

1.2.3 Methods to Reduce Peaks

The methods which this thesis will evaluate are; a change of control curves and the addition of solar energy.

A change of control curves means that the heat input into the building will be aimed at reaching a different indoor temperature. By switching between different control curves throughout the day the amount of energy taken from the district heating network can be decreased during periods with peak loads and then, to compensate, increased during the period between peaks. This thesis will investigate if the thermal mass, and with that the thermal storage capacity, of the different archetype buildings is sufficient to counteract the temperature fluctuation that would otherwise occur using this method.

By collecting solar energy locally, in the form of hot water, and then using it during energy peak periods the amount of energy taken from the district heating system could be reduced and thus the peaks in the district heating system will be reduced. This thesis will investigate if the solar energy is sufficient during the heating season, September to April, to create any noticeable peak reduction and if the solar energy could be used directly or if it needs to be accumulated locally at the building.

1.3 Limitations

This study is limited to buildings in the Göteborg area. This limitation is because of practical issues with both field studies and gathering of building data. In order to find some of the building data visits will be made at the Board of City Planning to access their database.

Only multi-family residential buildings will be analysed in this study. Single family buildings will be ignored since very few use district heating and they are quite uncommon in Göteborg when compared to the amount of multi-family residential buildings. Buildings which house commercial activity will also be ignored since the energy consumption of these varies a lot and would be very difficult to represent with just a few different archetype buildings.

There will also be a limitation to construction years between 1920 and 1975 since most of the houses in the Göteborg area were constructed during this time period.

2 Collecting Archetype Building Data

This chapter describes the process of the data collection. The resulting archetype buildings with their parameters are explained in chapter 3.

2.1 Field Study and Literature Study

By combining field studies with architectural and technical literature studies an idea of the Swedish and Göteborg multi-family residential building stock was achieved and different types of buildings and their locations in the Göteborg area could be identified.

2.1.1 Göteborg's Building Types

Since the end of the 1800, multi-family residential building design and the techniques to build these have been very alike in every part of Sweden, with only minor local differences. The general types of buildings have been the same but they have been built in different amounts in different parts of the country. (Björk C., Kallstenius P., Reppen L. 2002)

To identify which building types are most common in Göteborg some simple architectural designs, such as façade material, window design and size were looked for and the assumption was made that those buildings were built in similar ways and therefore belong to the same category.

Five different categories of building types in Göteborg could be identified during these studies as commonly occurring;

- *Landshövdingehus.* Three story houses built during the late 1920's and in the early 30's with brick façade covering the ground floor and wooden façade on the two floors on top. (Björk C., Kallstenius P., Reppen L. 2002)

- *Äldre Lamellhus.* Three to four story houses built between the 1930's and 50's. Facades are usually built out of bricks but facades in light-weight concrete are also common. Combinations of the two materials are sometimes used to increase the thermal performance. (Björk C., Kallstenius P., Reppen L. 2002)

- *Yngre Lamellhus.* Three to four story houses built between 1950's and 70's. Facades are usually built out of concrete sandwich elements with about 100 mm of insulation. (Björk C., Kallstenius P., Reppen L. 2002)

- *Höga Punkthus.* Tall and square-shaped nine to eleven story buildings. Built between 1940's to 1960's. The facades usually consist of a combination of concrete and light-weight concrete with some insulation. (Björk C., Kallstenius P., Reppen L. 2002)

- *Skivhus*. Long and tall buildings with eight to twelve stories. Built mainly during the Miljonprogrammet, which was a large building project between the 1960's and 70's. Facades are in general built using concrete, light-weight concrete or bricks, or a combination of the materials. All buildings are also insulated. (Björk C., Kallstenius P., Reppen L. 2002)

According to the history of architecture these types of buildings are some of the most common building types throughout Sweden. Other types of buildings such as *Stenhus, lägre Punkthus* and newer building types (from the 1980's and 90's) occur in the Swedish multi-family residential building stock. These types are however not represented in high numbers within the Göteborg area and therefore these are not taken into account. (Björk C., Kallstenius P., Reppen L. 2002)

The five identified categories of building types were used as the foundation for the archetype buildings.

2.1.2 Collecting Object Addresses

While working with identifying the different building type categories, addresses to several randomly chosen buildings that matched these descriptions were collected and sorted into the five categories.

These buildings could then be assumed to together represent the building stock of that category in Göteborg, and thereby represent one of the archetype buildings.

2.1.3 Possible Sources of Errors

The buildings were selected with care taken to avoid sources of errors. Sources of error in this case could be;

- Differences in age and building techniques between buildings in the same category. This was taken into account and checked when further information was gathered from the Board of City Planning, to make sure that all selected buildings in one category was about the same.

- Large commercial areas such as restaurants and stores built-in to the residential building. These types of activities within the building are not desirable since only residential buildings are to be analysed and commercial areas would interfere with the energy consumption pattern of a residential building.

- Only parts of an entire building body included in the collected buildings could cause errors in energy consumption calculations. This means that entire building bodies had to be included to avoid buildings that are affected by other buildings. One example is buildings that are built in a way that they are joined together and form a closed block. This could cause a mismatch between heated area and energy consumption due to that the block may consists of different building types or several buildings may be connected to the same district heating central. In older buildings such as *Landshövdingehus* this formation is very common and therefore the entire block had to be included. In cases where several independent building bodies are connected to the same district heating central, all buildings had to be included due to the lack of possibility to distinguish how much energy is used by each building.

2.2 Board of City Planning Database

By using the Board of City Planning's database of granted building permits further data for each building could be collected.

From this database the following data was collected;

- **Year of when the building documents were approved:** This is used to roughly determine how old the building is. The time between this approval and actual construction may vary and therefore the year of approval is used.

- **Number of floors:** Some buildings share the construction year and also the construction method. In this case the number of floors help to distinguish these from each other. An example here would be *Yngre Lamellhus* and *Skivhus* where the *Skivhus* have more floors.

- **Number of apartments in the building:** In order to help identifying buildings the number of apartments is useful. Different time periods had different standards when it comes to the size of the apartments.

- **Façade materials:** To identify the houses in the BESTI study the façade materials is one of the more important factors since it gives a good estimate of the U-value of the building.

- **Heated indoor area:** This area is assumed to be the heated area and only includes area above ground level, which means that basement areas are not included and assumed to not be heated.

- **Perimeter length:** Gives, combined with the building height, the building envelope area.

- **Ceiling height and slab height:** The height, both total and indoor, is used when determining the envelope area as well as the indoor air volume.

When all data was collected the data was checked to make sure that all buildings matched up with its corresponding category prerequisites as well as with the other buildings in the same category. For instance, the ratio between indoor volume and envelope surface area was checked to be about the same and the year of when documents where approved and façade materials was checked. These values turned out to correspond well to each other in each category and this way it was verified that the buildings were placed in the right category.

2.2.1 Possible Source of Errors

From the collection of data from the Board of City Planning's database some sources of error were identified;

- Since all drawings in the database are photo scans there might be an error in exact scale between the actual drawing and the scanned version. This was dealt with by measuring distances that was known, such as a stated length of a wall or a door opening to confirm the drawing scale.

- All measurements were done using the built in measuring tool in the viewing program, which is used to navigate the database. This tool is not precise and therefore a rate of error is included in these measurements. This was somewhat counteracted with the technique mentioned above but still some room for error is left. This is taken into account whenever verifying results which are based on these measurements.

2.3 The BETSI Study

The BETSI study was initiated by the Swedish government in December 2006 to increase the knowledge of both the technical characteristics and the condition of the Swedish building stock. The study was conducted by the National Board of Swedish Housing, Building and Planning with support from Statistics Sweden (Boverket 2012).

The study involved approximately 1400 residential buildings, both single and multi-family buildings, which were statistically selected to represent the total building stock in Sweden. Buildings were chosen from 30 different municipalities around Sweden (Boverket 2011).

Educated experts were engaged in conducting the study and performed inspections, measurements, interviews and gave out questionnaires to collect the data desired. The results were presented in 2009 and 2010 and the final reports came in early 2012.

In this study each building is also weighted as a rate of how common this exact building is in the total Swedish building stock.

It is important to note that the study is anonymous and the buildings included in the study cannot be identified.

The BETSI study data for the five different archetype buildings can be found in the Appendix A. It contains 41 parameters for each archetype building and is the result of the combinations of the entire BETSI study (Boverket 2009).

2.3.1 Source of Errors

In order to make sure the BETSI study is representable for the Swedish building stock the sources of errors has been identified and taken into account by Boverket in the study. (Boverket 2011).

Some sources of errors presented in the study are;

- Errors in documents, inspection protocols and drawings. This may have caused misinterpretations of the building technical designs. In about 40% of the selected buildings, drawings were of bad quality or were missing.

- Errors in inspection due to carelessness, lack of time, incorrect information from contact persons etc. This source of error was analysed by performing control audits of some of the buildings. Experts went through the data again to verify it. These audits had more time than the original analyses to be more precise.

2.4 Energy data from Göteborg Energi

By gathering real energy consumption data from existing houses within each archetype group we will be able to verify our Simulink model by comparing the results from the simulations with the real data. This data is composed of the mean value of all studied houses, within each group, and presented as energy consumption per square meter.

2.4.1 Anonymous Data

The energy data, which is required in order to verify the simulation model, is the property of each individual landlord and is therefore required to be kept anonymous since we would otherwise require the approval of each landlord to use and present their data. The data was kept anonymous by gathering a number of real houses and then compiling their energy data into one mean value and this part was carried out by Göteborg Energi. By using this method no house can be identified in the resulting energy data.

2.4.2 Separating Tap Water Energy from Total Energy

The energy data which is acquired from Göteborg Energi contains one value for each hour. This data resolution is detailed enough to give a precise description on how the different buildings behave. A higher data resolution would of course give an even more precise behaviour but it is not required since both the weather data and the simulation will run with one value each hour (van Rooij J. 2012).

All houses examined in this research use district heating for both heating of the house as well as heating of the tap water. In the data from Göteborg Energi there is no way to distinguish between these two usages and because of this a standard usage of tap water will have to be assumed. This is done under the assumption that the usage of tap water is not dependent on the type of building but rather on the inhabitants. It can therefore be assumed that each archetype house has got the same behaviour when it comes to tap water usage.

This standard usage of tap water is based on a report from the Swedish Energy Agency. The study states that 32% of the used water is hot water and that the total amount of water used is 184 litres per person and day. This results in a hot water usage of 58 litres per person and day (Energimyndigheten 2009).

The daily variation of water follows two different patterns. One pattern is used for the weekdays and another pattern for the weekends. The most significant change of tap water usage between weekdays and weekend is during the middle part of the day when, during weekdays, people are assumed to be at work while they are more likely to be at home during the weekends. The resulting two trends can be seen in figure 2.1 (Malm A. 2012).

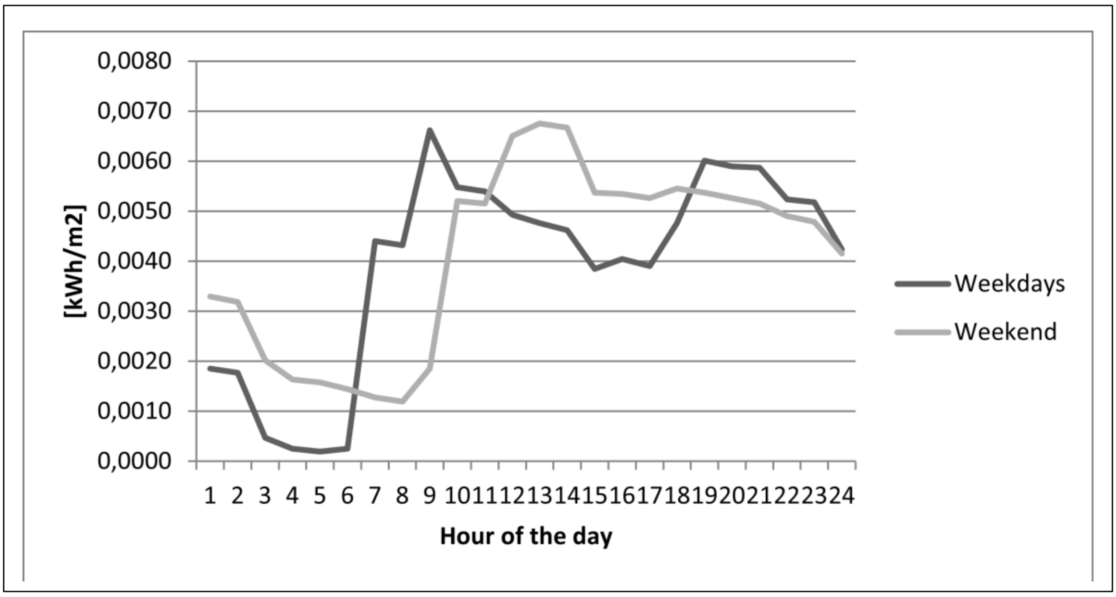


Figure 2.1 *Daily variation of tap water usage. Both weekdays and weekends are represented.*

The resulting energy used for heating water is then compared to the actual energy consumption of the archetype houses. Since it can be assumed that the heating system is turned off during the warmer summer months the energy used during this period will only come from the heating of tap water. As we can see from the trend lines in graph below the estimated energy usage is a bit too high. This can be a result of both a different water usage but also a different amount of square meter per person.

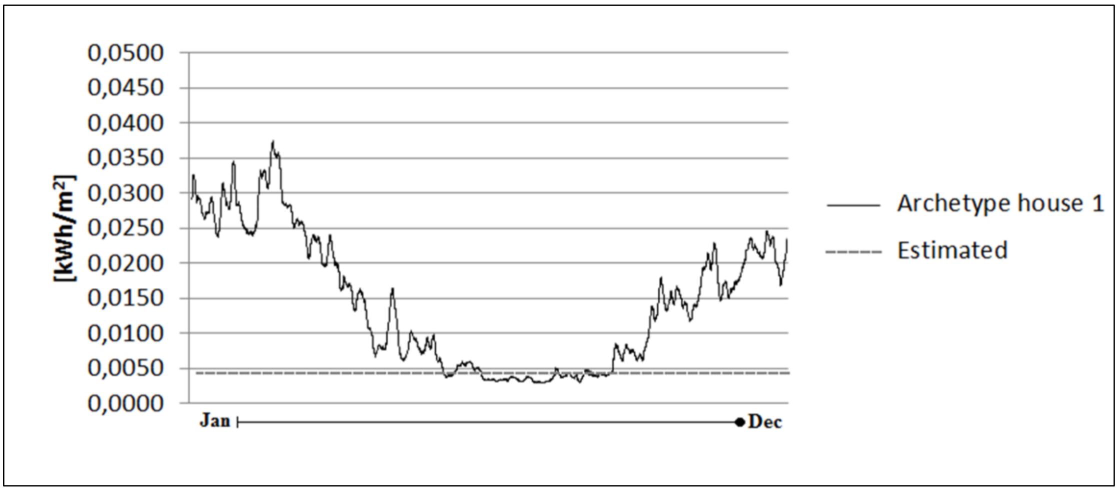


Figure 2.2 *Comparison of real energy data (for both space heating and hot tap water heat) and estimated hot tap water energy usage, before adjustment.*

By reducing 15% from the energy value of hot water we get a more correct value. This value is found comparing all the different archetype houses and using the value which works best for all of them. In both figure 2.2 and figure 2.3 the archetype building 1 is used as an example.

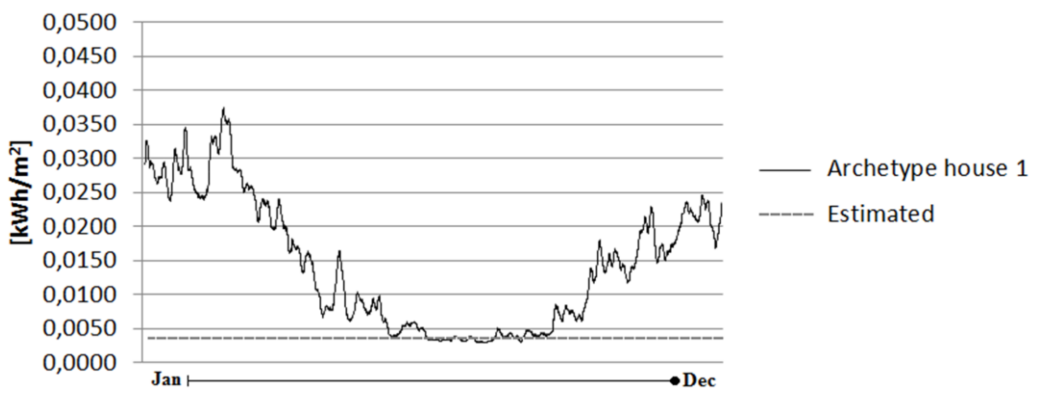


Figure 2.3 Comparison of real energy data (for both space heating and hot tap water heat) and estimated hot tap water energy usage, after adjustment.

2.4.3 Possible Source of Errors

There is of course a risk of getting errors when gathering this kind of real energy usage data and we will go through the different sources in this chapter.

- **Renovation of Objects:**
  When deciding on which objects we wanted to use for the purpose of gathering real energy data we had to decide on how many of the buildings we wanted to be renovated, with for example extra insulation added or new windows, and how many we wanted in its original shape. Since we are going to use the BETSI data as the foundation for our model we wanted to use the same amount of renovated objects as they have in their research. This is of course difficult to get exactly right when it comes to both the amount of buildings of each type but also to get the desired floor area of each type.

- **Measuring Floor Area:**
  As mentioned in the chapter 2.2 there is a risk of getting a slightly inaccurate size of the real buildings. This will of course affect the energy per square meter values. Though having several houses will decrease the probability of a large error, which could occur if we only had measured one house in each archetype category.

- **Risk of Getting Energy Data Which is Not Accurate:**

Since we had to keep the energy data anonymous we had to rely on Göteborg Energi to perform the mean value calculation as well as locating which district heating centrals were connected to which houses. This leaves a possibility for this data to be inaccurate and more importantly it is not possible for us to double check in order to avoid mistakes.

- **Water Usage Might be Different in Studied Houses:**
  There is of course a risk that the water usage in the studied houses might not match the estimated water usage, which is based on an average value from a study. There is also the fact that the number of people in these houses is based on the average square meter per person, which is discussed further in chapter 5.4. This can result in a change in the real water consumption if there are more people living in the studied houses than in the national average.

3 Resulting Archetype Buildings

This chapter explains the process of combining the collected building data into the final archetype buildings which will be based on all the data which were explained in chapter 2.

3.1 Combining Archetype Building Data

To combine the collected data, several parameters are chosen to work as identifiers. These parameters describe parts of each building and when combining several parameters that fit one type of building, these parameters can be used to identify such buildings. Hereby each one of the archetype building categories received a set of parameters used to identify buildings matching that exact category.

The aim is to use combinations (sets) of parameters that can easily identify a building of a certain type but at the same time not match a building of another type. The parameters used are also parameters that describe properties of the buildings that are interesting for this thesis. This way differences in energy performance between the different building types can be identified during simulations.

From the field study and the data collected from the database of the Board of City Planning, the first parameters can be identified. These parameters describe the geometrics and façades of the buildings, and thereby also describe what to look for when identifying buildings that match the same building type.

Parameters that are used from these two studies are;

- Year of when building documents were approved. This parameter is used to get an age of the building and to make sure that the building techniques, solutions and materials in the building construction are about the same for all chosen buildings of the same archetype category.

- Façade materials. This parameter is used to describe the thermal properties of the envelope in combination with the building age.

- Volume/Envelope surface area ratio (V/S ratio) and Envelope surface area/indoor heated area ratio (S/A ratio). These two parameters describe the geometric shape of the building and the relation between envelope surface area and indoor area/volume. A high V/S ratio means that a building is more energy transmission efficient compared to a building with a lower V/S ratio but with the same envelope building materials.

- Number of apartments and total indoor area. These two parameters are used as a final check to make sure that the data selected from the BETSI study is reasonable.

These parameters are now used to describe and identify buildings of each archetype category in the BETSI study, and thereby select buildings from the Swedish building stock that match the Göteborg building stock. Each category was once again represented by a group of buildings, but this time from the BETSI study.

To further develop the archetype building categories into specific archetype buildings, the amount of parameters that describes them had to be increased. All other parameters in the BETSI study were calculated by mean values from the buildings of each category. This way a mean building, an archetype building, was created with all its specific properties.

3.1.1 Possible Sources of Error

While combining the data from all different sources, some assumptions and estimations had to be made when the amount of data was not enough. This means that some sources of error occur.

- Naturally it turned out that some building types are more common than others and also that buildings built during certain periods of time are more common. This means that the number of buildings representing each archetype category varies between the categories and thereby also that each archetype building's foundation on which it is based on is more or less statistically representative. This issue has been dealt with by taking both parameters of buildings from the BETSI study and from the field study into account when calculating values for the archetype buildings. At the same time all parameter values have been checked and compared to architectural literature.

- Missing or obviously incorrect building data in the BETSI study. This source of error has been dealt with by either simply skipping this piece of data if the data foundation has been large enough or by estimating it from other available parameters. One example is when the number of apartments in a building has obviously been wrong.

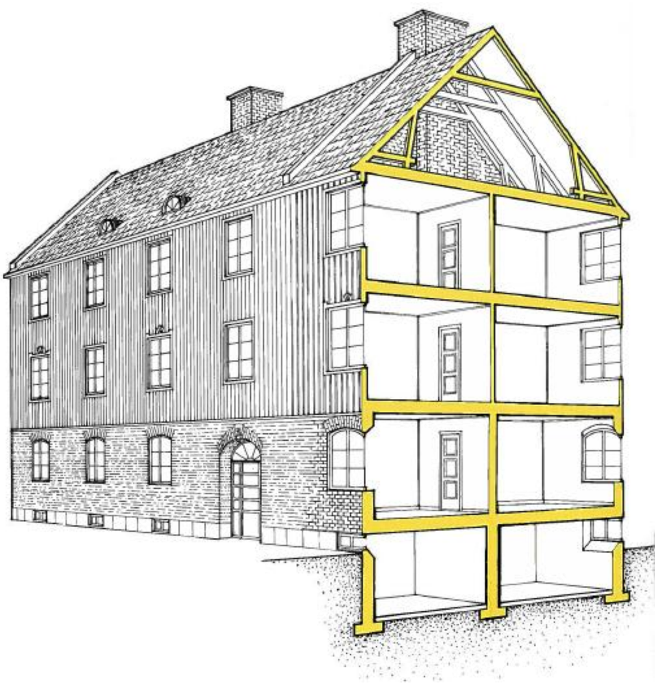
- Data from a categories' set of buildings has pointed in different directions. In this case buildings that are situated in Göteborg has been taken more into account due to that it is the Göteborg building stock that is interesting in this thesis. An example is when about half of the buildings use one type of ventilation and the other half uses another.

- There is always the possibility that some of the buildings in this study have had some kind of renovation which could increase the U-value of the building. This can for example be new windows, added insulation or new balconies. This could have the effect that the archetype buildings in this study have a U-value which represents a mean value between buildings with and without renovations.

3.2 Presentation of Archetype Buildings

Each archetype house is presented in this chapter with a picture, brief description and the more important parameters presented in a table (Björk C., Kallstenius P., Reppen L. 2002). More detailed description can be found in Appendix A.

3.2.1 Archetype Building 1 - *Landshövdingehus*



Three story houses built during the late 1920s and in the early 1930s with brick or stone façade covering the ground floor and wooden façade on the two floors on top. Slabs are constructed using wood and filled with sawdust. The roofs are of a pitched type and built with either brick or sheet metal.

These houses are built in a closed block structure which creates a closed courtyard between the buildings. A result of having these closed block structures is that the houses in this study has a very large heated area compared to its number of floors.

Figure 3.1 Archetype building 1 – Swedish name is Landshövdingehus (Björk C., Kallstenius P., Reppen L. 2002)

Table 3.1 Building data for Archetype Building 1.

Description	Data	Unit
Year of construction	1927-1935	[-]
Heated area	7570	[m^2]
Number of floors	3	[-]
Envelope area	9800	[m^2]
Window area	940	[m^2]
U-value	0.61	[$W/K,m^2$]
Thermal mass	14300	[$J/K,m^2$]
Ventilation system	Natural ventilation	[-]

3.2.2 Archetype Building 2 - *Äldre Lamellhus*

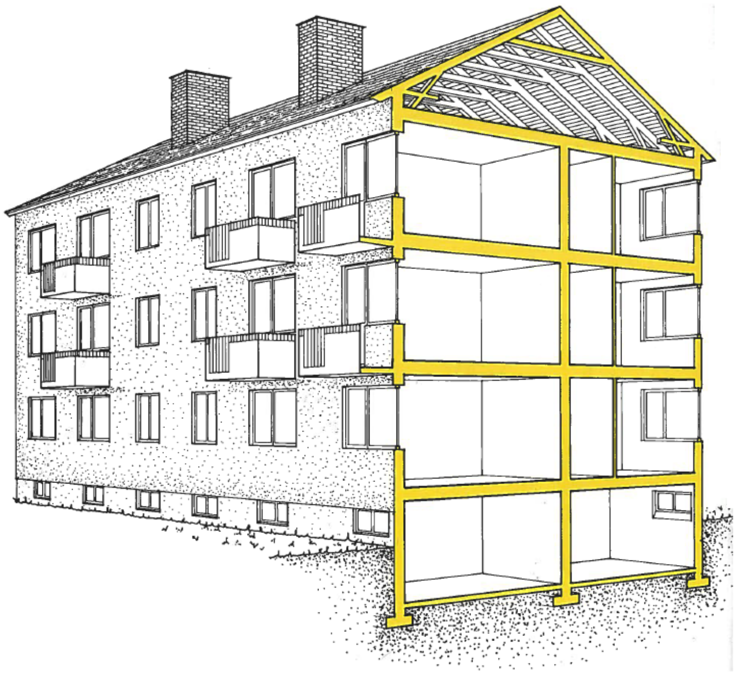


Figure 3.2 Archetype building 2 – Swedish name is Äldre Lamellhus (Björk C., Kallstenius P., Reppen L. 2002)

Three to four story houses built between the 1940s and 1950s. Façades are usually built out of bricks but facades in light-weight concrete are also frequent. Combinations of the two materials are sometimes used to increase the thermal performance. These houses can be of either a wide or thin type which means that the depth of the building varies between eight and twelve meters. This variation is usually seen between different cities. All buildings of this type share the same pitched roof with tiles.

Table 3.2 Building data for Archetype Building 2.

Description	**Data**	**Unit**
Year of construction	1946-1955	[-]
Heated area	1395	[m^2]
Number of floors	3-4	[-]
Envelope area	2000	[m^2]
Window area	140	[m^2]
U-value	0.75	[$W/K,m^2$]
Thermal mass	347000	[$J/K,m^2$]
Ventilation system	Natural ventilation	[-]

3.2.3 Archetype Building 3 - *Yngre Lamellhus*

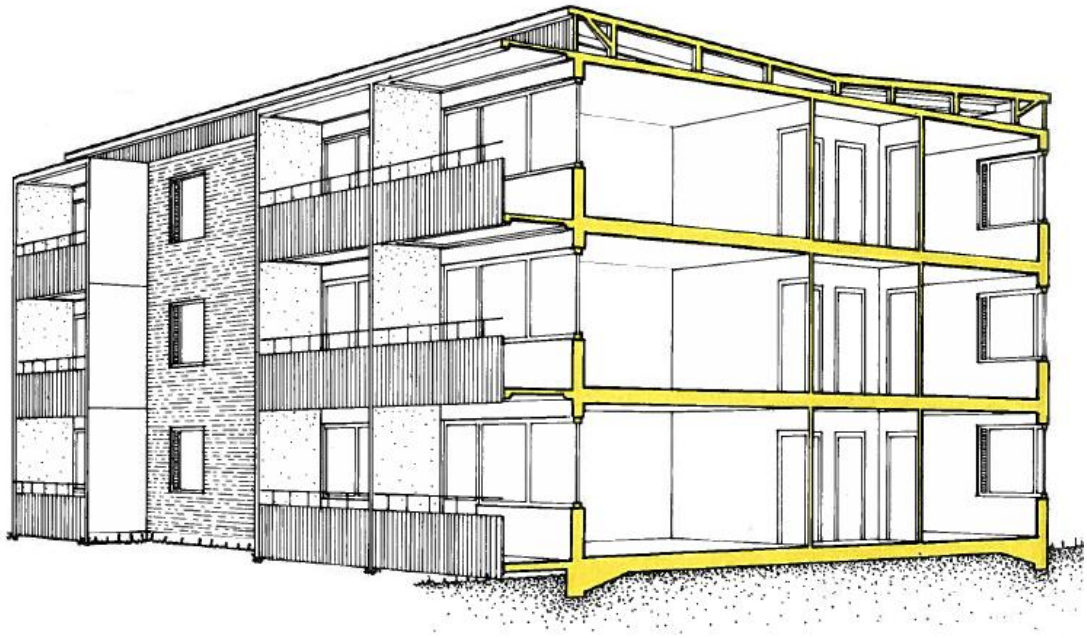


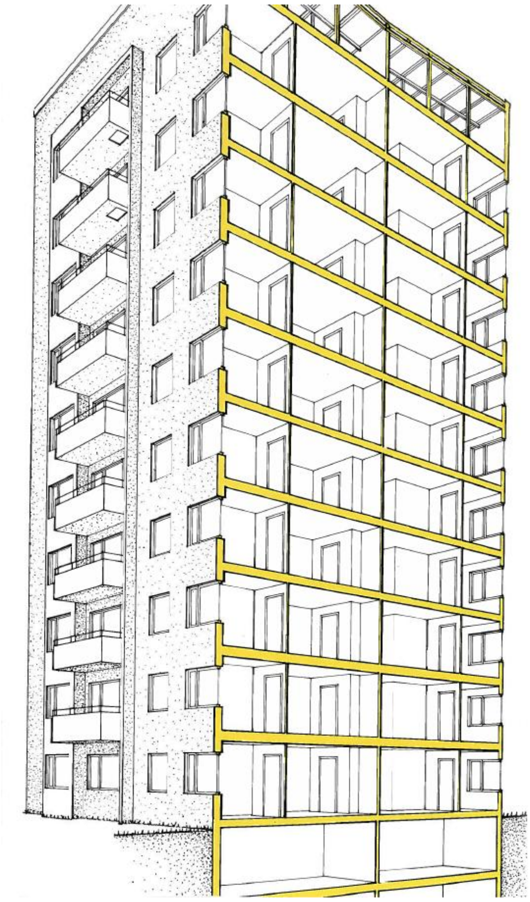
Figure 3.3 Archetype building 3 – Swedish name is Yngre Lamellhus (Björk C., Kallstenius P., Reppen L. 2002)

Three to four story houses built between 1950s and 1970s. Façades are usually built out of concrete sandwich elements with about 100 mm of insulation. The archetype building 3 shares much of its dimensional characteristics as well as geographic placement with the archetype building 2. On the other hand the aesthetic characteristics have changed with new construction methods which can be seen on the flat roofs and the element structure of the façade.

Table 3.3 Building data for Archetype Building 3.

Description	**Data**	**Unit**
Year of construction	1965-1975	[-]
Heated area	2343	[m^2]
Number of floors	3	[-]
Envelope area	3100	[m^2]
Window area	330	[m^2]
U-value	0.53	[$W/K,m^2$]
Thermal mass	353000	[$J/K,m^2$]
Ventilation system	Exhaust ventilation	[-]

3.2.4 Archetype Building 4 - *Högt Punkthus*



Tall and square-shaped nine to eleven story buildings built between 1940s and 1960s. The façades usually consist of a combination of concrete and light-weight concrete with some insulation. A wide variation of roof types as well as number of floors. This building type is usually found in small numbers in connection with a larger group of other building types, for example archetype building 3.

Figure 3.4 Archetype building 4 – Swedish name is Högt Punkthus. (Björk C., Kallstenius P., Reppen L. 2002)

Table 3.4 Building data for Archetype Building 4.

Description	Data	Unit
Year of construction	1945-1960	[-]
Heated area	3403	[m^2]
Number of floors	9-11	[-]
Envelope area	3800	[m^2]
Window area	390	[m^2]
U-value	0.73	[$W/K,m^2$]
Thermal mass	380000	[$J/K,m^2$]
Ventilation system	Exhaust Ventilation	[-]

3.2.5 Archetype Building 5 – *Skivhus*

Long and tall buildings with eight to twelve stories built mainly during the Miljonprogrammet, which was a large building project between the 1960s and 1970s. Facades are in generally built using concrete, light-weight concrete or bricks, or a combination of the materials. All buildings of this type are also fitted with a thin layer of insulation.

Figure 3.5 Archetype building 5 – Swedish name is Skivhus (Björk C., Kallstenius P., Reppen L. 2002)

Table 3.5 Building data for Archetype Building 5.

Description	**Data**	**Unit**
Year of construction	1960-1971	[-]
Heated area	5868	[m^2]
Number of floors	10	[-]
Envelope area	6000	[m^2]
Window area	880	[m^2]
U-value	0.76	[W/K,m^2]
Thermal mass	390000	[J/K,m^2]
Ventilation system	Exhaust ventilation	[-]

3.3 Resulting Energy Usage for Each Archetype Building

The energy data acquired from Göteborg Energi is as mentioned earlier in chapter 2 mean values of five different groups of real buildings that fit in each one of the five archetype building categories. Since the values are mean values they are considered anonymous because they cannot be associated with a specific building.

The data for each archetype building is specified with one value for each hour throughout the year 2011, 8760 values in total per building. The values have the unit Wh/m^2,hour which means that the values can be used independent of the original buildings heated area.

Below is the real energy data collected for the different archetype buildings. This data includes energy for heating of hot tap water and energy for space heating. The data is presented monthly which means that all energy consumption during a specific month is combined to one value.

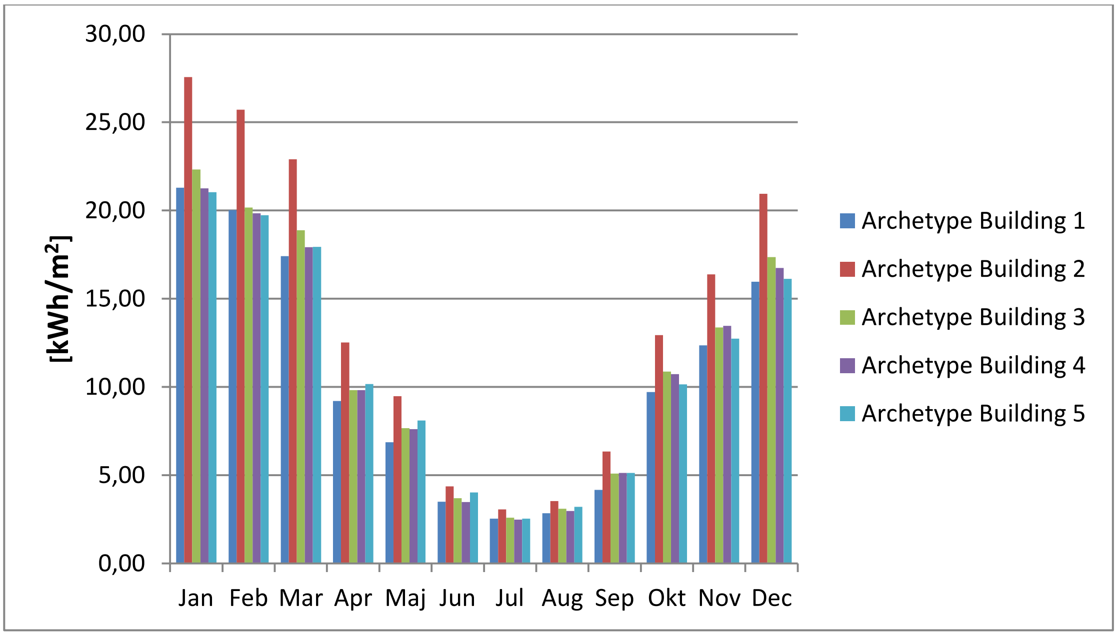


Figure 3.6 Comparison of annual energy consumption between archetype buildings during 2011. Both space heating energy and energy for hot tap water is included in this data. (van Rooij J. 2012)

We can see that the archetype house number 2 has much large energy consumption than the other houses in this study. The reason behind this could be that these houses have generally undergone fewer renovations that improve the thermal properties, than for example the archetype house 1 which is an older kind of building but with less energy consumption.

Table 3.6 Comparison of annual energy consumption of archetype buildings. Both with and without hot tap water.

Archetype building #	Annual energy consumption with hot water [kWh/m^2]	Annual energy consumption without hot water [kWh/m^2]
Archetype building 1	125.95	93.9
Archetype building 2	165.79	133.75
Archetype building 3	134.99	102.95
Archetype building 4	131.50	99.46
Archetype building 5	130.93	98.89

4 Verifying Simulation Model with Energy Data

To verify that the simulation model works in an accurate way that corresponds to the real world and the buildings that are investigated, the model is compared to the collected energy data.

4.1 Plotting of Energy Data to Acquire Control Curves

From the energy data acquired from Göteborg Energi, the mean power input during every hour throughout the year 2011 can be calculated for each one of the archetype buildings.

Since the data also show what hour of the year the energy data is connected to, a connection between the energy data and outdoor temperature during the same year can be made.

By plotting the power input values against the outdoor air temperature for each hour of 2011 a cloud of data points is obtained, as in figure 4.1. Each one of the points then represents a specific hour of the year, with its outdoor temperature and mean power input during this hour. By adding a trend line to the plot a control curve is created for each of the buildings. This curve is used by the district heating central to control how much energy is put into the building depending on the outdoor temperature. This way of controlling indoor air temperature is today the most common and easy way to do it.

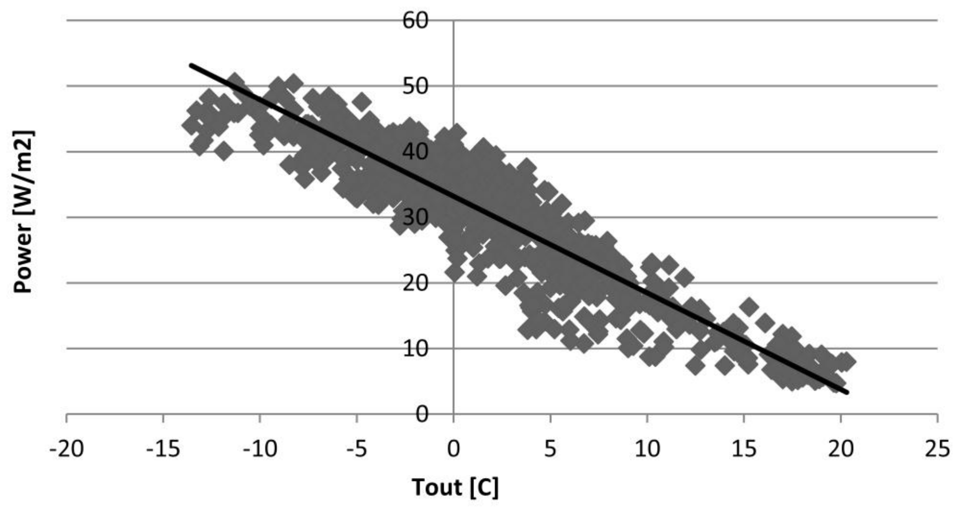


Figure 4.1 Example of the cloud of data points obtained from the collected energy data. The trend line gives the control curve and is a function of how much power input to the building depending on outdoor temperature.

4.1.1 Control Curve Properties

Control curves are used to control the indoor environment as described earlier in this chapter. The indoor environment is affected by several factors such as outdoor temperature, ventilation rate, solar radiation and air leakage due to wind. This chapter will only take external factors into account, which are temperature, solar radiation and wind, to make the explanation simpler to understand.

Curves acquired with the method of plotting a cloud of data points, as described in figure 4.1, can be described as mean control curves. They take the outdoor temperature, wind and solar radiation into account but only to the extent that one linear curve can be used to represent them all. This part of chapter 4 will therefore describe the influences wind and solar gain has on the design of the control curve.

Wind causes air leakage through the building envelope. This is assumed to be an energy loss due to the fact that this thesis mainly focuses on heating and thereby only when the outdoor temperature is below the indoor temperature. Solar radiation on the other hand causes energy gains, mainly through windows, which heats the building.

If the indoor environment was only affected by the outdoor temperature, the cloud of data points in a plot would form a straight line because the energy losses would be proportional to the outdoor temperature, as the black diamond data points in figure 4.2.

When wind and solar radiation affects the indoor environment, the power demand for heating is also affected. Solar gains reduce the need of heating power while wind increases the need of heating power. Because of this the heating power demand is based on all three parameters, outdoor temperature, solar radiation and wind.

Figure 4.2 visualize how the three external factors affect the power demand. The black diamond points represent the power demand as a function of only the outdoor temperature. The grey circular and grey triangular points represent the effects of solar radiation and wind. Solar radiation causes energy gains, which reduces the power demand. Wind causes energy losses which increases the power demand.

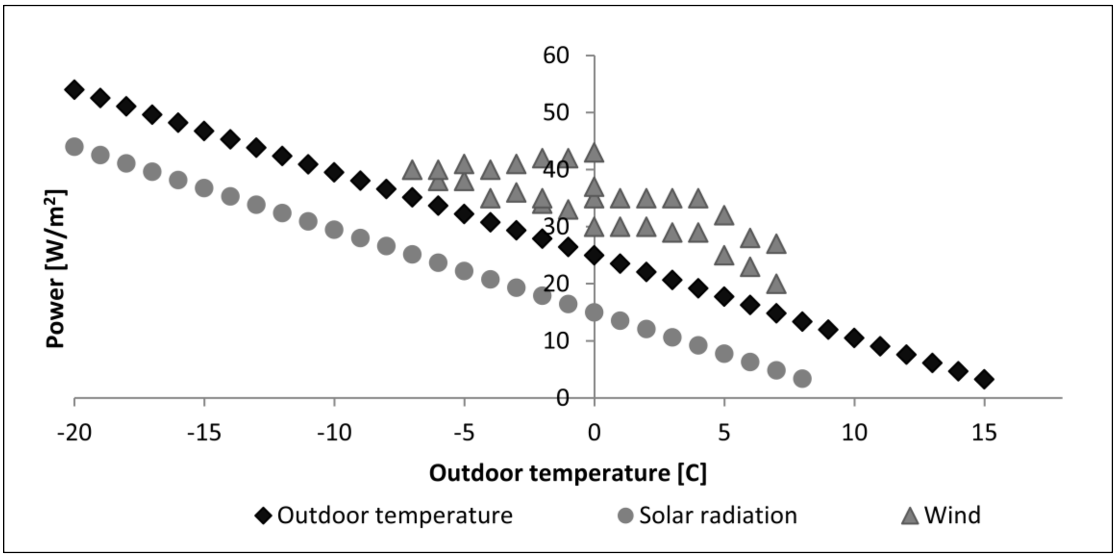


Figure 4.2 Example of where power demand data points occur in the plot due to the external parameters outdoor temperature (losses), solar radiation (gains) and wind (losses).

Winds usually occur when the outdoor temperature is about -5°C to 5°C; this is the reason for the wind points to only occur in this region.

When drawing control curves onto the plot with the cloud of data points, the curve is affected by which data points are on the plot.

In figure 4.3 two control curves have been drawn. The blue curve is the control curve when only outdoor temperature is affecting the power demand. The grey curve represents the control curve when solar radiation is taken into account. This causes energy gains and thereby reduces the power demand, hence moving the curve downwards.

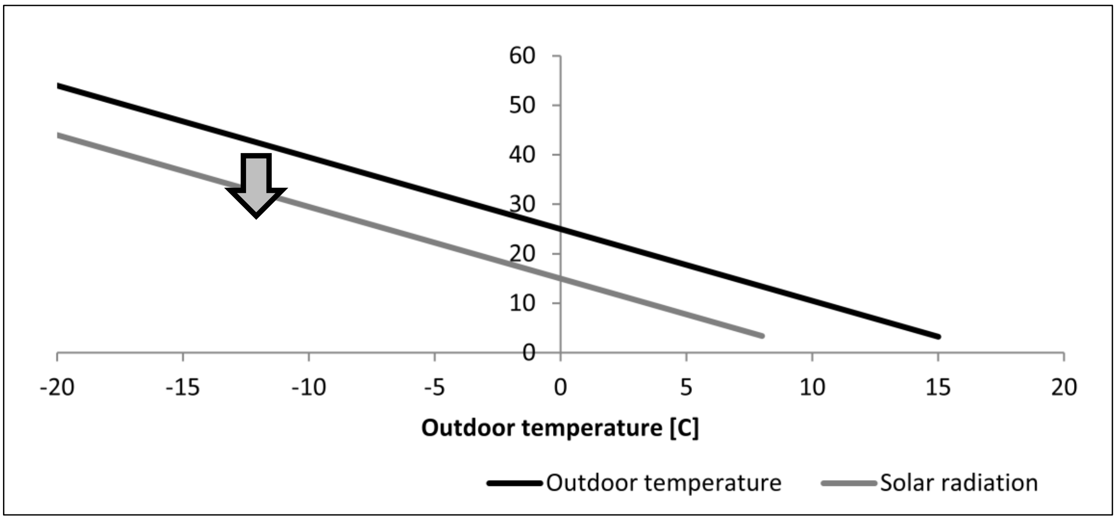


Figure 4.3 *Example of how control curves are affected by temperature and solar radiation. Solar radiation causes energy gains which reduce power demand, hence moving the curve downwards.*

In figure 4.4 the wind is taken into account. This affects the control curve to bend like a bubble in the temperature interval where wind mainly occurs.

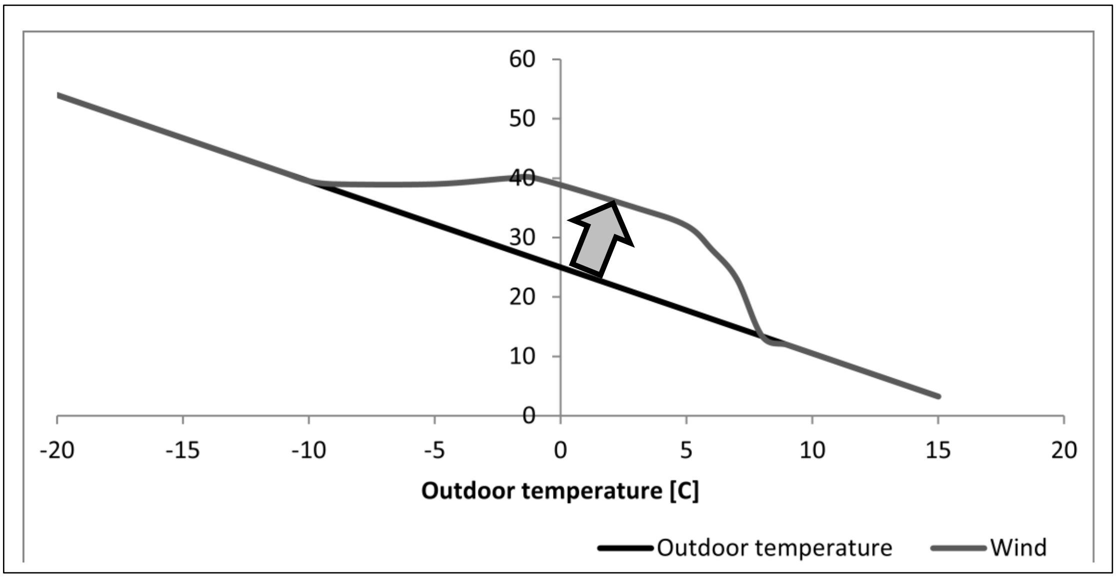


Figure 4.4 *Example of how control curves are affected by wind. Wind creates energy losses and thereby increases the power demand. The curve is therefore raised in the temperature region where wind mainly occurs.*

If all the three parameters are put into the plot, they will all affect the final control curve. The control curve will then be a representation for all three parameters using only one linear line, as a linear trend line, as seen figure 4.5.

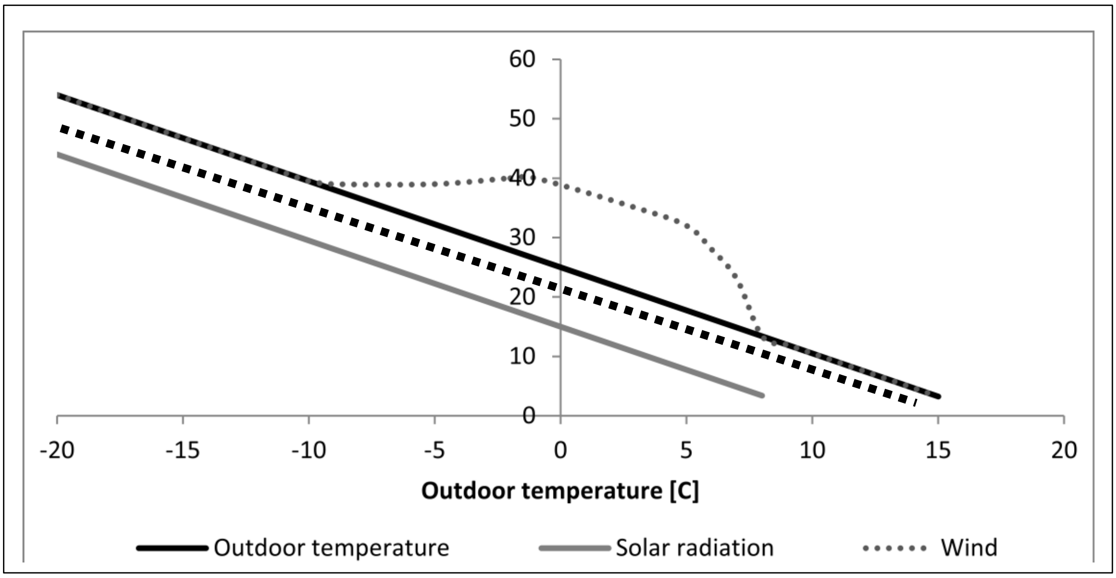


Figure 4.5 The control curve (dotted black curve) affected by all three external parameters.

Control curves are in reality affected by the same parameters that affects the buildings indoor environment, such as U-values, ventilation rate, internal gains from people, and more.

In a plot of data points, a cloud, as the one presented earlier in figure 4.1 each point is therefore a total representation of the momentary heating power demand, which includes all sorts of gains and losses.

Additional parameters affect the control curve in a similar way as wind and sun does, moving the data points up or down depending on the amount of energy gains and losses at the moment, and thereby also moving the final control curve. Energy gains (such as solar gains and people gains) move it downwards and energy losses (such as air leakage and ventilation) move the curve upwards.

4.2 Calibration of Simulation Model

The model has to be calibrated in a way that all archetype buildings follow the same behavior pattern as their corresponding real energy data has. To do this the control curves acquired in the previous step are put into the model and used as the source to determine how much heating is put into each archetype building. This way the model can be calibrated by changing some parameters such as thermal bridges and air leakage to match the consumption pattern of the collected data, both in amounts of energy and when the energy is consumed.

To verify the match between the simulation model and the real energy data the energy consumption for each square meter is monitored as in figure 4.6. This figure shows the curves of the accumulated energy for one square meter during a year in both the simulated archetype building and for the collected energy data of that building. The two curves should lie on top of each other through the year to verify that the model consumes energy according to the same pattern as the collected energy data.

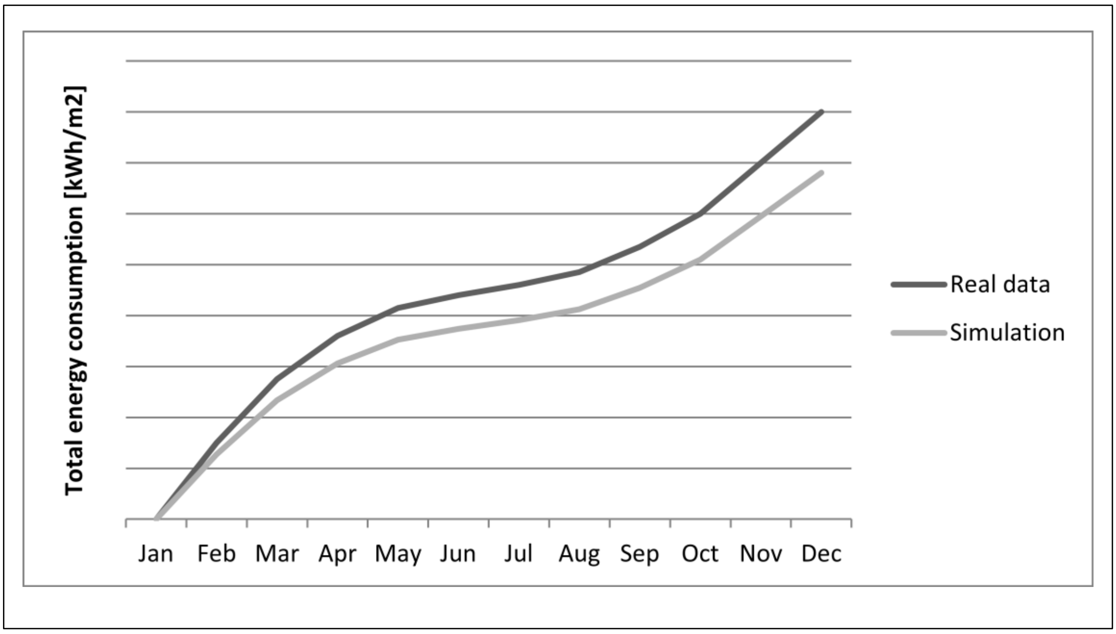


Figure 4.6 *Graph of the energy consumption pattern throughout a year. The two curves represent the accumulated energy of one square meter of both a simulated archetype building and the real energy data of that building.*

At the same time the indoor temperature is monitored and it should be within a reasonable range of about 20-21 °C, a temperature which can be found in the BETSI study.

If the energy consumption pattern match and the indoor temperature is within reasonable range then the model is assumed to be verified.

4.3 Parameters Used to Calibrate the Simulation Model

For calibration, some parameters can be changed to make the simulation model match with the collected energy data which represents the archetype buildings' real world energy consumption.

The amount of thermal bridges and the volume of air leakage are the two parameters that are changed in this case. These two are additional parameters to the BETSI study and field study that are needed to perform the simulations.

5 Assumptions Made in Model

This chapter aims to describe the different parts of the simulation model and which assumptions that has been made in each part.

5.1 Transmission Losses

A quite significant part of the energy losses occurs through the building envelope through thermal bridges and air leakage. How large these are and where they can be found are however quite difficult to determine. Therefore an assumption is usually made of an added transmission loss which includes both thermal bridges and air leakage. The magnitude of this is assumed to be an addition of about 15% to the transmission losses (Sasic A. 2012).

In this thesis the air leakage is handled separately and calculated by using the data from blow door tests combined with the weather data for the specific place and time. The leakage at 50 Pa pressure difference varies between 0.6 and 1.2 $l/s,m^2$ in the different buildings.

From these calculations, which are described further in chapter 6, it was found that the air leakage was responsible for roughly 10% of the 15%, which was mentioned earlier in this chapter. It is then assumed that the thermal bridges will be the additional 5%. These numbers works very well with the verification process of the model and give reasonable results.

5.2 Ventilation

All houses in this study have some kind of ventilation system. The types of ventilation systems which can be found are either natural ventilation or mechanical exhaust ventilation. The ventilation rate of the different archetype houses was described in the BESTI study and varies between 0.28 and 0.38 $l/s,m^2$.

No buildings in the study use a heat exchanger and are therefore completely ignored in this thesis.

5.3 Solar Radiation

The solar radiation through the windows will significantly contribute to the indoor heating load. Since the archetype buildings which are simulated in this thesis are composed of many real objects the average window location could be considered to be equal in all directions. By doing this assumption we can use the global radiation to calculate the indoor solar radiation heat effect.

To compensate for the amount of windows in each direction a constant of 0.65 will be added to all solar radiation calculations. This number is derived from a study on buildings in Sweden and how their windows are located. (Mata E., Sasic A. 2009)

5.4 Internal Energy

The internal energy load derives from both human activity as well as electricity usage. These two different sources are described individually and then combined and presented as one source.

Energy from People:

Each person produces around 80 Watts. This number is an average and varies from person to person and is also affected by different kinds of activities. One could argue that a person produces less heat while asleep since the body activity is at a minimum but in the simulations the average number will be used for the entire time (Boverket 2007).

To be able to use this number in the simulation there need to be a ratio between number of people and amount of square meters in the archetype house. Data from Statistics Sweden states that the average flat size in Sweden is 70 m^2. This corresponds well to the archetype study were the average flat size is 69 m^2 (Statistiska Centralbyrån 2009).

The average number of people living in each flat in Sweden is, according to a study from Statistics Sweden 2.1 persons. If this is combined with the flat size the average square meter per person is found at around 33 m^2 (Statistiska Centralbyrån 2010).

In order to get a correct daily variation for the energy gains from people it will have to be compared to the energy production with a percentage that tells us how many of the residents that are at home at a specific time. This percentage is calculated hourly and is based on activity of different age-groups during the day. Children and people within the working ages are assumed to be away during the day while people who are above 65 are assumed to be at home. The numbers used to calculate the size of these different age groups are found in a report from Statistics Sweden (Statistiska Centralbyrån 2012).

The results can be seen in figure 5.1 below where the energy production is presented as watts per square meter for each hour of the day.

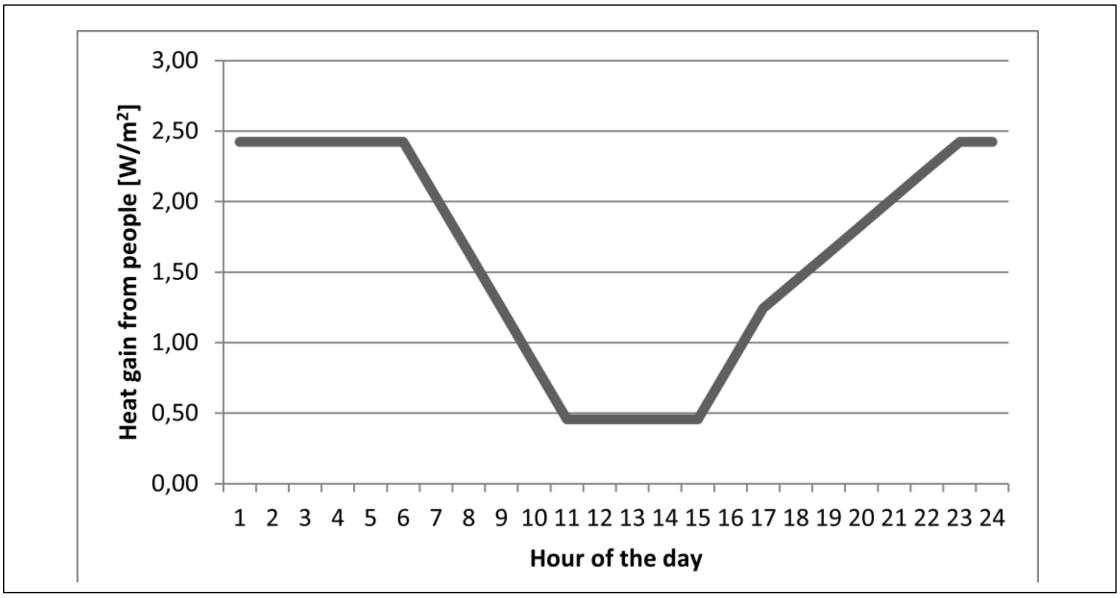


Figure 5.1 Daily variation of heat gain from people, W/m^2.

Energy from House Hold Electricity:

The electrical energy used in household equipment and other applications as well as lighting will be considered to directly contribute their effect to the heating effect of the building. In similarity to the usage of tap water it is assumed that the behaviour of electricity usage is not related to which type of building a person lives in but rather on the person itself. Therefore it is possible to study a number of randomly chosen apartments and their energy consumption and then make a statistically representative usage pattern of house hold electricity (van Rooij J. 2012).

Eon states that the average sized flat uses 2500 kWh per year and from the previous part of this chapter it is stated that the average flat size is 70 m^2. Combining these two facts provide the final energy consumption per square meter which will be used for the simulations, 36 kWh / m2,year (Eon 2012).

The randomly chosen apartment's energy consumptions are used in two ways. First to investigate how the energy consumption varies throughout the day and secondly to find out how it varies over the year.

The variation over the day is calculated by using the daily energy consummation from a number of days from each month. The electricity usages from these days are first weighted against each other so that each day contributes equally to the final result. This is done because it can be assumed that the electricity usage is somewhat higher during the winter months. This assumption is further explained in the next paragraph. Figure 5.2 shows how the daily variation in electricity consumption and its values is used to create the daily variation in our simulation model.

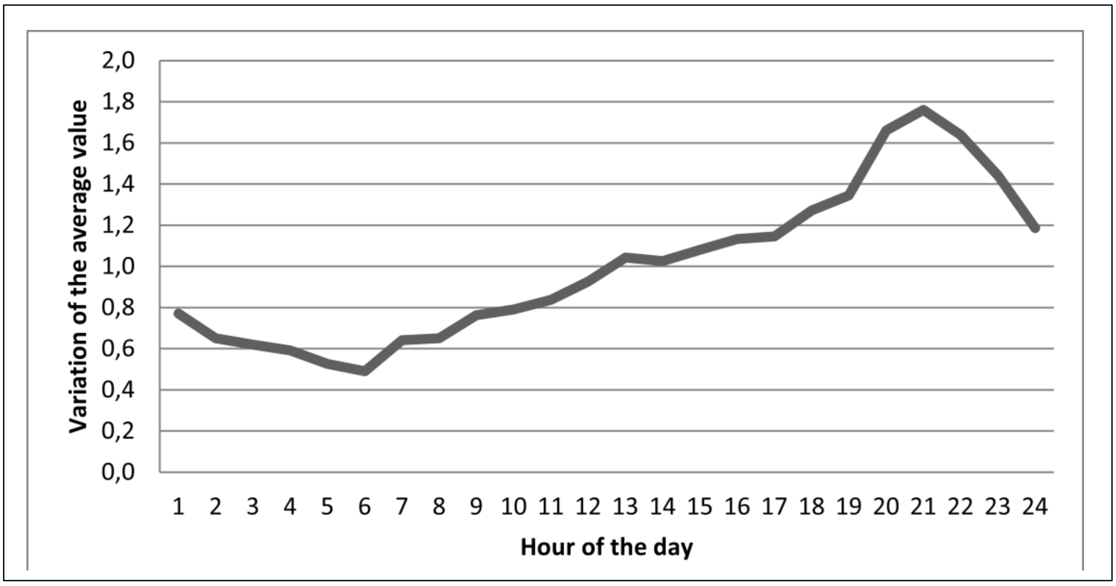


Figure 5.2 Daily variation of heat gain from house hold electricity. Graph shows how the average value varies with 1.0 as the mean value.

For the annual variation, which can be seen in figure 5.3 below, there is a dip in energy consumption during the summer months. This is due to several reasons. There is less need for lighting since there is much more natural sun light during summer months than during winter months. It can also be assumed that people spend less time indoors during these months as well; it is not only the lighting that is used less but also things like TVs, computers and other similar appliances. Further, there is also the tendency to travel more during the summer months which will dramatically reduce the electricity consumption during those weeks.

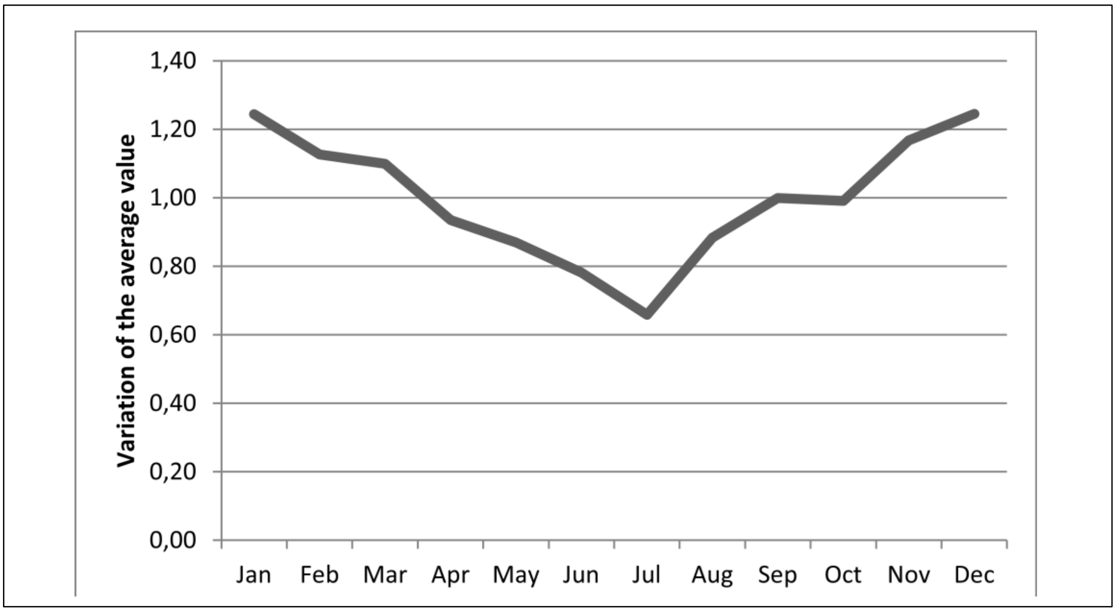


Figure 5.3 Annual variation of heat gain from house hold electricity. Graph shows how the average value varies with 1.0 as the mean value.

By combining these two graphs a final graph which incorporates both types of variations is found and used in the simulations. This gives a much more realistic usage behavior than just using the average value of 36 kWh/m^2,year during the entire year.

5.5 Internal Heat Capacity

The internal heat capacity is a value which described how heavy a building is; which means how much energy it can store in walls, floors, ceilings and so on. In these simulations it is assumed that all the mass of the building will store energy. In reality there could be a case where the penetration depth of the heat is smaller than the width of the wall and in that case only some of the wall would store heat. Since no buildings in this study is of the very heavy type this problem is ignored.

The value used for the internal heat capacity in each archetype building is found in the BETSI study, Appendix A.

5.6 Heat from Fans

While the energy created by the fans might not be as large as other sources it is still important to add its contribution to the overall energy balance. In these simulations all energy used by the fan is assumed to contribute to the heating of the building. This will of course only apply to the mechanical ventilation systems. Houses which use natural ventilation will therefore not have this added heat load.

5.7 Weather Data

The simulation model requires data input for the temperature, solar radiation and wind speed. These data are supplied through a weather file which contains one value of the variables for each hour of the year. The weather data is gathered by the Swedish Meteorological and Hydrological Institute, SMHI.

6 Simulation Method

The simulations are carried out in MATLAB and Simulink. The model uses the assumption of a lumped system where every part of the building is assumed to have the same temperature and ventilation flow, i.e. no local variations are taken into account.

All calculations are based on the current outdoor weather conditions which are provided in the weather file.

The term "losses" is used in this chapter as a way to describe parts of the building that loses energy during temperatures below indoor temperature. In contrary, these parts work as energy gains during periods with warmer outdoor temperatures than the indoor temperature.

All equations in this chapter are derived from the book (Hagentoft C. 2001).

6.1 Energy Gains and Losses

This chapter explains all equations which handles either energy gains or energy losses.

6.1.1 Transmission Losses

All energy that is either lost or gained through the walls, floor, roof and windows by transmission is calculated using equation 6.1.

$$Q_{trans} = U * A * \Delta T \tag{6.1}$$

Where:

U is the thermal transmittance of the building envelope. This includes the windows. [W/m^2, K]

A is the surface area of the building envelope. The area of the windows is included here. [m^2]

ΔT is the current temperature difference between the outdoor temperature and the indoor temperature. [K]

6.1.2 Thermal Bridges

Equation 6.2 is used to calculate the added transmission losses caused by thermal bridges. As mentioned in chapter 5.1 the contribution to transmission losses caused by thermal bridges will be an addition of 5% to the transmission losses through the building envelope.

$$Q_{trans,tb} = Q_{trans} * C_{tb} \tag{6.2}$$

Where:

Q_{trans} is the transmission loss through the building envelope [W]

C_{tb} is the percentage addition the transmission loss due to thermal bridges [-]

6.1.3 Air Leakage

As mentioned in chapter five the air leakage is calculated for each archetype building by using the results of blow door tests as well as taking the current wind speed into the equation. The pressure coefficients are found by looking at a typical house and investigating how large the maximum pressure is; this is then used for all archetype houses. This means that the direction of the wind is of no importance; only the speed is taken into account.

Equation 6.3 is used to calculate the pressure difference between indoor and outdoor caused by the wind.

$$P_w = (C_p - C_{pi}) * \frac{\rho_a * v^2}{2} \tag{6.3}$$

Where:

C_p is the outdoor pressure coefficient. [-]

C_{pi} is the indoor pressure coefficient. [-]

ρ_a is the density of air. [kg/m^3]

v is the wind speed. [m/s]

The air flow through the building created by the pressure difference is calculated using the equation 6.4. This equation uses the leakage measured in a blow door test to calculate the current air leakage.

$$V_{leakage} = \frac{C_{door}}{50^{0.6}} * A_{tot} * P_w^{0.6} \tag{6.4}$$

Where:

C_{door} is the air leakage measured using a blow door test at 50 Pa overpressure. [m^3/s]

A_{tot} is the building envelope area. [m^2]

P_w is the pressure difference between indoor and outdoor. [Pa]

Finally the energy loss caused by the air leakage is calculated using equation 6.5 which is basically the same equations 6.6 which describes the heat loss through forced ventilation.

$$Q_{leakage} = V_{leakage} * \rho_a * c_{pa} * \Delta T \quad (6.5)$$

Where:

$V_{leakage}$ is the air leakage through the building envelope. [m^3/s]

ρ_a is the density of air. [kg/m^3]

c_{pa} is heat capacity of air. [J/kg,K]

ΔT is the current temperature difference between the outdoor temperature and the indoor temperature. [K]

6.1.4 Ventilation Losses

All energy lost through either natural or forced ventilation is calculated using equation 6.6. This equation does not include air leakage which is handled separately in chapter 6.1.3 and calculated with equation 6.5.

$$Q_{vent} = V * \rho_a * c_{pa} * \Delta T \quad (6.6)$$

Where:

V is the combined air flow through the building envelope. This includes mechanical ventilation, natural ventilation and air leakage. [m^3/s]

ρ_a is the density of air. [kg/m^3]

c_{pa} is the heat capacity of air. [J/kg,K]

ΔT is the current temperature difference between the outdoor temperature and the indoor temperature. [K]

6.1.5 Solar Radiation

The solar radiation contributes to the heating of the building during the entire year. The amount of solar radiation that enters the building is dependent on how large window area the building has and how well shaded the windows are. Equation 6.7 is used to calculate the final solar radiation which enters the windows after all coefficients have been added. To compensate for the difference in amount of windows in different orientations the value of the solar radiation is multiplied with a constant 0.65.

$$Q_{sol} = G * A_w * T_s * W_c * W_f * 0.65 \quad (6.7)$$

Where:

G is the global radiation. [W/m^2]

A_w is the window area of the building. [m^2]

T_s is the window transmittance, 0-1. [-]

W_c is the window shade coefficient, 0-1. [-]

W_f is the window frame coefficient, 0-1. [-]

6.1.6 Internal Heat Gains

All energy used inside the building envelope is assumed to directly contribute to the heating of the building, except hot water usage. Equation 6.8 explains what sources contribute heat as well as how they are taken into account.

$$Q_{int} = Q_{people} + Q_{app} + Q_{light} + Q_{fan} \tag{6.8}$$

Where:

Q_{people} is the heat generated by the people living in the building. [W/m^2]

Q_{app} is the heat generated by appliances. [W/m^2]

Q_{light} is the heat generated by lighting. [W/m^2]

Q_{fan} is the heat generated by ventilation fans. [W/m^2]

The area used in the different internal heat sources is the heated area of the building.

6.2 Volumetric Heat Capacity

The volumetric heat capacity of a building is found by summarizing the heat capacity of all the internal layers which are in contact with the interior climate. This includes the inner layers of the building envelope, internal walls and the slabs.

$$C = \sum \rho * cp * d * A \tag{6.9}$$

Where:

ρ is the density of each individual internal layer. [kg/m^3]

c_p is the heat capacity of each individual internal layer. [J/kg,K]

d is the thickness of each individual internal layer. [m]

A is the area of each individual internal layer. [m^2]

6.3 Basic Energy Balance Calculation

As described in (Hagentoft C. 2001) the equation 6.10 is the basic formula for the energy balance in a lumped system.

$$C * \frac{dT_{in}(t)}{dt} = Q_{losses}(t) + Q_{gains}(t) \quad (6.10)$$

Where:

Q_{losses} are the combined losses from Q_{trans}, $Q_{trans,tb}$, $Q_{leakage}$ and Q_{vent} [W]

Q_{gains} are the combined gains from Q_{sol} and Q_{int} [W]

C is the internal heat capacity. [J/K]

In Simulink this is calculated by numerical integration shown in equation 6.11.

$$\int_t^{t+\Delta t} \frac{dT_{in}(t)}{dt} dt = \frac{Q_{losses}(t)+Q_{gains}(t)}{C} \quad (6.11)$$

By using the temperature from the previous step we can calculate the current temperature as show in equation 6.12.

$$T_{in}(t + \Delta t) = T_{in}(t) + \frac{Q_{losses}(t)+Q_{gains}(t)}{C} \quad (6.12)$$

This is the basic form of the lumped system model without any heating added. This is also how the building works during the cooling period of the year.

6.4 Heating System

To calculate how much energy that is needed two different methods are used, equation 6.13 and equation 6.14. Only one type of heating system is used in one simulation run and which of the two methods is used depends on the goal of the current simulation. The first method can be used to acquire control curves for a specific indoor temperature in the same way as described in chapter four. The second is used to simulate real life behaviour of the buildings.

The first method, equation 6.13, is used to control the temperature using the indoor temperature. The indoor temperature is controlled very strictly and is never allowed to fall below the target temperature. This method will show exactly how much energy that is lost and subsequently how much energy the heater need to supply to keep the indoor temperature steady.

$$Q_{heating} = \left(T_{target} - T_{in}\right) * P \quad (6.13)$$

Where:

T_{target} is the target indoor temperature. [K]

T_{in} is the current indoor temperature. [K]

P is the power of the heater. This number is arbitrary. [W/K]

The second method is to control the heater using a control curve. The control curve describes the relationship between heating power and outdoor temperature. The heating system is told exactly how much power it must supply at the current outdoor temperature from reading this curve.

$$Q_{heating} = T_{out} * F \tag{6.14}$$

Where:

T_{out} is the current outdoor temperature. [K]

F is the power of the heater. The amount of heating comes from an equation which is given by the control curve. [W/K]

6.5 Final Energy Balance Equation

Equation 6.15 shows the final energy balance equation with the contribution of the heater added.

$$T_{in}(t + \Delta t) = T_{in}(t) + \frac{Q_{losses}(t) + Q_{gains}(t) + Q_{heating}(t)}{C} \tag{6.15}$$

Where:

Q_{losses} are the combined losses from Q_{trans}, $Q_{trans,tb}$, $Q_{leakage}$ and Q_{vent} [W]

Q_{gains} are the combined gains from Q_{sol} and Q_{int} [W]

$Q_{heating}$ is the power from the heater which is needed to keep the temperature constant [W]

C is the volumetric heat capacity. [J/K]

7 Methods to Reduce Peaks in Power Demand

Because of varying outdoor climate, with changing temperature, wind and solar radiation, the heat losses from a building vary. This loss of heat, i.e. energy, creates a demand for more energy in the heating system, to be able to achieve and keep an indoor climate with a certain temperature. This demand, together with the amount of energy needed to produce hot tap water, is the total power demand.

Since the power demand depends on several changing parameters the power demand will change accordingly. This creates an unequal distribution of energy to the building throughout the day and year which sets high requirements on the energy distribution system and production system. These two must be designed and built according to the highest levels of energy demand which occurs during very cold weather. Though most of the time only a small part of the total capacity is used.

A peak reducing method is a method that simply reduces the power demand peak and redistributes the energy usage to other times. This creates a more homogenous power demand curve. As seen in figure 7.1 the method's goal is thereby not necessarily to reduce the total amount of used energy.

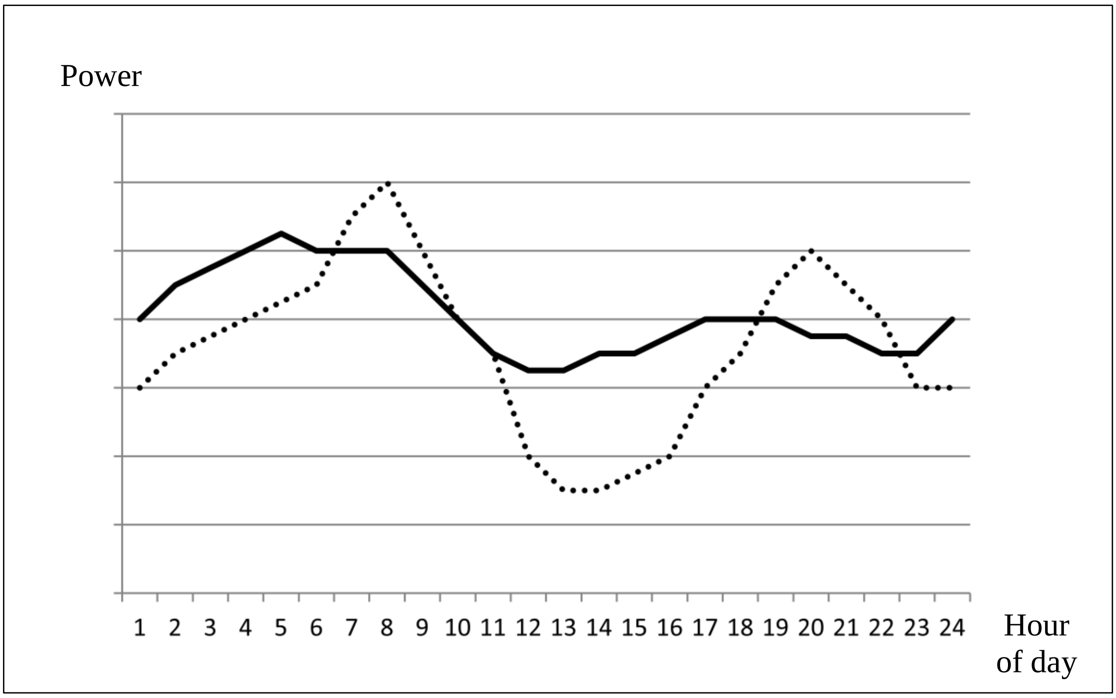


Figure 7.1 Example of power demand peaks (dotted line) and reduction of the peaks (solid line).

7.1 Control Curves

Control curves are used to control the indoor temperature without a complex controlling system. The curve describes the relationship between outdoor air temperature and the amount of energy that is to be put into the building at the current time, i.e. the power needed to keep the current indoor temperature. Figure 7.2 is an example of a control curve.

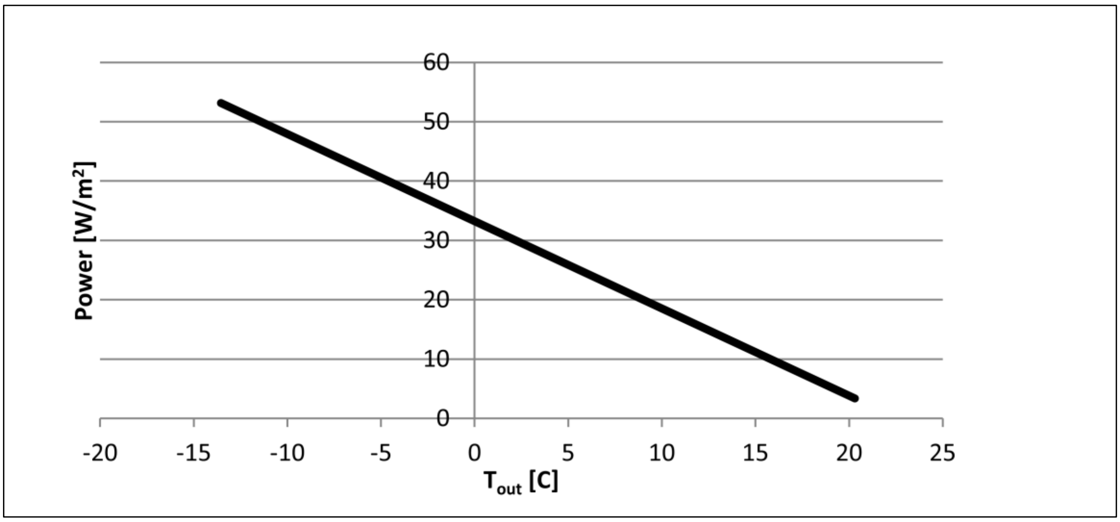


Figure 7.2 Example of a control curve.

The system used with control curves is described in figure 7.2. The basic idea is that the building is heated with district heating using a district heating central which is connected to the building. This central is also connected to an outdoor temperature sensor. Built into the district heating central's control unit is the control curve which controls how much energy the central will distribute to the radiators inside the building based on the outdoor temperature (Sasic A. 2012).

This is a cheap and simple way to control the indoor environment in residential buildings and is therefore widely used in Sweden (Johansson G. 2012).

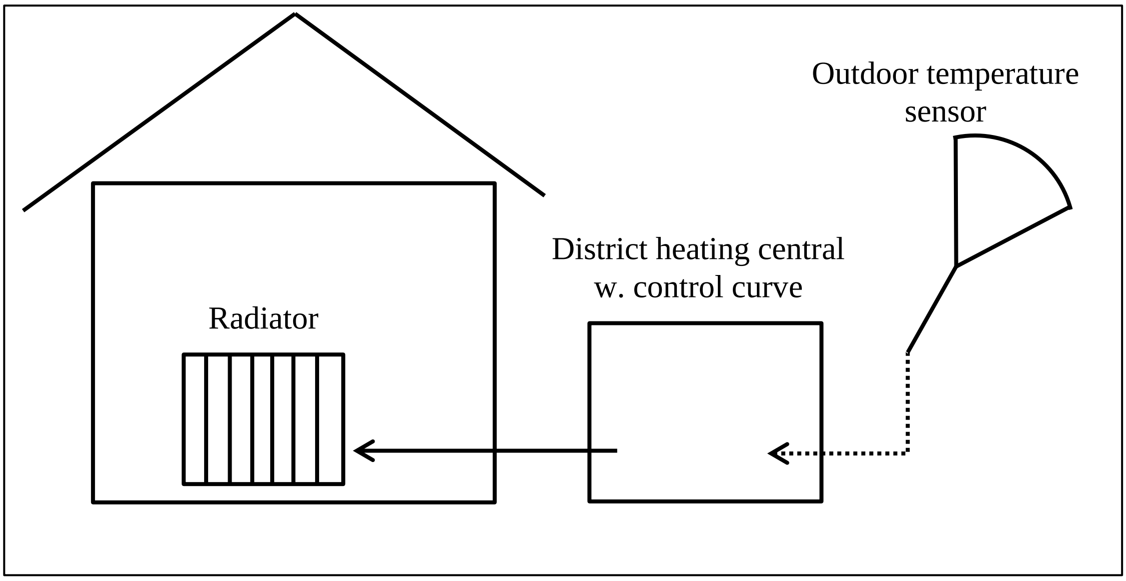


Figure 7.3 Example of a simple temperature controlling system that uses control curves.

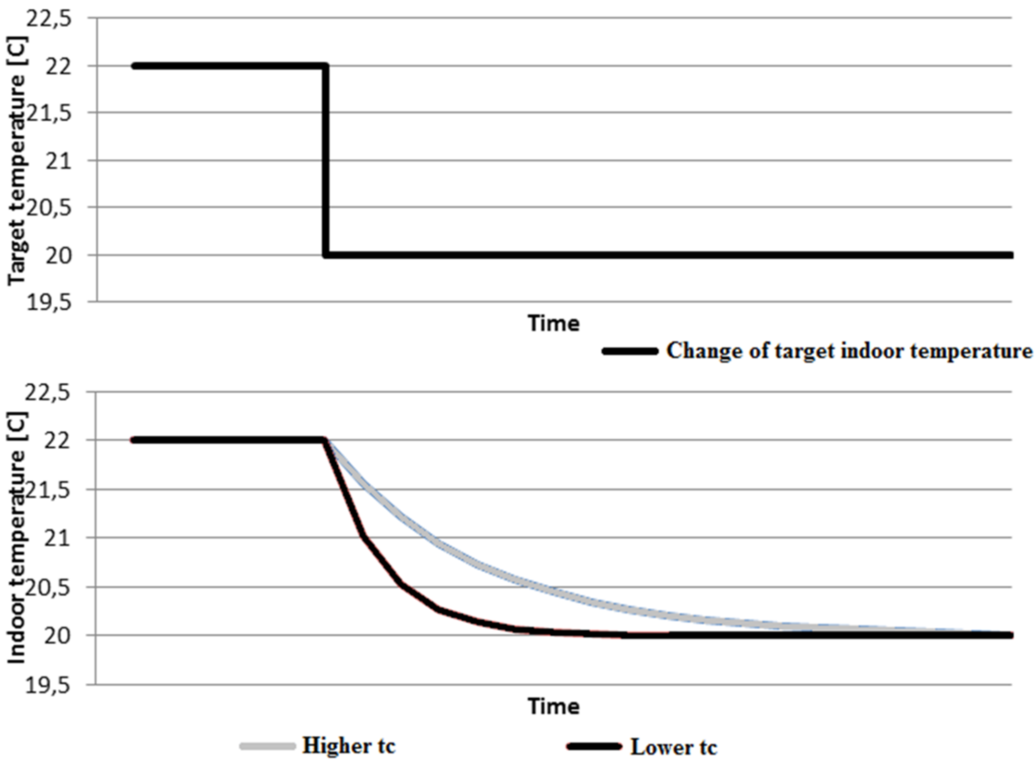
The curve is designed to describe the amount of power that is needed to keep a certain indoor temperature according to the buildings' thermal properties. As described earlier, this type of control system is very simple and only takes the outdoor air temperature into account. This means that solar radiation, wind and the resident's way of life, i.e. the size and pattern of the internal gains, will affect the indoor temperature in a way that the control system does not compensate for. Thereby the indoor temperature will vary depending on the time of day and year. When designing a control curve it is therefore desirable to create a curve that is well suited for all properties of the building, including location climate and residents' usage pattern. But the simple control system will still give an indoor temperature that varies.

7.1.1 Periodic Switch of Control Curves

When using a control curve to control the indoor temperature the power demand will vary in proportion to the outdoor temperature, as the control curve states. This means that when temperature drops the power demand will increase and create a peak, but also usage of hot water contributes to the power demand.

A method to reduce the peaks created by a simple control curve is to work with a set of different curves designed for different indoor air temperatures, and switch between them during a period of time, but without losing the comfortable indoor climate.

In theory, this method could redistribute the energy usage while keeping a good indoor environment, by taking advantage of the thermal mass (the thermal storage capacity) of the building. The thermal mass stores energy for short periods of time and can be used as an energy buffer. This buffer is then used during times when a peak would have occurred. The thermal mass buffering is described in figure 7.4.



$$t_c = \frac{Thermal\ mass}{K}\ [\mathrm{s}]$$

The time constant t_c depends on the thermal mass and the K-value (energy losses) of the building. T_c describes the time it takes for 63% of a temperature change to occur. (Hagentoft C. 2001)

In this example the target indoor temperature (or control curve with the target temperature) is changed from 22°C to 20°C in the district heating central, as seen in the upper part of the figure. This means that the energy input to the building is changed from what it takes to keep 22°C to what it takes to keep 20°C. In the lower part of the same figure the graphs of change in indoor temperature for two buildings are shown. One of the buildings have more thermal mass than the other, and therefore it responds slower to the change in power input because the thermal

Figure 7.4 Example of how thermal mass buffers energy and the time constant t_c can describe the delay in temperature change.

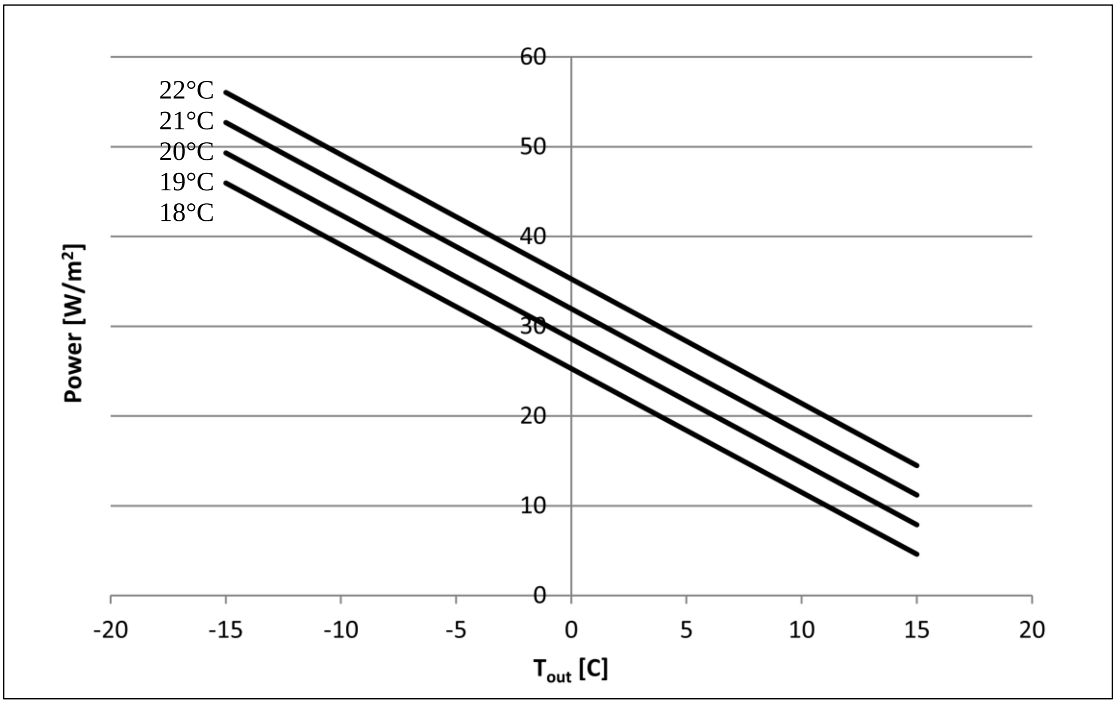


Figure 7.5 Example of control curves with different target temperatures.

This means that during a day the district heating central switches between curves designed for example 18, 19, 20, 21 and 22°C, see figure 7.5. The periods when to use which curve is decided from how the internal gain pattern looks, how hot water is used and what time of day and year it is. If the main target temperature is 20°C and the 18°C curve is currently in use, the power demand decreases but the indoor temperature will of course also decrease. But if this curve is only used for a short period of time the thermal mass will help stabilize the temperature and decrease the temperature drop. To regain the temperature to 20°C, a curve with a higher target temperature, such as 22°C, can be used when the outdoor temperature increases or when usage of hot water is low. Thereby the power demand is more constant throughout the day.

7.1.2 Creating Control Curves with Different Target Temperatures

To create new control curves with different target temperatures the simulation model is first set to use a heating system that is controlled by the indoor temperature, described as method one in chapter 6.5. With this method the indoor temperature is controlled strictly and the heater puts in the exact amount of energy that is required in the building. The target indoor temperature is set to the desired temperature before running the simulation; in this case each building is simulated with 18, 19, 20, 21 and 22°C as target temperatures.

The simulation model is set to simulate the time period January 1 to April 30 for year 2011 and 2009. All heating power data is saved during the simulations and divided into the two time periods January/February and March/April. These two sets of data are then plotted in the same way as the energy data from Göteborg Energi, as described in chapter four. From the cloud of data points a linear trend line is introduced. This represents the control curve for the current target temperature and time period, figure 7.6.

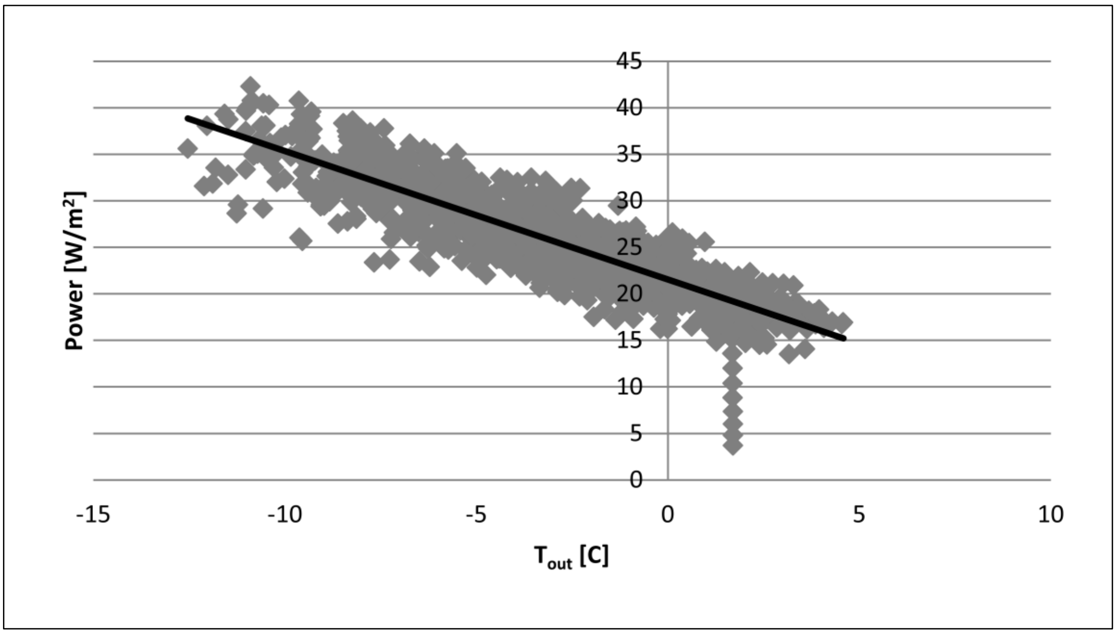


Figure 7.6 *Example of the cloud of data points with trend line obtained from heating power data saved during simulations. Due to the model not being stable during the first 7-8 simulated hours, the data points dropping down at about 2°C occur.*

To make sure that the acquired control curves are correct the curves from the two different years are compared to make sure that they are about the same. The curves are also put into the simulation model to be checked if they correspond to the target temperatures.

7.1.3 Simulations of Periodic Switch of Control Curves

A total of ten control curves are put into the simulation model for each one of the five archetype buildings. These curves represent target indoor temperatures of 18, 19, 20, 21 and 22°C, for the two periods of time (blocks) January/February and for March/April. See figure 7.7.

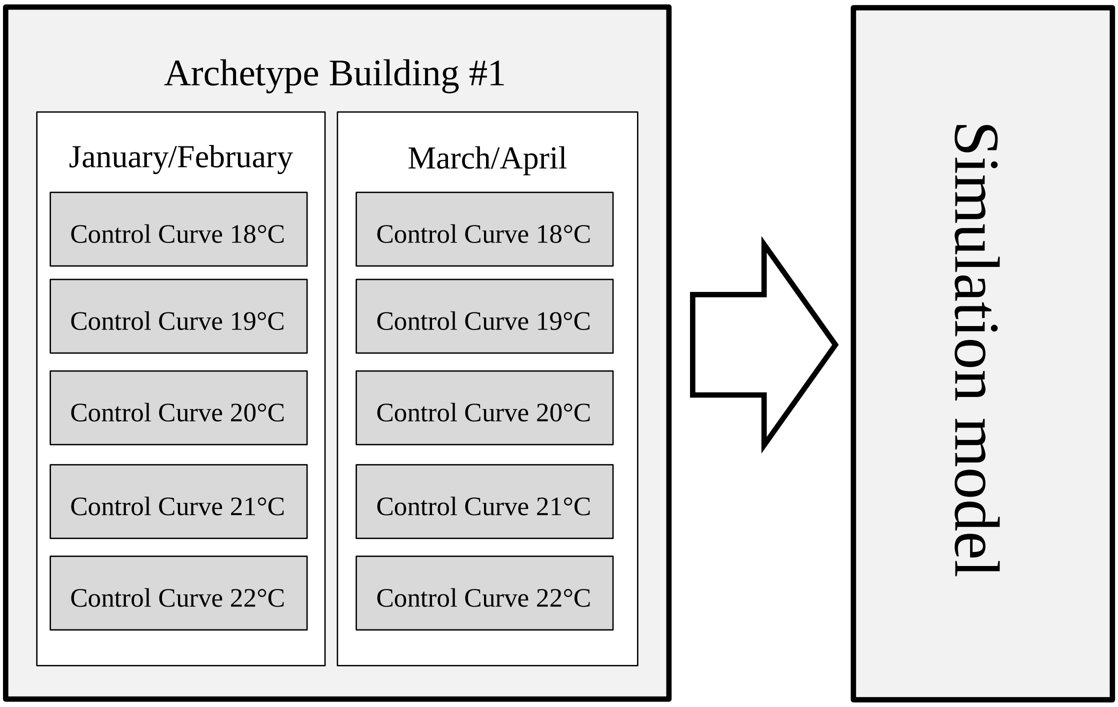


Figure 7.7 The simulation model contains ten control curves divided into two blocks for each archetype building.

The reason for using two blocks of curves is that the temperatures and solar radiation is different between the two periods January – February and March – April. If only one block of curves was used during both periods of time then the resulting indoor temperature would vary significantly and the results would not be as satisfying.

The scheme of when to use which control curve during the day is in this thesis called a setup. The setup is an instruction for the simulation model to decide which curve to use at what time, so the setup contains 24 values representing the 24 hours of the day, as in figure 7.8.

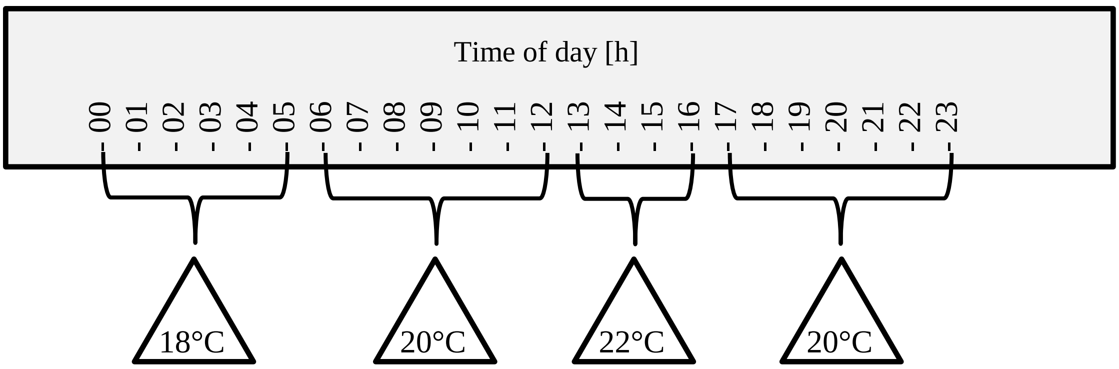


Figure 7.8 Example of a scheme of when a certain control curve is to be used during the day; in this thesis this scheme is called a setup.

The basic setup only uses the 20°C control curve and this setup is used as the reference of power demand peaks, which is to be reduced through alternative setups.

By running simulations and meanwhile changing the setup to achieve peak reductions an individual setup for each building is found. When doing this it is important to make sure the indoor temperature stays within reasonable values from the reference setup. In this way peak reduction can be obtained without compromising the indoor climate.

The way that the setup is designed is based on when energy is generally used during the day, both for space heating and to produce hot water, as well as the general outdoor temperature level. For example, when the hot water production is high the setup tries to minimize the space heating. Also, when the outdoor temperature is low the setup tries to minimize the space heating, and tries to compensate for this during the day when outdoor temperatures are higher.

7.1.4 Simulating Building Districts

To evaluate the method in a larger scale, such as building districts, the same simulation model has been used. The results from individual building simulations have been saved and then combined together with other individual building simulations using Microsoft Excel and Matlab. This way results can easily be combined and compared.

7.2 Local Energy Production Using Solar Panels

As a way to reduce peaks in power demand from district heating an additional energy source can be used. Solar radiation is an inexhaustible source which is easy to collect using a system that does not require much maintenance.

Solar energy can be collected in different ways, mainly using solar panels which produce electricity and by using solar thermal collectors that produce hot water. In this thesis a type of solar thermal collector will used, called evacuated tube collector. This collector consists of glass tubes with vacuum on the inside. Pipes run through the tubes with water that is heated by the solar radiation. Since the tubes are vacuumized, energy losses from the water to the surroundings are prevented.

The solar collectors are assumed to be placed on the roofs of the buildings and are therefore limited to this area.

7.2.1 Solar Energy to Reduce Power Demand Peaks

In theory, by introducing energy from the solar collectors at the time of power demand peaks the load on the district heating system could be reduced as seen in figure 7.8. This figure is an example of the potential of the system and may not be representative for the actual results.

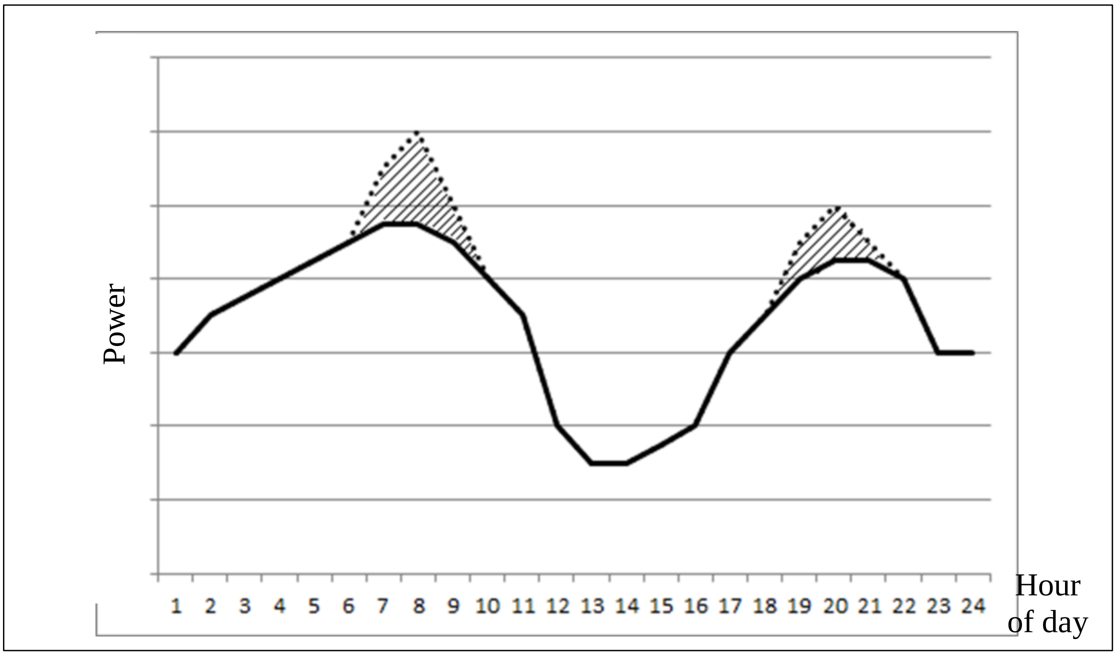


Figure 7.8 *Example of peak reduction by introducing solar energy into a building's heating system. The lined area represents the power gained from solar collectors to replace the peaks, and thereby reduce the district heating power demand from the dotted line to the solid line.*

In reality it is not as simple as figure 7.8 shows. Naturally, solar energy can only be collected during times when the solar collectors are exposed to solar radiation, sun light. This occurs during daytime, with a gradual increase until a peak is reached in the middle of the day, and thereafter a gradual decrease until the sun sets.

Due to the fact that outdoor temperatures are generally lower during night time than during day time, and that the usage of hot water is more concentrated around mornings and evenings, the power demand peaks do not occur during daytime. This means that power demand peaks and peaks of energy collection from solar collectors occurs at different times during the day, as described in figure 7.9. From this figure it is simple to state the fact that solar energy production does not take place at the same time when energy is needed the most (power demand peaks). The difference in amount of solar radiation during the day throughout the year is also an important factor. During cold periods such as January the amounts of solar radiation is small but the need for heating energy is large. In figure 7.10 the mean amount of solar radiation during the days of January, February, March, April and May is represented.

By simulating the method the results will determine whether or not it is possible to supply sufficient energy for solar collectors, both during the entire day and during times of peak load in the district heating system.

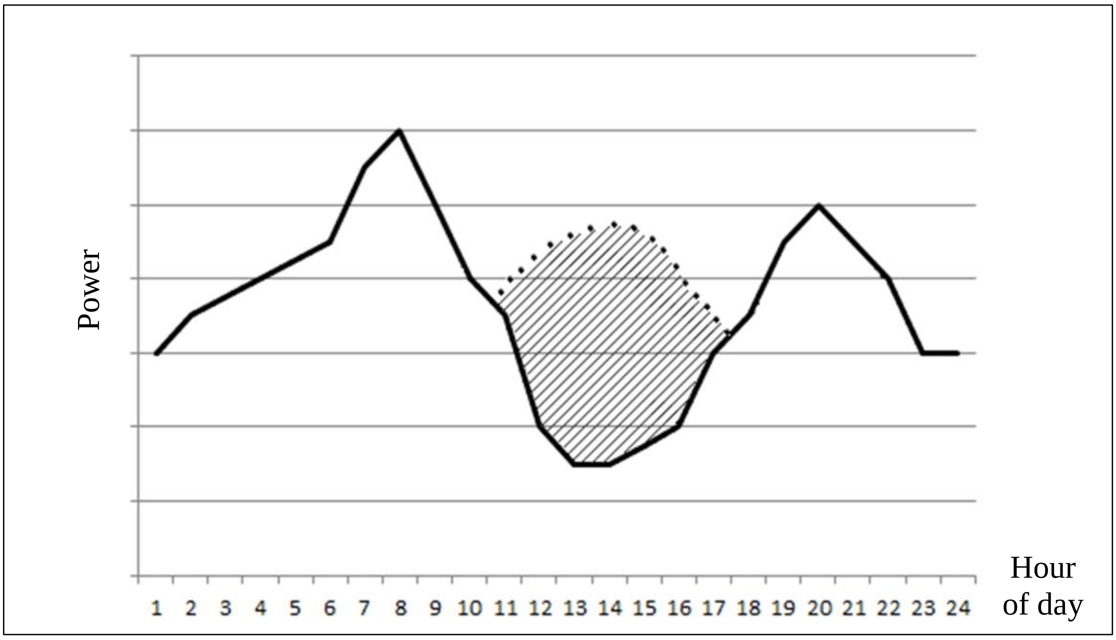


Figure 7.9 *Example of when energy is collected by solar collectors (dotted line with lined area) during the day in comparison to when actual peaks in power demand occur during the day.*

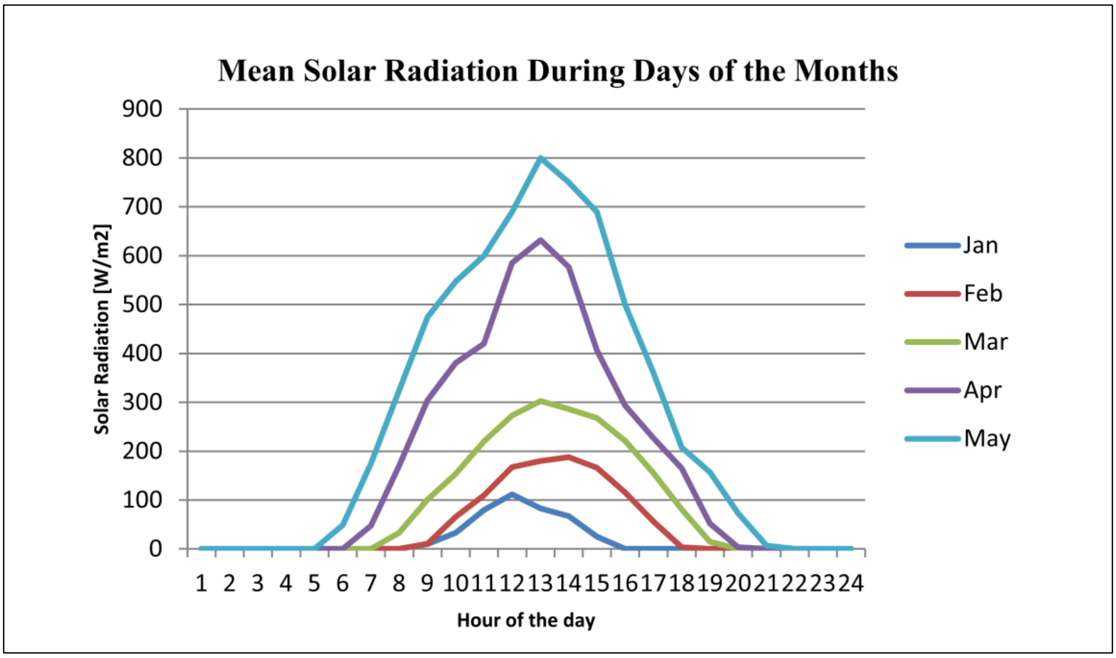


Figure 7.10 *Mean amounts of solar radiation during days of January, February, March, April and May in 2011.*

7.2.2 Different Approaches to the Method

Because of the difference in time when peak loads occur and when peaks of solar energy production occur, this thesis concentrates on two different approaches to utilization of the energy collected with solar collectors to reduce power demand peaks.

The two different approaches to this method are both based on the idea to redistribute the collected energy to times when power demand peaks occur. The first method is to introduce the collected energy into the building without any delays. This means that the solar collectors distribute the energy straight into the building right after the energy has been collected, without any temporary storage on the way.

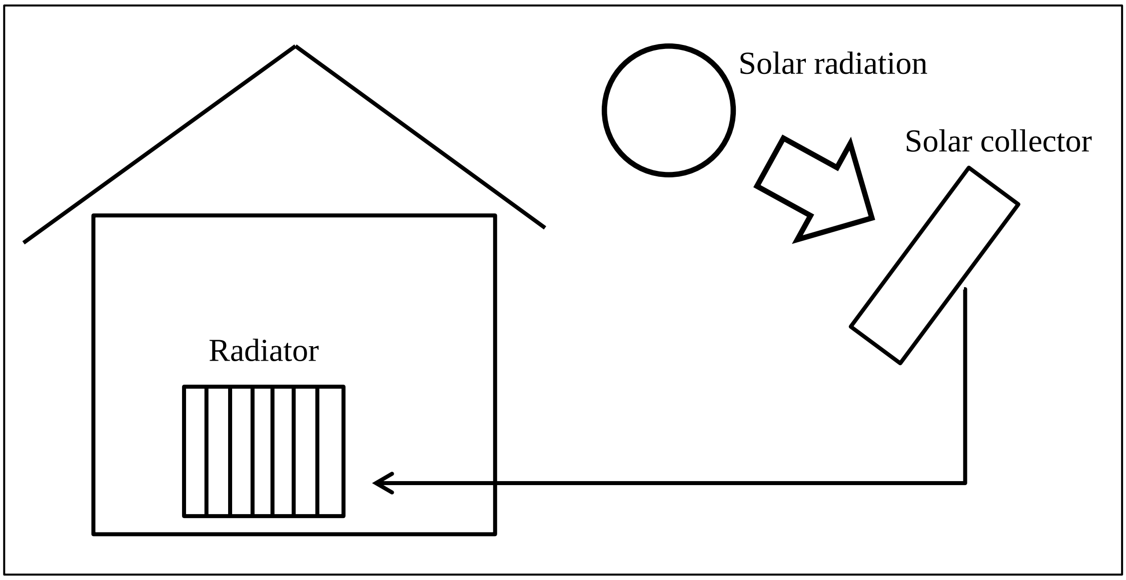


Figure 7.11 The first (out of two) approach to the peak reducing method of using solar energy to reduce power demand peaks. Solar energy is directly distributed into the building's heating system without temporary storages.

This approach is based on the idea that a surplus of energy, both from solar collectors and heating system, is put into the building during the day. The thermal mass is then used to keep the energy inside the building until dusk and this way the heating system can run on low capacity during evening and possibly during night, when power demand peaks occur.

The second approach is similar to the first but uses an accumulator tank between the solar collectors and the heating system in the building. The tank is used to store the collected solar energy and allows it to be used when desired, such as during power demand peaks.

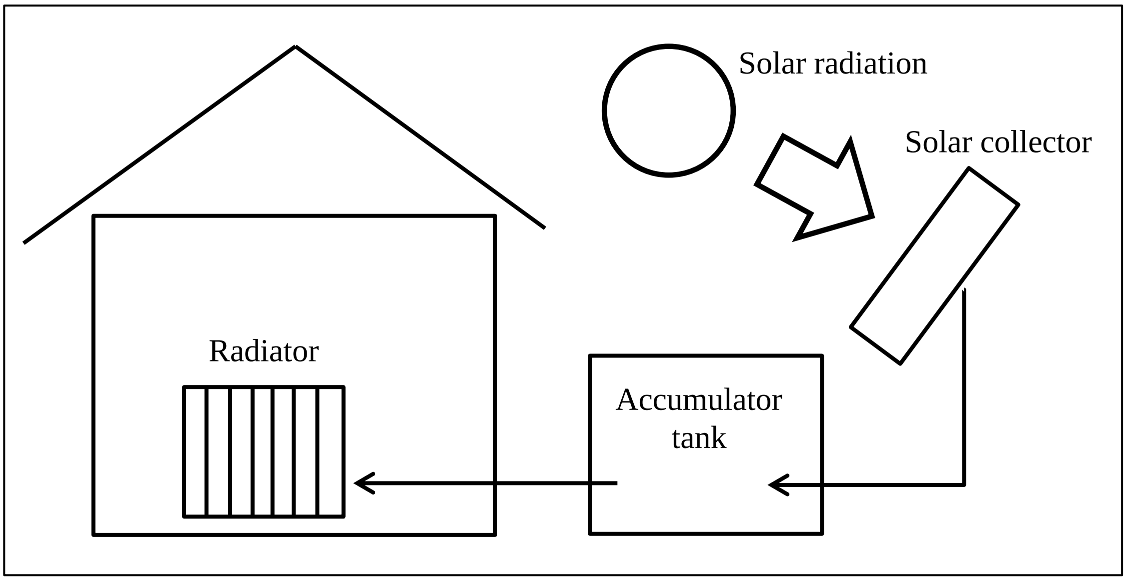


Figure 7.12 The second approach to the peak reducing method of using solar energy to reduce power demand peaks. Solar energy is distributed into an accumulator tank where it is stored. The energy is then distributed into the building whenever needed.

7.2.3 Simplifications in Simulation

When simulating this method, some simplifications are made.

The solar collectors will be assumed to have an efficiency of 80% and the total panel area is set to vary between 50-150m^2 depending on the total heated indoor area. Having atleast 0.02 m^2 solar panel per heated square meter worked the best which was found by empirical tests. The maximum panel area is limited to the roof area of each building. This is further discussed in chapter 10.

The panel inclination is assumed to be optimized at all times, meaning that maximum amount of solar radiation hits the panels.

Both approaches to the method are controlled according to a scheme similar to the setups used in the previous method. The approach using solar energy directly is set to lower its heating system a couple of hours after dusk and the second approach is set to only energy from the accumulator tank during certain hours when power demand peaks occur.

The second approach is also set to only use a maximum of 2 W/m^2 from the tank during January, and 4 W/m^2 during April. These values were empirically found to fit with the available solar energy and still be able to reduce most of the peaks. Other control parameters than these would of course be used if the method was applied in a real case, this is discussed more in chapter 10.

Difficulties to combine district heating centrals with a solar collecting system are not taken into account. Neither does it account for times when the solar collecting system cannot be used due to too high pressures or other mechanisms that could prevent its function (Johansson G. 2012). For evaluation purposes it is assumed that the solar collecting system will run at all times when there is solar energy available.

8 Theoretical Simulation Days

In order to evaluate the different methods and to be able to get an idea of the potentials without getting interference from general trend changes in the weather a simplified weather profile was created. This contains a continuously and fixed variation of the outdoor temperature and is based on a sinus function. It also contains wind and solar data which is based on the mean values from the real weather data.

The chosen days are one day in January and one day in April. The January day represents the winter season and the April day represents the spring and fall seasons. The summer season was ignored since we focus on heating and most heating systems are turned off during this season. The Gothenburg weather data will be used when creating these weather profiles.

The two created days can be seen in figure 8.1 below. The biggest difference between the two days is the amount of solar radiation where the April day has roughly 10 times as much solar radiation as the January day.

The temperature variation of the representative day is calculated by using equation 8.1.

$$T_{out}(t) = T_{mean} + T_{amp} * sin\left(2\pi * \frac{t}{24} - \pi * \frac{16}{24}\right) \quad (8.1)$$

Where:

T_{out} is the outdoor temperature. [K]

T_{mean} is the mean temperature of the day. This value is found in the weather data and is the mean value of all temperature data from the current month. [K]

T_{amp} is the temperature variation throughout the day. This value is found in the weather data and is the average between all daily variations of the current month. [K]

t is the hour of the day. [-]

The reason for using the sinus formula to calculate the temperature, instead of using the mean values from the corresponding month, is that the temperature trend of the months has a very large impact on the mean values. This will result in a temperature profile without any daily variations.

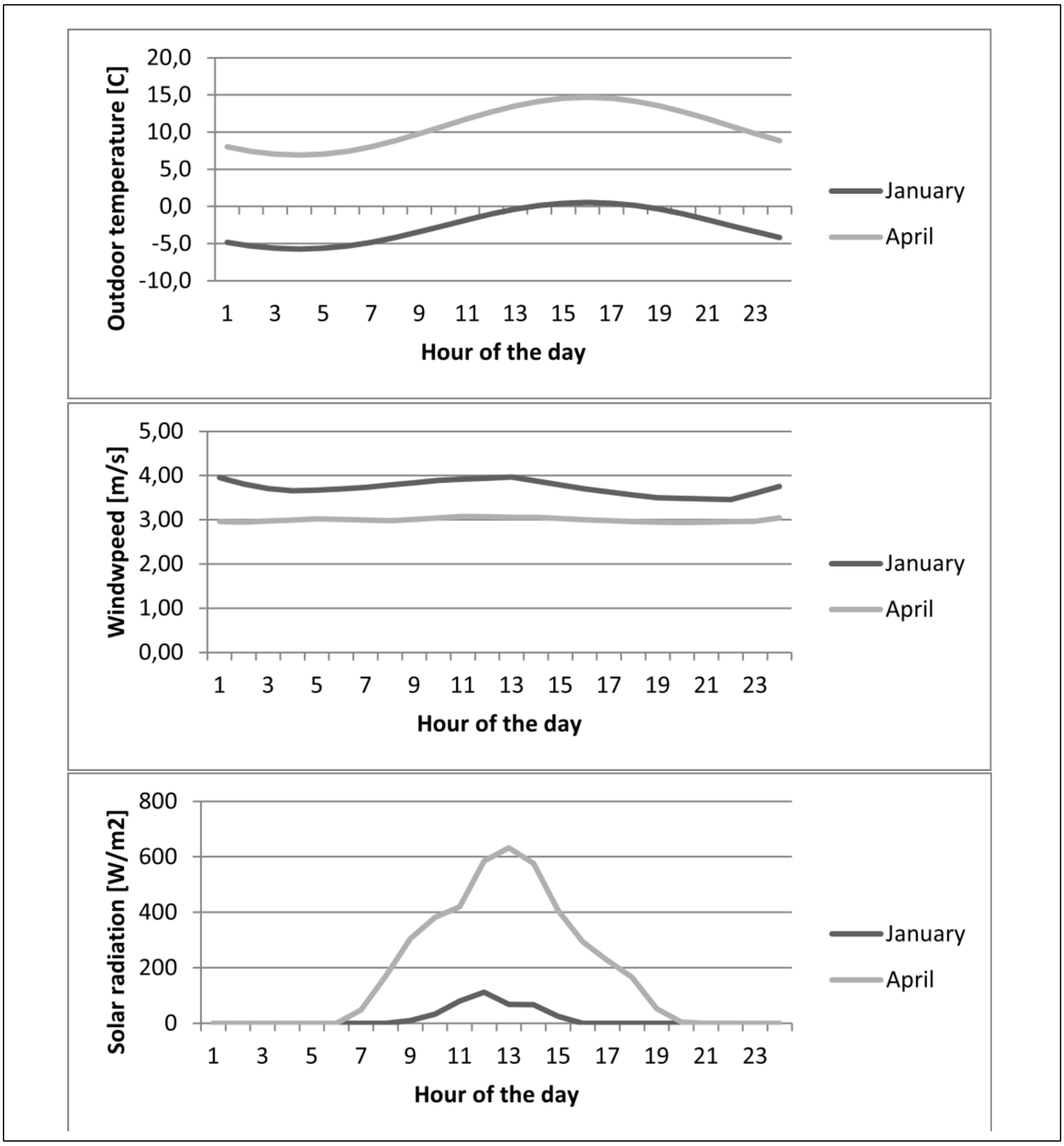


Figure 8.1 Comparison of weather January and April. Note that this is the created representative day and not the real weather during this period.

9 Results

In this chapter the final results of the peak reducing methods are presented. Note that the results are not discussed or analysed in this chapter, this is done in chapter 10. All results are based on the weather in Göteborg if nothing else is mentioned in connection to the specific result.

9.1 Periodic Switch of Control Curves

As described in chapter 7.1.3, the scheme of when to use which control curve during the day is called a setup. By empirically changing the reference setup which uses the 20°C control curve throughout the day, an alternative setup is achieved. The reference setup is called setup 1 and the alternative setup is called setup 2 in the figures. In all setup figures, the curve number represents the target temperature of the control curve, i.e. curve 21 represents the curve with target temperature 21°C.

The alternative setups are achieved by running simulations using the theoretical days for both January and April, described in chapter 8. This gives the possibility to change the setup between January and April, which is the case for archetype building 1.

Two requirements has to be taken into account while designing the alternative setups, as mentioned earlier the indoor temperature has to be within reasonable limits from the temperature that was given by the reference setup. The second requirement is that the total energy consumed during the simulated period is also within reasonable limits from the amount of energy consumed by the reference setup.

All alternative setups for each one of the archetype buildings have satisfied these two requirements. The total consumed energy for each building and setup is presented in table 9.1.

Table 9.1 Total consumed energy by the reference setup (setup 1) and the alternative setup (setup 2) and the difference in consumption, during a simulated 30 day period.

Archetype Building 1		**Archetype Building 2**		**Archetype Building 3**		**Archetype Building 4**		**Archetype Building 5**	
30 theoretical days in January									
Setup 1	Setup 2	Setup 1	Setup 2	Setup 1	Setup 2	Setup 1	Setup 2	Setup 1	Setup 2
21.87*	21.77*	26.11*	26.10*	21.82*	21.81*	20.73*	20.72*	21.14*	21.13*
-0.46%		-0.04%		-0.05%		-0.05%		-0.05%	
30 theoretical days in April									
Setup 1	Setup 2	Setup 1	Setup 2	Setup 1	Setup 2	Setup 1	Setup 2	Setup 1	Setup 2
7.72*	7.66*	9.28*	9.19*	7.83*	7.81*	7.40*	7.38*	7.77*	7.70*
-0.78%		-0.10%		-0.26%		-0.03%		-0.90%	

* *In [kWh/30 days]*

The resulting alternative setups can be viewed in figure 9.1. Note that these turned out to be the same for both periods January/February and March/April for all buildings except for archetype building 1, which uses two different setups for the two time periods. This is discussed further in chapter 10.

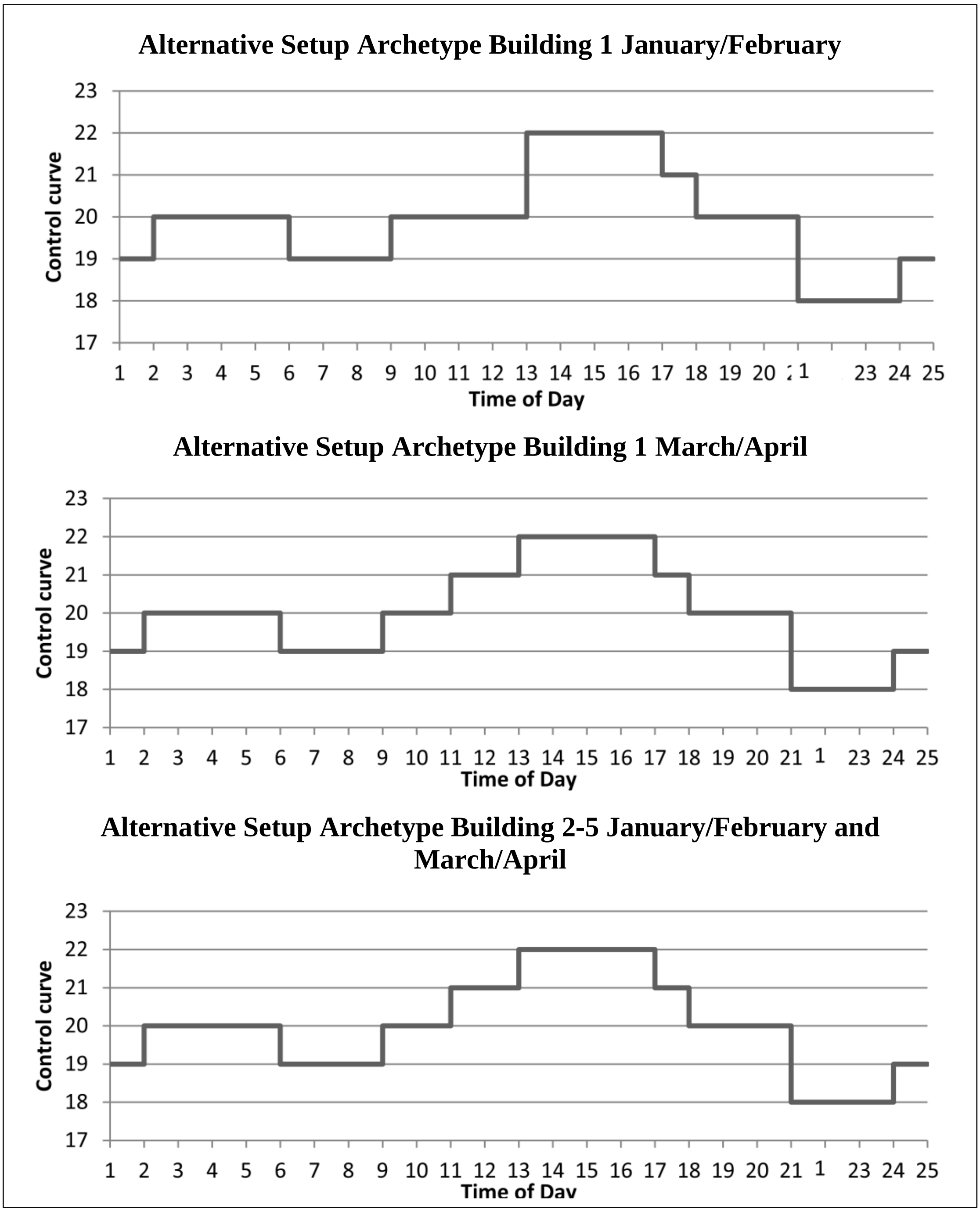


Figure 9.1 Final alternative setups for all archetype buildings. The control curve number represents the target temperature of the control curve.

In figure 9.2 and 9.3 the resulting alternative setups for archetype building 3 is presented together with power demands and indoor temperatures for both theoretical days in January and April. Note that this is a simulated weekday. During weekends these graphs change a bit due to different usage pattern of hot water; this is further discussed in chapter 10. The figures show the total power demand from the district heating central, which is space heating and hot water heating combined.

The final alternative setups, power demands and indoor temperatures from simulations of theoretical days for all archetype buildings can be found in appendix B. The results are presented in the same way as the archetype building 3 results included in this chapter.

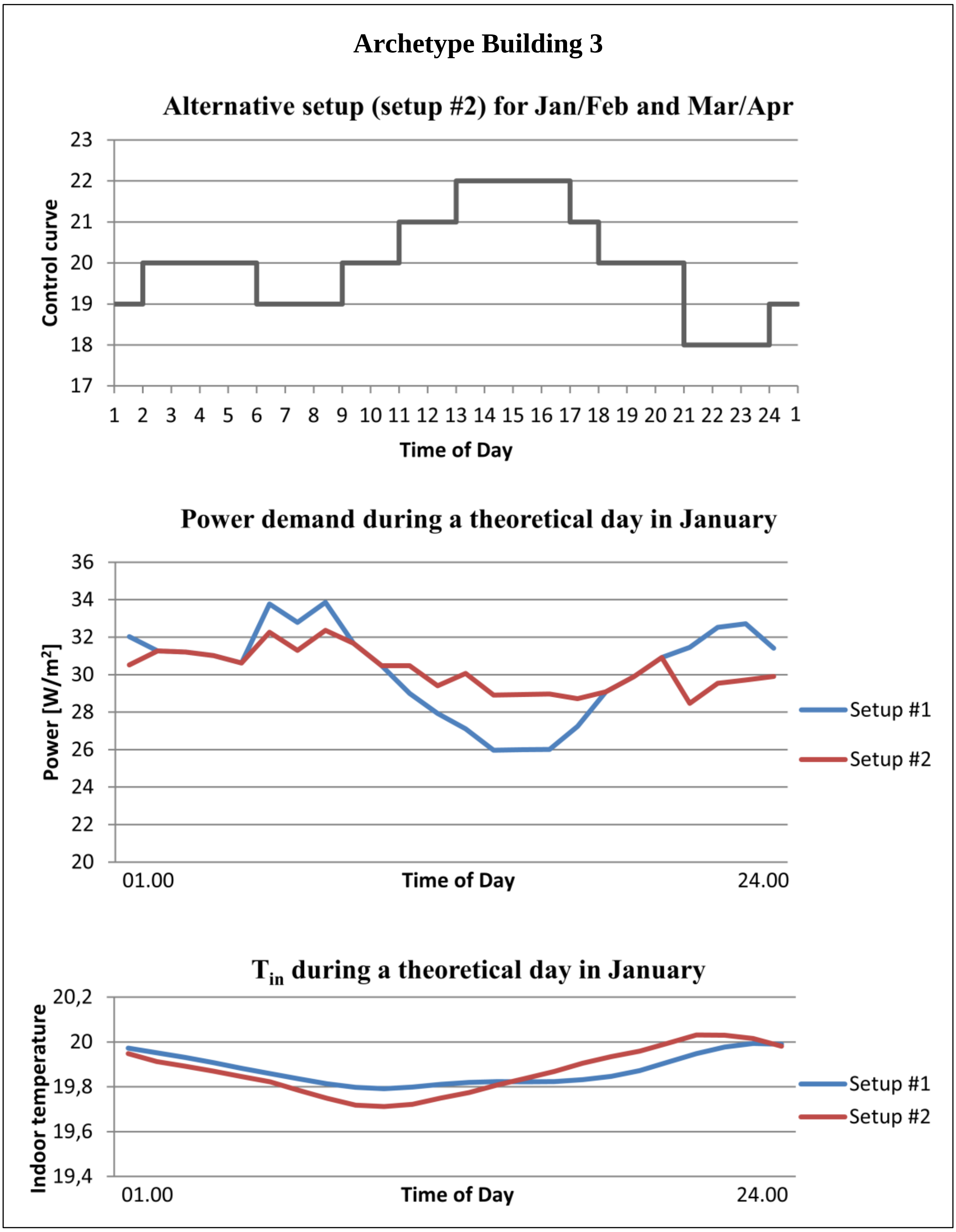


Figure 9.2 *Results for archetype building 3 when simulating a weekday with the theoretical day for January. Setup 1 is the reference setup and setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.*

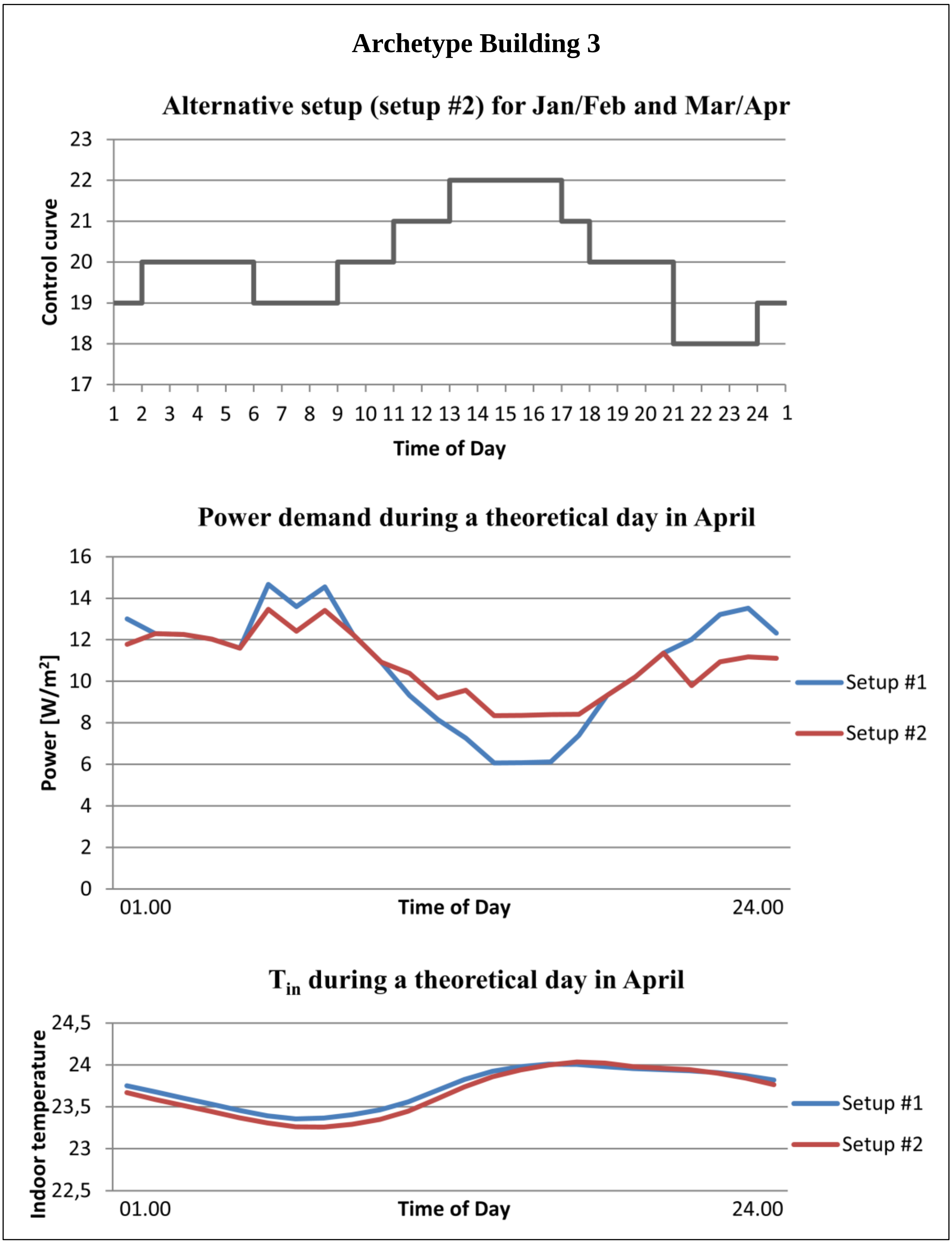


Figure 9.3 *Results for archetype building 3 when simulating a weekday with the theoretical day for April. Setup 1 is the reference setup and setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.*

To investigate how the alternative setups change the power demand under the influence of more realistic weather data, simulations are run with real weather data.

Simulations are carried out using weather data for Göteborg from 2009 and 2011, and the power demand is monitored. To show the results, two weeks have been chosen from 2009, the fourth week in January and the fourth week in April. The results from archetype building 2 are presented in figure 9.4 and 9.5, while the results for the remaining archetype buildings can be found in appendix C.

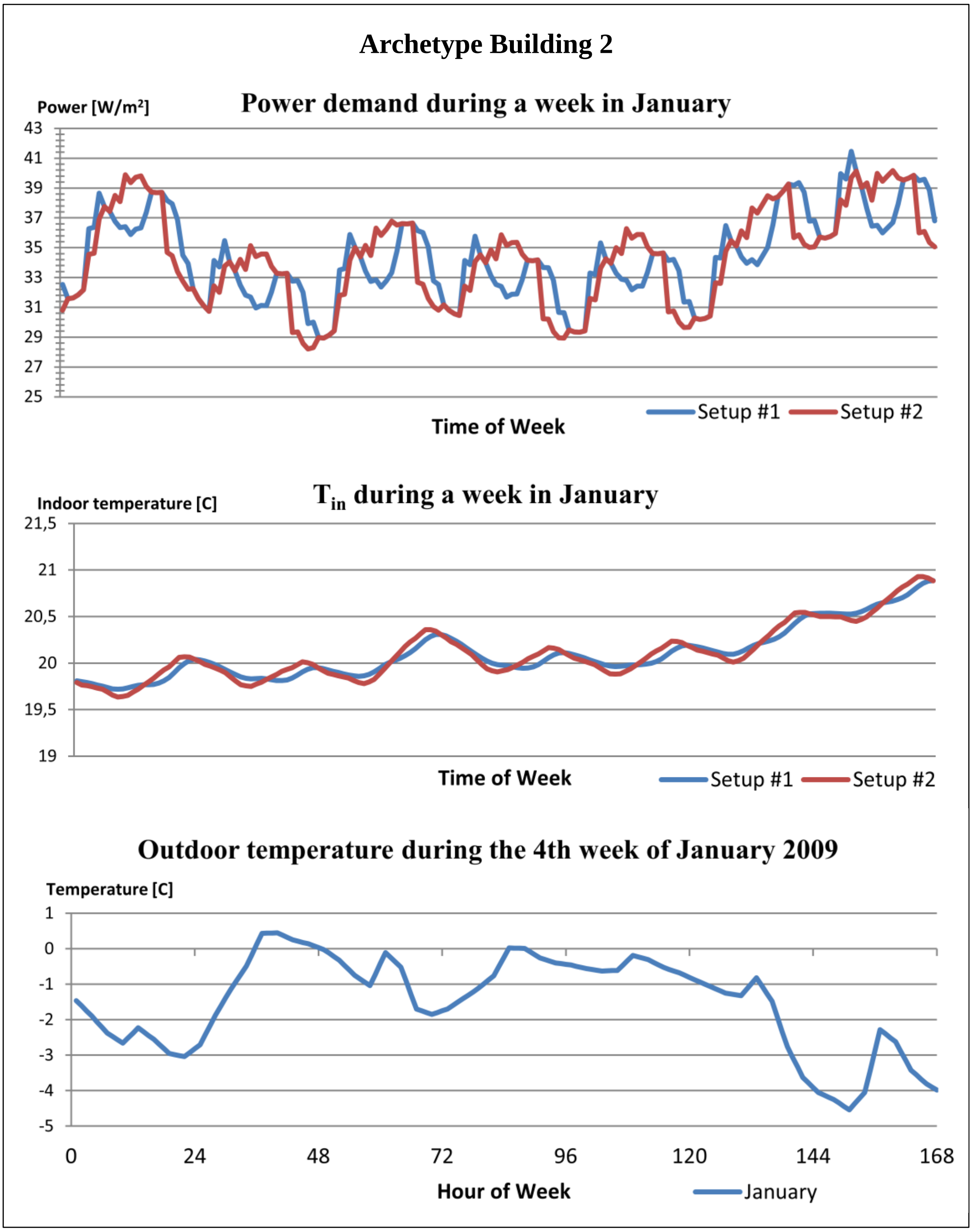


Figure 9.4 *Results for archetype building 2 when simulating the fourth week in January 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.*

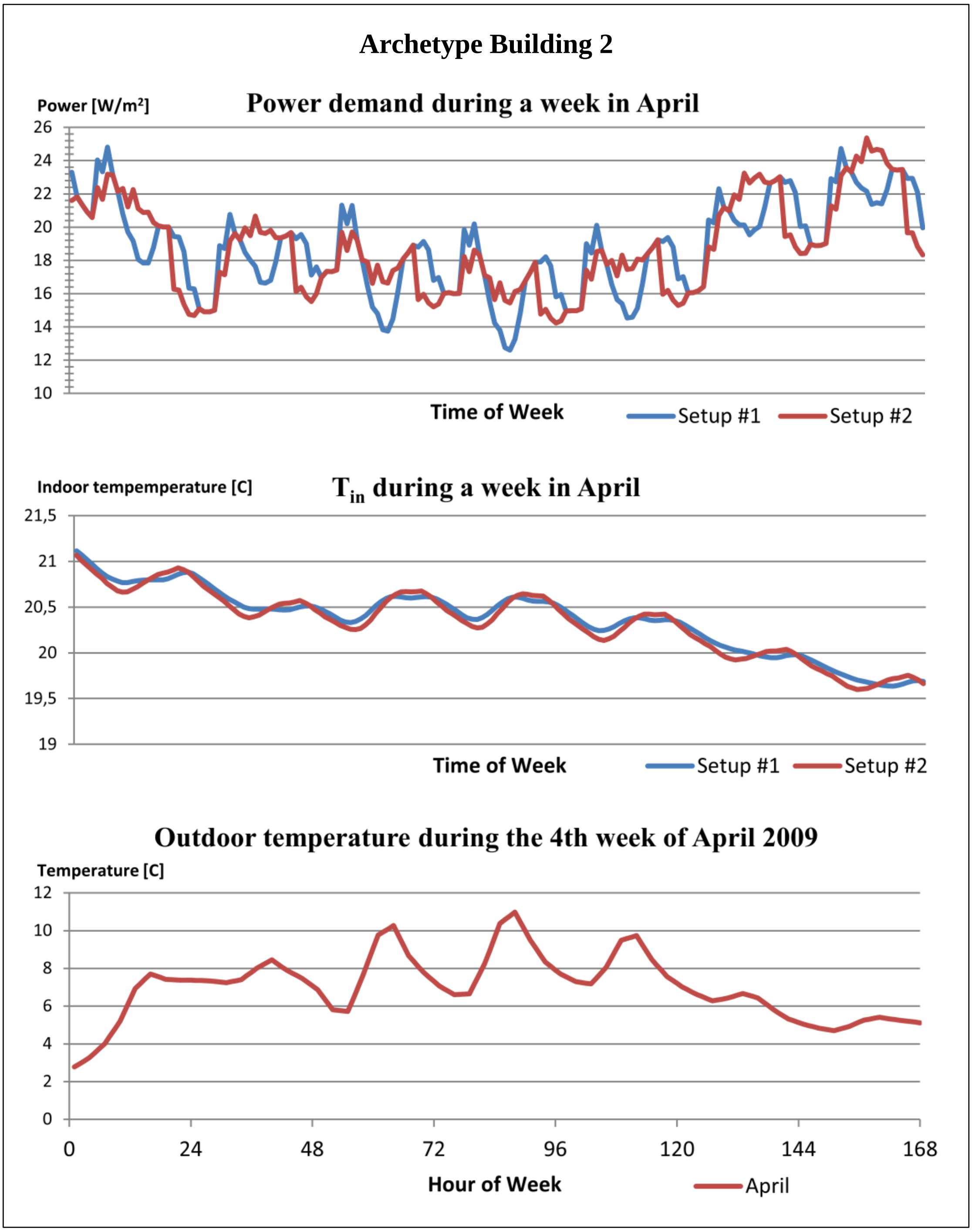


Figure 9.5 *Results for archetype building 2 when simulating the fourth week in April 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.*

To further investigate the behaviour and potential of this peak reducing method, simulations were carried out using weather data from Denver in Colorado, USA. Denver is known for its rapid weather changes due to its high altitude location at the foot of the Rocky Mountains. The temperature varies a lot throughout the day with big temperature differences between day and night, which resembles a sinus curve pattern.

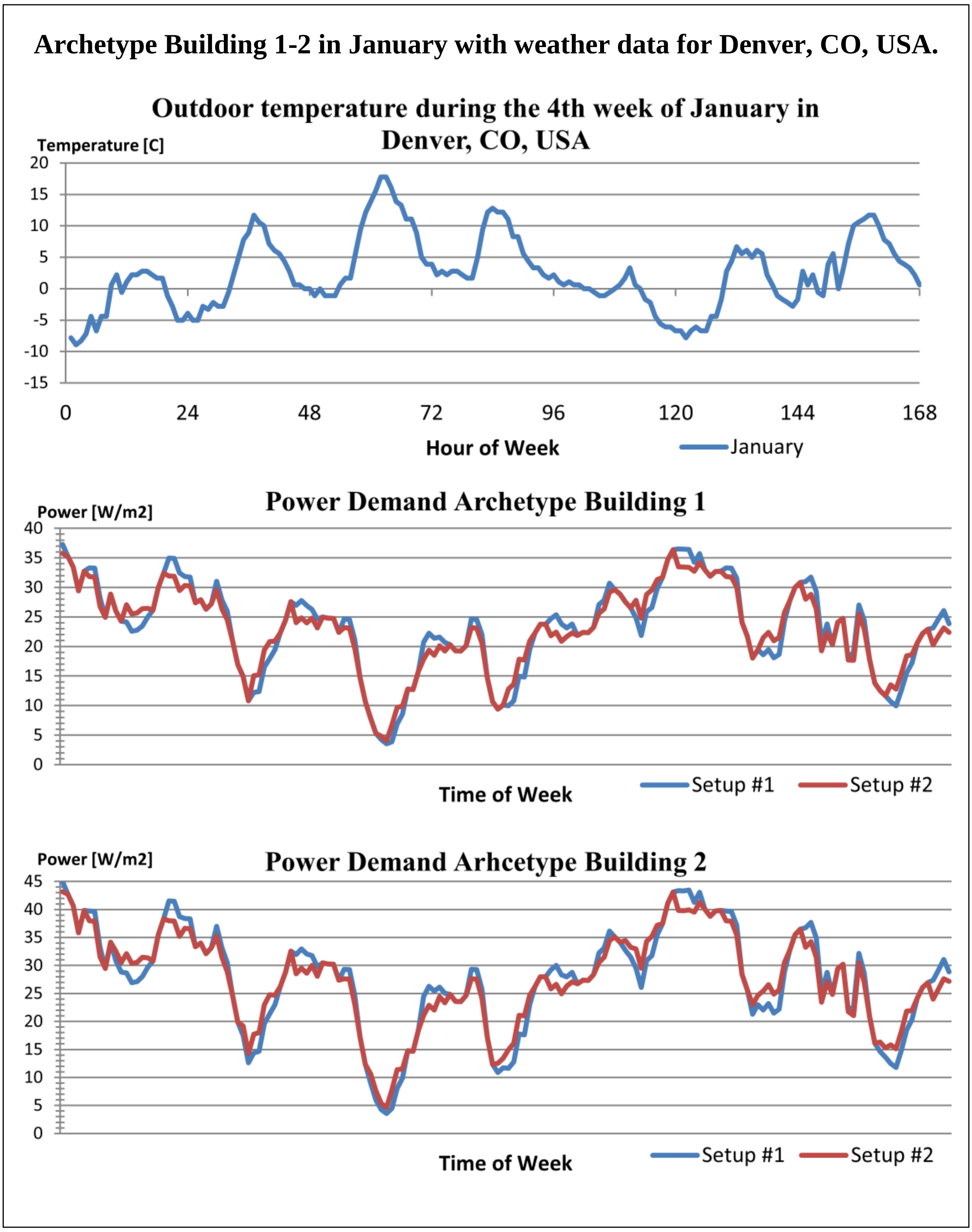


Figure 9.6 *Results for archetype buildings 1 and 2 when simulating the fourth week in January in Denver, CO, USA. Setup 1 represents the reference setup and setup 2 the alternative setup.*

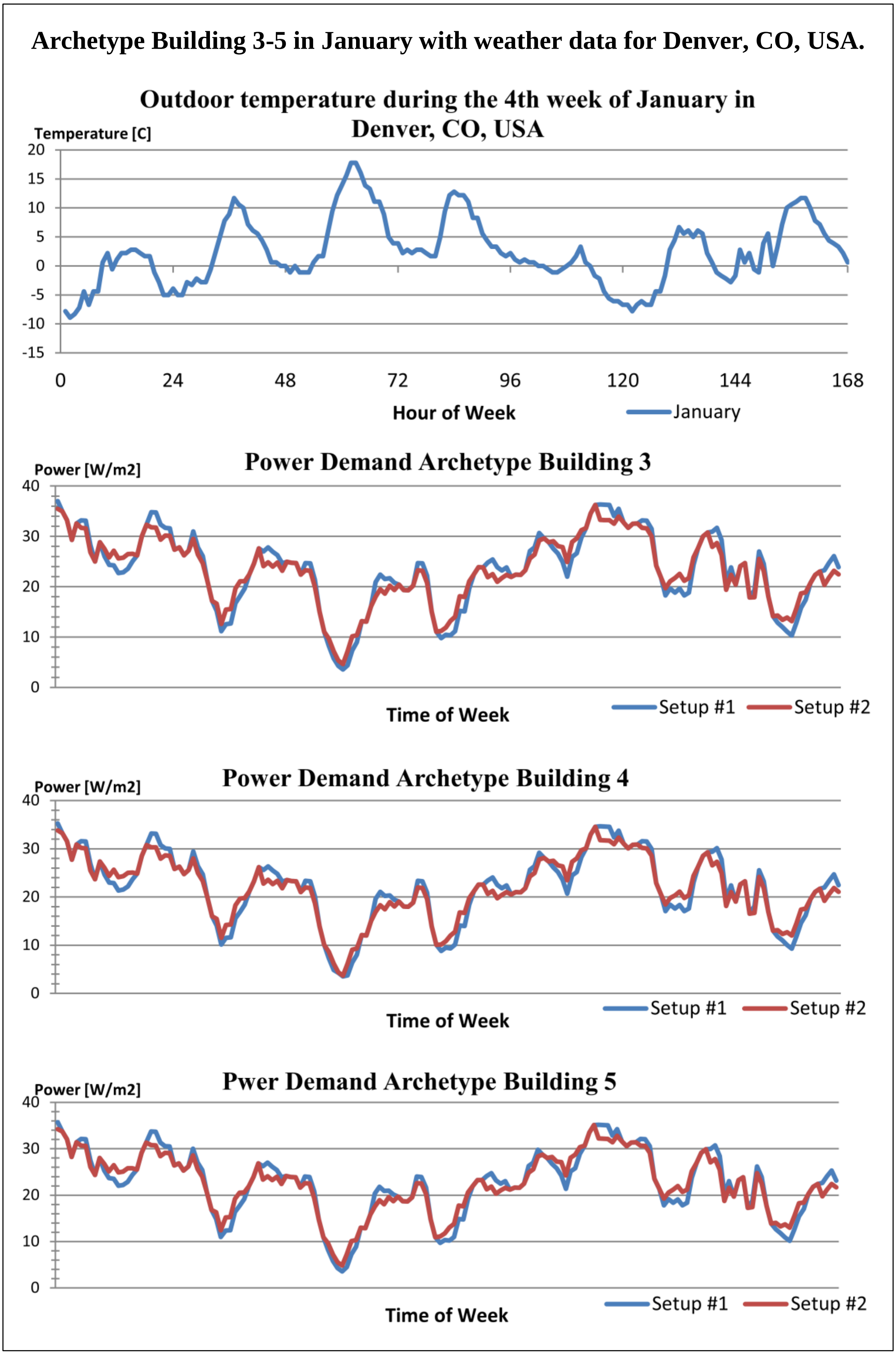


Figure 9.7 Results for archetype buildings 3, 4 and 5 when simulating the fourth week in January in Denver, CO, USA. Setup 1 represents the reference setup and setup 2 the alternative setup.

9.2 Solar Energy to Reduce Power Demand Peaks

As mentioned in chapter 7.2.2 there are two different approaches to the method which adds solar energy into the heating system. These two different approaches will be presented in separate chapters.

9.2.1 Direct Addition of Solar energy

The first approach to the method adds the solar energy directly to the building in order to heat the building volume and subsequently heat the thermal mass of the building. This stored energy will then be used to reduce the next upcoming energy peak that occurs; the afternoon peak, see figure 9.8. If enough solar energy is available this approach might also be able to be used to reduce the morning power demand peak.

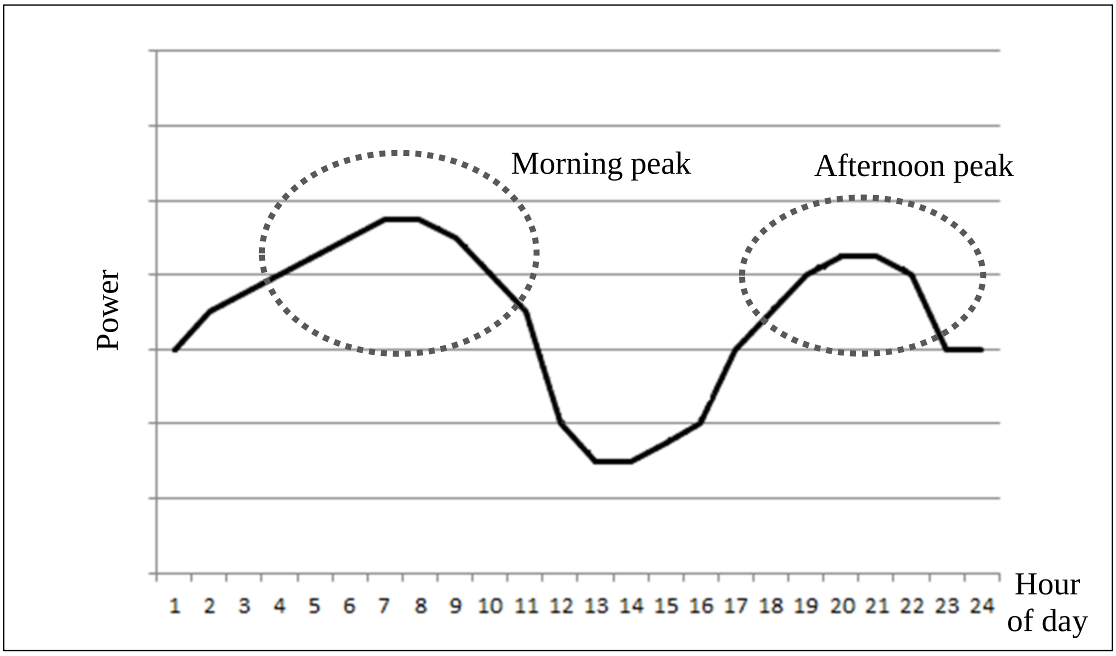


Figure 9.8 Example of power demand peak distribution during a typical day, with two main peaks during the day, in the morning and afternoon.

Simulations were first carried out using the theoretical days for January and April, as described in chapter 8. The results were not satisfying enough to work as a foundation for calculating potentials. Instead they can mainly be used to describe a general behaviour trend of the building when this method is applied. In figure 9.9 the result from simulations of archetype building 1 with theoretical days are presented. Results with theoretical days from the other archetype buildings have not been included in this thesis due to the lack of importance.

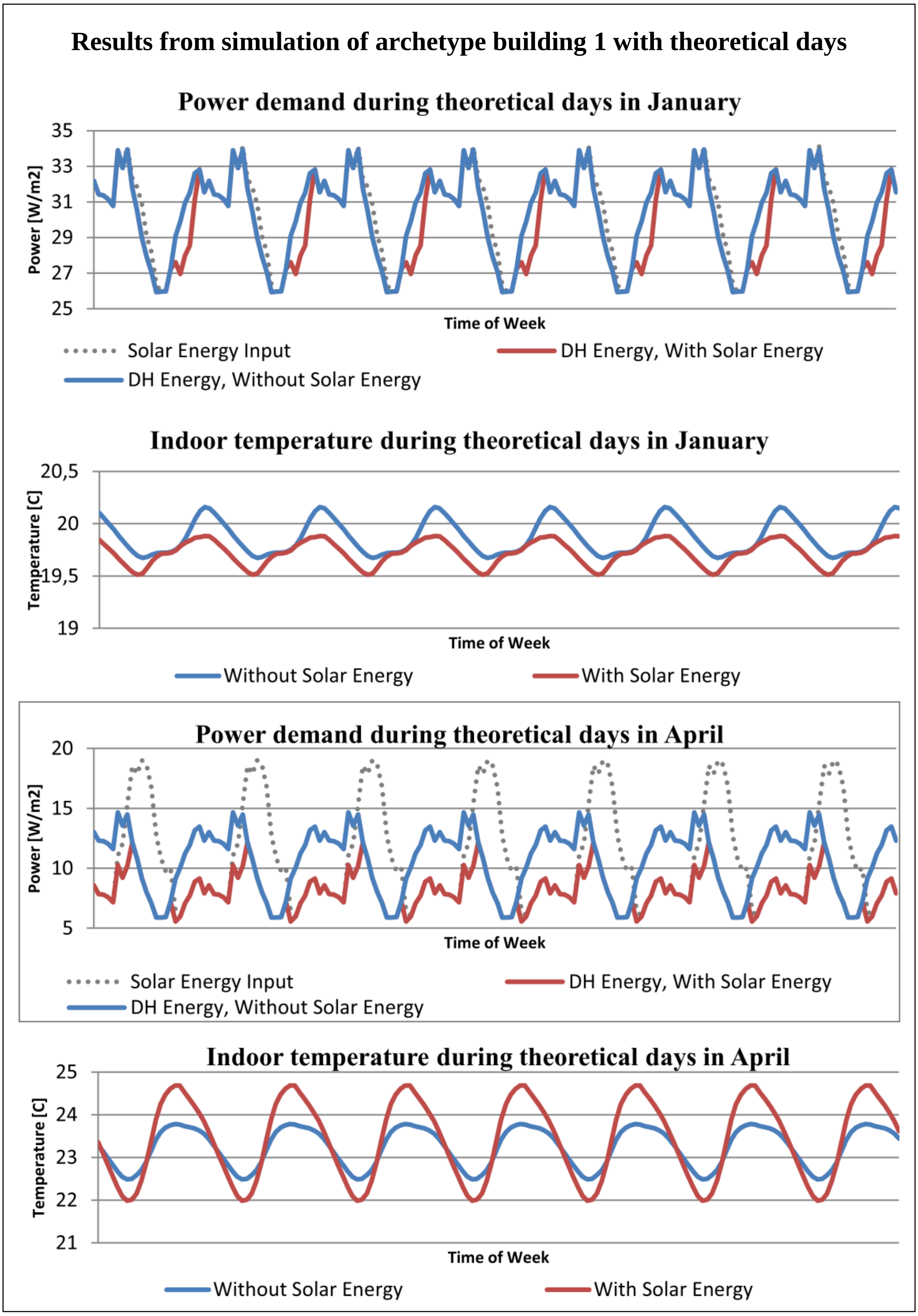


Figure 9.9 *Results from simulations of archetype building 1 using weather data for a theoretical day in April. The solid curves represents the power demand from district heating (DH) during a simulation with and without the peak reducing method. The grey dotted curve describes the solar energy input into the. Power demand includes both space heating and hot water.*

To be able to investigate the potential of the method, simulations have to be carried out using real weather data. By doing it this way the effects of differences in solar radiation between days and months can be investigated and the method's potential can be estimated.

Simulations were carried out using weather data for January, February, March and April from 2009. One week from each month was selected to determine the effects of changing solar radiation between days, and the potential this method has.

The results of power demand in archetype building 3 during the four simulated months are presented in figure 9.10. The remaining archetype building's results can be found in appendix D. The presented power demands include both district heating power for space heating and hot water heating.

In figure 9.11 the corresponding indoor temperature results are presented. These are the achieved indoor temperature variations caused by the power input described in figure 9.10. The temperature results of remaining archetype buildings can also be found in appendix D.

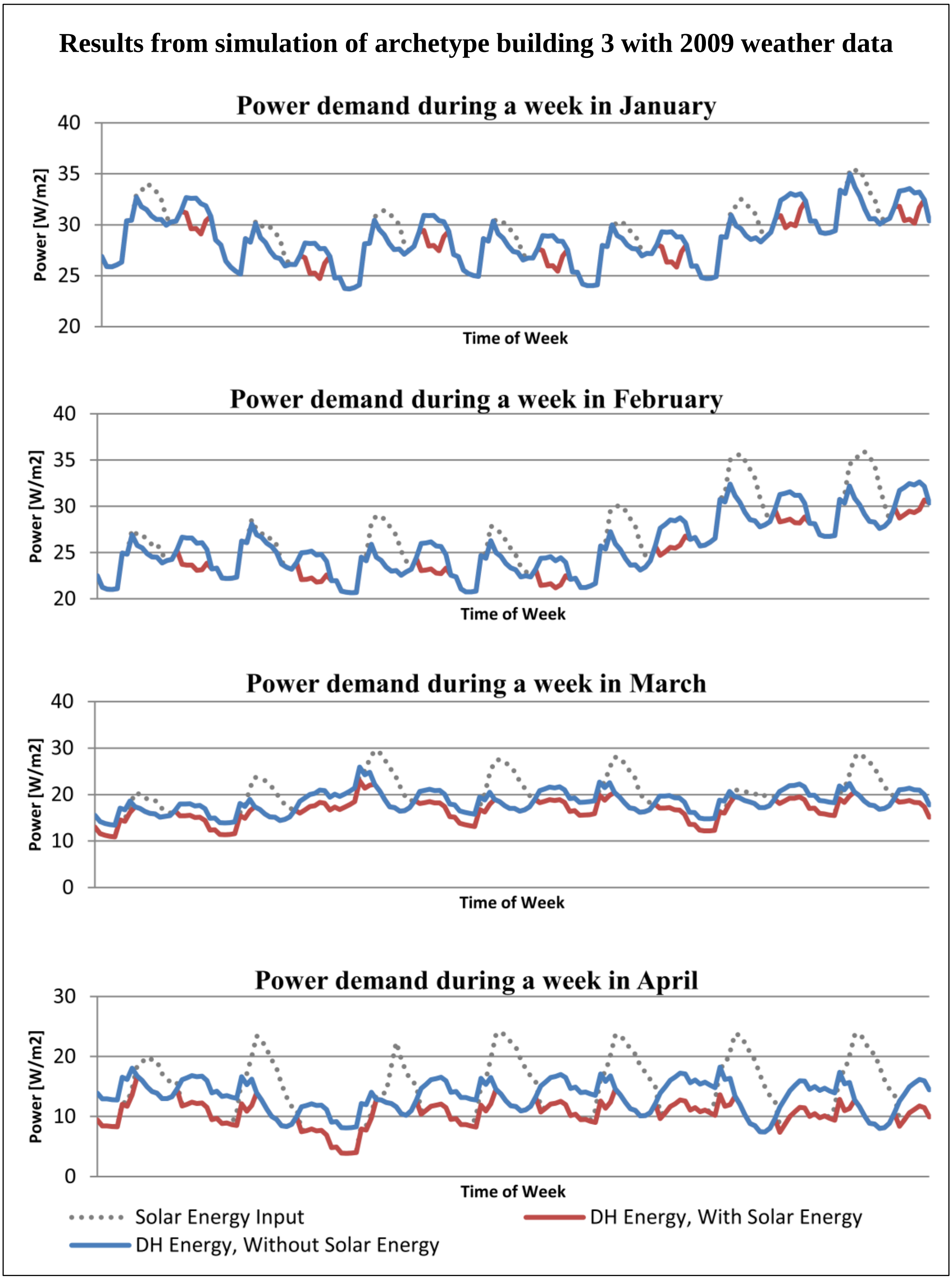


Figure 9.10 *Results from simulations of archetype building 3, using weather data from four months in 2009. The solid curves represents the power demand from district heating (DH) during a simulation with and without the peak reducing method. The grey dotted curve describes the solar energy input into the. Power demand includes both space heating and hot water.*

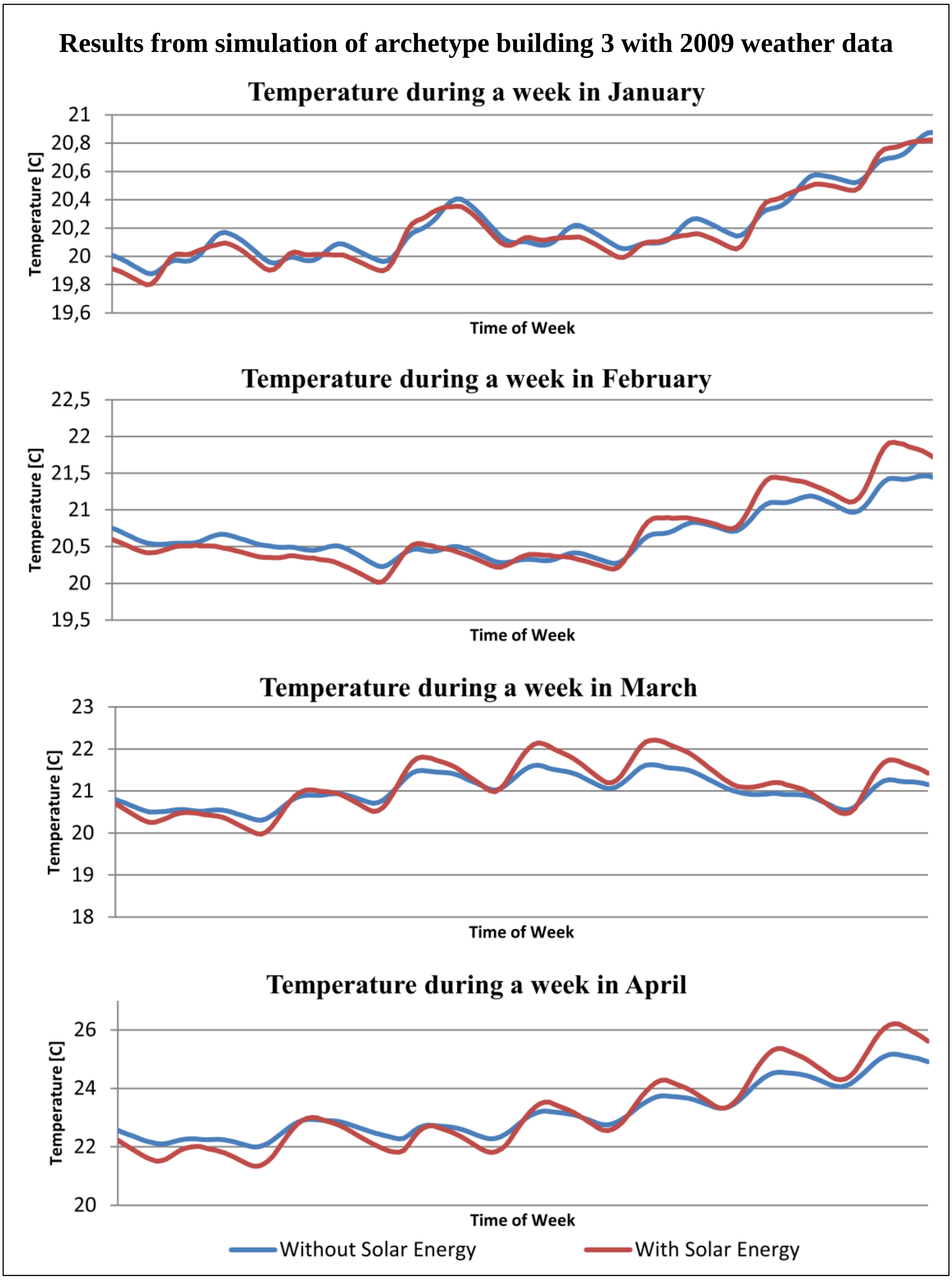


Figure 9.11 Indoor temperature results from simulations of archetype building 3, using weather data from four months in 2009. With and without solar energy means with and without the peak reducing method.

To investigate how overheating can be counteracted while using this method, simulations have been performed with increased time constants. Results from archetype building 1 are presented in figure 9.12. Results for the remaining archetype buildings are presented in appendix D.

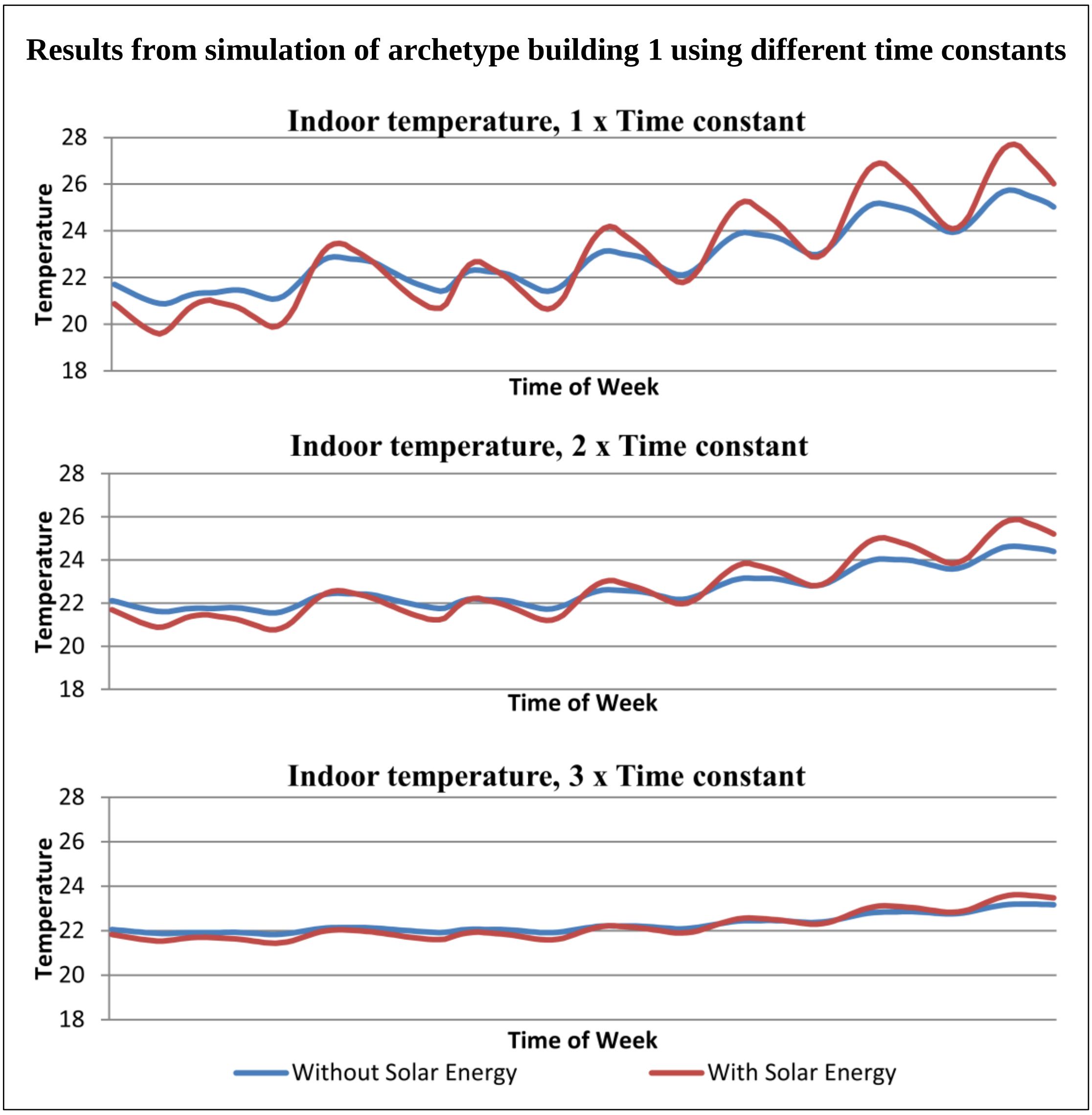


Figure 9.12 Indoor temperature results from simulations of archetype building 3, using different time constants and weather data from April in 2009. With and without solar energy means with and without the peak reducing method.

These simulations have been carried out using only weather data from April 2009. This month is most subjected to solar radiation of the four months which were investigated earlier and presented in figure 7.10. The simulations have also used the same power demand as described in figure 9.11, meaning that the power demand does not change in this case despite changing the time constant. Hence, only indoor temperatures are presented.

9.2.2 Accumulation of Solar Energy

The second approach to the method stores the solar energy in a local energy storage system, such as an accumulator tank. This energy is then used when power demand peaks occur to directly reduce the peaks in the district heating system. As opposed to the first approach to the solar energy method, it does not rely on the thermal mass of the building to cut the peaks, since the stored energy can be released into the building at any time desired.

Simulations have been done using weather data for both January and April 2009. The results are presented in figure 9.13 for archetype building 4, one simulated week of January and one of April.

Since the accumulation tank method works in the same way for all buildings only results from building 4 is presented.

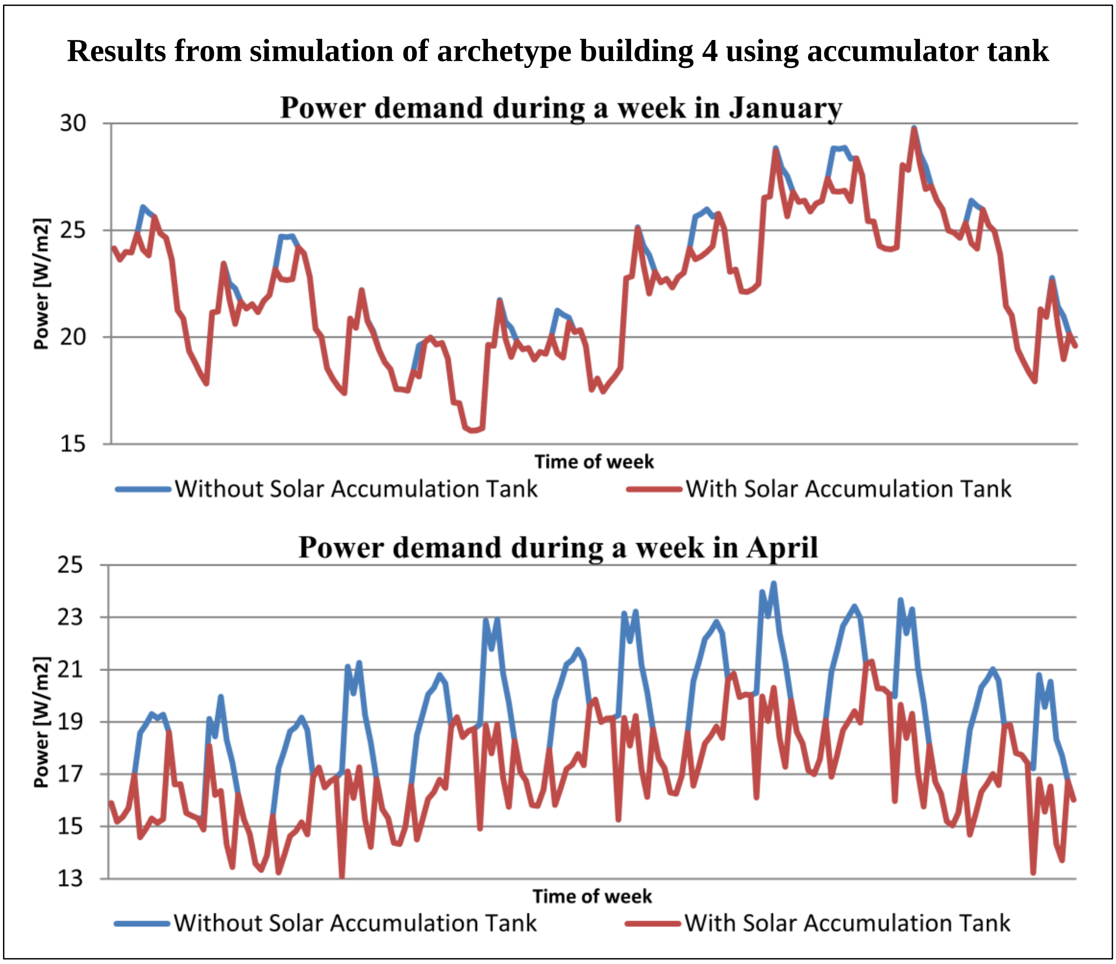


Figure 9.13 Results for archetype building 4, with peak reduction using accumulator tank to store solar energy in January and April 2009. With and without solar energy means with and without the peak reducing method. Both space heating and hot water heating is included.

In appendix E the results from the entire month simulation is presented for archetype building 4.

10 Discussion

This chapter will discuss and analyse all the results which were presented in the previous chapter.

10.1 Periodic Switch of Control Curves

As a result of all performed simulations two main parameters can be identified as very important for the outcome from using this method. The first parameter is the time constant, t_c, of the building, which is defined later on, and the second parameter is the outdoor temperature pattern.

10.1.1 Time Constant, Thermal Mass and Alternative Setup

A building's time constant, stated as t_c, is the relation between the buildings' energy losses (or gains), K, and the amount of thermal mass, also called volumetric heat capacity, in the building, TC. This relation is stated in equation 10.1. The time constant represents the buildings response time to thermal changes, such as a temperature change. View figure 7.4 for information about t_c and thermal mass.

$$t_c = \frac{TC}{K} \tag{10.1}$$

Where:

t_c is the time constant of the building. [s]

TC is the thermal mass of the building. [J/K]

K is the buildings energy losses [W/K]

K is all the losses and gains combined as a resulting K-value in Watt per Kelvin, which describes the losses per temperature difference between indoor and outdoor temperature. TC is the amount of thermal mass, which is the energy storage capacity in the building materials.

As mentioned in chapter 7, the method to use different control curves during the day uses the possibility of energy buffering with the thermal mass. Energy can be put into the building when suitable to avoid power demand peaks and the thermal mass temporarily stores it and releases it when necessary. This means that this method needs thermal mass to work. If for example a building is very heavy then all energy could basically be put in at constant power throughout the day, almost independent of the outdoor temperature, and create a constant power demand.

The alternative setups ended up as similar or the same between the different archetype buildings as seen in figure 9.1. What is different is the setup during the period January/February for archetype building 1. This building uses a different alternative setup for this period in comparison to the other archetype buildings, which all uses the same setup for both January/February and March/April.

The reason for this difference between archetype building 1 and the rest of the archetype buildings is the amount of thermal mass, and thereby the difference in t_c. Archetype building 1 is mainly a wooden structure and therefor has less thermal mass in comparison to the other archetype buildings which are all built out of mainly bricks and/or concrete. A well-known fact in building physics states that a small amount of thermal mass limits the buildings possibilities to store energy in its mass and thereby also limits its possibilities to use it as an energy buffer. The thermal mass helps the indoor climate to be more stable and less sensitive to changes of affecting parameters, such as outdoor temperature and heat input.

10.1.2 Outdoor Temperature Pattern

The theoretical days follows a temperature pattern of a sinus wave. This allows the thermal mass to work as a buffer since no steady-state is reached in the outdoor temperature. If, on the other hand, the outdoor temperature is constant, then the energy input to the building's heating system would be constant. This means that a steady-state would be achieved after a while and no particular changes in the indoor temperature would occur, meaning that the thermal mass buffering potential vanishes.

This tells us that in order for this method to work, change in indoor temperature has to occur, because that is a requirement for energy buffering to occur.

The indoor temperature changes because the building loses energy. One of the main sources of energy loss is through transmission and ventilation losses, which occur due to the outdoor temperature being lower than the indoor temperature. When the outdoor temperature changes the transmission losses change with it. This will cause a change in the indoor temperature, which enables the thermal mass to buffer energy.

It is thereby important for this method to have a temperature pattern that is similar to a sinus wave in order for this method work.

10.1.3 Potential of the Method

By looking at the results from simulations of theoretical days, which can be studied in Appendix B, the potential of this method in the different buildings can be analysed. All buildings had to fulfil the requirement of an indoor temperature that did not deviate too much from the reference setup, and this has been achieved.

The theoretical days represents the general day of January and April, with the assumption that the daily temperature variations follows the sinus pattern, as was show in figure 8.1.

The reductions of the peaks are measured in the graphs and a potential is calculated, as seen in figure 10.1.

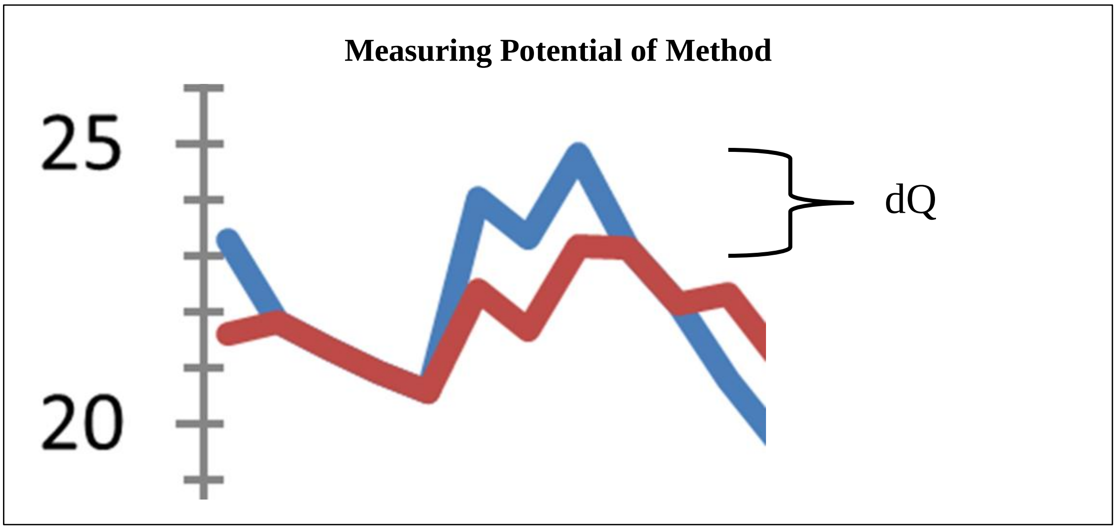


Figure 10.1 Peak reductions are measured to calculate the potential of the method for each building.

The different measured potentials can be viewed in the table 10.1 below. These potentials are calculated in the same way as was described in figure 10.1.

Table 10.1 Method potential, calculated from theoretical day simulations. The percentage value represents a reduction in power demand peaks.

Building No.	Archetype Building 1	Archetype Building 2	Archetype Building 3	Archetype Building 4	Archetype Building 5
Month:			**January**		
Potential:	4.3 – 4.4 %	2.5 – 4.4 %	4.4 – 4.6 %	4.4 – 4.8 %	4.4 – 4.8 %
Month:			**April**		
Potential:	8.6 – 8.7 %	3.7 – 9.0 %	8.2 – 9.0 %	8.8 – 10.3 %	8.3 – 10.4 %

As can be seen in table 10.1, the potential peak reduction slowly increases with increased thermal mass. The thermal mass of each building is presented in table 10.2. For archetype building 1 the potential is about as good as for the other buildings, but note that the indoor temperature fluctuate a bit more from the reference temperature. The results for archetype building 1 using this method are thereby not as satisfying as for the other buildings.

The reason for the potentials to drastically increase between the January and April simulations is because the temperatures are higher in April and therefore the heating power demand is lower. Since the control curves of different target temperatures are linear and follow each other, as in figure 7.5, the peak reduction from changing curve from 20 to 18 for example would give a reduction of about 0.5 – 2.5 W/m^2. This amount of power then represents different proportional amount in comparison to the total power demand. For example, if the peak reduction is 1 W/m^2 and the total power demand in January is 35 W/m^2 and 13 W/m^2 in April, the potential peak reduction is 1/35 ≈ 2.9 % in January and 1/13 ≈ 7.7 % in April.

The potential is of course also affected by the time constant, t_c, as described earlier. Archetype building 2's potential during simulations with theoretical days is within a wider interval. This can be explained by parameters that affects the K-value (as in equation 10.1) such as a high U-value and a large envelope area in comparison to the total heated area.

Table 10.2 Thermal mass and time constants of the archetype buildings.

Building No.	Archetype Building 1	Archetype Building 2	Archetype Building 3	Archetype Building 4	Archetype Building 5
Thermal Mass [kJ/m^2]	143.16	347.16	353.72	380.13	388.05
Time Constant [h]	30	60	71	83	80

The potentials presented in the previous table are based on the assumption of outdoor temperatures following a sinus wave. But what is the potential when the method is used with real weather data?

The results from simulations using real weather data for Göteborg from January and April in 2009 are presented in appendix C and in figure 9.4 and 9.5. It is very clear in these graphs that the peak reduction only occurs with this method when the outdoor temperature follows the pattern of the sinus wave, as shown in figure 10.2. It is also apparent that when the temperature does not follow this pattern, but rather a more general increase or decrease in level over several days, the power demand peaks are not reduced. The peaks are instead displaced to another time, which is the case for all buildings when simulated with real January weather data.

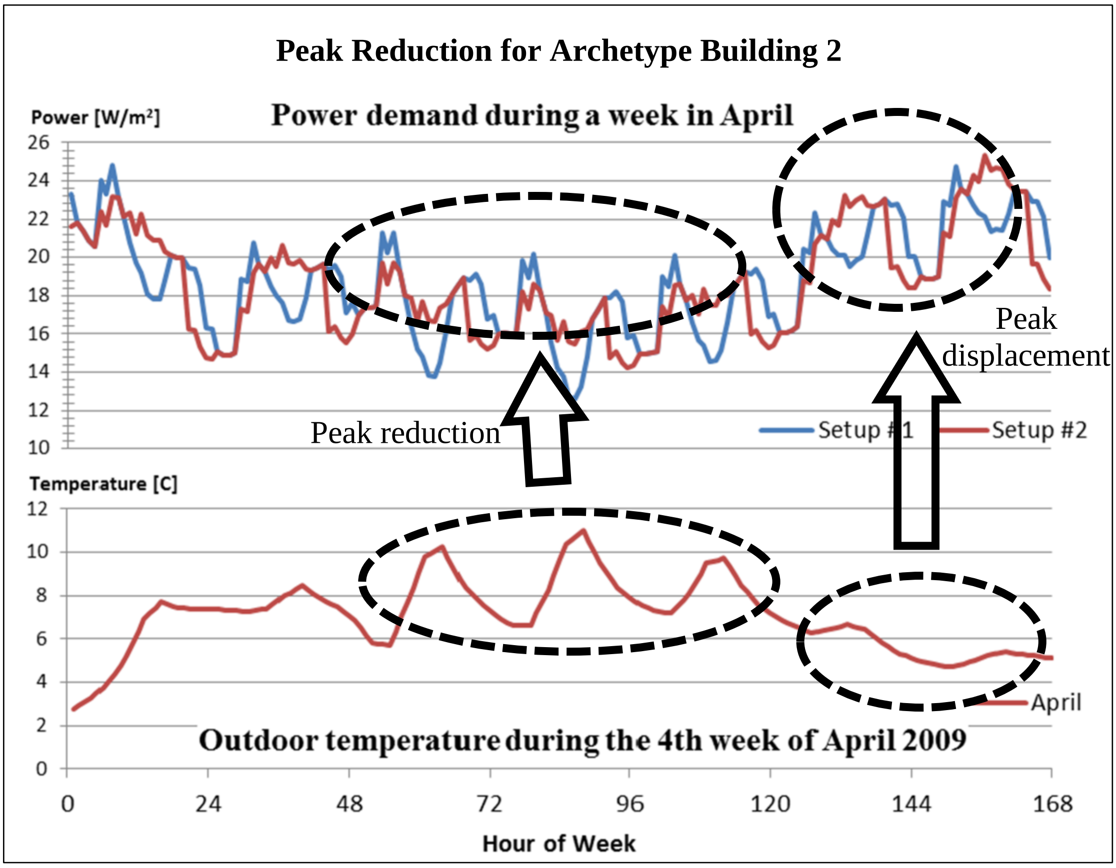


Figure 10.2 Reduction in power demand peaks mainly occurs when the outdoor temperature resembles a sinus wave; otherwise the peaks are mainly displaced. These graphs are from the results of archetype building 2.

To further investigate this, weather data of a more extreme climate were used for simulations. Data from Denver, Colorado, USA, was chosen due to Denver's location. As mentioned in chapter 9, this city is located at high altitude next to the Rocky Mountains, which creates a climate of high temperature variations throughout the day.

The results of these simulations are presented in figure 9.6 and 9.7. It is clear that the temperature variation resembles the sinus wave pattern, and the method works to reduce most of the power demand peaks.

By closer examinations the potential can be calculated and is about 3 – 14% and varies depending on the outdoor temperature. This proves that the potential increases with warmer temperatures as it did when simulating the theoretical days. This is due to the fact that the peak reductions in absolute amounts (in W/m^2) are the same independent of temperature.

10.1.4 The Method Applied to Building Districts

So far this chapter has been focused on the use of the peak reducing method in single and independent buildings. In reality the power demand from entire districts have to be supplied by the district heating provider, which of course means that the entire district affects the power demand pattern and its peaks.

It has been showed earlier in this chapter that depending on the outdoor temperature pattern, this peak reducing method gives different results. When used during periods of time when the temperature variations within a single day are small, but changes generally over several days (such as January in Göteborg), the power demand peaks tend to only be displaced and not reduced, as in figure 10.2.

From this, a conclusion has been developed. If all buildings within a district apply the method to switch control curves according to a scheme (a setup) and they all use the same setup, then all power demand peaks would occur at the same time. This would then cause the power demand peaks to be amplified.

An option would be to apply this method in building districts during months with small daily outdoor temperature variations, such as January, and using different setups for each building, or for small groups of buildings, within the district. This way the setups used for all buildings could be designed in a way that all building have their power demand peaks during different times of the day. This would cause the total power demand to be less amplified and almost cancel out some peaks using another buildings power demand low point.

This principle is shown in figure 10.3 and 10.4 where three theoretical buildings use different theoretical setups. Figure 10.3 shows how the power demand peaks can be displaced to different times using different setups for each building.

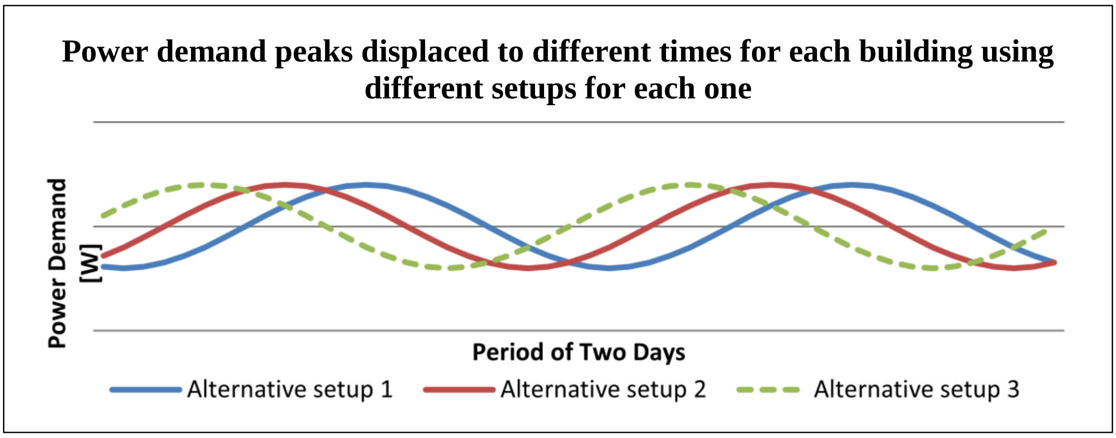


Figure 10.3 Displacement of power demand peaks using different setups for each of the three buildings.

The total power demand of the three buildings is showed in figure 10.4. The curve with different setups represents the total power demand from the three theoretical buildings from figure 10.3 and the other curve represents three buildings that all use the same setup. The different setups curve's power demand is more equally distributed due to that the different buildings have their power peaks at different times, so they cancel each other out. The other curve's power demand is amplified due to that all included buildings use the same setup.

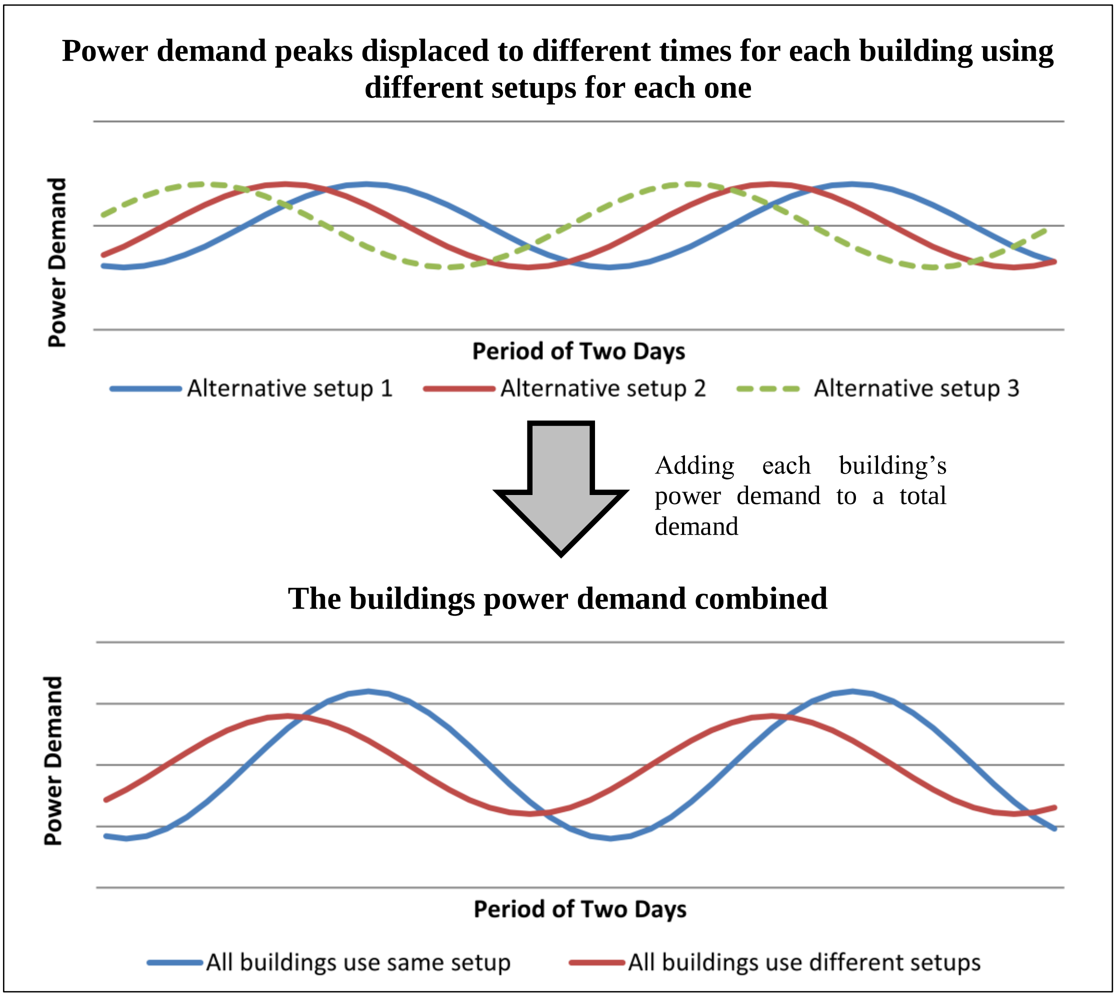


Figure 10.4 The total power demand when three buildings are combined using;

- *The same setup (peaks at the same time)*
- *Different setups (peaks displaced to different times)*

To simulate this option, using the archetype buildings, two additional alternative setups where designed in a way that they created power demand curves with peaks at different times than the setup used for the earlier results. Still attention was paid to the fact that indoor temperature had to be within reasonable limits of the reference setup. An important fact to note in this case is that the additional two setups are not in any way optimized. This would have taken too long time for this thesis, and they are only used to show a potential of the method when applied in larger districts.

Weather data from Göteborg for January in 2009 were used because of the fact that the peaks can be displaced with setups using the January days which have small daily temperature variations.

The building district to use for the simulations was a theoretical district, but with a combination of buildings that occur in some districts in eastern Göteborg. The district consists of archetype buildings 2 (*Äldre Lamellhus*), 3 (*Yngre Lamellhus*) and 5 (*Skivhus*) as described in table 10.3.

Table 10.3 Buildings included in the theoretical district simulated.

Building No.	Archetype Building 2	Archetype Building 3	Archetype Building 5
Area/Building [m²]:	1395	2343	5868
No. of buildings:	10	10	5
Total size [m²]:	13950	23430	29340
Total [m²]:	66720		

The resulting power demand for each type of building is presented in figure 10.5. This figure is similar to figure 10.4, with the curves for power demand when all buildings use the same setup (blue curve) and the power demand when all building types use different setups (red curve).

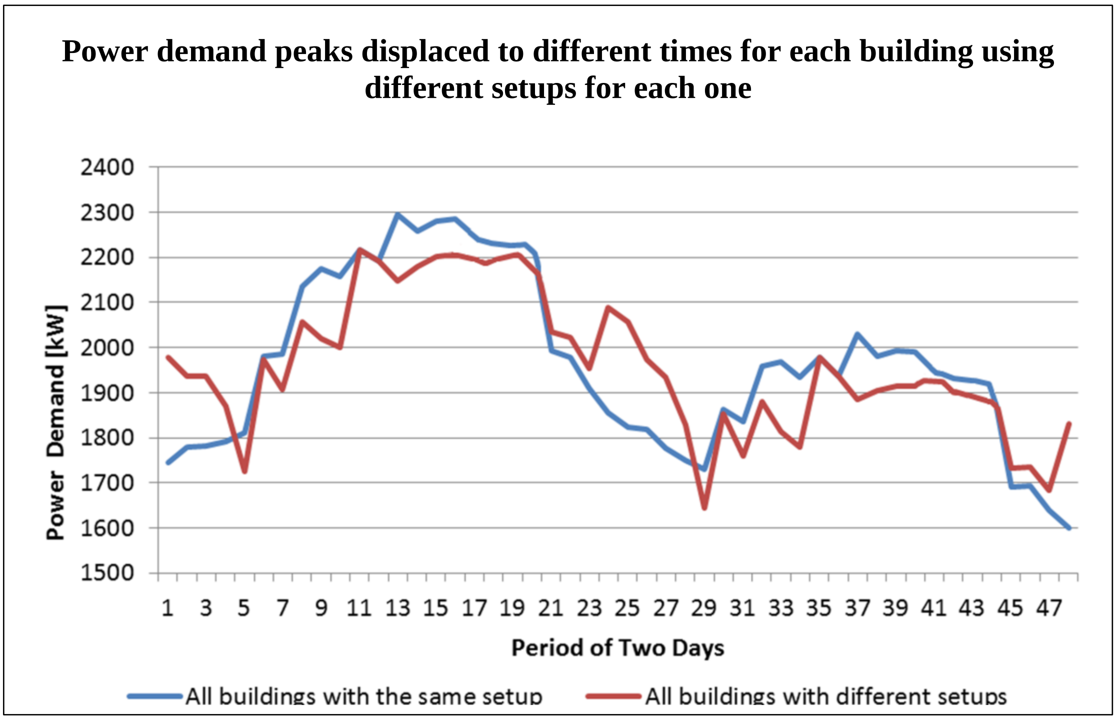


Figure 10.5 The total power demand when three buildings are combined using;

- *The same setup (peaks at the same time, blue curve)*
- *Different setups (peaks displaced to different times, red curve)*

Simulations are carried out using weather data from January 2009.

The results in figure 10.5 show that there is a potential in reducing the power demand peaks in a district by using this method, even during months such as January which is simulated in this figure.

By applying this method the total power demand peaks in districts could be reduced even when reducing each individual building's power demand peaks is not possible.

The simulations behind this result assumes that all building of one certain type uses the same setup, which would not necessarily be the case if the method was to be applied on a real district. Each building could then have its own setup, which would smoothen out the power demand curve even more and optimize the method.

10.1.5 Adapting this Method to Reality

As will be described further in this chapter, the method to switch between different control curves works under certain circumstances, but some real-life problems might occur.

The setups that are used are based on assumptions of weather pattern and usage patterns. In this thesis the setups have been adapted to the usage patterns of weekdays, meaning that people are mostly not at home during the days and that hot water usage mainly occurs during two distinct periods of the day (morning and evening). During weekends this usage pattern changes, as presented in figure 2.1. This might cause a conflict between the power demand for heating, created by the setup and control curves, and the power demand for production of hot water. This could cause a larger power demand peak than would have occurred if only one control curve was used (as in the reference setup and in most buildings today).

The same type of problem also occurs when the weather does not follow the assumed pattern. As shown in figures 9.4 and 9.5 the peak reduction will not occur when the outdoor temperature diverges from a daily variation pattern and instead the peaks will be displaced. This is because the setups are based on a 24-hour schedule. The assumed changes in temperature are assumed to happen within these 24 hours, such as lower temperature during the night than during the day.

A solution to these problems could be that the control system in the district heating central would also switch between different setups. The setups are then adapted to fit with the upcoming changes. For example, the system could use specific weekend setups during weekends to cope with the different usage pattern.

Another solution is to use more input data to the control system, such as weather prognosis that tells the system what will happen with the temperature in the future. Different setups could then be used depending on if the trend in temperature levels is increasing or decreasing, and also if the sinus wave pattern will occur.

10.1.6 Conclusions of this Method

In the early parts of this discussion chapter, conclusions are made about the importance of thermal mass in the buildings and long time-constants. The thermal mass is used as a buffer and thereby energy can be put into the building without being used directly. Buildings with less thermal mass, such as archetype building 1 (*Landshövdingehus*) are therefore less suitable for this type of peak reducing method. Where the limit for amount of thermal mass and time constant is needs to be further investigated.

The second important conclusion made in this chapter is the importance of the outdoor temperature pattern. Temperature variations are very important to make the thermal mass buffering effect to take place. Without temperature patterns that resembles a sinus wave the method is not suitable for peak reduction in individual buildings. As shown with simulations of January in both Göteborg and Denver, the method works better in climates with larger daily temperature variations throughout the year, such as Denver and even Stockholm. Figure 10.6 shows the daily temperature variations in Göteborg for each month. From this figure the conclusions can be drawn that as a peak reducing method it will not work well for individual buildings during the months when the power demands are the highest and peak reduction is needed.

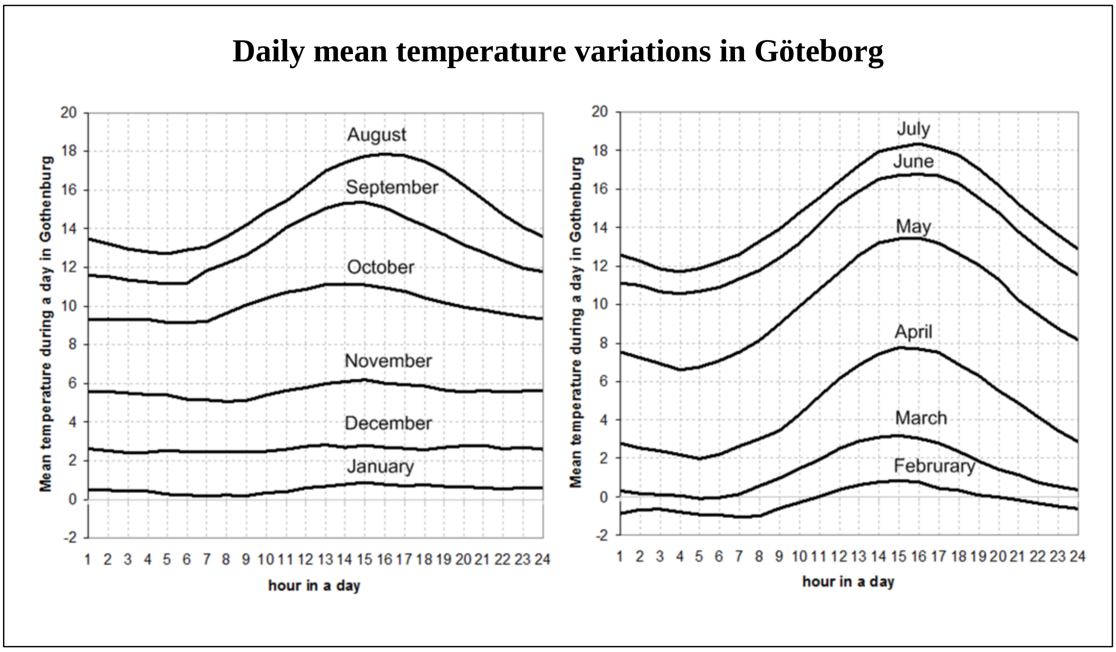


Figure 10.6 Mean temperature variations in Göteborg for each month of the year. (Sasic A. 2012)

Though as described in chapter 10.1.4 this method do have peak reducing potential even in Göteborg for months such as January if applied to districts. In order to increase the potential for all types of weather patterns and usage patterns, more parameters could be taken into account, as discussed in 10.1.5.

10.2 Solar Energy to Reduce Power Demand Peaks

The discussion about the addition of solar energy will follow the same layout as the presentation of the results, with one chapter for each approach to the method.

10.2.1 Direct Addition of Solar energy

The direct addition of solar energy into the building means that a surplus of energy is inserted since the heating system is operating at the same time. This excess of energy will be both stored in the thermal mass and in the air, raising the indoor temperature.

This means that to keep the amount of energy in the building even, the heating system can be switched off later in the day, in this case when a district heating peak would have occurred. This enables peak reduction. The amount of peak reduction is dependent on the amount of solar energy that can be added to the building. At the same time attention has to be paid to the indoor temperature that will rise during the day.

As described in chapter 9.2.1, the results from simulations using weather data from the theoretical days are hard to interpret in a way that potentials of this method can be measured and calculated. This means that the theoretical day simulations are better to be used as a simple way to investigate if the approach with direct addition of solar energy is applicable to the buildings. The simulations give a hint if the amount of solar radiation during a month is somewhat of the magnitude required.

Simulations of the months January to April can be used to see the effects of a changing amount of solar radiation between the days and months, and the simulations can also be used to estimate the potentials of the method.

By measuring in the same way as described in figure 10.1 the potential of this method can be calculated for each building during each month. The calculated potentials are presented in table 10.4.

Table 10.4 Method potential, calculated from real month weather data simulations. The percentage value represents a reduction in power demand peaks.

Building No.	**Archetype Building 1**	**Archetype Building 2**	**Archetype Building 3**	**Archetype Building 4**	**Archetype Building 5**
Month:	**January**				
Potential:	2.1 – 4.2 %	2.0 – 4.9 %	2.1 – 4.4 %	2.4 – 5.0 %	2.2 – 5.4 %
Month:	**February**				
Potential:	5.1 – 6.8 %	4.4 – 6.2 %	5.0 – 6.9 %	5.3 – 7.3 %	5.0 – 6.7 %
Month:	**March**				
Potential:	8.4 – 11.4 %	7.7 – 12.8 %	7.9 – 12.8 %	8.8 – 13.0 %	8.2 – 12.8 %
Month:	**April**				
Potential:	8.5 – 25.0 %	18.5 – 27.2 %	17.6 – 26.0 %	16.0 – 26.8 %	15.4 – 27.8 %

From the table it is clear that the potential increases for each month closer to the summer. There are two reasons for this, the first reason is that the amount of solar radiation increases with each month and thereby also the amount of energy that can be added to the building, as visualized in figure 10.7.

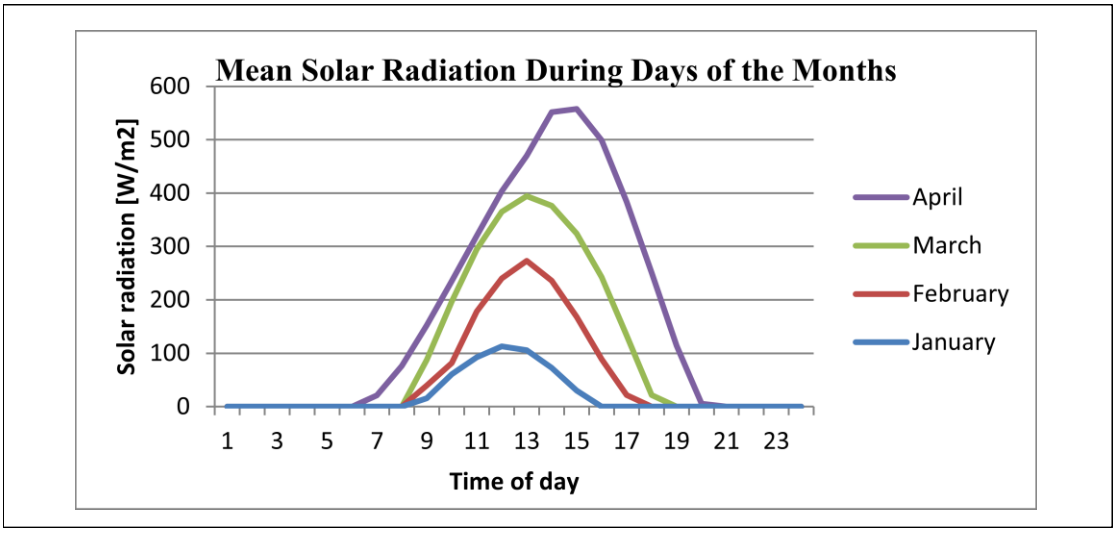


Figure 10.7 Mean amounts of solar radiation during days of January, February, March and April 2009.

The second reason for the increase in potential between months is that the outdoor temperature is generally higher closer to summer. This will decrease the power demand and thereby change the proportions between total power demand and the amount of peak reduction, increasing the peak reduction potential in a similar way as explained in chapter 10.1.3.

Another thing that increases with the months is the length, in time, of the peak reduction. Since the input of solar energy increases with increasing amount of solar radiation it is possible to increase the lengths of the peak reduction as well as it is possible to increase the reduction magnitude (potential). In figure 10.8 the increase in time of peak reduction is visualized.

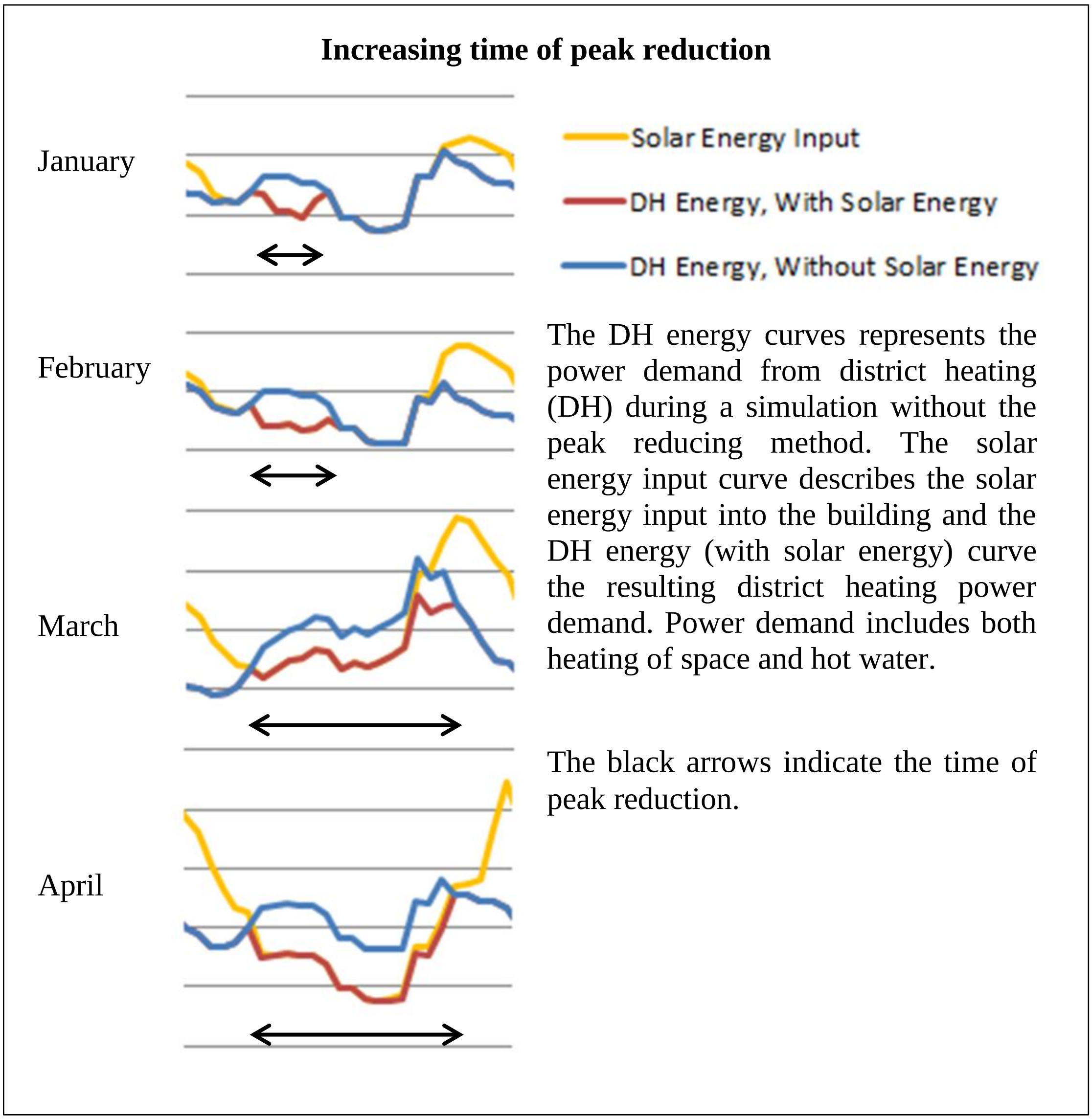


Figure 10.8 Increasing time of peak reduction.

The lengths and magnitude of the peak reduction can be increased with increasing solar energy input due to that the amount of solar energy put in during a day can be subtracted from the upcoming power demand peak, as showed in figure 10.9. The solar energy is stored in the thermal mass and makes the building keep its indoor temperature despite reducing the power input from the heating system. This creates the peak reduction. Thought, as this figure describes, the amount of energy (areas) are not exactly the same due to that some amount of solar energy is lost through energy losses from the building.

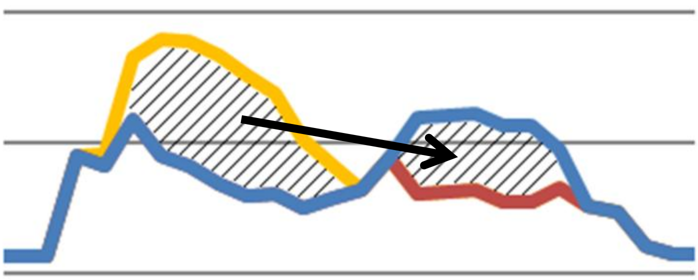


Figure 10.9 Amount of solar energy added to the building can be subtracted from the upcoming power demand peak.

This means that with increasing solar radiation the possibilities to reduce power demand peaks increase, and there is also a possibility to save energy.

This approach to the method has a downside though, which is the indoor temperature. As showed in figure 9.11 the indoor temperatures fluctuate more and more with the increasing amount of solar energy added to the building. This is of course because of the increasing energy surplus. When comparing the indoor temperature results for the same months between different archetype buildings it is clear that the less thermal mass and time constant, the more fluctuation of the indoor temperatures.

With further examination of the potentials, in table 10.4, a small increase in potential can also be seen between the archetype buildings themselves. The potential slightly increases with increasing thermal mass and time constant (table 10.5), but only small increases occur.

Table 10.5 Increasing peak reducing potential with increased time constant.

Archetype Building	Archetype Building 1	Archetype Building 2	Archetype Building 3	Archetype Building 5	Archetype Building 4
Time Constant [h]	30	60	71	80	83
January Potential:	2.1 – 4.2 %	2.0 – 4.9 %	2.1 – 4.4 %	2.2 – 5.4 %	2.4 – 5.0 %
February Potential:	5.1 – 6.8 %	4.4 – 6.2 %	5.0 – 6.9 %	5.0 – 6.7 %	5.3 – 7.3 %
March Potential:	8.4 – 11.4 %	7.7 – 12.8 %	7.9 – 12.8 %	8.2 – 12.8 %	8.8 – 13.0 %
April Potential:	8.5 – 25.0 %	18.5 – 27.2 %	17.6 – 26.0 %	15.4 – 27.8 %	16.0 – 26.8 %
Increasing potential with increasing time constant →					

These potentials are based in simulations with the same parameters for all archetype buildings, with the same amount of solar collectors per heated area and also the same control scheme has been used.

Archetype building 1 and 4 are the two buildings with lowest and highest time constants of the five buildings. According to the potentials just discussed, these two buildings (along with the rest) have about the same potential for all months. But the greater difference here is in how the indoor thermal climate behaves while the peak reduction and solar energy addition is applied (appendix D).

In figure 10.10 the difference in temperature fluctuation between building 1 and 4 is presented. Here it is showed that while having the same peak reducing potential archetype building 4 has a more stable indoor climate with less fluctuation. This means that the peak reduction does not create an indoor temperature that differs from the ordinary temperature as much in building 4 as much as in building 1.

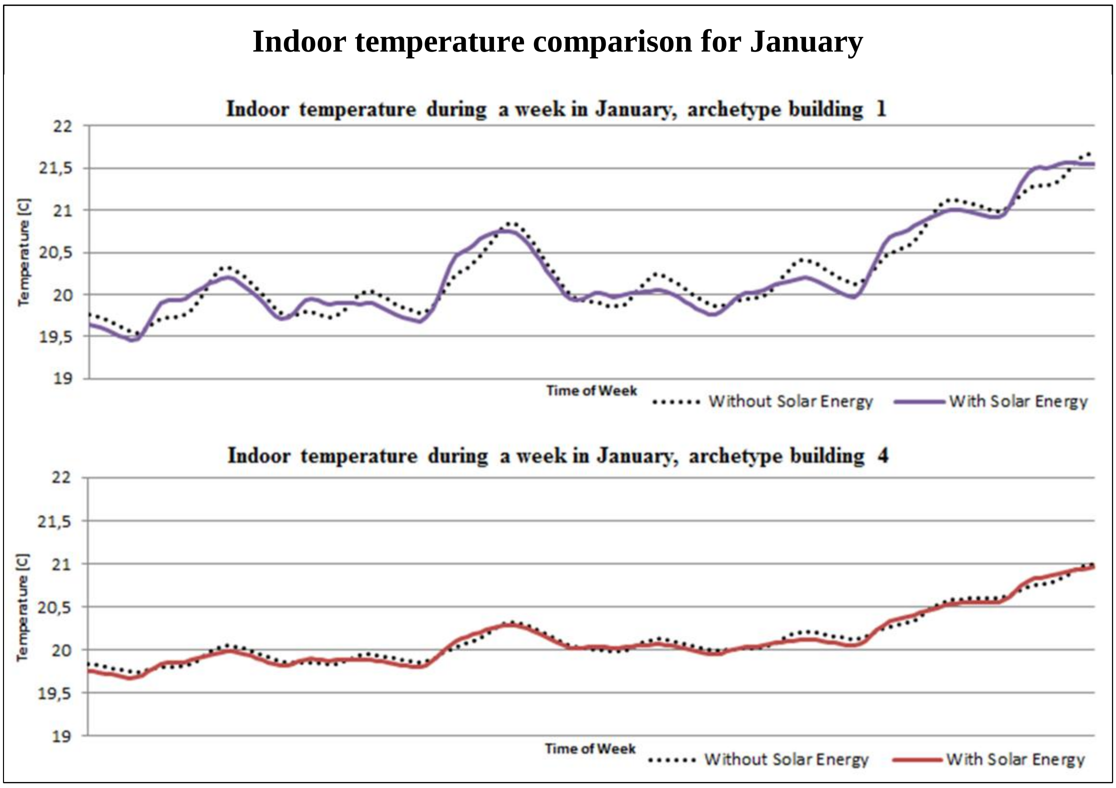


Figure 10.10 Comparison between the indoor temperature for archetype building 1 and 4, whit the same amount of peak reduction. The dotted black curves represent the indoor temperatures without the addition of solar energy, solid curves represent indoor temperatures with addition of solar energy.

To investigate the fluctuating indoor temperatures further and to see if indoor temperature fluctuation can be kept to a minimum while at the same time applying the method, simulations were performed with different sizes of time constants and weather data from April 2009. April was chosen because of the high amounts of solar radiation.

The time constant is, as described earlier in this thesis, depending on the thermal mass and the overall heat losses and gains. Simulations were performed with each building's original time constant, with double time constant and triple time constant. This was achieved by simply multiplying the thermal mass. The results from archetype building 1 are presented in figure 9.12.

In this figure it is visible that as the time constant increases, the indoor temperature fluctuation is stabilized. This means, for April, that if a building's time constant is large enough, then this approach to the peak reducing method could be applied without the consequences of overheating while maintaining the same indoor climate as before.

If these simulations were carried out using weather data for January instead of April the stabilization of indoor temperature with increasing thermal mass and time constant would almost not occur. This is because the amount of available thermal mass is enough in each one of the archetype buildings in comparison to the amount of solar energy available.

This means that if the method was only to be used during colder months, such as January, then there would be no need to increase the time constant, but when applied during warmer months, such as April, the time constant is of more importance and need to be increased.

10.2.2 Accumulation of Solar Energy

The second approach to using solar energy to achieve peak reduction utilizes an accumulation tank to store the collected solar energy before using it. As mentioned earlier, this way the energy can be added to the building at any time desired, such as when power demand peaks occur. Thus the peak reduction is not affected by the buildings time constant and thermal mass, as with other methods discussed in this thesis.

The amount of solar collectors stands in direct proportion to how much energy can be collected and thereby also how much peak reduction can be achieved by using this collected energy. Since the input of energy can be totally controlled by the heating system, using this method to reduce peaks is not limited by the risk of lowering the indoor thermal comfort. This makes this approach almost unlimited in its potential to reduce peaks in power demand, and thereby calculating potential from the boundaries set up in this thesis is of no practical importance.

What could be stated about potential is that the peak reducing potential decreases with the magnitude of power demand of a building. This is because a certain area of solar collectors produces a certain amount of energy. Since the building have different power demands the same amount of solar energy from the collectors would have different impact on the peak reducing potential. This means that a building with high power demand needs a larger amount of solar collectors to achieve the same amount of peak reduction, in percentage. From the performed simulations in this thesis it is clear that archetype building 2 has a higher power demand than the other buildings, and therefore requires a higher amount of solar collectors. The other buildings have power demands that only vary slightly amongst them, and thereby they require somewhat the same amount of collectors.

Theoretically, the amount of solar collectors could be set to an amount that would cover the buildings entire power demand, including hot water. But this would require a large area of collectors and other technical issues would occur.

The main question for this approach is if the amount of solar radiation during a cold month, such as January, is enough to make peak reduction possible, without using more space for solar collectors than available on the building roof. Preferably the solar collector area should also be within reasonable limits.

When performing the simulations, each building was given 0.02 m^2 solar collector area per heated indoor square meter. This fulfilled the requirement of fitting all solar collectors on the roof with a great margin and also fulfilled the preference to use reasonable solar collector areas. The collector area varies between 50-150m^2 and these are absolutely within limits. According to building objects presented by *Solar Region Skåne*, this is an amount that is definitely possible to install with today's limits. (Solar Region 2012)

The simulations presented figure 9.13 and appendix E are based on weather data from January and April 2009. If the solar energy collected and used in January is enough to achieve some peak reduction, then the method is assumed to work during months with more solar radiation, such as April.

Peak reduction is possible in January with this method and boundaries according to the simulations. In the beginning of January only some peaks are reduced, but by the end of the month almost every peak is reduced. This is because the end of January is sunnier than the beginning. In April the system has no problems to achieve peak reduction due to the large amounts of solar radiation.

10.2.3 Solar Energy in a Building District

Applying these methods to a building district will have a slightly different effect than when applying the method which uses change of control curves. By changing the control curves the total energy consumption was not changed but merely moved. When solar energy is introduced the total energy consumption, from the district heating system, will be lowered. Solar energy can be seen as a local energy production.

When looking at the potential in a district it is important to look at the individual buildings solar collectors to heated area ratio, which will be called the C/A ratio henceforth. Buildings with a high C/A ratio are buildings with a large roof area compared with the number of floors. Examples of this are archetype buildings 1, 2 and 3. Subsequently, buildings with a low C/A ratio are buildings with a small roof area compared to the number of floors. Examples of this are archetype buildings 4 and 5. The potential of the district will then be dependent on the distribution of buildings with different C/A ratios, shown in figure 10.11. Note that this is under the assumption that only the area of the roof is used for collecting solar energy.

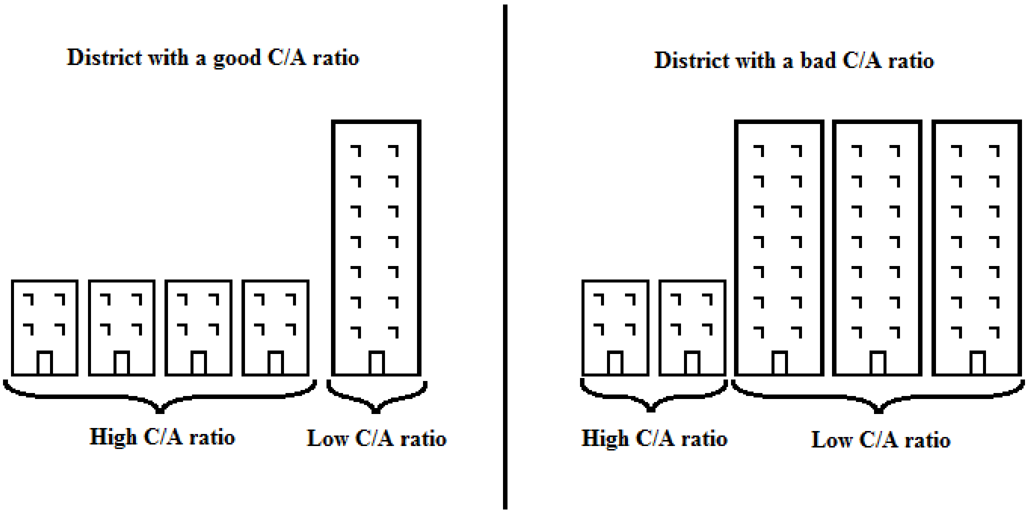


Figure 10.11 Example of two different building districts; one with a good P/A ratio and one with a bad P/A ratio. The potential to reduce peaks in a district is dependent on the combined P/A ratio. P/A ratio is the ratio between the amount of solar panels on a building and the total heated area of the building.

Both solar energy methods will have the same limitations of the C/A ratio when it comes to the interaction between buildings in a district. One interesting aspect that opens up when discussing potential in a district is the different ways of accumulating energy, shown in figure 10.12. The means of accumulating energy can be made more effective when constructed in large scale and other methods to store the energy might be possible, compared to the normal way of using water tanks. Such methods are discussed in the bachelor thesis *Säsongslagring av solvärme (Seasonal Storage of Solar Heating).* The common denominator of these alternative methods is that they use the ground as the energy storage vessel. These can be filled either with a fluid or the ground itself can act as the heat buffering material. (Landergren S., Skogsäter N. 2011).

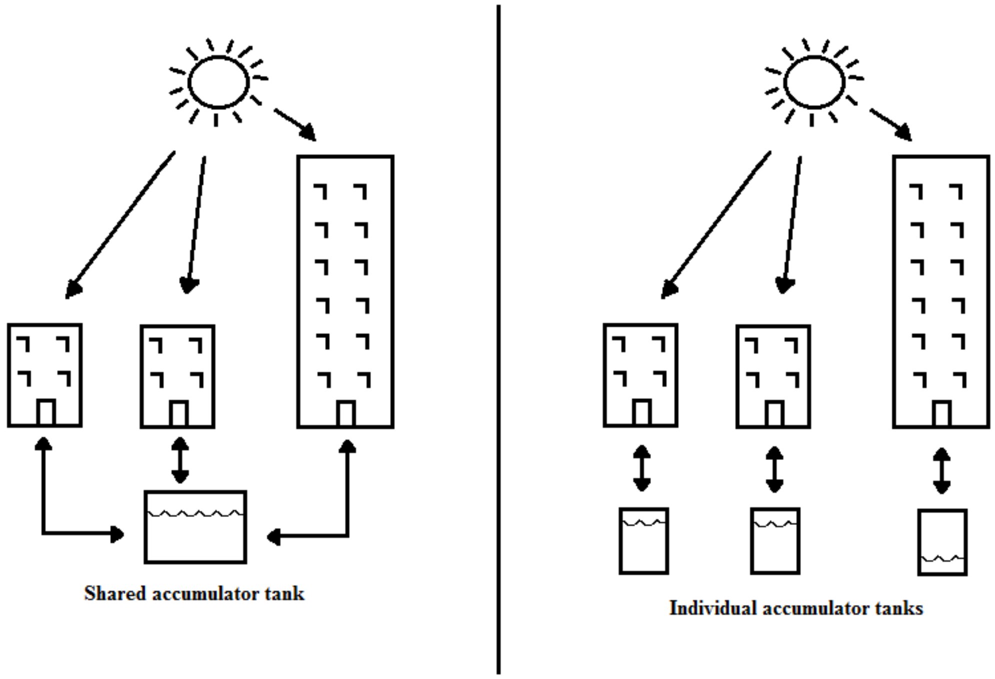


Figure 10.12 When using the method of accumulating solar energy in a district the possibility to use a shared energy storage system opens up. This would redistribute the solar energy and thus creating an even reduction in the peaks over the district.

10.2.4 Conclusions of the Two Solar Energy Approaches

From the simulations and discussions in this thesis some conclusions can be made about using solar energy to reduce power demand peaks.

The two approaches to the solar energy methods have the same basic idea, to produce solar energy locally and to store it in a way that it can be used for peak reduction.

The first main conclusion that can be made is that the amount of peak reduction is direct proportional to the amount of solar collectors connected to the system, and also to the amount of solar radiation available.

The limitation to peak reduction is different between the two approaches due to the way that solar energy is added to the building. The approach with direct solar energy is limited by when the energy can be added, and also by the indoor thermal climate, which can be overheated. Buildings with large time constants prove to work better with this approach, since they can handle more solar energy while keeping a stable indoor temperature.

When using an accumulator tank the method is less limited due to that energy can be put in whenever desired. The amount of solar energy is subtracted from the amount of district heating energy that would have been put in. This approach is basically only limited by the solar energy production capacity and the energy storage capacity. For this reason, buildings with large roof areas, in comparison to the heated floor area, are more suitable for installing systems with very high proportional capacity (energy production capacity per heated area).

The reason to try to use solar collectors without an accumulator tank is that by using an accumulator tank the problem of having large energy storage systems in order to fill the energy demand during peak loads will just be moved from the energy producer to the energy consumers. So in that aspect, a system without an accumulator tank would be much more favourable.

More general conclusions that can be made about this method and its two approaches are that it demands further investments. Both approaches require installations of solar collectors and all systems that come with it.

The main difference in the amounts of investments is that if high peak reductions are desired, the direct input of energy approach might require changes to the building envelope or ventilation to increase the time constant.

11 Conclusions

The aim of this thesis was to investigate methods for reduction of peaks in heating demand, in buildings in Göteborg. To achieve this, two methods of peak reduction were defined and applied to five archetype buildings with the help of a simulation tool. The methods which were investigated in this thesis are:

- To implement a change of the control curve during the day, where each control curve have different target indoor temperature.

- To gather solar energy and:
    - Use it directly to heat the building.
    - Store it in a local energy storage until the power demand peak occurs.

Thorough conclusions for each method are presented in chapter 10. This chapter aims to give some general conclusions which compare the methods with each other and to explain some of their positive and negative effects.

It was found that both methods gave peak reductions of at least 3-5% in January, which was selected as a typical cold month in Göteborg. Higher potentials will be achieved in warmer months, as well as in regions with larger daily temperature variations. At least 10-15% peak reduction can be achieved in the latter cases.

As all methods affect the indoor temperature, it was found that the archetype buildings with the largest time constant responded best to all methods, except for when using accumulation of solar energy, where only the amount of solar collectors affected the results.

The potential of the methods in this study should be treated as a first indication of how well the methods work. By optimization, a larger potential could be achieved and the methods would work even better.

Technical difficulties when implementing the methods have not been treated in this study and not taken into account. There will be a varying amount of technical challenges that would have to be overcome with all methods. One example of this is that solar collectors will sometimes not work due to too high vapour pressure inside the pipes, which is a result of too high temperatures.

A significant difference between the two methods is that the method, which uses switching of control curves, takes less technical installations. Though, this method requires a knowledge about coming outdoor temperature variations in order to perform well. This is because the different control curves appear in a predefined pattern, which is adjusted to the expected outdoor temperature variations. The most optimal performance was achieved when the outdoor temperature followed a sinus shaped pattern.

A common weakness of all methods is that there will have to be an increase in the control demand. Additional parameters will have to be taken into account such as time of day, temperature trends and amount of solar radiation.

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Appendix A: Archetype Building Data

Table A.1 Archetype building data. The data used as input in simulations. N.V means natural ventilation and E.V means exhaust ventilation

Archetype Building #	1	2	3	4	5	Units
Year of construction	1927-1935	1946-1955	1965-1975	1945-1960	1960-1971	[-]
Location of Building	1480	1480	1480	1480	1480	[-]
Thermal Capacity	1083721200	484288200	828754245	1293578987	2277095004	[J/K]
Window Coefficient	0,64	0,61	0,7	0,68	0,78	[-]
Frame Coefficient	0,7	0,7	0,7	0,7	0,7	[-]
SFP	0	2	2	2	2	[kW/m3/s]
Natural Ventilation through Windows	0,7	0,7	0,7	0,7	0,7	[l/s/m2]
Natural Ventilation Set Point	24	24	24	24	24	[C]
Ventilation Flow	0,28	0,303	0,3589	0,375	0,28	[l/s/m2]
Typ of Ventilation System	N.V	N.V /E.V	E.V	E.V	E.V	[-]
Number of appartments	160	16	30	37	73	[-]
Facade Material	Wood	Brick	Concrete	Concrete / bricks	Concrete/ bricks	[-]
Heated Area	7570	1395	2343	3403	5868	[m2]
U-value	0,61	0,75	0,53	0,725	0,76	[W/m2,K]
Envelope Area	8857	1841	2765	3395	5111	[m2]
Window Area	939	137	325	389	874	[m2]
Window Transmittance	0,7	0,73	0,7	0,69	0,697	[-]
Air leakage (Blow door Test)	1,2	0,9	0,8	0,8	0,8	[m3/s]
Number of Floors	3	3	3	9	10	[-]
Ceiling Height	2,7	2,77	2,5	2,6	2,5	[m]

Appendix B: Results from the Simulations on Switch of Control Curves Using Theoretical Days

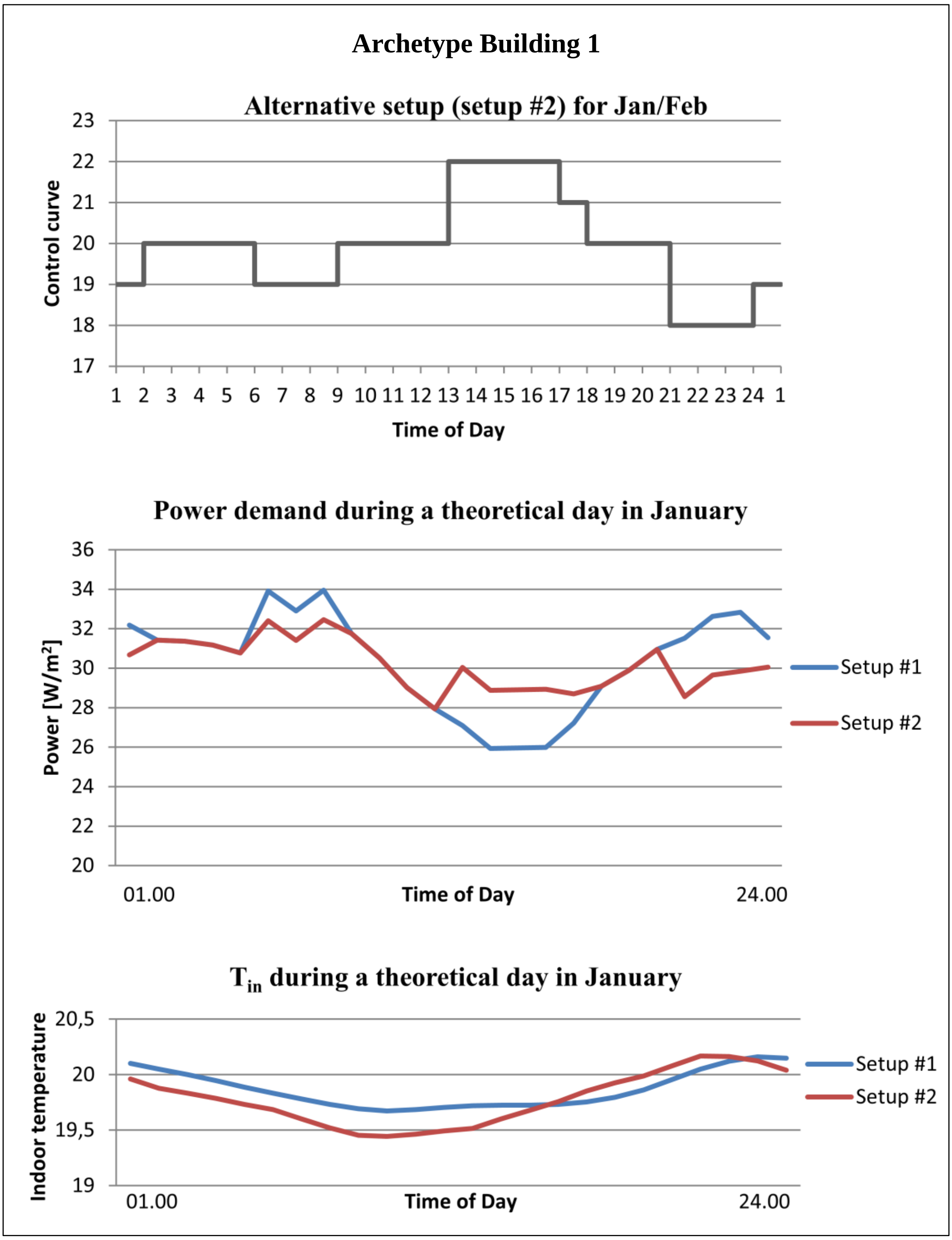


Figure B.1 *Results for archetype building 1 when simulating a weekday with the theoretical day for January. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.*

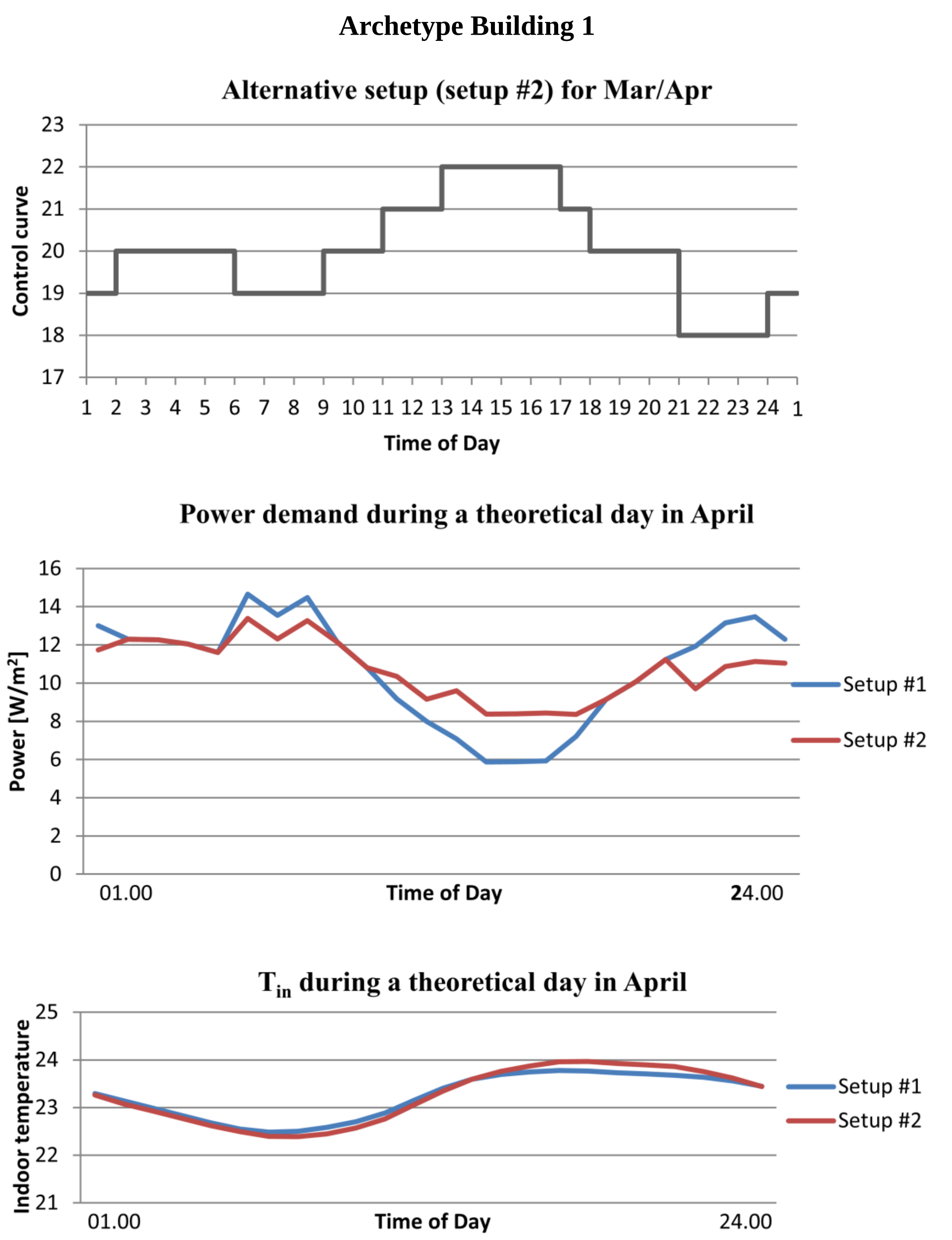


Figure B.2 Results for archetype building 1 when simulating a weekday with the theoretical day for April. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.

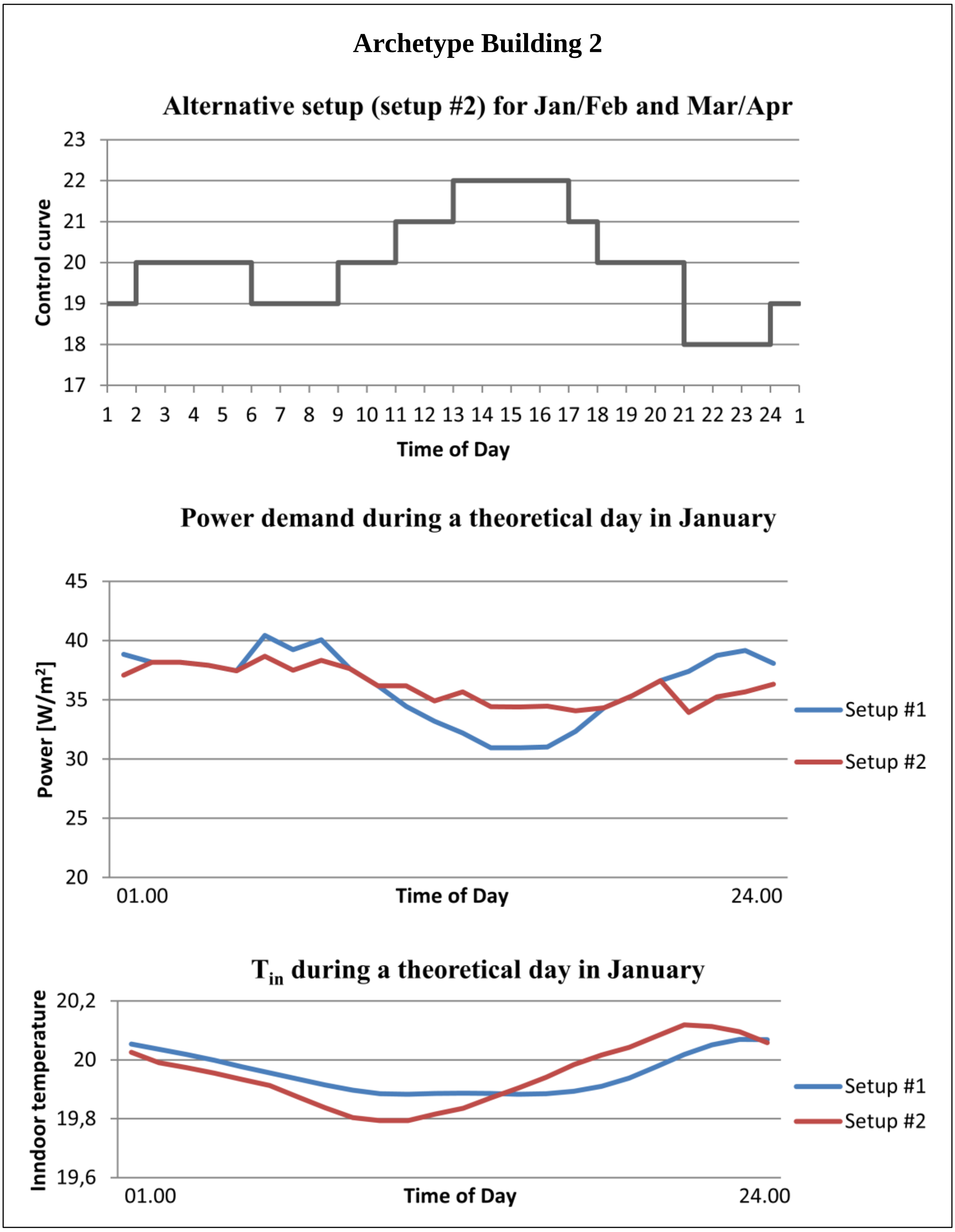


Figure B.3 *Results for archetype building 2 when simulating a weekday with the theoretical day for January. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.*

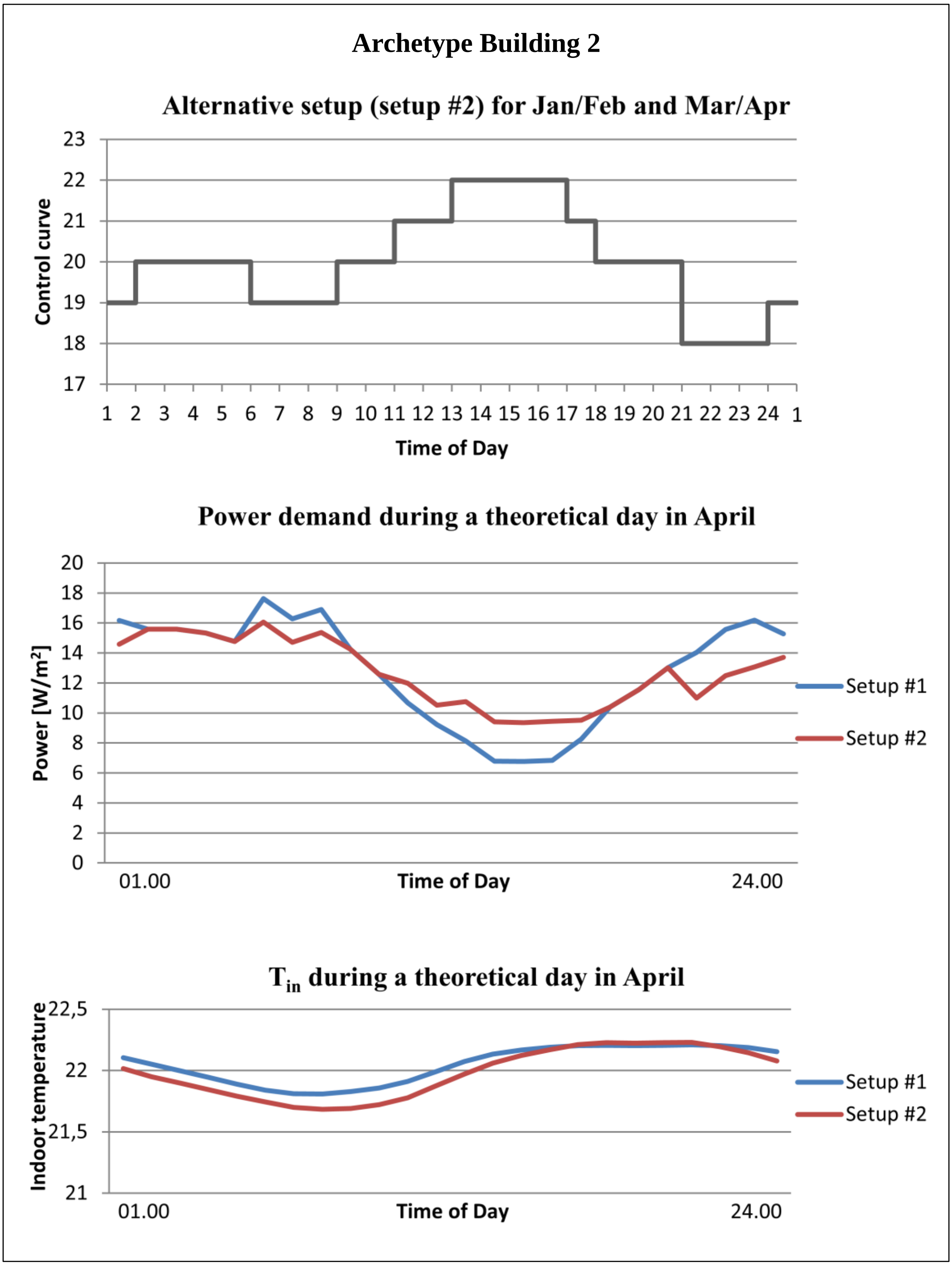


Figure B.4 Results for archetype building 2 when simulating a weekday with the theoretical day for April. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand *is for both space heating and hot water.*

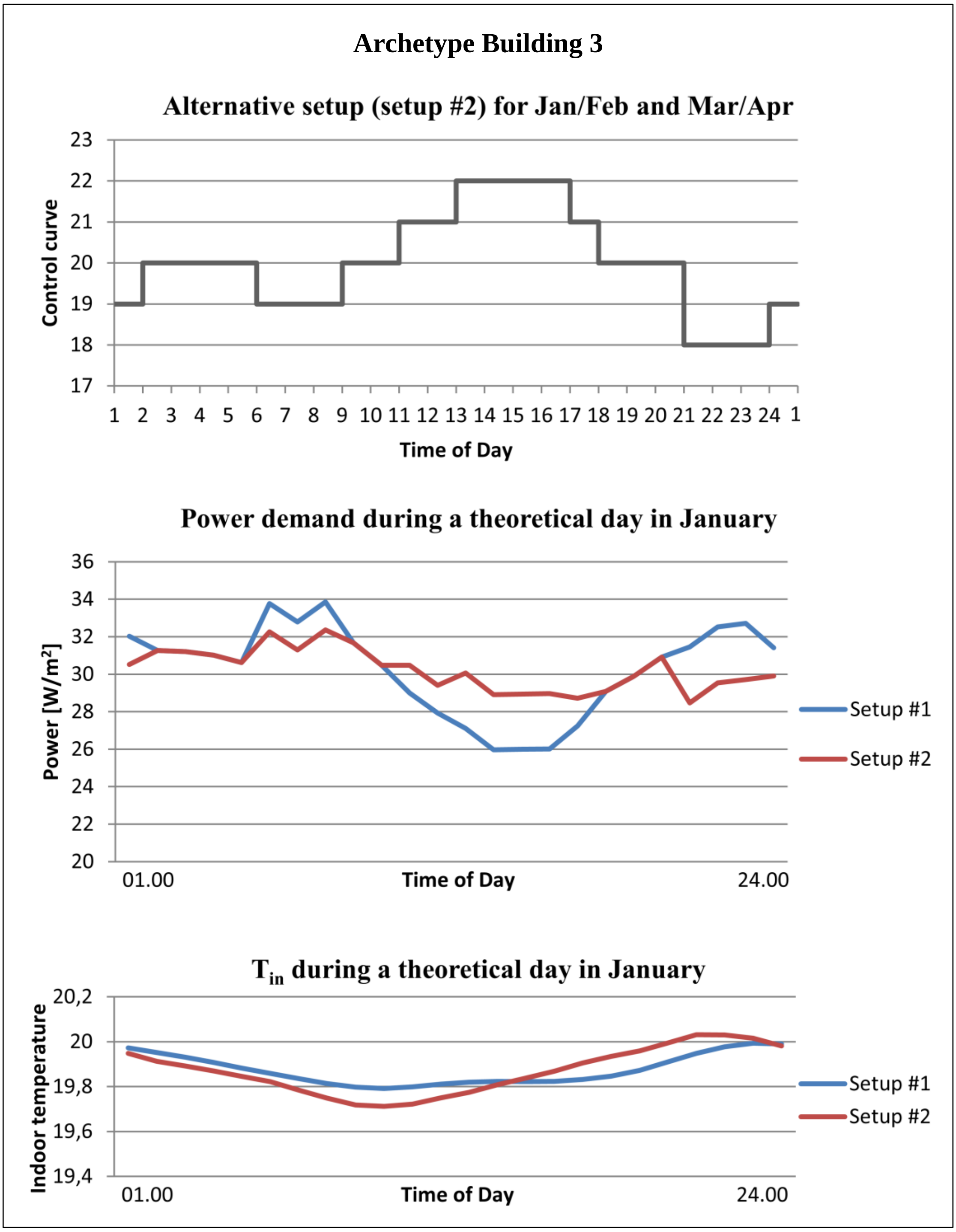


Figure B.5 *Results for archetype building 3 when simulating a weekday with the theoretical day for January. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.*

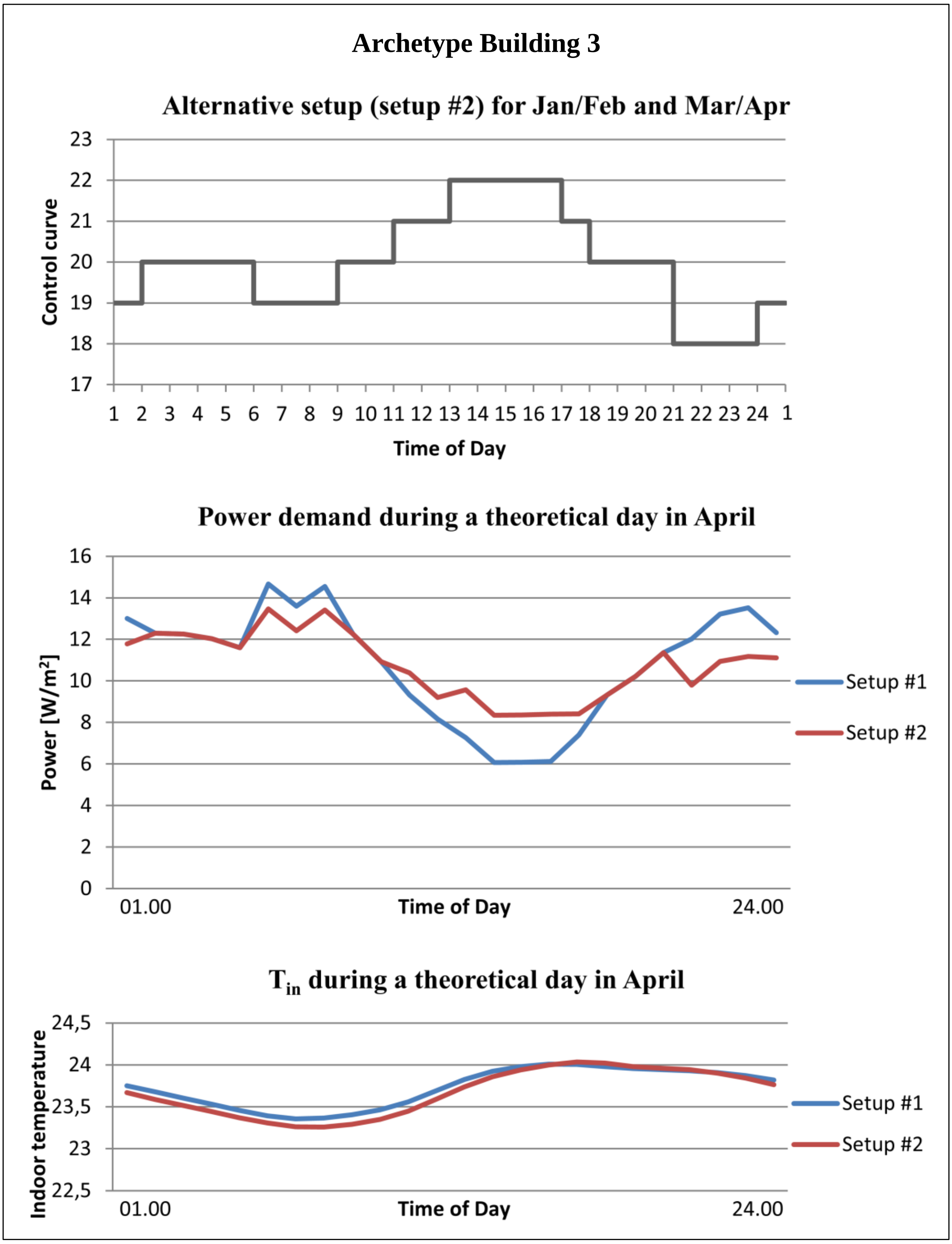


Figure B.6 Results for archetype building 3 when simulating a weekday with the theoretical day for April. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.

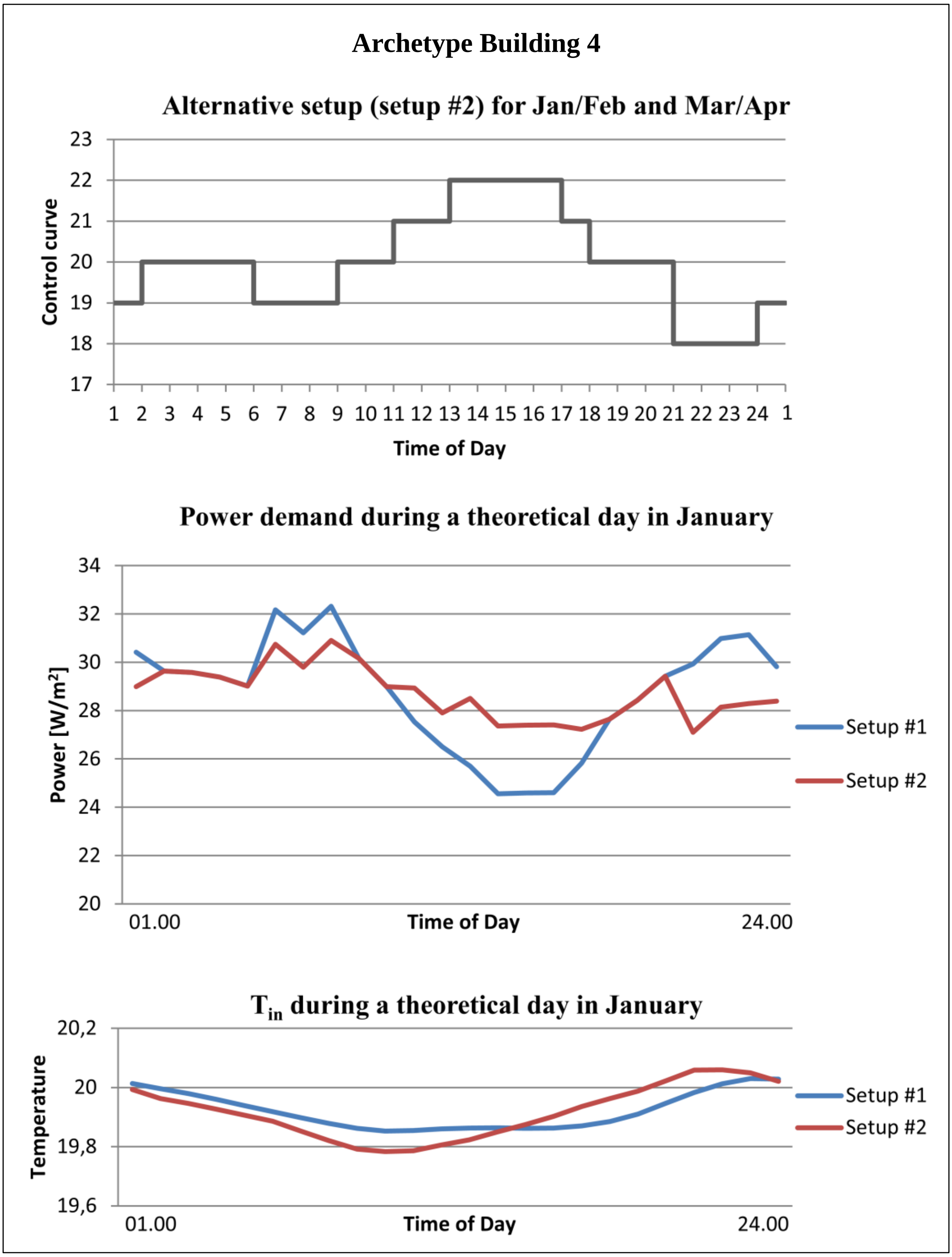


Figure B.7 *Results for archetype building 4 when simulating a weekday with the theoretical day for January. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.*

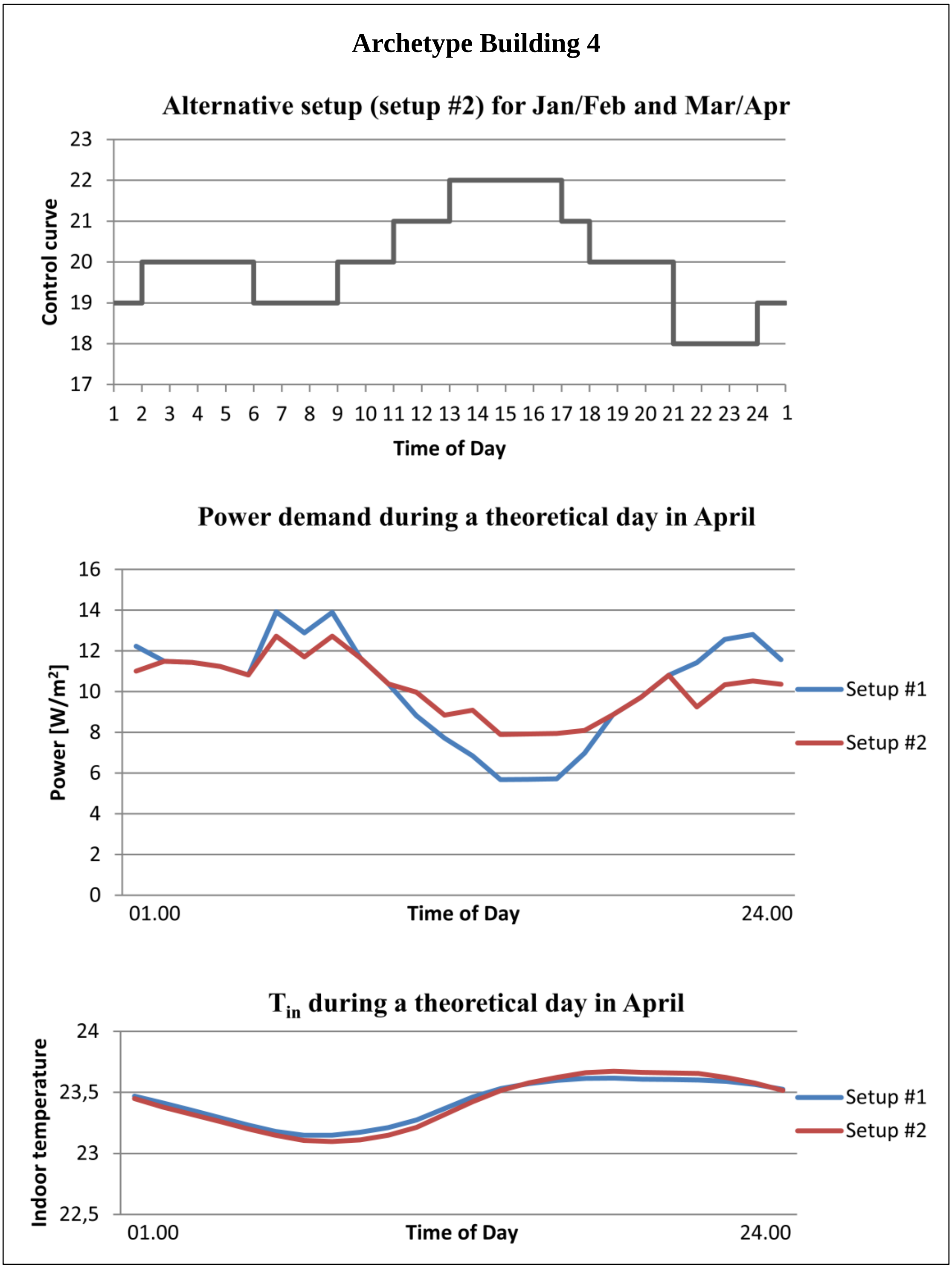


Figure B.8 *Results for archetype building 4 when simulating a weekday with the theoretical day for April. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.*

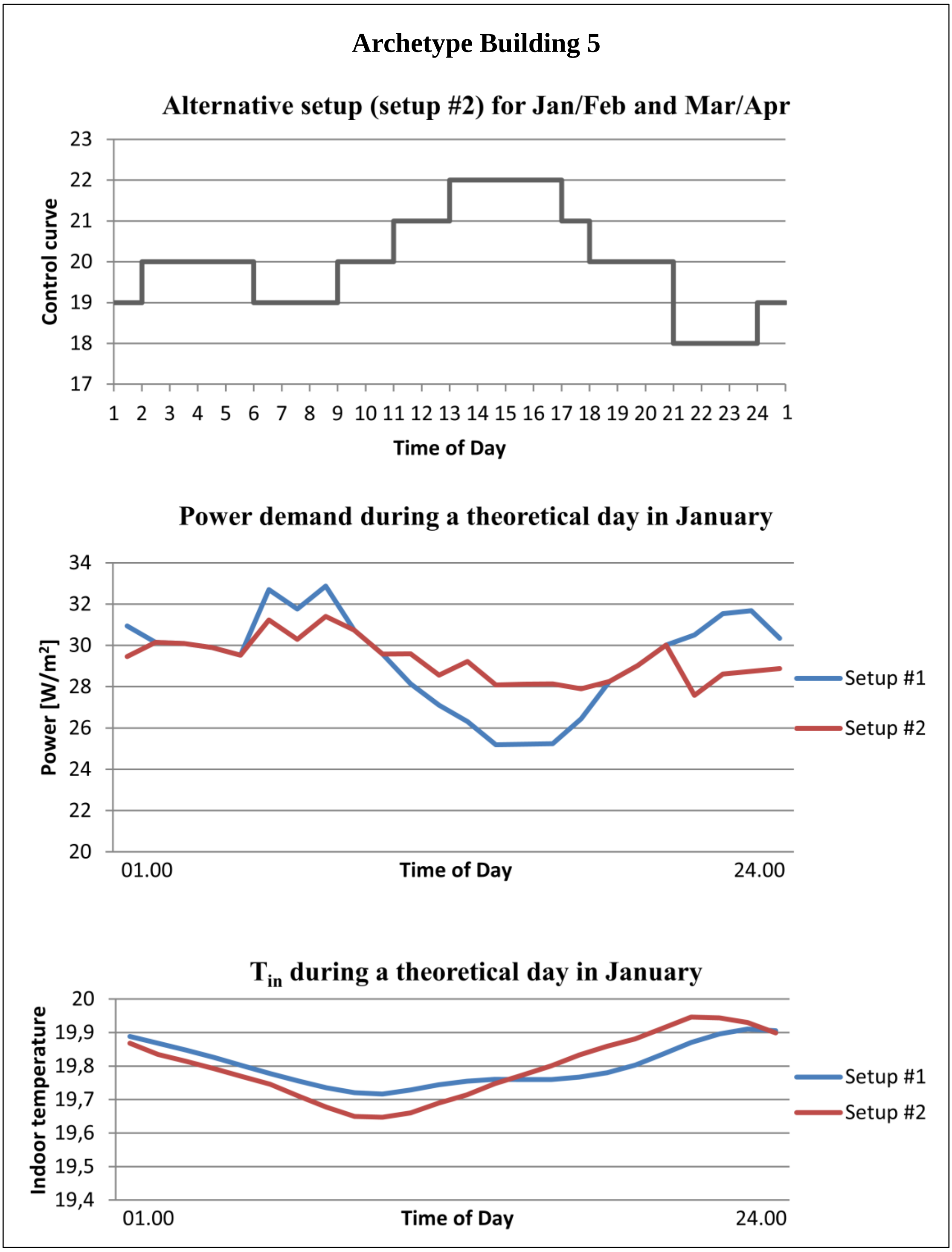


Figure B.9 *Results for archetype building 5 when simulating a weekday with the theoretical day for January. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.*

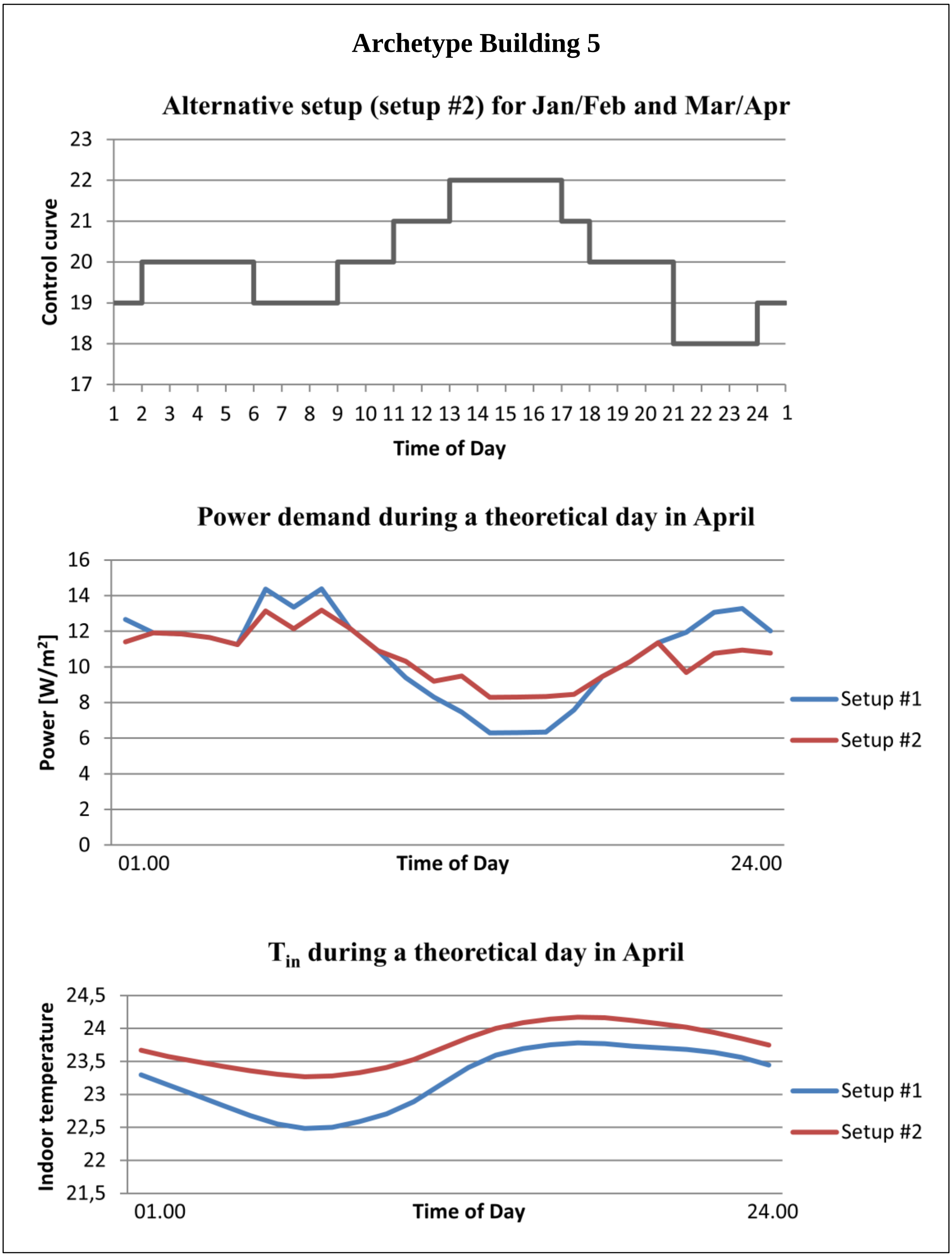


Figure B.10 Results for archetype building 5 when simulating a weekday with the theoretical day for April. Setup 1 is the reference setup; setup 2 is the alternative setup which should reduce setup 1's peaks. Power demand is for both space heating and hot water.

Appendix C: Results from the Simulations on Switch of Control Curves Using Real Days

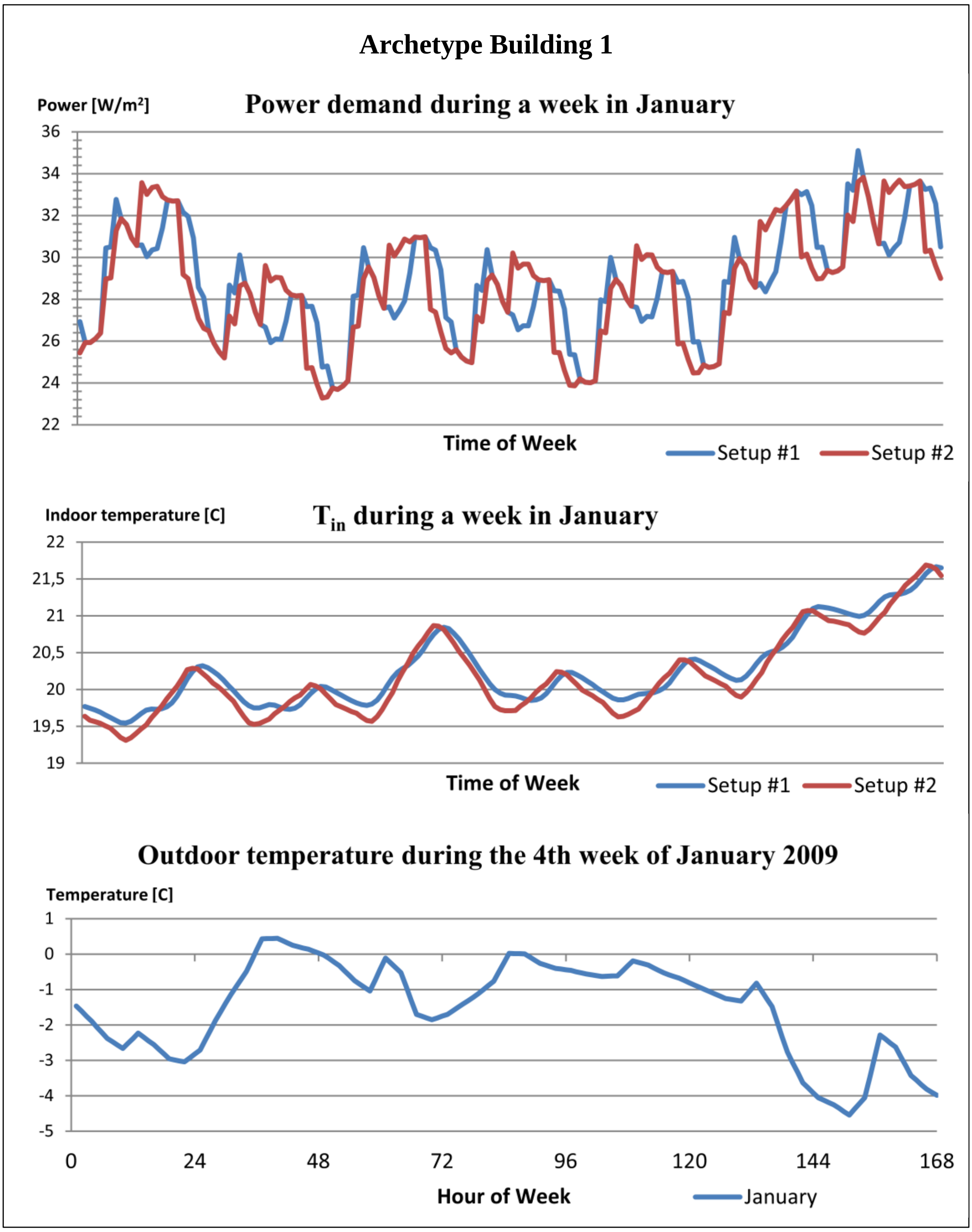


Figure C.1 *Results for archetype building 1 when simulating the fourth week in January 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.*

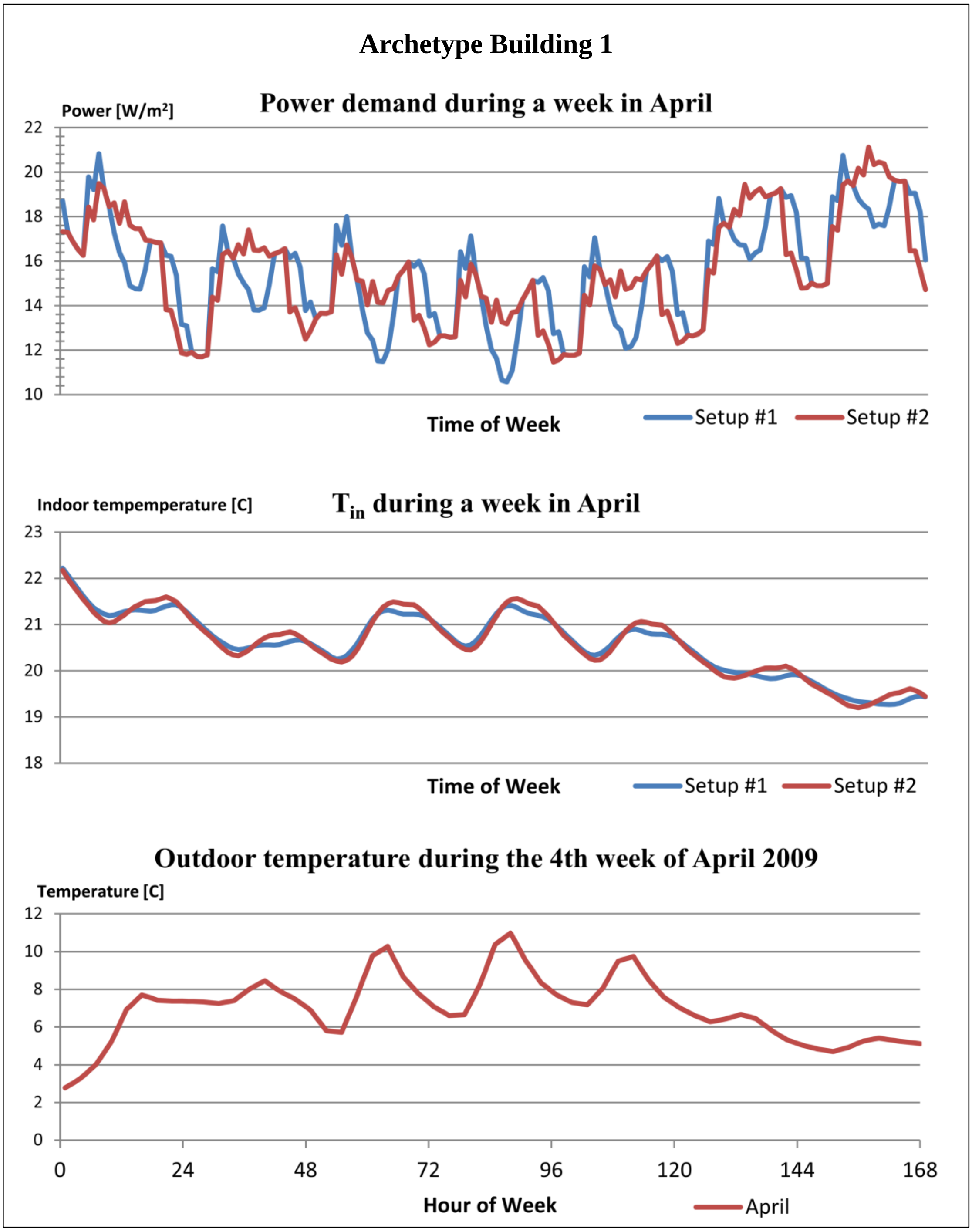


Figure C.2 Results for archetype building 1 when simulating the fourth week in April 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.

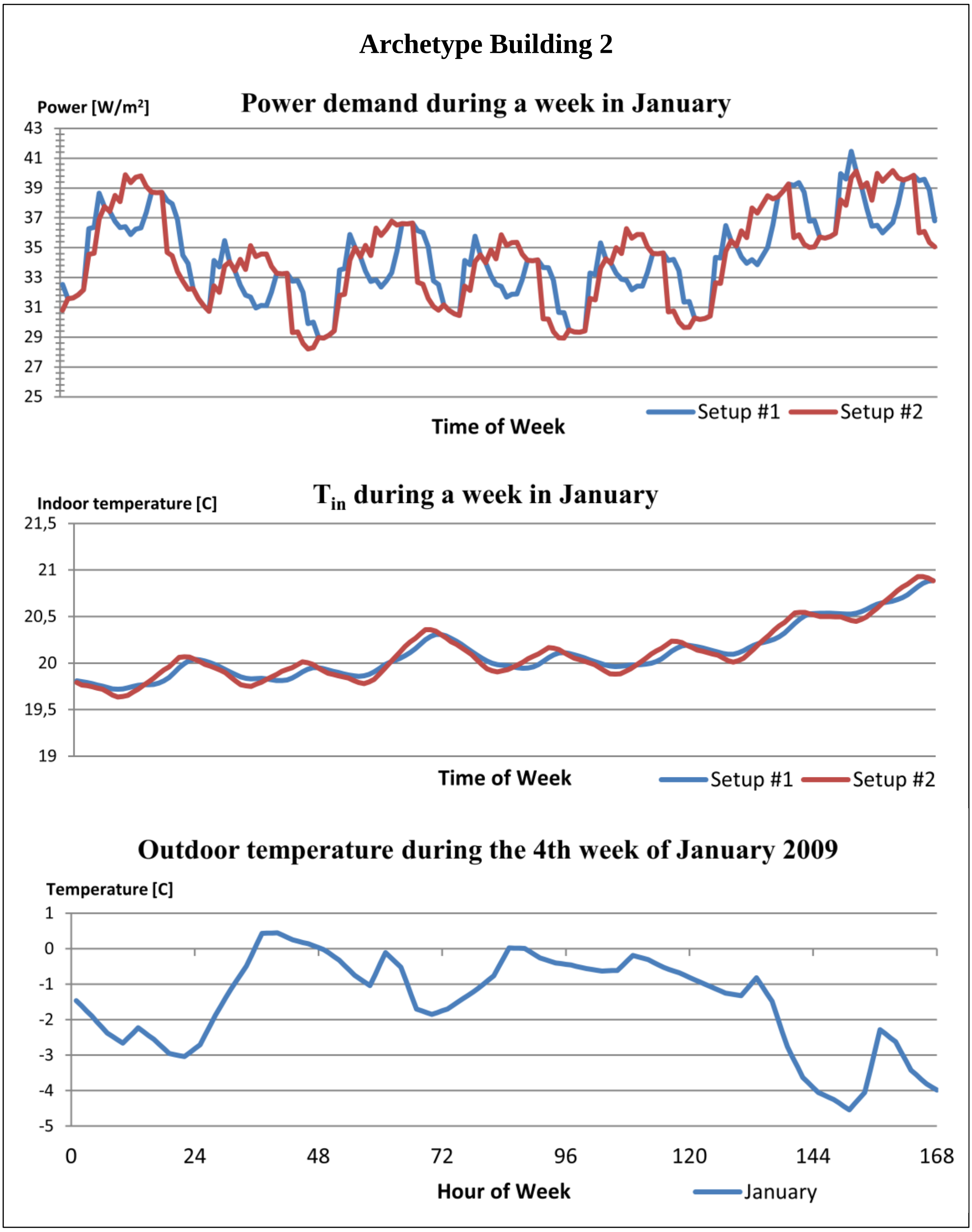


Figure C.3 *Results for archetype building 2 when simulating the fourth week in January 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.*

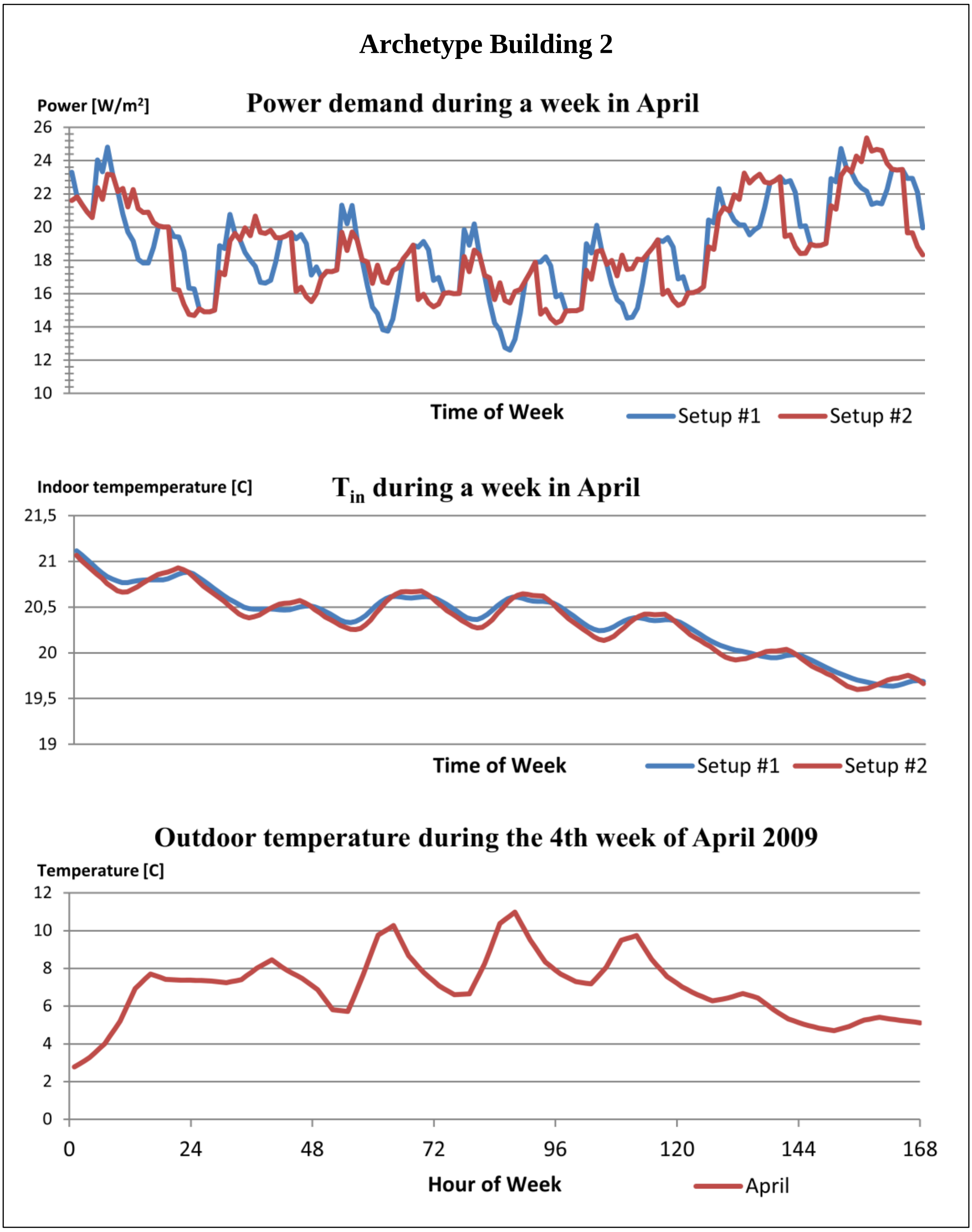


Figure C.4 Results for archetype building 2 when simulating the fourth week in April 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.

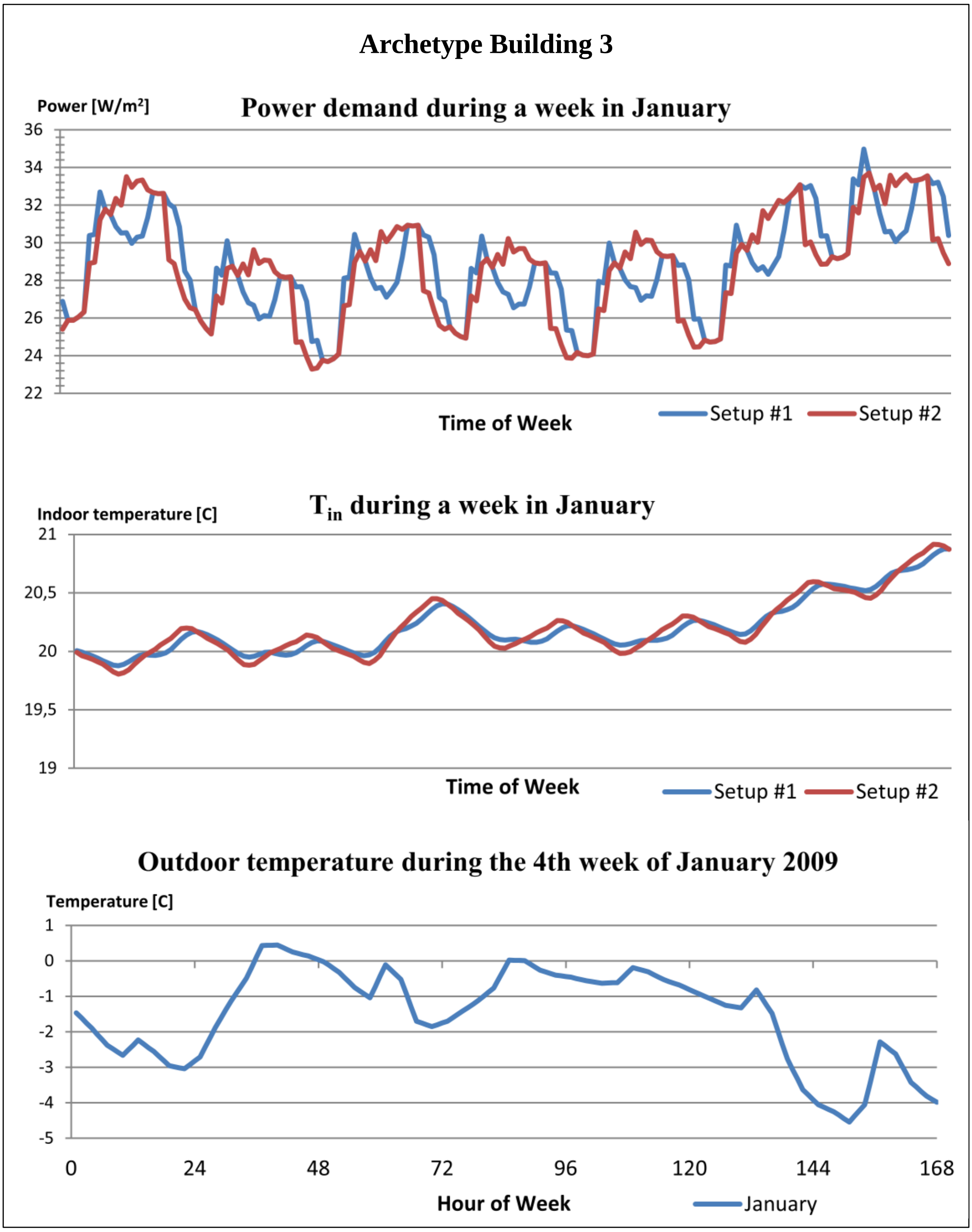


Figure C.5 *Results for archetype building 3 when simulating the fourth week in January 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.*

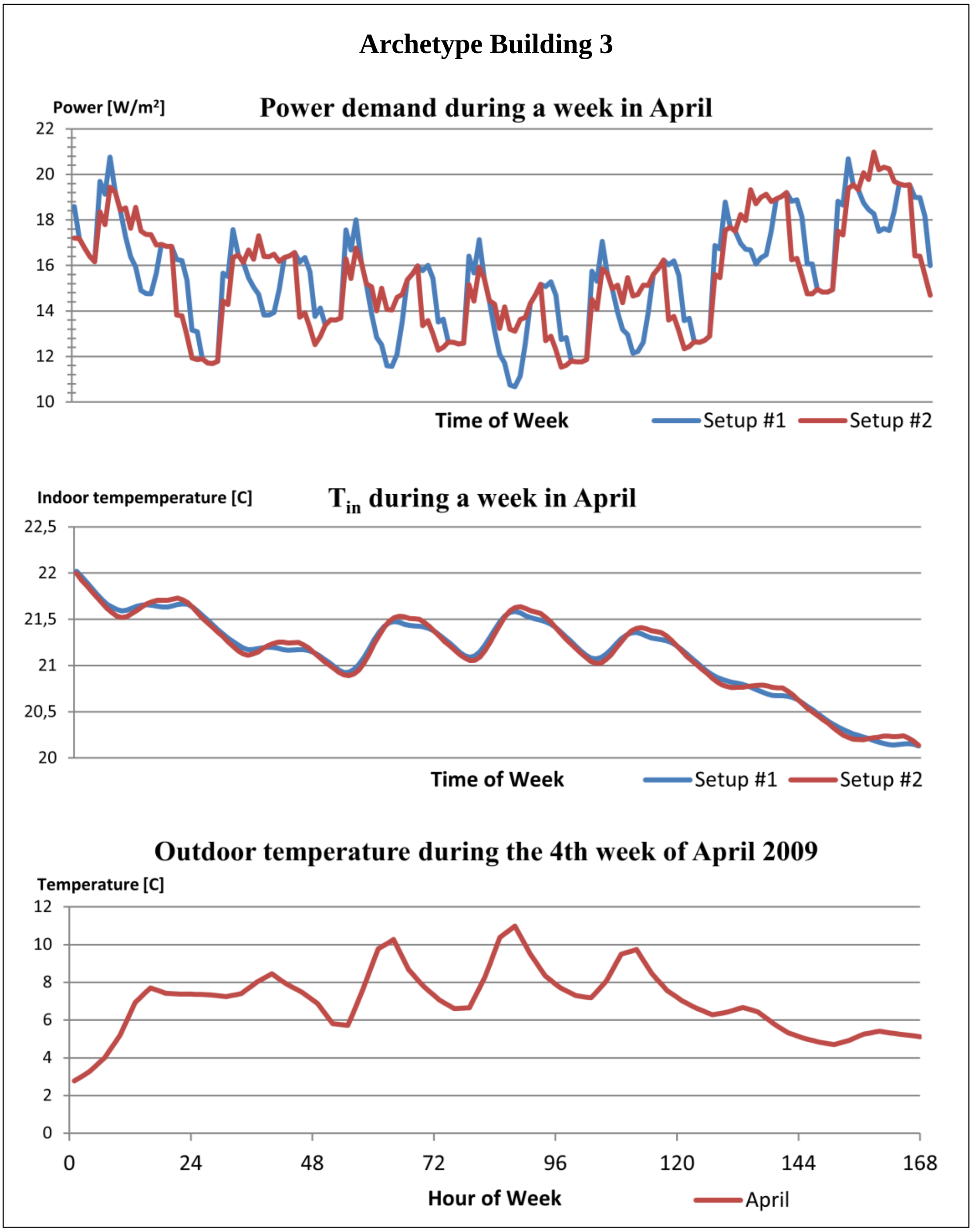


Figure C.6 Results for archetype building 3 when simulating the fourth week in April 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.

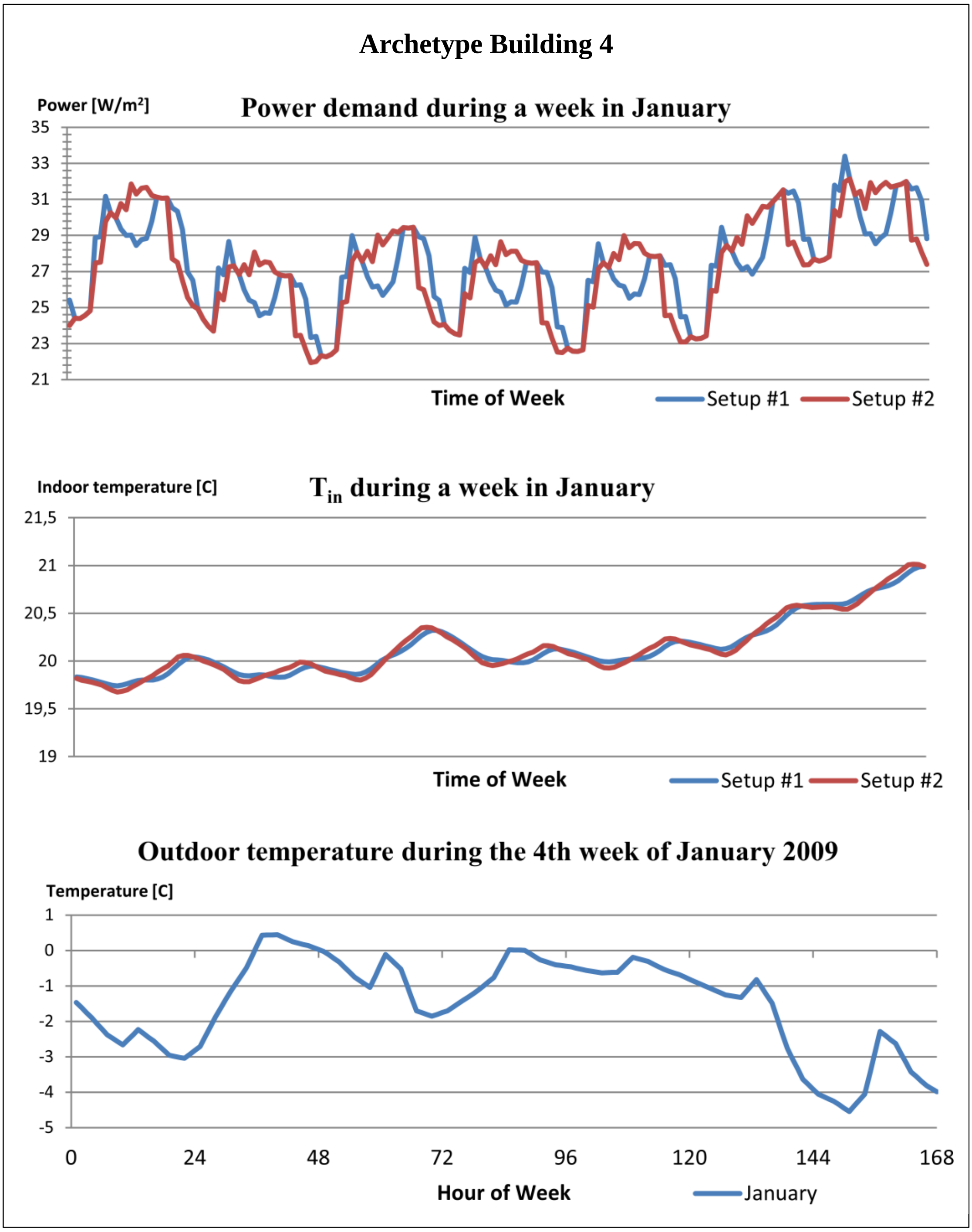


Figure C.7 *Results for archetype building 4 when simulating the fourth week in January 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.*

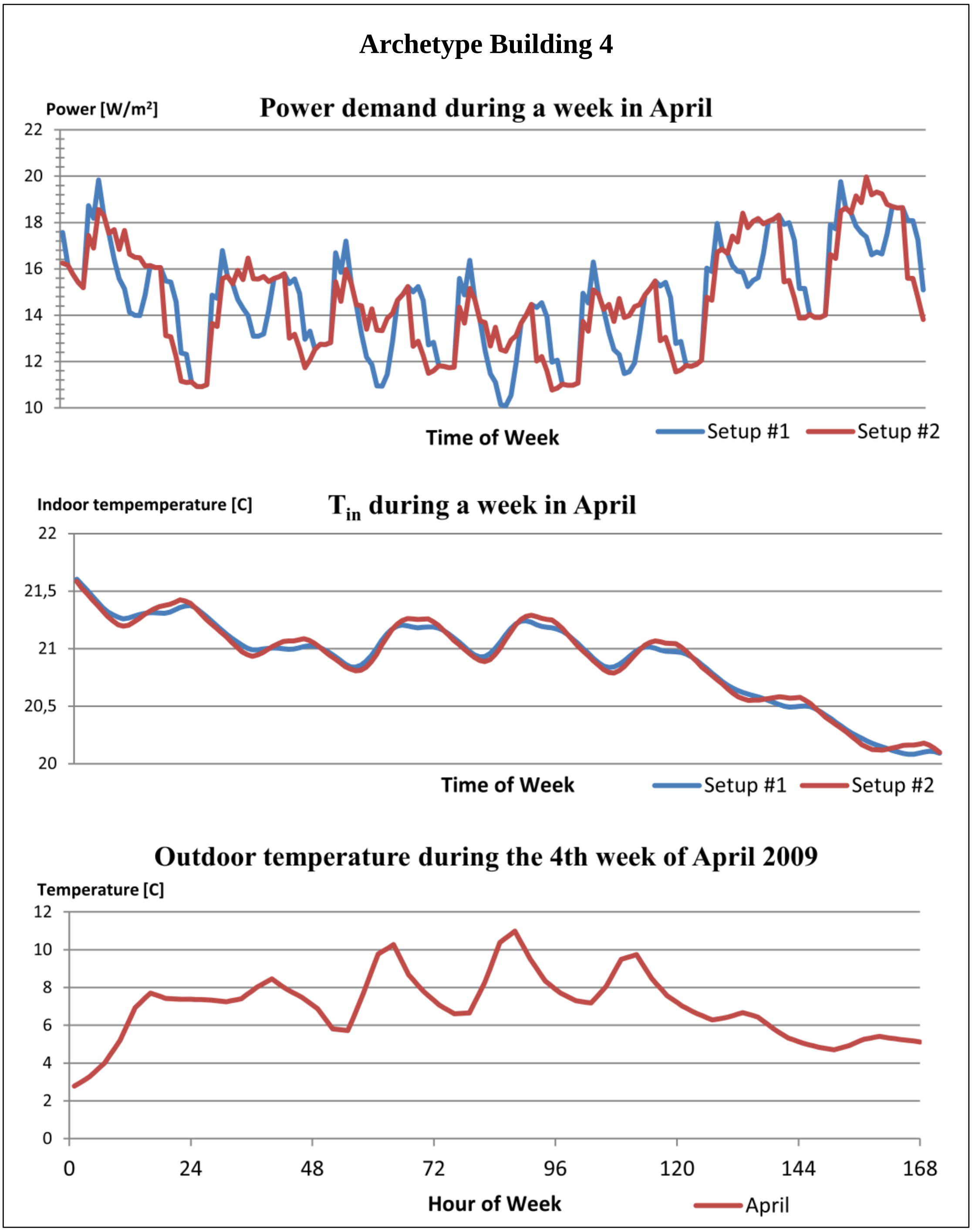


Figure C.8 *Results for archetype building 4 when simulating the fourth week in April 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.*

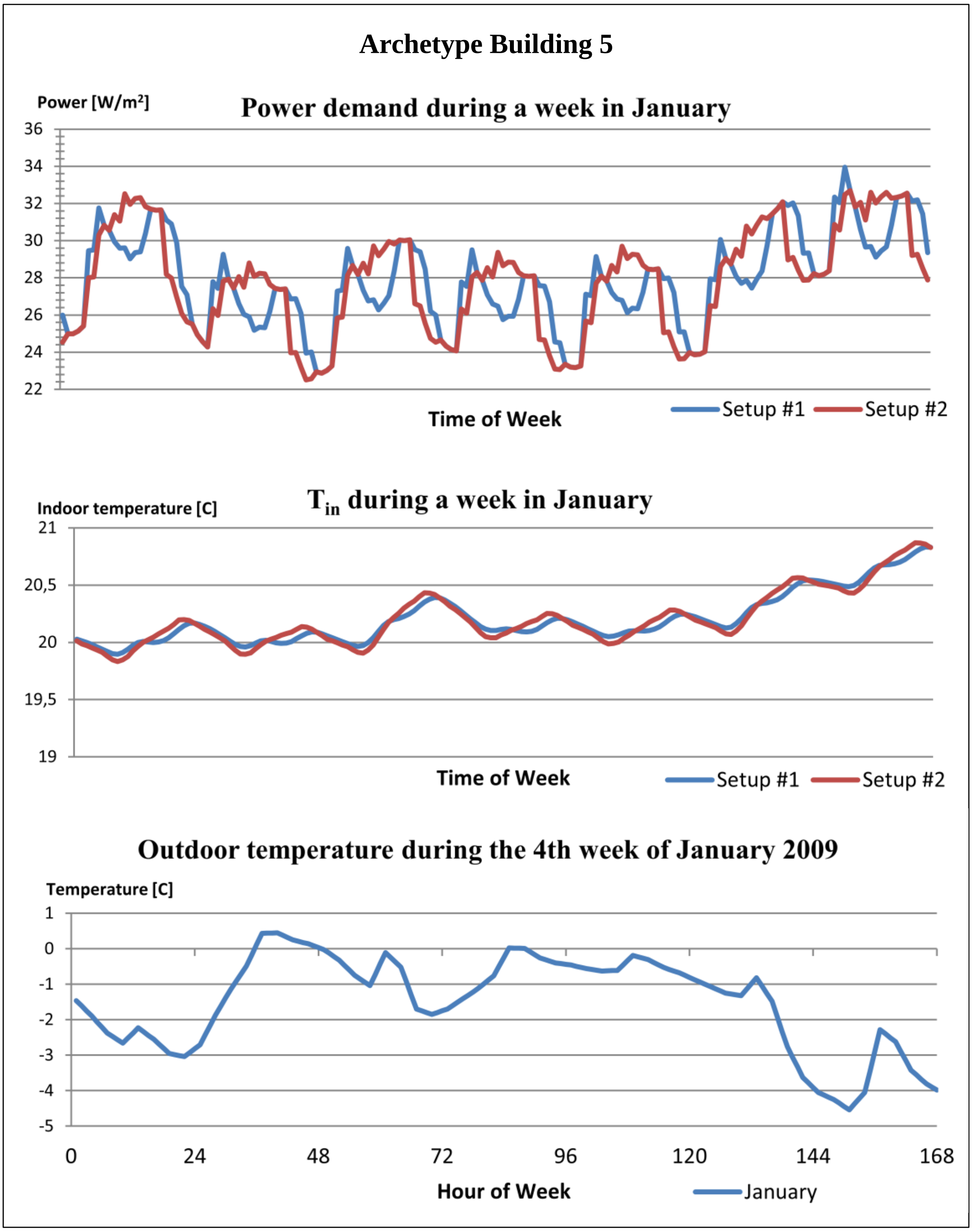


Figure C.9 *Results for archetype building 5 when simulating the fourth week in January 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.*

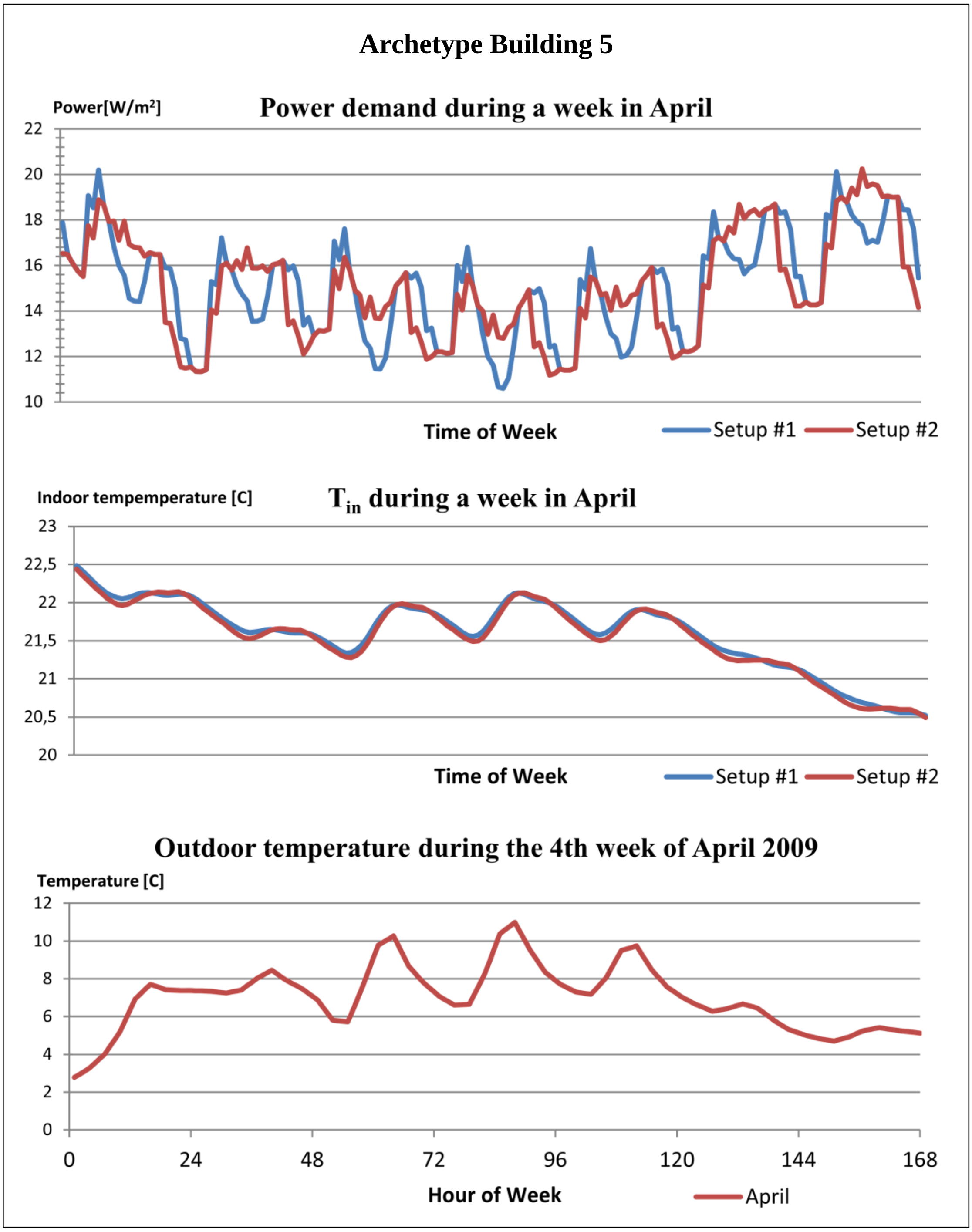


Figure C.10 Results for archetype building 5 when simulating the fourth week in April 2009. Setup 1 represents the reference setup and setup 2 the alternative setup.

Appendix D: Results from the Simulations with Direct Addition of Solar Energy

Graphs in this appendix shows the district heating input, called DH in the graphs, in the different archetype buildings both with and without the addition of solar energy. The amount of solar energy which was collected by the building is also shown as the yellow line. The corresponding temperature are presented in the same figure.

All simulations are done using weather data from 2009. Which simulated building and month each graph represens is specified in the figure text.

Archetype building 1 – Landshövdingehus

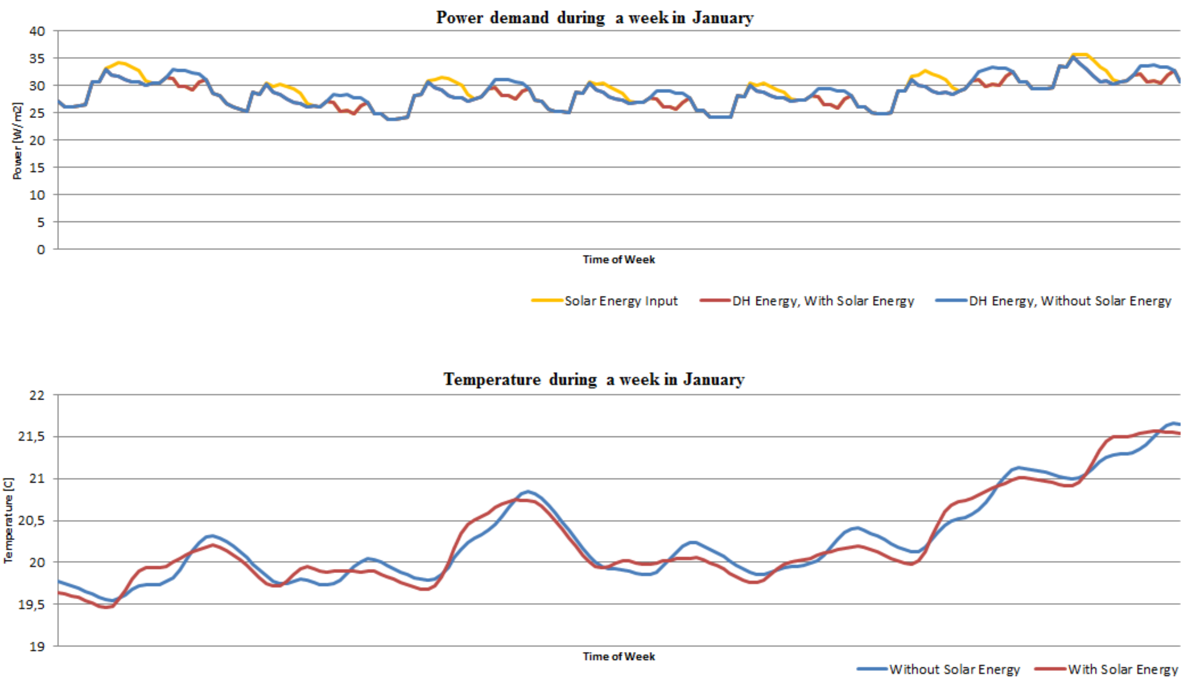


Figure D.1 Archetype building 1 - January

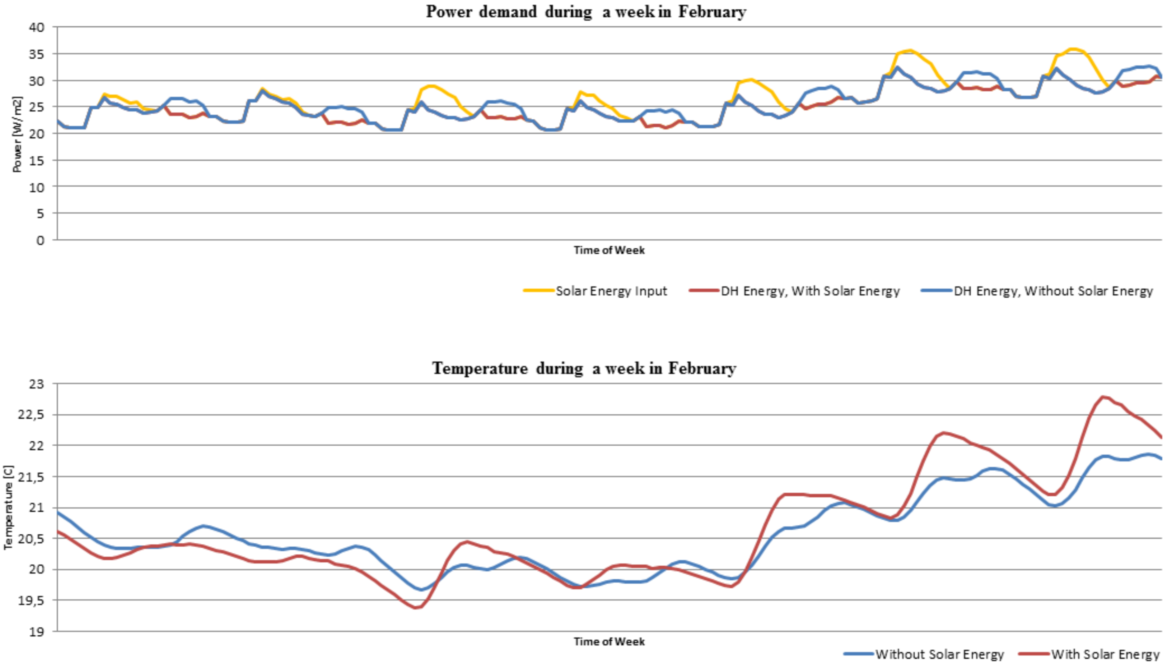


Figure D.2 Archetype building 1 – February

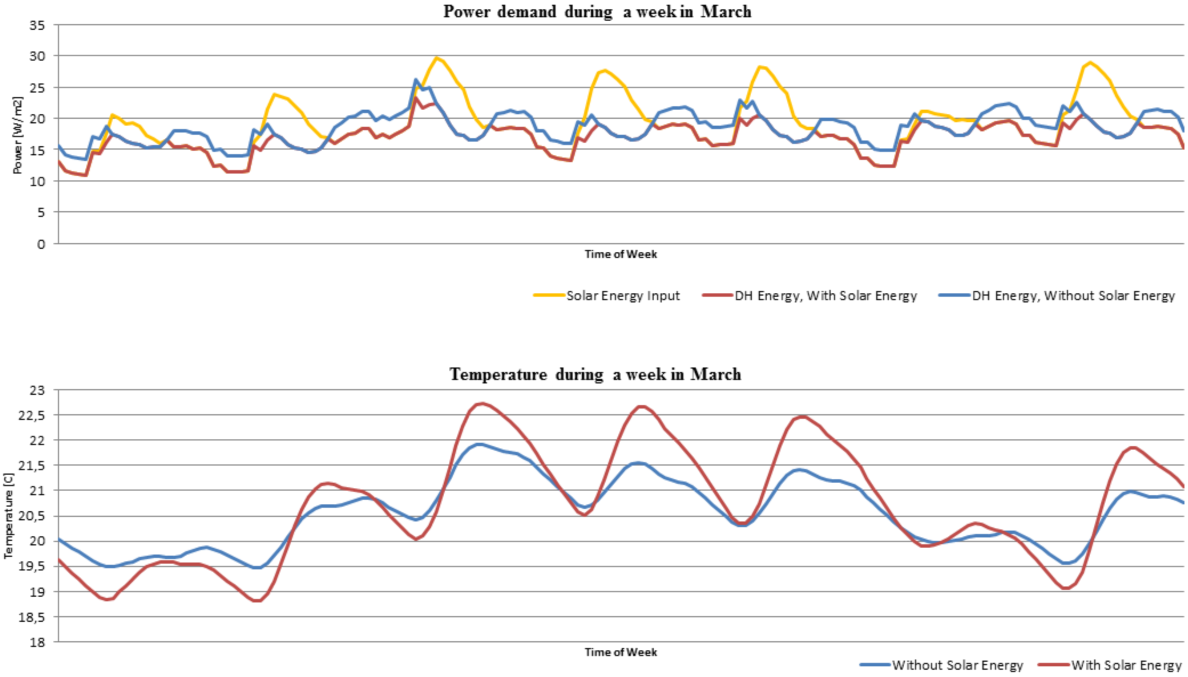


Figure D.3 Archetype building 1 – March

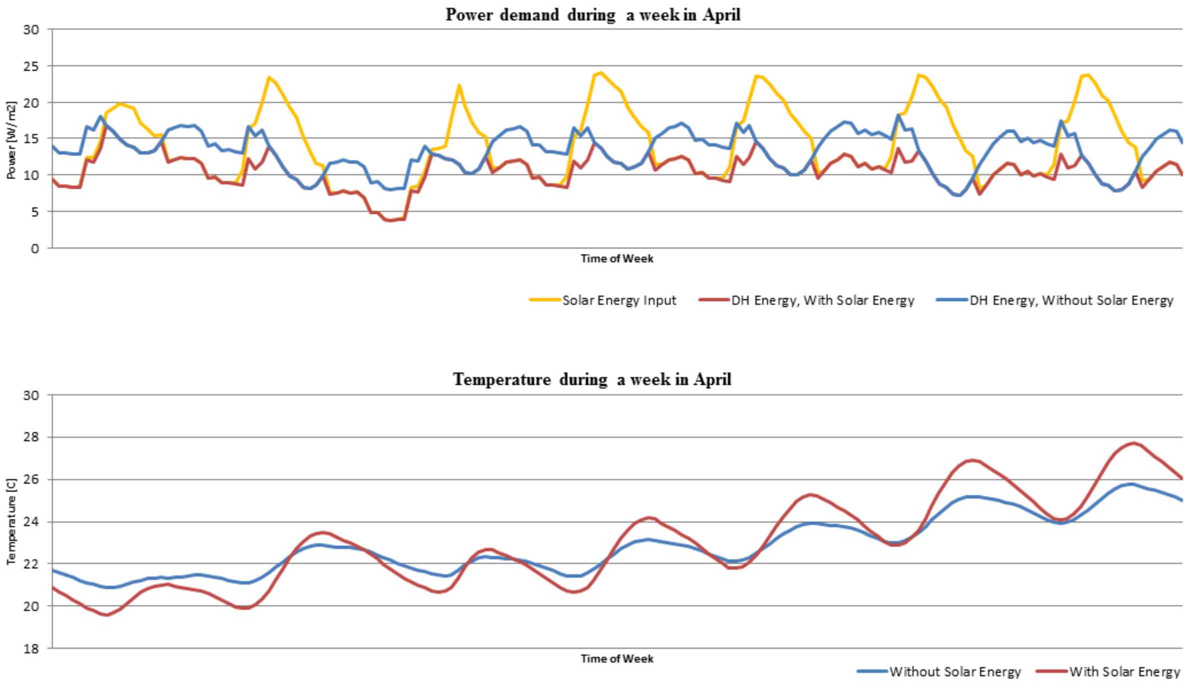


Figure D.4 Archetype building 1 – April

Archetype building 2 – Äldre Lamellhus

Figure D.5 Archetype building 2 – January

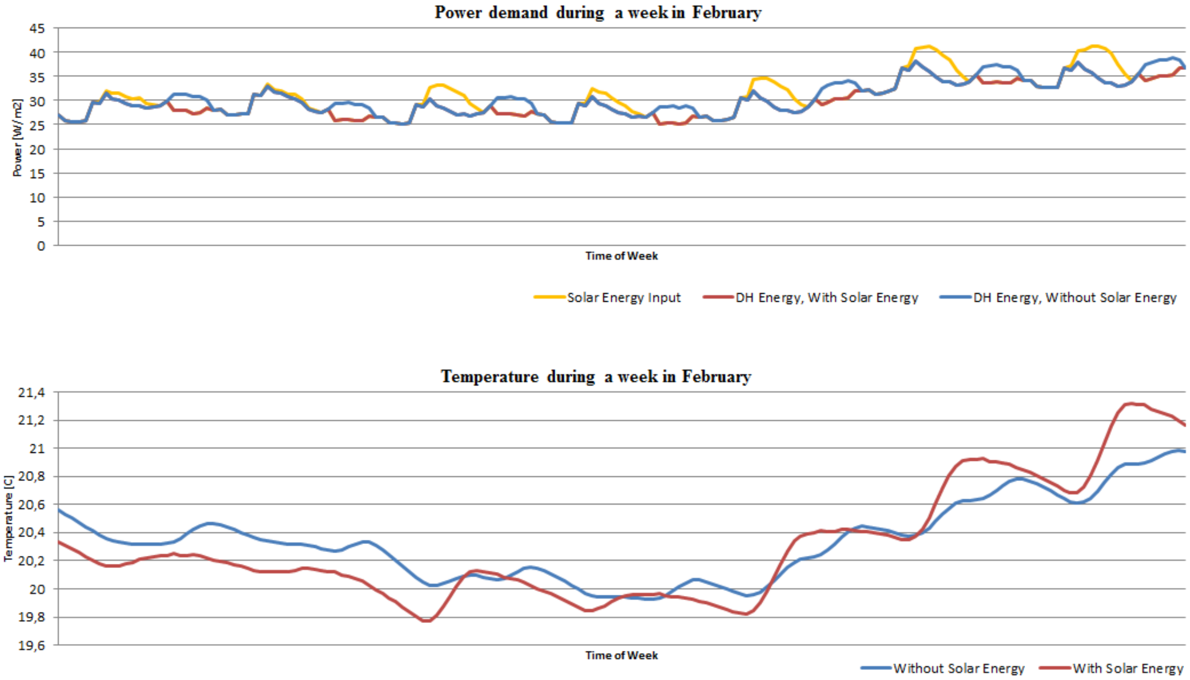


Figure D.6 Archetype building 2 – February

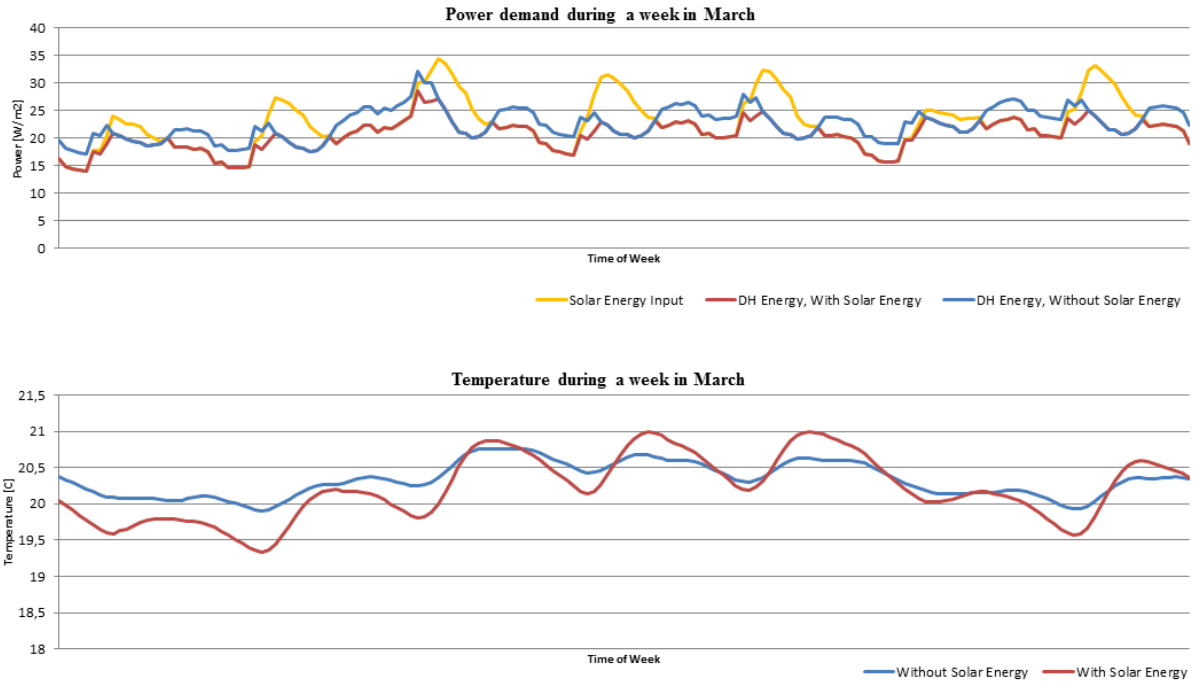


Figure D.7 Archetype building 2 – March

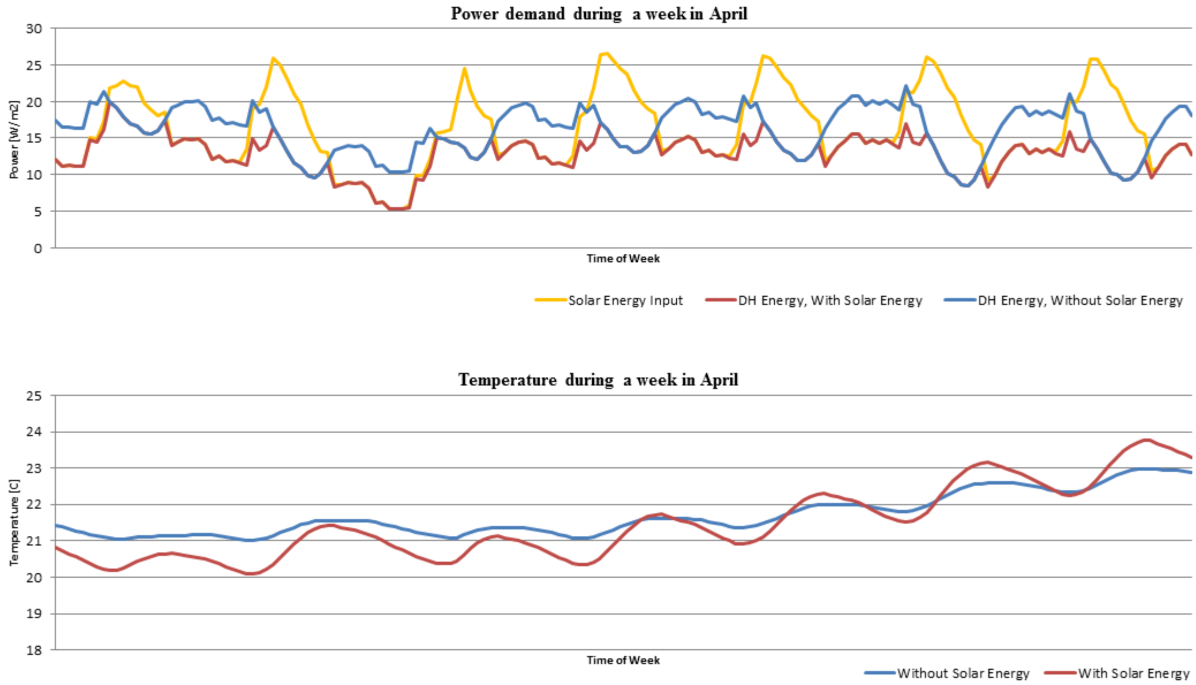


Figure D.8 Archetype building 2 – April

Archetype building 3 – Yngre Lamellhus

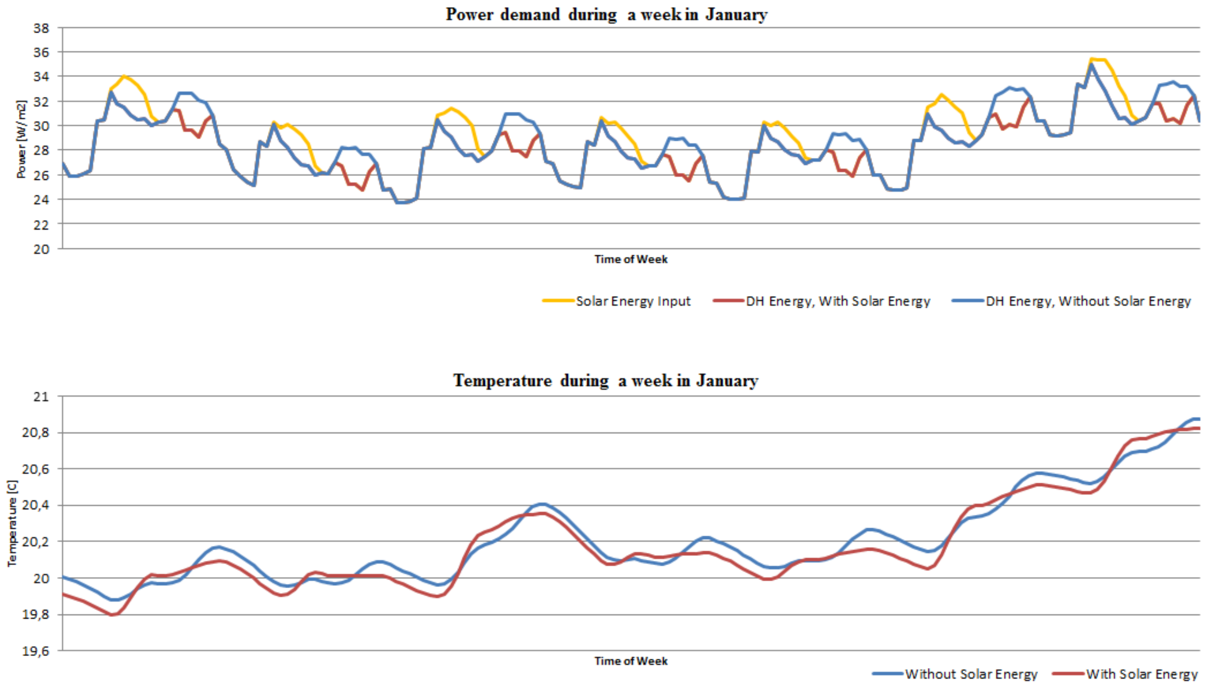


Figure D.9 Archetype building 3 – January

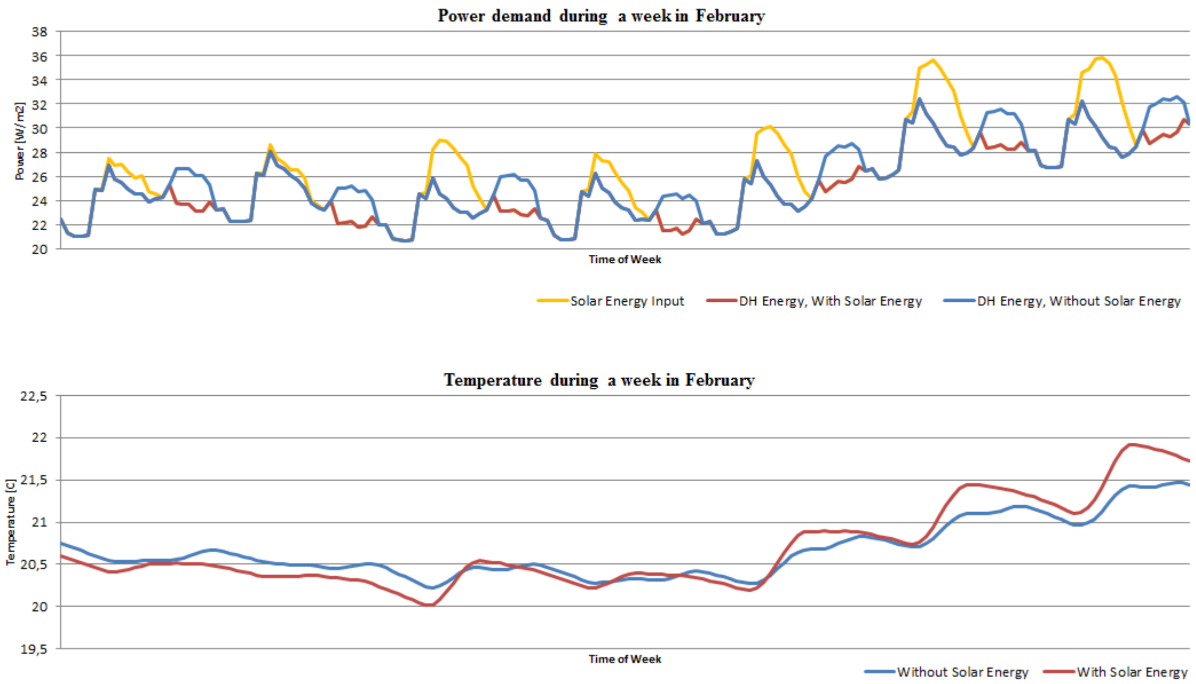


Figure D.10 Archetype building 3 – February

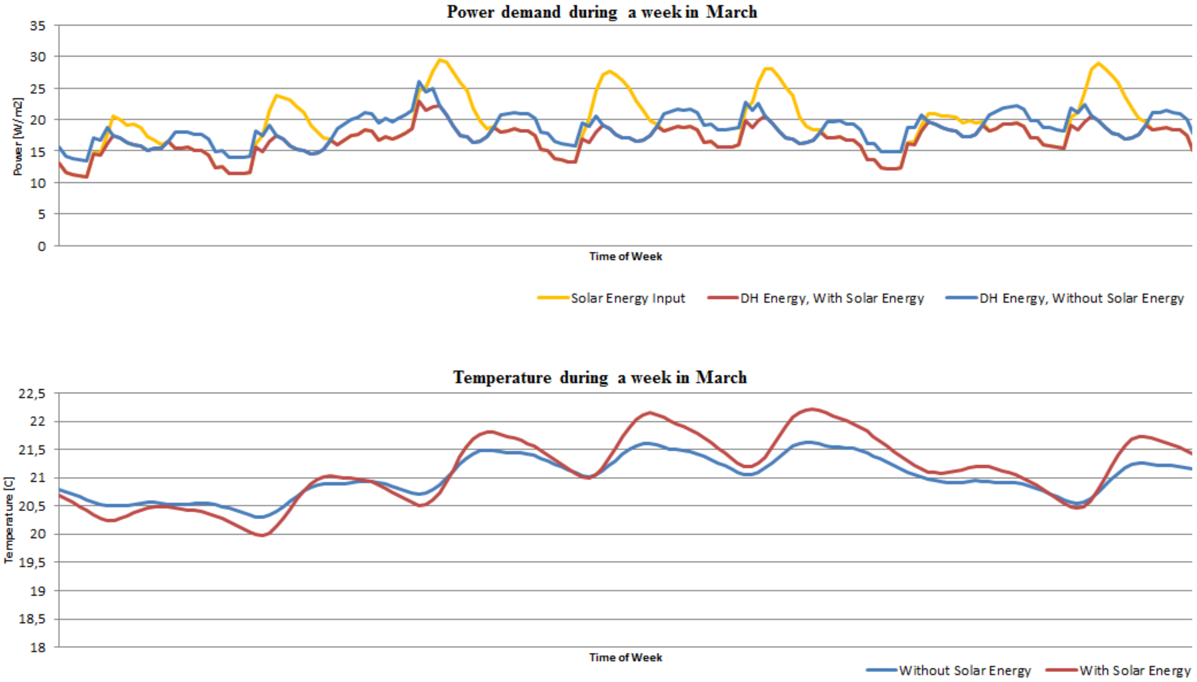


Figure D.11 Archetype building 3 – March

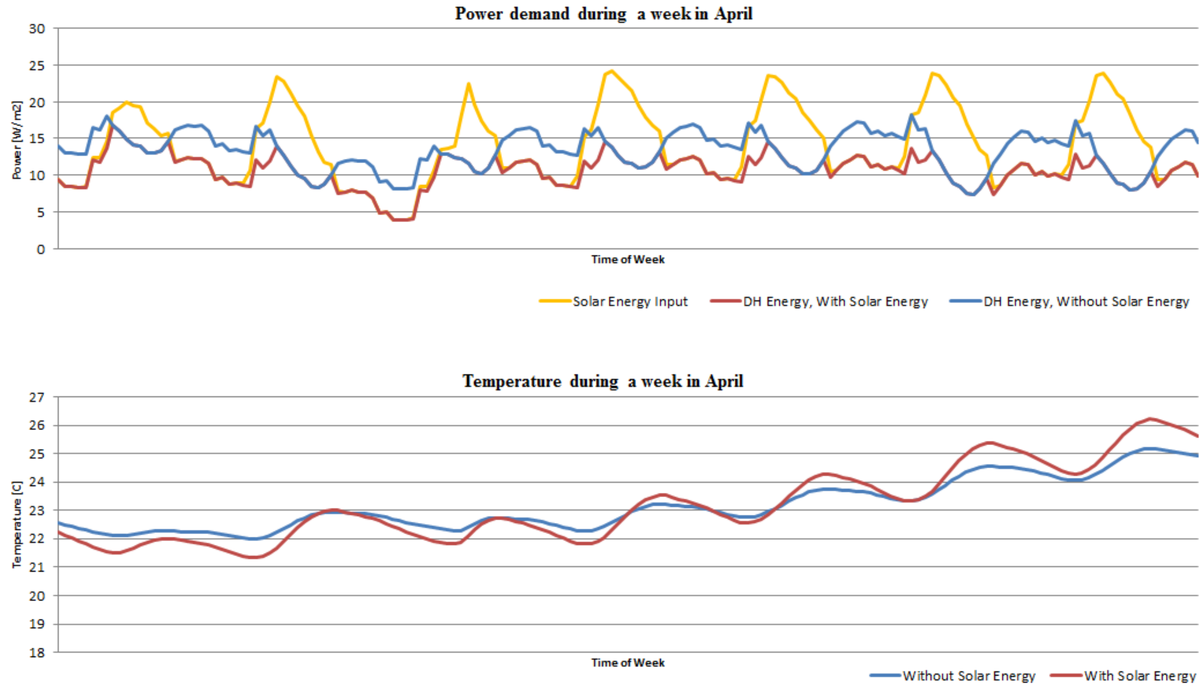


Figure D.12 Archetype building 3 – April

Archetype building 4 – Punkthus

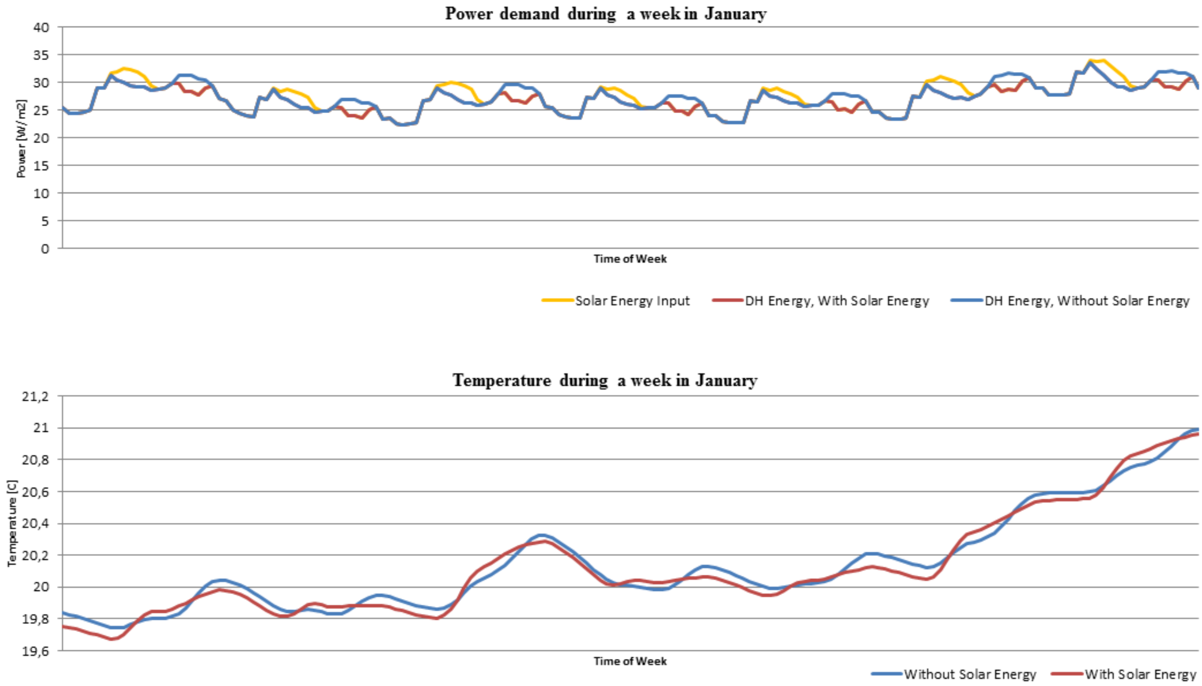


Figure D.13 Archetype building 4 – January

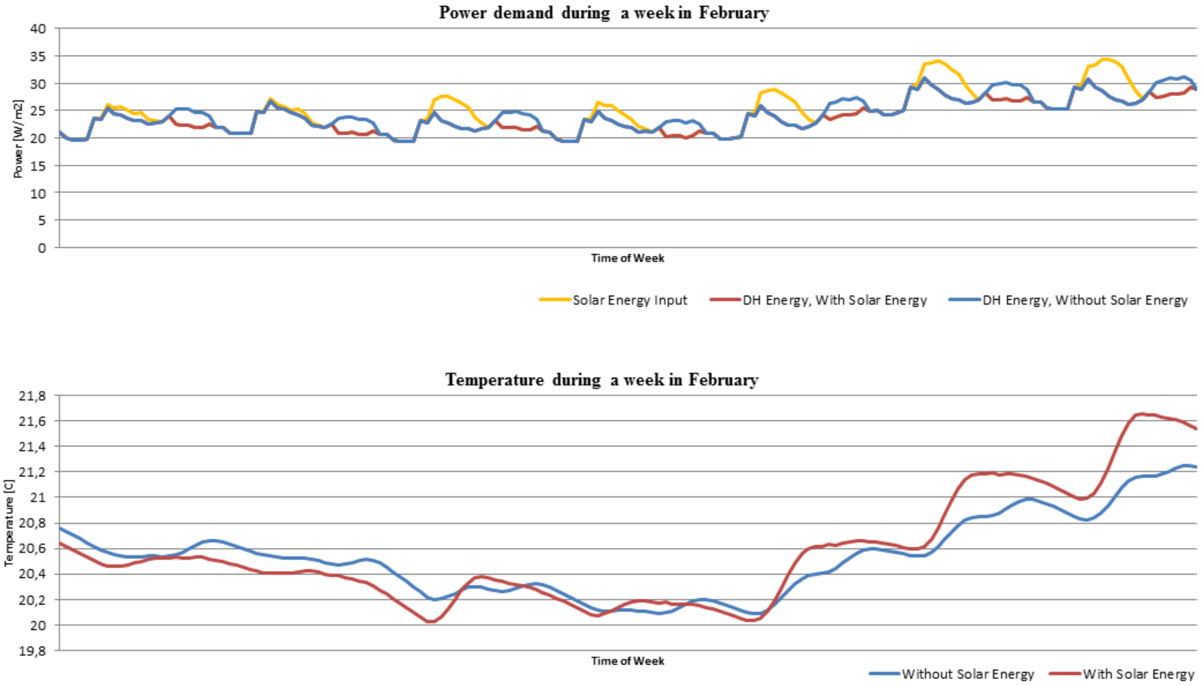


Figure D.14 Archetype building 4 – February

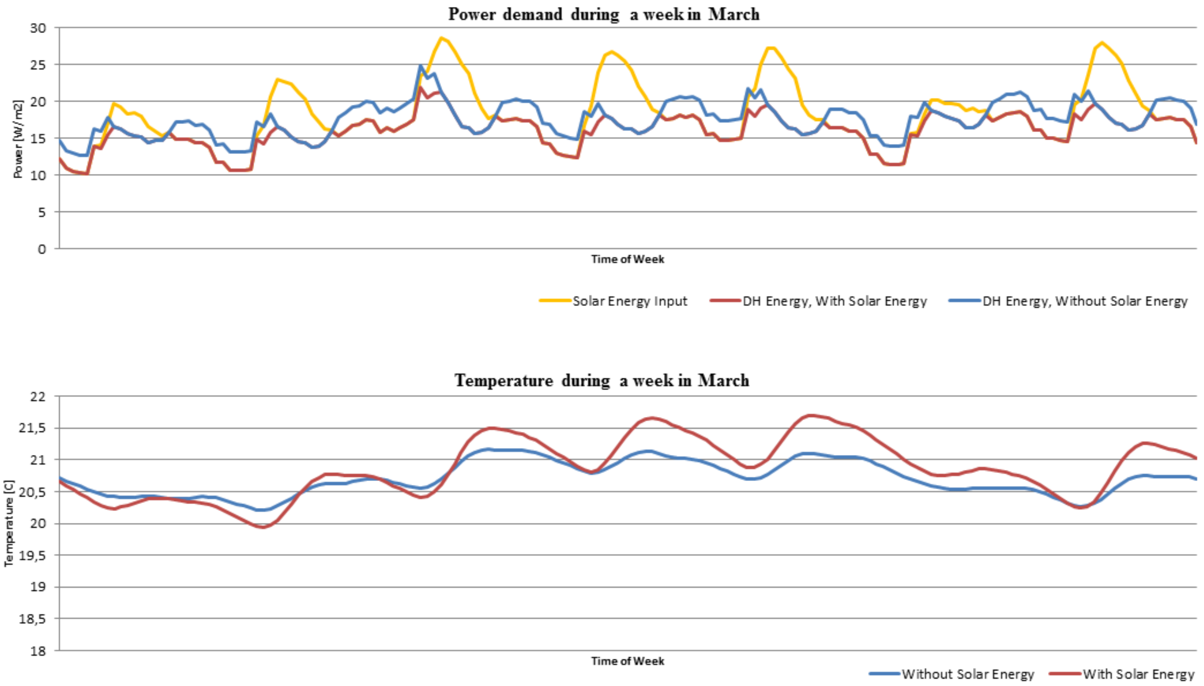


Figure D.15 Archetype building 4 – March

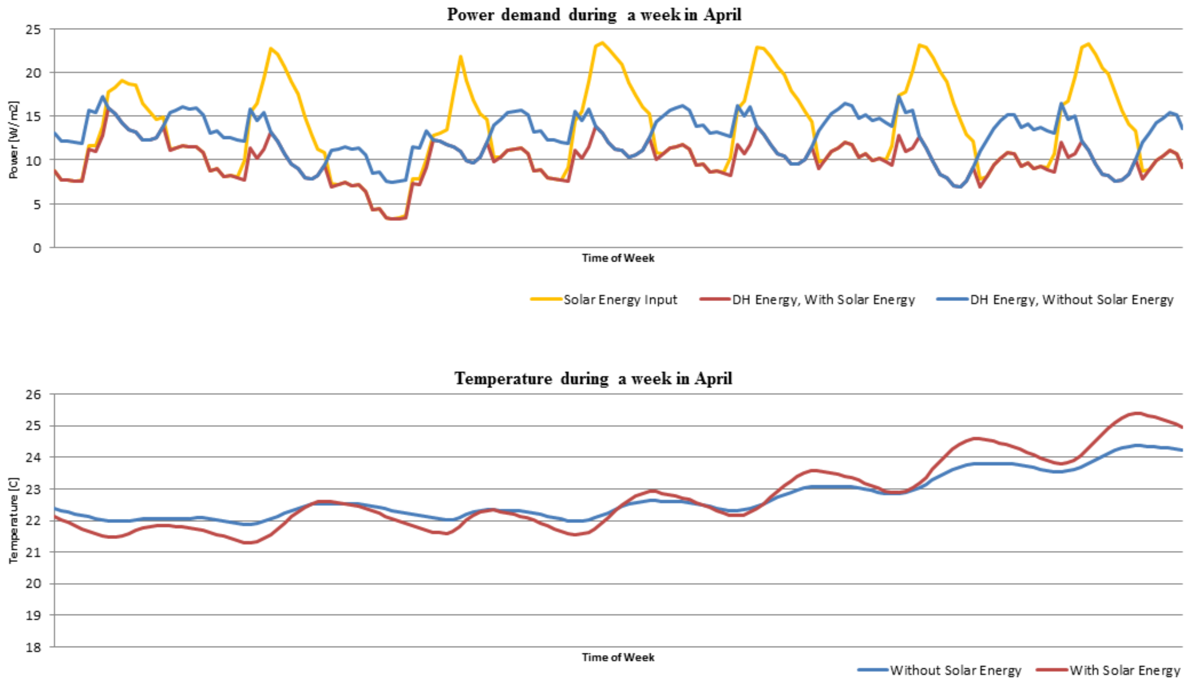


Figure D.16 Archetype building 4 – April

Archetype building 5 – Skivhus

Figure D.16 Archetype building 5 – January

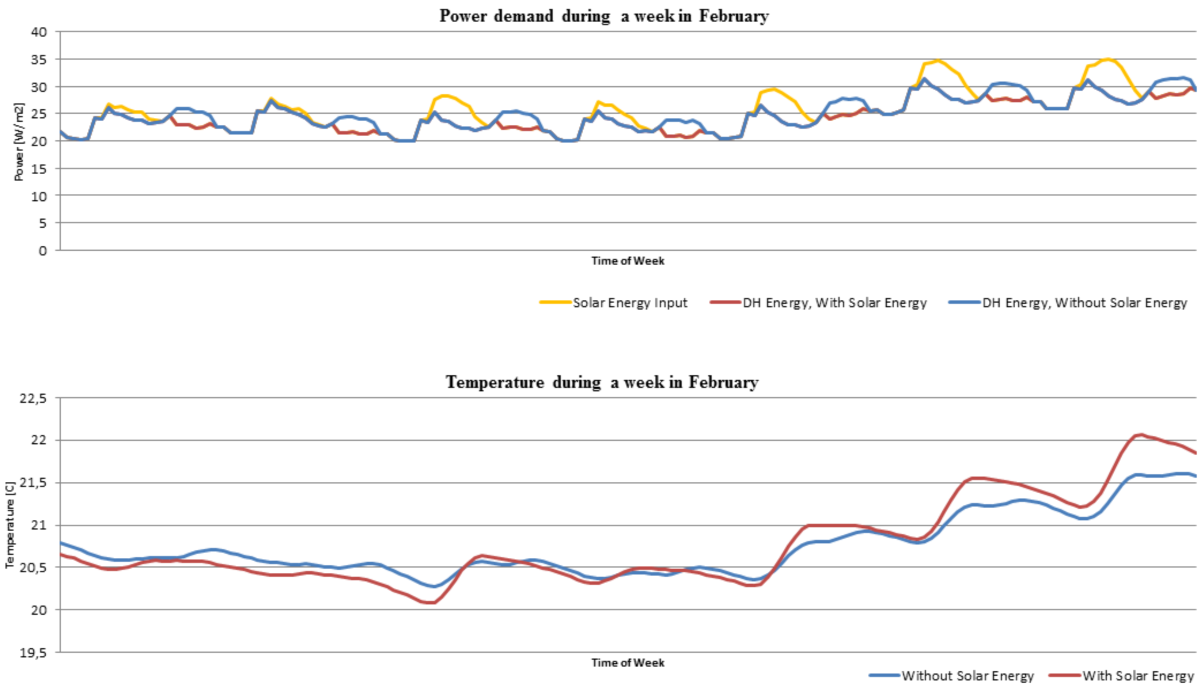


Figure D.17 Archetype building 5 – February

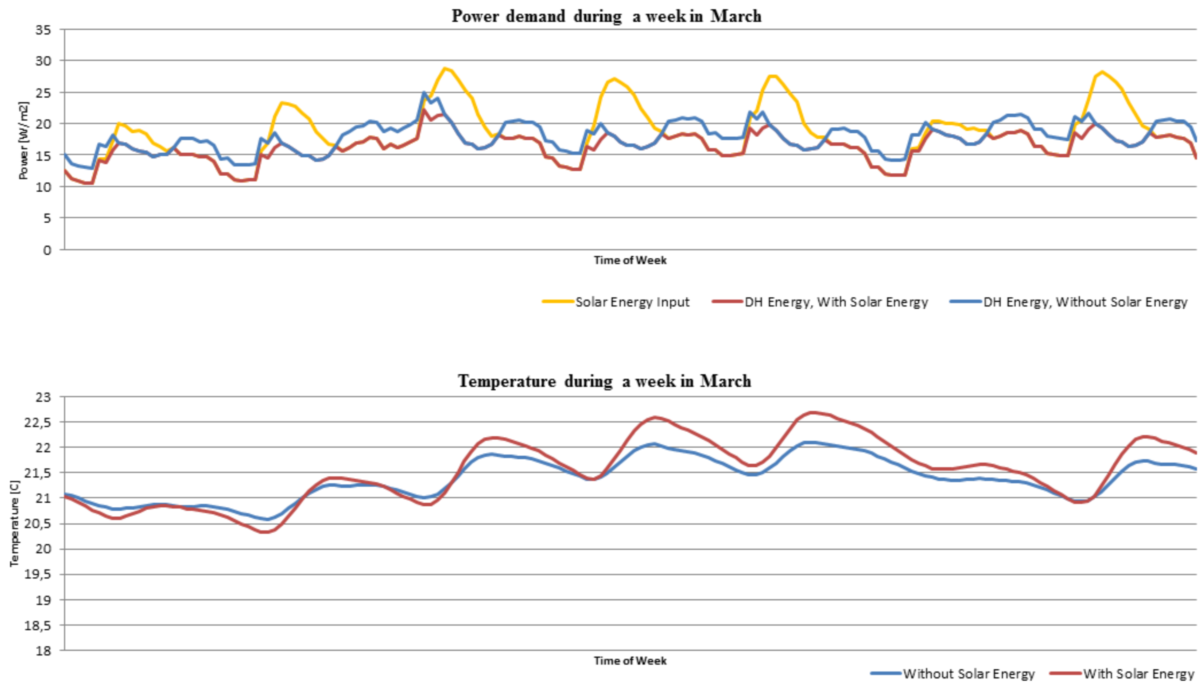
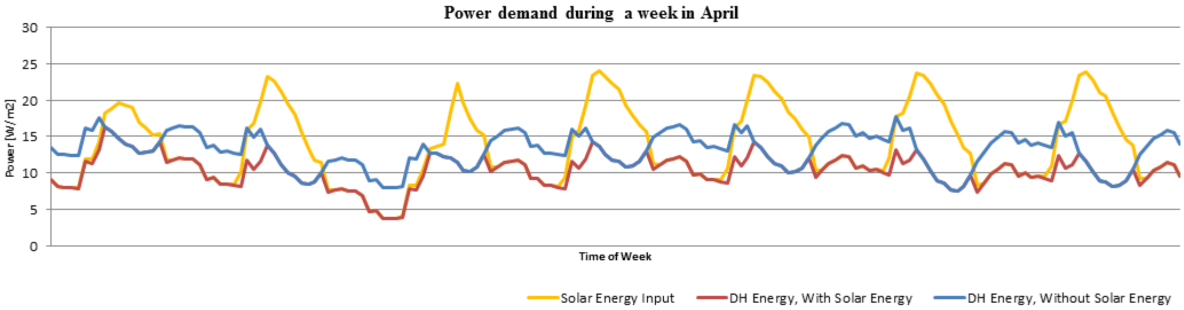


Figure D.17 Archetype building 5 – March



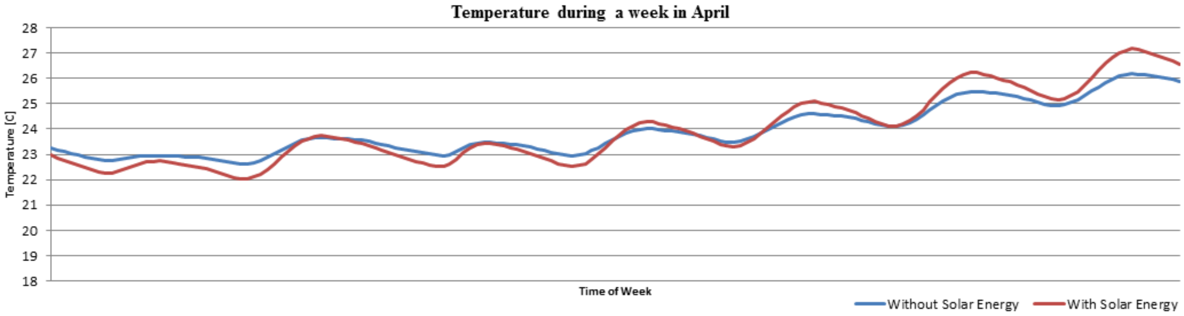


Figure D.18 Archetype building 5 – April

Appendix E: Results from the Simulations with Accumulation of Solar Energy

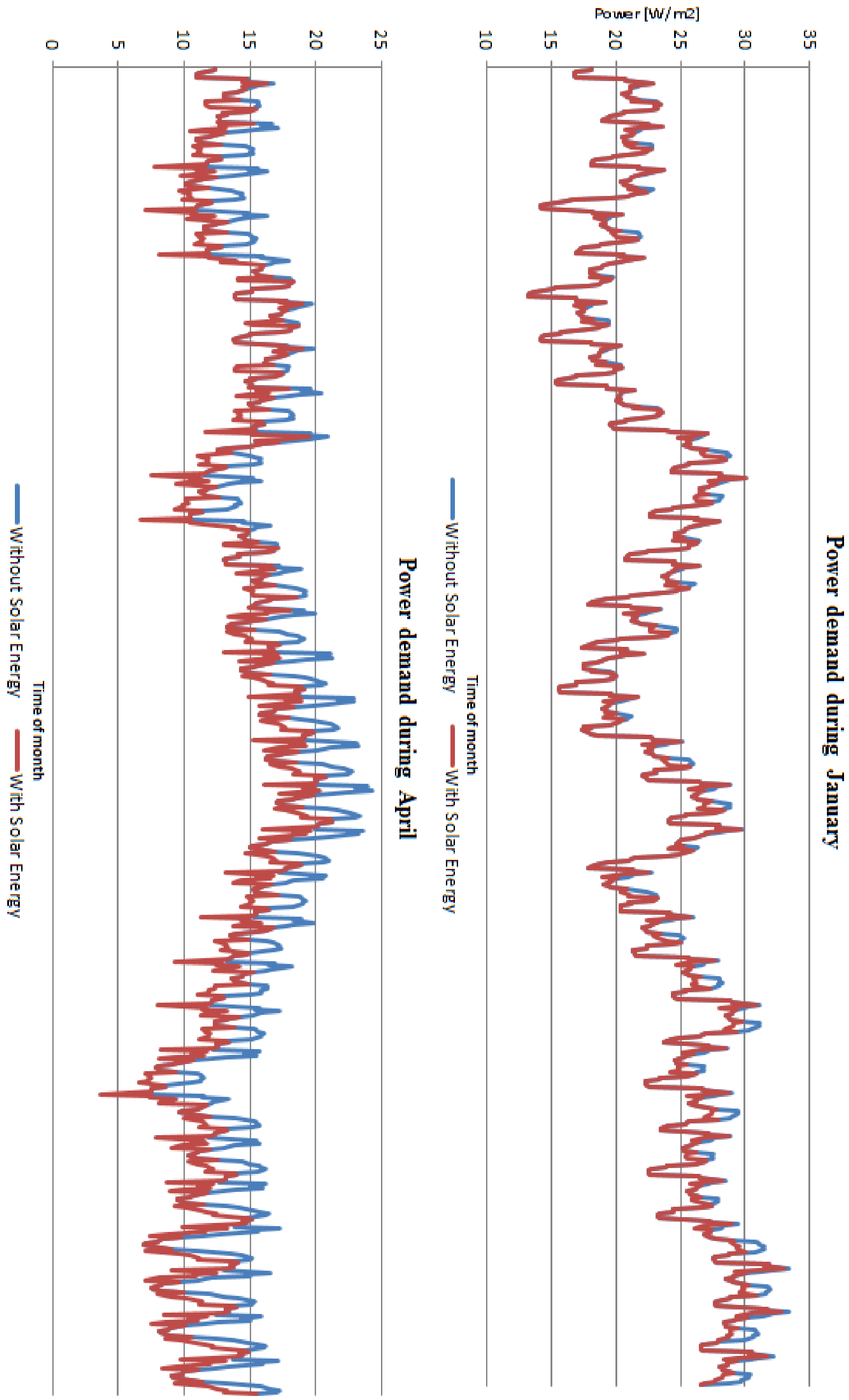


Figure E.1 *Resulting district heating power demand during entire months of January and April 2009, archetype building 4, with peak reduction using accumulator tank to store solar energy. The power demand includes both space heating and hot water production.*