CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF ENVIRONMENTAL ENGINEERING

SIMULATION-BASED ASSESSMENT OF BUILDING ENERGY FLEXIBILITY IN THE FRAME OF SMART GRID CONCEPT

MASTERS THESIS

DANIEL PETROVIČ 8 – TŽP – 2021

ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Studijní obor: **Technika životního prostředí**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Simulační posouzení energetické flexibility rezidenčního domu v rámci koncepce chytré sítě

Název diplomové práce anglicky:

Simulation-Based Assessment of Building Energy Flexibility in the Frame of Smart Grid Concept

Pokyny pro vypracování:

Práce se zabývá simulačním posouzením energetické flexiblity rezidenčního domu. Student má za úkol shrnout stav poznání týkající se energetické odezvy budov v rámci konceptu chytré sítě a navrhnout simulační experiment pro vyhodnocení energetické flexiblity rezidenčního domu. Pro tyto účely je třeba vyvinout na základě projektové dokumentace numerický model budovy a jejích systémů. Pro vývoj numerického modelu budou využity nástroje pro energetické simulace budov (např. IDA-ICE, E+ TRNSYS atd.).

Seznam doporučené literatury:

Hensen, Jan LM, and Roberto Lamberts, eds. Building performance simulation for design and operation. Routledge, 2012.
CIBSE AM11, Building performance modelling, 2015, ISBN 978—906846-67-1
IEA EBC Annex 67 Energy Flexible Buildings http://www.annex67.org
Hynek Beran, Vladimír Wagner, Václav Pačes a kolektiv, Česká energetika na křižovatce, 2018, ISBN 978-80-7261-560-5

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Datum zadání diplomové práce: **30.04.2021** Termín odevzdání diplomové práce: **04.07.2021**

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací.
Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

Datum převzetí zadání	Podpis studenta

Abstract

This work is focused on evaluating buildings energy flexibility of a residential building. To achieve that, a numerical model was created in building simulation software (TRNSYS). Subsequently, a step response experiment was designed, using the numerical model. In addition, a parametric study aiming at impact of different combinations of source heating capacity and storage tank size was conducted. Influence of varying ambient air temperature was also investigated. Together with flexibility analysis at the building side, an approach from grid perspective was undertaken in form of an analysis of day ahead electricity market. Results show that studied building has enough flexibility potential to delay operation at minimum for 4 days without disrupting users' thermal comfort. Available potential is thus larger, than window in day ahead market analysis, which showed favorable outcomes for shifting loads by 8 to 24 hours. Outcome of this work can help acknowledge potential for building energy flexibility necessary for development of new solutions in transition to smart grid.

Abstrakt

Tato práce se zabývá vyhodnocením energetické flexibility bytového domu. Pro její zjištění byl vytvořen numerický model v simulačním softwaru (TRNSYS). Následně byl navrhnut experiment jako odezva na skokovou změnu, který používá numerický model. Zároveň byla provedena parametrická studie zabývající se dopadem různých kombinací výkonu zdroje tepla a velikosti akumulační nádoby. Vliv měnící se venkovní teploty vzduchu byl také uvažován. Společně s analýzou flexibility na straně budovy, byla provedena analýza denního trhu s elektřinou, která zaujímá pohled ze strany sítě. Výsledky ukazují, že uvažovaná budova má schopnost odložit spotřebu energie minimálně na 4 dny, bez narušení tepelného komfortu uživatelů. Dostupný potenciál je větší než ukazuje analýza denního trhu s elektřinou, kde se ukázalo výhodné odložit spotřebu v rozmezí 8 – 24 hodin. Výsledky této práce by měly poukázat na dostupný potenciál flexibility v budovách, který je potřebný při vývoji nových řešení přechodu na smart grid.

Declaration

I declare that the master's thesis titled: SIMULATION-BASED ASSESMENT OF BUILDING ENERGY FLEXIBILITY IN THE SCOPE OF SMART GRID CONCEPT, was written with the use of literature presented at the end of my work in the list of references.

In Prague: …………………… Daniel Petrovič

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List of abbreviations

ADR – Active Demand Response

AHU – Air Handling Unit

CAV – Constant Air Volume

COP – Coefficient of Performance

CZ – Czech Republic

DR – Demand Response

DSM – Demand Side Management

EU – European Union

GE – Germany

HVAC – Heating Ventilation and Air Conditioning

IEA – International Energy Agency

KPI – Key Performance Indicator

MRC – Mass remote control

nZEB – Nearly Zero Energy Building

PV – Photovoltaic

RES – Renewable Energy Source

RH – Relative Humidity

SK – Slovakia

SOC – State of Charge

TRNSYS – Transient Systems Simulation Software

List of used symbols

E	Energy	[kWh]
Q_{source}	Source heating capacity	[kW]
U	Heat transfer coefficient through wall	[W/m^{2}K]
U_g	Heat transfer coefficient of glazing	[W/m^{2}K]
U_f	Heat transfer coefficient of window frame	[W/m^{2}K]
T	Time	[h]

List of Indexes

ref	Reference
flex	Flexible
Dis	Discharge
Char	Charge

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Thesis outline

Section 1 serves as an introduction to the topic of energy flexibility and mentions current state and why it is important to study it. In Section 2 energy flexibility is put into context of smart grid. Also, analysis of day ahead electricity market in CZ, GE, and SK is made. Section 3 gives insight into methods how to evaluate building energy flexibility and what tools are used in form of a review of current literature. Description of studied building is found in Section 4 and provides information about constructions and HVAC systems, which are necessary in Section 5. Which explains how chosen software tool (TRNSYS) works and then how a model was made is said software. Section 6 talks about experiment proposal, settings, and results, including discussion of obtained results. Lastly Section 7 is conclusion of what the thesis is about and states significant results.

1. Introduction

Recently the tendency in energy sector is to increase the number of renewable energy sources (RES) in the grid. In Europe in year 2020, 20 % of consumed energy was supplied by RES [1]. This is in accordance with the plan to completely reduce emissions of CO_2 by the year 2050 and have energy systems without fossil fuels. Another step in this plan is to have at least 32 % share of energy generated by RES by the year 2030 [2]. However, generation of electricity form RES like wind turbines or photovoltaics is heavily dependent on weather conditions. And increasing dependency on these intermittent sources has a consequence of mismatching the generation and demand. More RES in the grid thus require more complex control and increased flexibility on the side of demand. To ensure the grid is stable, reliable, and economically sustainable we need a way to store or better manage energy.

To allow better and more efficient use of RES a different control strategy is needed. With increasing decentralization of sources, demand side management (DSM) is becoming crucial in enabling RES integration to the grid. Even though building sector is dominant consumer of energy (40 % in EU) [3] and can offer relatively high degree of flexibility on day to day basis (e.g. battery storage, hot water storage, or building thermal mass), it is on individual level of buildings. For meaningful realization of DSM aggregation of buildings is suggested [4]. Also, transition to more renewable sources for space heating and hot water preparation, means buildings will be even more dependent on electricity. Combination of these factors puts demand on buildings to realize the flexibility potential to keep the grid stable. Building systems that can be operated by such control include space heating, cooling, and ventilation in both commercial and residential buildings.

Illustration how the buildings energy systems or appliances can be flexible is shown in Figure 1.

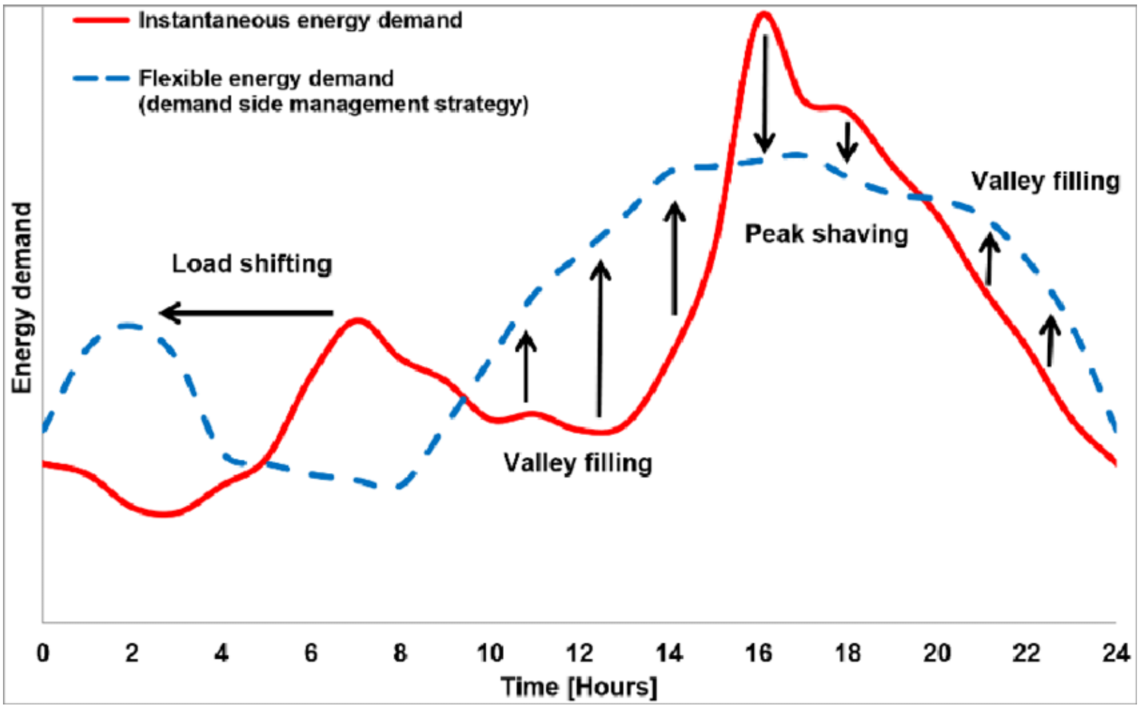


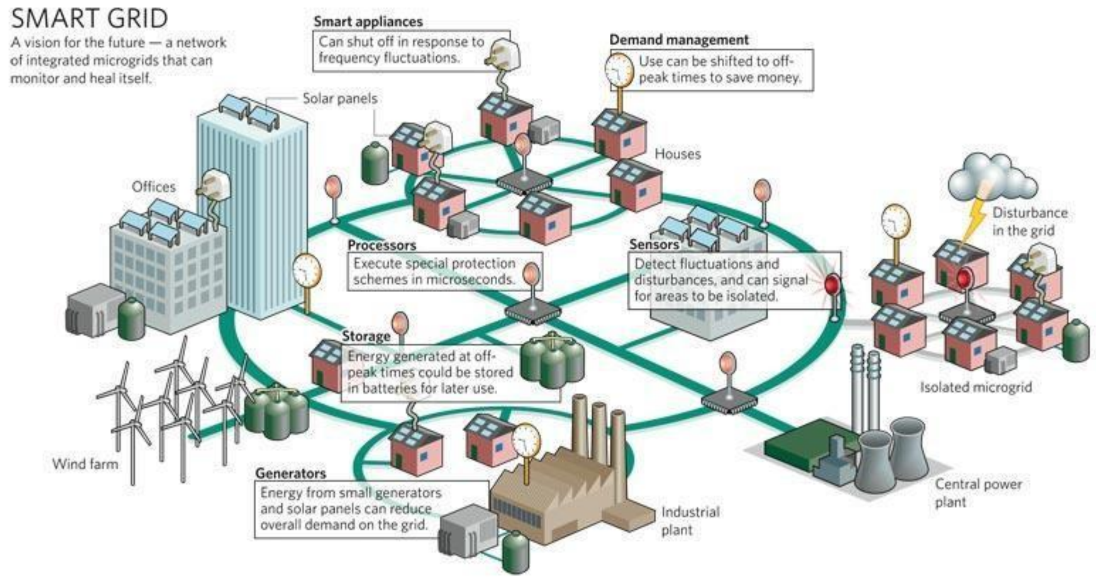
Figure 1 - Comparison of flexible vs instantaneous demand adopted from [5]

Load shifting is a way to delay or force demand in different time, most likely the loads are shifted from high price periods to low price periods. Valley filling is used to describe increasing demand in current timeframe. For example, during instantaneous demand the source uses 20 kW out of 30 kW possible. Valley filling would then mean that the source is forced to increase the power consumption to 30 kW. In contrast to valley filing, the next strategy is peak shaving. This means reducing power consumption at times where the demand is peaking. Flexible behavior on demand side then allows for less drastic control actions by grid operators making the grid more stable. Also, allows for higher penetration of RES into the grid. All these strategies aim to increase flexibility of all energy systems, but to stay on topic only buildings and its systems will be considered.

Buildings energy performance is regulated through EU directive on the energy performance of buildings [6]. Part of this document is framework how to evaluate the capability of the building to adapt to the grid needs. Also, the International Energy Agency (IEA) Energy in Buildings and Community program (EBC) Annex 67 is focused solely on building energy flexibility. Here we can find the definition what building energy flexibility means. It states that “Energy flexibility of a building is the ability to manage its energy demand and generation according to local climate conditions, user needs and grid requirements”. This is expected to enable DSM or load control based on the state of surrounding energy networks [7]. This isn’t the only definition used. However, describing energy flexibility is problem in itself.

2. Smart grid

To utilize energy flexibility, there has to be continuous exchange of information between the grid and the end-user. Communication will be most likely realized through dynamic price signal, which indicates the needs of the grid. Dynamic pricing is part of a concept of Smart Grid, which can be defined by following characteristics. The system is fully automated and includes digital control systems, sensors monitoring the grid behavior and data lines that allow communication between the user and provider. Users are integrated into the grid by installing a smart meter, which is capable of real-time data exchange. Those meters then react to the dynamic pricing based on the state of the grid. This should enable the users to shift demand to lower price periods if possible.



A vision for the future — a network of integrated microgrids that can monitor and heal itself.

Smart appliances Can shut off in response to frequency fluctuations.

Demand management Use can be shifted to off-peak times to save money.

Processors Execute special protection schemes in microseconds.

Sensors Detect fluctuations and disturbances, and can signal for areas to be isolated.

Storage Energy generated at off-peak times could be stored in batteries for later use.

Generators Energy from small generators and solar panels can reduce overall demand on the grid.

Figure 2 - Smart Grid illustration adopted from [8]

The concept of Smart grid can be better understood with the help of Figure 2. It is assumed, that there will be more decentralized energy system with more on-site generation. Also, RES will make up higher percentage of the central grid system. Information about the real time generation and consumption will be shared. Based on those data, along with status of short-term energy market, most likely day-ahead market. the dynamic pricing will be estimated. Users with smart meters, will then pay according to the dynamic tariff and the grid operators will have to make fewer or less drastic control measures. Essentially the users will provide what is currently called system services to the grid.

Transition to Smart Grid isn’t without obstacles. First problem lies in lack of installed smart meters in current situation. However, this is going to change as with new EU directive realized in Czech Republic through public notice about electricity metering, every end user with annual consumption over 6 MWh/year has to be equipped with smart meter. Date, when this should be mandatory is 1.7.2027 [9]. Additionally, there are concerns about data security. Data exchange between the grid and the user can be prone to various forms of cyber-attacks. More information about different types of possible attacks can be found for example in [10] or [11]. Given that dynamic pricing will be based on interaction between users and the grid, there is a possibility of price manipulation. In paper presented by Navid Azizan Ruhi [12], opportunities for price manipulation by aggregators in electricity market are discussed.

2.1.Current grid state and analysis

In current situation smart grid technologies are only deployed at small scale. For that reason, it is important to describe the current situation. Not many users have smart meters and use system for mass remote control (MRC). Tariffs on this principle usually work on two price levels. Most common used pricing is Day/Night tariff like [13]. Pricing for kWh of electric energy is decided by the provider. At night, when there is less demand on the grid, the prices are lower to encourage more consumption. And during the day, when the demand is already high, the price is higher. Difference against smart meters is that the information flows only one way, from the grid to the user.

However, small number of users already own smart meters. Mainly owners of PV panels. Some providers even have options, which allow the users to buy electricity for the prices on day ahead market with some fees included. This day ahead market functions like a stock exchange, where price is speculated by supply and demand. Providers purchase energy for actual price and then create tariffs for the end consumer.

Since dynamic pricing will most likely be based on situation on day ahead market, an analysis of the day ahead market price of electricity during the year 2019 was made. Countries selected consist of Czechia, Slovakia, and Germany. Mostly because they are considered one bidding zone. Also, to see what impact different energy mix has. Hourly data were taken from [14].

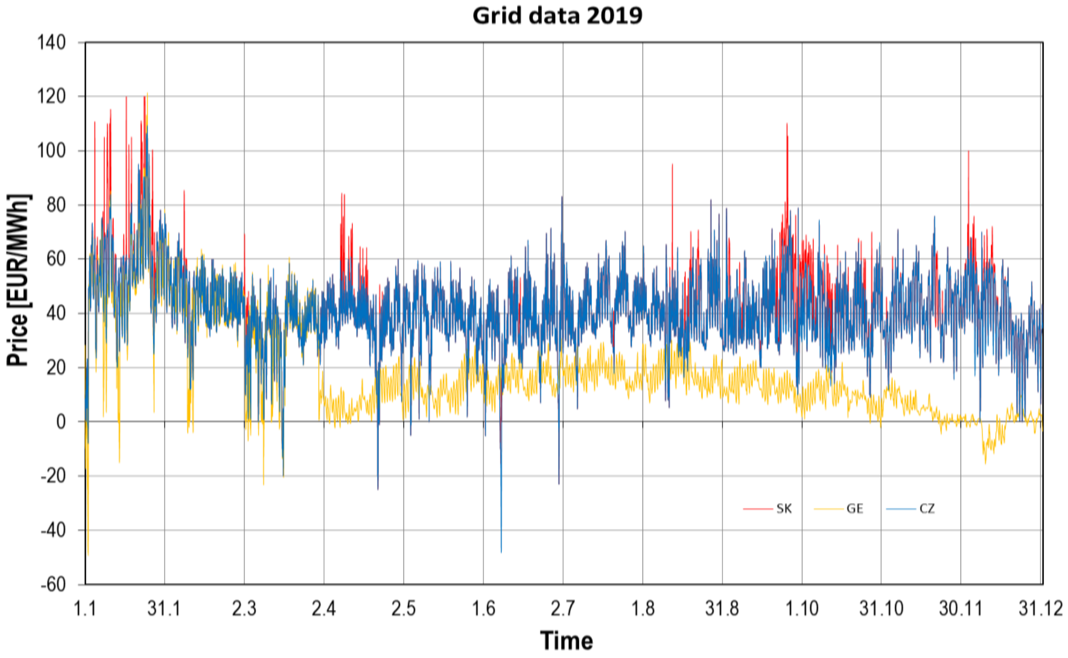


Figure 3 - Annual grid data

From the annual data in Fig 3. we can see that price per MWh ranges from -40 to 120 €. But mostly stays around average value of 40€ for CZ and SK and 20€ for Germany. Overall, the prices are similar, except sudden drop on 1.4.2019 in Germany carrying out for the rest of the year, which is a result of change in policy according to Bundesnetzagentur [15]. Another observation is that CZ and SK prices are nearly similar except few weeks. Negative prices were likely result of sudden increase in renewable electricity generation. The market indicates imbalanced state in which surplus energy has to be stored or immediately consumed to keep the grid in balance. To motivate the user's consumption the price may be dropped below 0 € and both parties can benefit. User benefits from savings in electricity price and the grid is kept in balance.

From the point of building energy flexibility daily patterns in the price can provide crucial information. Those patterns serve as an indicator when the flexibility is desired and help determine the time frame in which load can be shifted.

For better understanding a closer look on weekly data has been made in Figure 4. Week between 5.2 and 12.2. was chosen. Mainly to show differences and daily patterns. First three days have almost identical course, only exception being Slovakia with sudden increase in price around 18:00. Reason could be behind unexpected rise in demand or lack of regular resources. Another interesting point is very low price in Germany during 9.2. Possible explanation is that due to their offshore wind generation experiencing sudden increase, the price was dropped. This drop in price in Germany, even had impact on next day price in CZ and SK bringing down peak price by 15 €. But main focus should be on the daily patterns throughout the whole week. Each day has a similar pattern, that reflects demand. Disturbance mainly in form of sudden renewable energy generation can disrupt the pattern in daily price on the day ahead market. Typical profile without disturbances in described in the next paragraph.

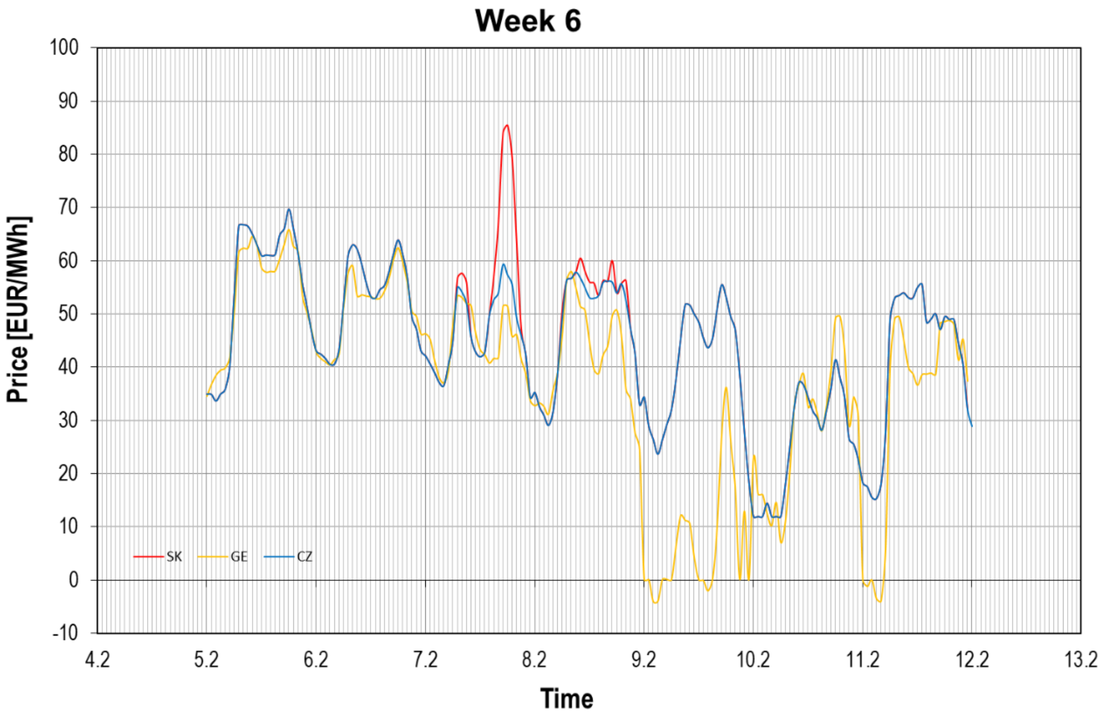


Figure 4 – Weekly price data

Few hours after midnight, the price is at minimum (off peak), slowly rising to a first peak of the day around 8:00. Then following a slight decrease period from 14:00 to 16:00. Next comes a second peak in the evening maxing out around 18:00. After that the price slowly drops and the pattern repeats. From flexibility standpoint the smallest time frame is around 4-6 hours for the midday drop in price. To be able to shift the load from peak to off-peak area, at least 20-hour window is necessary.

2.2.Pilot projects utilizing energy flexibility

Research in energy flexibility relies mostly on simulation data, but there are few real-life applications that can help to better understand the problem. Possible candidates are either new or renovated buildings equipped with systems that are capable to operate under flexible behavior. As an example, two projects are mentioned to give context.

In Copenhagen, Denmark is a full-scale smart city energy lab with the name EnergyLab Nordhaven. Finished construction in 2019 under joint effort of Technical university of Denmark, City of Copenhagen, and companies from the field of building energy systems. Its purpose is to help research and demonstrate the capability of modern energy system. Consisting of residential buildings, school, parking house, ship terminal and shops. The district is utilizing large scale battery storage located in the parking house, to charge during low price electricity periods. This capacity then helps with peak demand. Similarly, a large hot water storage is placed by the terminal, where a large-scale heat pump converts excess electricity into heat during high generation of electricity from renewables. This heat is then used to supply neighboring buildings. With smart control strategies in place, the goal is to study user behavior and demand response in real life application. More information is available on [16].

Next running project is +Syn.ikia. The project is aiming at positive energy buildings/neighborhoods with the implementation of on-site RES, along with flexible behavior on demand side, to exploit renewables as efficiently as possible. The project is divided into four different neighborhoods/locations that represent a specific climate. New development of cooperative housing in Norway as a representative for northern climate, mid-size town with renovated residential buildings in the Netherlands to capture marine climate, a small village in Austria consisting of both new and reconstructed buildings to describe continental climate and finally a new residential building in Spain as a Mediterranean climate case. Each location uses different technology to reach the goals, but common signs are reduction in energy demand and improved control strategies operating with flexibility in mind. Since its focus is on positive energy, on site generation is also part of these projects. Important part of the neighborhoods is sharing of infrastructure, energy, and spaces to better utilize the technology. This project is in cooperation of Norwegian University of Science and Technology, Technical university of Denmark, Building Performance Institute Europe, Institut de Recerca en Energia Catalunya (IREC), OBOS Nye hjem, Heimat Österreich and partner development or construction companies. [17]

3. Review of methods, indicators, and tools for building energy flexibility

With building energy flexibility being complex problem, there are multiple approaches to assess it. A unified or universal approach hasn't been found yet. Most indicators vary from study to study, due to highly individual nature of characterizing energy flexibility. Ideal indicator is one which captures information about both the grid and the building. Is easily interpretable by both sides and can be used universally with different boundary conditions like climate, building type and grid. To better understand the topic a brief review of methods to determine energy flexibility has been made.

3.1. Quantification of energy flexibility

As a starting point a review of methodologies and quantification of energy flexibility applied to thermal storage done by Reynders et. al [18] was chosen. An analysis of recent approaches was done and compared on a case study. In summary the methods can be divided into categories, by what parameter they focus on. First group is time related indicators. They usually refer to duration of the flexibility event, for example time to get the system from charged state to discharged and vice versa. Another type can be defined as capacity indicators, which describe the power (kW) or amount of energy (kWh). These indicators refer either to available capacity that can be shifted in time or give information about the energy demand during a flexibility event in comparison to reference scenario. Next category are economic indicators and usually describe the associated costs of flexibility behavior. Important note is that in this study the characterized energy is thermal and not electrical. Conversion to electrical can be done with the knowledge of the heat sources COP. Focusing on methodology C in Reynders's work proposed by Stinner et. al [19], where they use following indicators. The method starts by running two simulations. First a hot water storage tank is completely charged (SOC =1) and then depleted. Second, a reverse case where empty tank (SOC = 0) is charged to full capacity. Based on those simulations they define time to delay operation $\tau_{delayed}$ and time to charge the tank as τ_{forced}. Also, to capture the energy aspect of flexibility, they use energy flexibility ΔE as a difference in consumption between flexible and reference scenario. Authors comment, that this approach quantifies the upper limit of energy flexibility.

In another study focused on energy flexibility quantification [20], Tang and Wang propose the use of flexibility indexes comprising of flexibility capacities and flexibility ratios. This approach is more focused on grid operation. Flexibility capacities take form of power and energy that the grid can utilize. They include five absolute values, which reflect the maximum contribution that a building can make to the power grid. Flexibility ratios are defined as corresponding capacity divided by the demanded power or energy respectively from the building. All indicators are in form of electrical power or capacity. Value in this method is that it can be applied to buildings with different constructions or systems and the method doesn't need to change. Also, it includes flexibility from appliances and lighting on top of HVAC systems and thermal mass.

Different approach from the previous studies, can be found in [21] by Junker et al. Assuming penalty aware control strategy, where penalty signal can be for example real time CO2 emission, real time cost or constant. They divide resulting load on the system into two parts, responsive to the penalty signal (response) and a non-responsive part. From the responsive part they define a flexibility function. Using this flexibility function, they propose two indicators for energy flexibility. First an Expected flexibility savings index (EFSI) that is related to the actual cost. EFSI of 0,1 implies expected savings of 10 % for the smart building. Authors comment, that due to its tie to the actual penalties it is difficult to get EFSI larger than 0,25. Second indicator is Flexibility index (FI), which is designed such that the values can range from 0 to 1. This is done by using reference penalties. Explained on a peak shaving scenario, if the FI is equal to 1, then power consumption in peak period is completely avoided. Benefits of this approach are in the fact, that this method doesn't require a reference building to calculate its flexibility. Also, it can be used to capture dynamic behavior of the flexibility itself.

In summary, there are multiple approaches to evaluating building energy flexibility. However, there are common elements throughout the field. Methods can be separated into two main categories.

- Building energy flexibility potential
- Demand response control strategies

First category usually uses indicators tied to the building itself and describes the boundaries in which flexibility behavior can occur, without disrupting the indoor environment or normal use. Most methods rely on some kind of reference scenario, where flexibility is not required, to evaluate flexibility indicators. These models can predict the energy flexibility without the knowledge of past data. Examples of indicators can be time to reach charged or discharged state, energy needed to do that and comparison against reference case without flexibility.

The other category are methods more focused on control strategy, rather than the systems itself. Models from this group assume specific system and involve past data to optimize the control. Indicators tend to represent end results of operating on flexible behavior like savings in energy, cost, or CO_2 emission.

3.2. Tools used in evaluating energy flexibility

Energy flexibility is a phenomenon that is present in dynamic behavior of building energy systems. To describe it, comprehensive data from the building and its systems is required. Because evaluation of energy flexibility is so complex and requires inputs and relations between indoor environment, weather, constructions, building systems and grid, the calculations would be hardly possible without simulation tools. They can also give us control over variables, we wouldn't have control in the real world, for example the weather. Some of recognized softwares are EnergyPlus, ESP-r, TRNSYS and IDA-ICE. Each one is suitable for different kind of applications.

Following the review done in previous section, where two main categories of approaches were described. To revise, methods, which focus on buildings energy flexibility potential and methods that realize found flexibility. In this chapter an insight into used tools for each type is done. But first a description of types of modelling techniques available.

White-box models are based on fundamental laws of physics, like mass balance, heat transfer, flow balance or conservation of momentum. From those laws a set of mathematical equations is derived and solved. These types of models allow to predict the outcome using simulations. There are commonly used to describe dynamic behavior of slow-moving temperature and humidity processes (e.g. zone temperature, zone humidity, heating/cooling coil dynamics, etc.). Their strength is in detailed description of the system and being able to link change in output to a specific change in input due to knowledge of physical equations. However, they require enough data initially to be able to describe the situation. [22]

Black-box or data driven models fall under another category. They work with collected data from real practice and then establish a relationship between inputs and outputs. Techniques used to get the relationship are based on mathematical methods for example statistical regression or artificial neural networks. Suitable use is in optimization of already existing systems, where enough training data has been collected. [22]

To begin with a review, first a study done by Kathirgamanathan et al. [23]. Focus of this study is to analyze different indicators for energy flexibility a test their performance on a range of case studies with different DR strategies, building types and climate. Their method is based on creating a detailed white box model, obtain a reference power demand profile and then test DR strategies. From the simulation results, flexibility indicators are evaluated. Total of 4 cases are presented. First a commercial building located in Dublin, focused on flexibility of cooling system they used EnergyPlus to model this case. Second case is based on a residential building in Spain. Heating and cooling are covered by air to water heat pump, but only heating is part of the evaluation. Only one flat from the whole building is taken into account. Model is created in TRNSYS interface. Third and fourth case are the same building, but with difference in control type. In case 3 a rule-based control is assumed and in case 4 a model predictive control. Representing a residential building (detached house) located in Montreal. Again, heating is of interest in these cases. Both last cases were modeled in TRNSYS. Indicators were calculated from the information about length of DR event, power consumption during that event and power consumption during reference scenario. Power consumption was in form of electrical energy.

In another study, Wang and Tang were testing flexibility indicators on a case study building. It involved a ten-story office building in Hong Kong and also charging station for 50 electrical vehicles. To evaluate flexibility of the system, they used a performance simulation in TRNSYS. After obtaining data for reference scenario, they conducted a parametric study to evaluate influence on energy flexibility. Lastly, an application study to optimize flexibility in operation. As a method they chose to solve the optimization problem with genetic algorithm in MATLAB. [20]

Next study by Chen et al. is focused on optimizing energy management with the integration of demand side management flexibility measures. The work is based on multi-energy flexibility utilizing both thermal and electrical storage capacity. Main part of the study is detailed look into load recovery caused by the rebound effect. In first part, a building energy system is modelled, and the flexibility measures are defined. With the knowledge of this data a second part of the study follows with optimization. The measures are optimized with regards to maximal profit using MILP (mixed integer and linear programming) method in Gurobi software. [4]

To summarize the results of the review, there are common signs in chosen software. For evaluating buildings flexibility potential, a white-box model is suitable. It is capable of describing the problem with desired accuracy and the results can be applied further as a starting point for optimization problems. That leads us to the use of black-box models, which are applied mostly in optimization tasks. Combined with the data about the building model, energy market or past data during operation, they can prove useful in designing a better control strategy.

4. Description of studied residential building

For purposes of this thesis a residential building in Prague was chosen. It represents modern type of building and has available project documentation, which was part of the assignment. The complex consists of two residential buildings, which can be seen on Figure 5. For further description we will call them building A and building B. Both buildings have six floors above ground and two underground levels.

Figure 5 – Photo of the studied buildings. Building A on the right and building B on the left adopted from [24]

First underground level consists of storage units, and utility rooms. Technical room for building systems is located under object B in the 1st underground level. Second underground level connects both objects and serves as a parking space for the residents. Both buildings have entrances oriented to the north and most of the glazed surfaces on south are equipped with external shading. Floors 1-5 have balconies located on east and west facades, while 6th floor has two apartments with roof terraces. Both buildings are equipped with an elevator. Whole complex was finished in 10/2014. For the use in the numerical model, only object B has been chosen to reduce the complexity of the problem. Further description will then be only for object B.

Building B has 22 apartment units. There are four units per floor 1-5 and two units on the 6th floor. Disposition of the units is either 4 rooms with kitchen and bathroom or 3 rooms with kitchen and bathroom. Detailed layout is available in Appendix 1

4.1.Building properties

Whole complex was designed in nearly zero energy building standard (nZEB). This means optimizing the building orientation and constructions to achieve low heating demand. Mainly by clever utilization of heat gains and minimizing heat losses. More information on nZEB can be found in [25] which was novelized by [6] in 2018. In addition, all new buildings built from 1.1.2020 onward have to be nZEB.

Load bearing constructions are made out of monolithic concrete blocks or limestone-sand blocks with added insulation from extruded polystyrene (EPS) or mineral wool. First ground floor is anchored into concrete slabs with additional layer of bricks and insulation. Ceilings between floors are made out of concrete slabs, layered with plaster from the bottom and insulation and wooden flooring on top of the slab. Terrace construction has additional insulation and system for sloping the surface but without the wooden flooring on the outside. Roof construction is flat, with sloping realized using the same system as terrace. Construction wise its concrete slab with thermal and hydro insulation. Composition of mainly used constructions with corresponding thickness and U-value is listed in Table 1.

Table 1 – Constructions information

Construction	Layers	Thickness (mm)	U-value (W/m^2.K)
External wall	Concrete + insulation 200 mm + plaster	415	0,19
Internal wall	Bricks + plaster	260	2,3
Ground floor	Wooden flooring + insulation + anhyment + concrete slabs + bricks	550	0,17
Floor/Ceiling	Wooden flooring + insulation + anhyment + concrete	300	0,7
Terrace floor/ceiling	Concrete + insulation 130 mm + plaster	625	0,14
Roof	Concrete + insulation 260 mm + plaster	525	0,13

Glazed surfaces consist of windows and balcony doors. Windows have wooden frames with $U_f = 0{,}8\ W/m^2.K$ and triple pane glazing with $U_g = 0{,}8\ W/m^2.K$. Balcony doors have the same properties as windows.

4.2.HVAC systems

To provide optimal thermal comfort for the residents, the building is equipped with HVAC systems. Main and necessary part is heating system, which consists of hot water radiators with design temperature difference 70/50 °C. Radiators are located under windows with pipes hidden under the flooring. In 1^{st} ground floor, fan coils are put near the glass doors leading to the front porch on the southern side. They are also supplied with the same water as mentioned radiators. Each radiator is controlled by thermostatic valve and room temperature is controlled via thermostat, which opens/closes the hot water supply to the apartment circuit. Throughout the building there are four riser pipes distributing hot water. Heating water is prepared together for both buildings in the technical room under building B. Here are two condensation gas boilers with weather compensation control, which directly supply the heating system. Rated power for both boilers is 45 kW each. For object B those 45 kW are divided into 32 kW to cover heat loss via radiators and 13 kW to supply the AHU heater.

Domestic hot water is also prepared together for both buildings in the same gas boilers as heating water but stored in two 1500 l water tanks connected in parallel. From there its distributed to the apartments in similar way as the heating.

Air exchange in the building is realized through forced ventilation. The central air handling unit (AHU) is located on the roof. It is equipped with fans, filters, heater, and heat exchanger. Heat exchanger has heat recovery factor $\Phi_{HR} = 76\ \%$. Distribution and extraction of air to the rooms is realized via duct system leading through the building. In every room a CAV regulator is installed. The AHU is controlled by autonomous regulation for constant pressure. Air flow is regulated based on relative humidity and CO_2 concentration. Each flat is equipped with RH and CO_2 sensors. Heater inside the AHU is supplied through glycol circuit connected to the hot water heating via water/glycol heat exchanger. Design heating power of the heater is 13 kW. All ventilation heat losses are covered by the radiators.

5. Development of the numerical model

In order to simulate dynamic behavior of the building and its systems, and to evaluate energy flexibility, a numerical model of the residential building presented in previous section was made. First a geometric model was made. In the next step, construction properties were added to the geometry and lastly a heating system was modelled.

5.1. Selected software (TRNSYS)

Since the focus of this study is to evaluate building energy flexibility potential, a white box modelling software was chosen. In this case TRNSYS. Decision to choose this software comes from the review and a knowledge of how the program works thanks to optional class.

TRNSYS is a simulation software aimed at dynamic behavior of systems. Mainly used for thermal and electrical energy systems. TRNSYS consist out of two parts. Engine called kernel, which is responsible for reading the inputs, iteratively solving the system, determining convergence, and plotting the variables. It is also able to determine system properties, invert matrices, perform linear regression and interpolate external data files. The second part is a library of components (so-called types). These components are models of individual systems for instance gas boiler, variable speed pump or AHU. In the library there are multiple components for HVAC systems, PV systems but also building models, data processors, economic routines. These models can be modified by users or created from scratch to add new models of emerging technology. [26]

Main work is realized in Simulation studio, which is graphical interface allowing access to the kernel and library. Users can add components from the library and connect them using a link tool. This links outputs from one component as inputs into the next one. Due to modular nature, models can range from simple to complex ones. Once the system has been modeled with the components and connected, a simulation can be started. TRNSYS allows to run at most one year long simulations with desired time steps. Results can be saved into output file and/or plotted in real time as the simulation progresses. Interesting feature is parametric run, which allows to automate running simulation, changing specific parameters of components, and doing the same run. This feature allows to test multiple variation on the same model without the need of manual change of the inputs.

Regarding modeling building systems, there are two options to model a building. Either single zone model (type 660) or detailed multi-zone model (type 56). The latter can be set up in an assistance tool called TRNBuild. This is a supporting application intended for more user-friendly modelling of detailed building models. In here the user can create or upload geometry, assign construction properties or create new ones, create schedules, and model simplified building systems. Also functions like infiltration, internal gains or thermal comfort evaluation can be set up in this interface.

5.2. Geometry

The building was divided into zones that are used in the modeling softwares multi-zone model (type 56). Zone can be described as a volume of perfectly mixed air that has the same temperature in every point of the zone. The building is represented by 64 zones in total. Only above ground floors of the real building are considered. Zones were defined by rooms that have the same design air temperature, but with several simplifications. First the model is made symmetrical along its center axis going from North to South. Second, details of the room layouts have been reduced. And third, neighboring rooms with same design air temperature were joined into one zone. This allows to reduce inconsistencies and minimize surfaces, which helps with the numerical calculations, making them more robust and faster. Another assumption is that floors 1-5 have identical zoning. Again, this helps with reducing the surfaces and provides robustness to the model. Grouping zones with same design air temperature can affect the thermal mass, however in some parts the walls were included, in some left out. Zoning of the layout can be seen in Appendix 1. Zones on are highlighted in different colours to identify the zones design temperature. Red represents 24 °C, orange 20 °C and blue 15 °C.

To verify accuracy a comparison between floor area has been made. The model has total floor area of 2132 m^2, while the real building has 1972 m^2. Difference can be explained by the fact, that the zones in the model calculate air volume of the zone before thickness of walls. Resulting floor area is then bigger than in reality. Also internal dimensions were used to ensure continuity, meaning the walls thickness was neglected. However, when comparing the heated floor area, the difference is much smaller as according to the project documentation the real building has heated floor area of 1844 m^2 and model case has 1862 m^2. This is accurate enough for continuing the modelling process.

After creating the zones, a full 3D model has been made. While creating the 3D geometry windows and shading elements have been added. A simplified model of building A was also added as a shading geometry. Whole model is depicted on Figure 6.

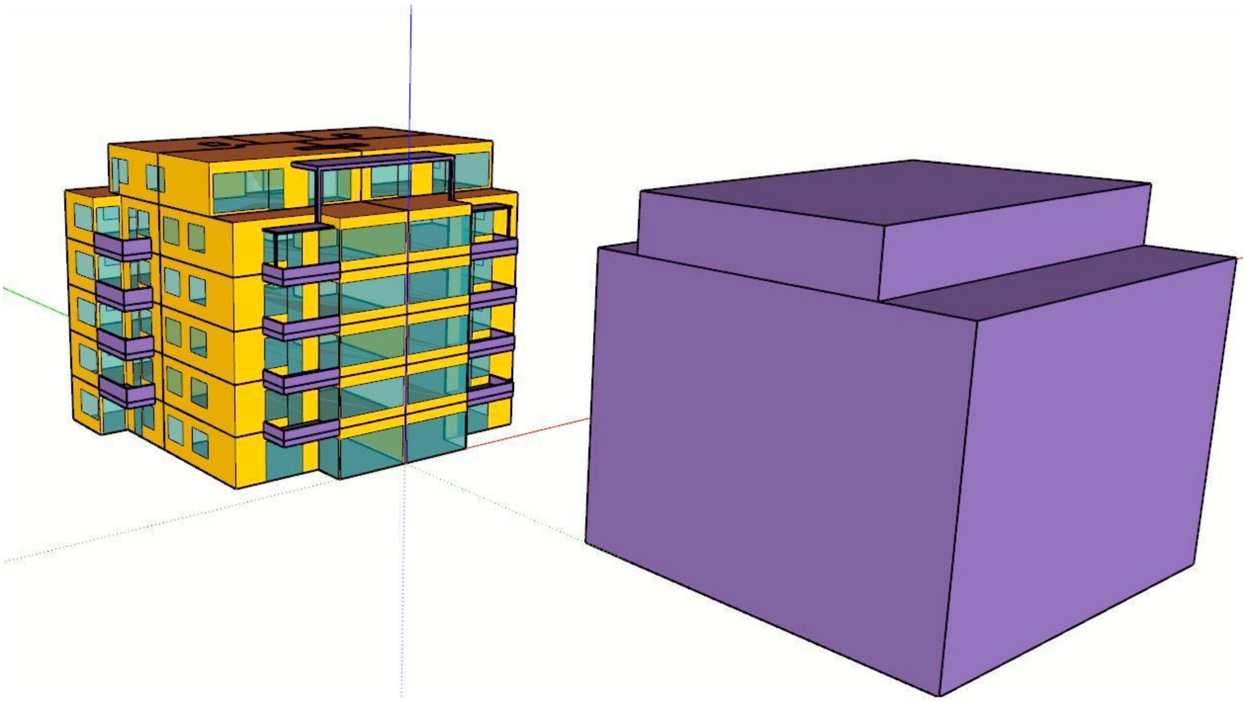


Figure 6 - 3D model of the studied object

5.3.Construction properties

Once the geometry was made, it is necessary to assign construction properties, because the numerical simulation relies on solving heat transfer through the constructions. List of used constructions along with comparison to the real values can be seen in a Table 2.

Table 2 - Properties of model contructions

Construction	Thickness (mm) REAL/MODEL	U-value (W/m².K) REAL	U-value (W/m².K) MODEL
External wall	415/415	0,19	0,18
Internal wall	260/225	2,3	2,36
Ground floor	550/550	0,17	0,21
Floor/Ceiling	300/300	0,7	0,71
Terrace floor/ceiling	625/464	0,14	0,14
Roof	525/532	0,13	0,13
Window	triple glazing	0,8/0,8*	0,8/0,8*

**Values for windows are described in form* U_g/U_f

The idea is to add the most important layers with the biggest impact on thermal mass or conductivity. For this reason, the hydro insulation wasn't taken into account due to its negligible thickness and relatively high thermal conductivity. All necessary parameters like thickness, density, specific heat and thermal conductivity were already available in the project documentation.

Regarding the glazed surfaces, the software has library of different windows built in. The properties of the real window are only defined by U-values of the frame and glazing $U_f = 0{,}8\, W/m^2.K$ and $U_g = 0{,}8\, W/m^2.K$ respectively. With these conditions, a window type was selected from the library with properties described in Table 2. The real building is equipped with external shading, however no useful information that would help set it up in the model wasn't found. This means the windows in the model have no external shading device. Also, windows installed on the façade mean that the building is not airtight. To account for that fact, infiltration was set to $0{,}03\ 1/h$. Air volume considered for infiltration is the volume of heated zones.

5.4.HVAC systems

To create the model of building systems a Simulation studio (TRNSYS) was used. The software works with predefined "Types", that can be linked together. With this interface, we can create complex models from relatively simple parts. The model went through multiple revisions, but further described will be only the final one.

5.5.Assumptions

The model was built with the intention to study energy flexibility, mainly the relationship between buildings thermal inertia and the electricity grid. Originally, the real building is heated by gas boilers. For creating a link between grid and the building, they have been swapped for electricity powered source, in this case electric boiler with hot water storage tank. Domestic hot water system was not part of the study. Main focus was on the heating system, which has been modelled in detail. In the real building weather compensation control for the source is utilized, however for simplification a basic ON/OFF control is used in the model. From the zoning available in Appendix 1, each flat has multiple zones, but to simplify the HVAC model only zones with design air temperature of 24 °C (highlighted in red) are considered to be heated. Fan-coils in the ground floor are not modelled and their heat load is instead added to the radiator in corresponding zone. From the project documentation a heat load for all the flats is known. So, each heated zone in the model is paired with one radiator with the capacity to heat the whole flat.

Internal gains

For assessment of internal gains in the building only occupancy was considered. Assumption that three people live in each flat was made and their occupancy schedule was estimated (Table 3). Considered heat gain is 40 W per person.

Table 3 - Occupancy schedule

Day	Time range (h)	Number of people (-)
Weekdays	0-8, 18-24	3
	8-16	0
	16-18	2
Weekends	0-15, 18-24	3
	15-18	0

5.6.Heating system

As previously mentioned in the assumptions, the source of heating is in this case electrical boiler coupled with hot water storage tank. From the tank, the water is distributed to radiators in the zones, where it can transfer heat. Each zone has its own radiator. In total there are four riser pipes, two of them have 5 radiators and the rest has 6 radiators connected. This roughly reflects the system layout as in the documentation except, the simplification of one radiator per flat. Detailed description with system layout in TRNSYS Simulation studio is in Appendix 2.

Radiator side

For heating the rooms, hot water radiators “Type 1231” were chosen. Heating output is controlled by room thermostat represented by “Type 970”. Signal from thermostat controls a three-way valve located on the pipe leading from the riser to the radiator. When the zone temperature is below setpoint (24 °C) the valve is in open position, otherwise it is closed. Riser pipes are then connected into one collector pipe linked to the storage tank. Demand side pump is on the hot side of this system. If at least one zone needs to be heated, the pump is turned on. If all zones reached desired setpoint temperature, the pump is turned off. An element representing the heat losses through piping “Type 31” is added on each riser pipe. Radiators heating output is used as available heating power in the building model “Type 56”. This completes the feedback loop between the radiators and zone air temperature. Radiators design heat load is in Appendix 3.

Source side

From the radiators total heat demand, we know the source power. With the assumption that in the model, the boiler is also coupled with storage tank we have more options. For verifying the model, a source with heating capacity of 30 kW was chosen, along with 1000 l storage tank. Source heating capacity is selected closely to the heat load of the zones. It doesn’t have to be higher, because the storage tank can serve as a buffer for short term increases in demand. Tank volume is obtained by recommendations for designing storage tanks for air to water heat pumps with ON/OFF compressor drive. Minimal recommended size is 20 l/kW for 100% power [27]. In the next step a closest higher volume tank size was chosen from series of available tanks on the market.

Connections here are simple as the hot water from the heat source is going into the storage tanks “Type 158” top left port. Storage tank is without heat exchanger or auxiliary heater. Since it serves only as a buffer to delay generation/demand and there is no change in temperature parameters, no heat exchanger is needed. Bottom left port is used to take cold water from the tank through variable speed pump “Type 110”. Right side serves to supply the radiator side. Tank thermostat is located in 0,75 height of the tank. Both source and pump are controlled based on the signal from tank thermostat, which is realized by “Type 970”. If the desired setpoint temperature (70 °C) has been reached, the pump and heat source are turned OFF. For the ON signal the heater is ON, because “Type 138” doesn’t allow to modulate power. To smooth the operation out a proportional controller is used for the water pump. Based on the temperature of the water in the tank, the pump modulates flow. Limits for the controller are 70 °C (100%) and 25 °C (20 %).

5.7. Ventilation system

For modelling the ventilation system, a simplified approach was used. Instead of creating detailed model like in the case of heating system, a built-in model was chosen. This decision is based on the fact, that detailed model would extend complexity. Also, with air being able to be quickly heated or cooled, the buffer time in comparison to the heating system is much smaller a thus not considered in this work.

The built-in model represents forced ventilation through central AHU with heat recovery. Heat recovery rate is 76 % and assumed air flow satisfies air change of $0{,}3\ h^{-1}$ in each heated zone. It is set as a constant air volume system.

5.8. Verification

After creating the model, a simulation to determine the annual heat load of the building was made. This is to make sure that the model accurately represents the real building. Over the course of the simulation heat demand was monitored. Along with average air temperature and minimal and maximal temperatures in each heated zone. Average temperature is calculated as a mean value of each heated zones air temperature. Minimal and maximal temperatures help to show a range that describes the buildings behavior (Figure 7). Weather data are taken from typical meteorological year for Prague. Data are available in database provided by TRNSYS.

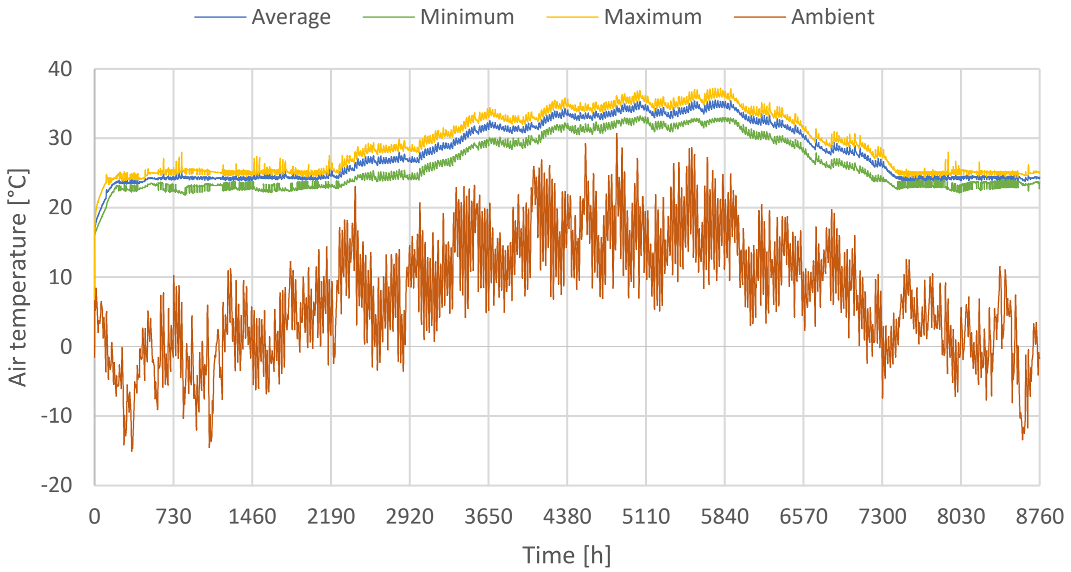


Figure 7 – Course of temperatures during the year

Initial conditions for the zones are 15 °C to make sure the simulation starts, with the heating power limited to 30 kW. After a brief ramp up period, the system keeps the zone temperatures around the setpoint temperature (24 °C). During the summer the zone temperature is higher than desired. This could be explained by two reasons. In the model geometry there is greater window area, than in the real building. This combined with the fact, that the shading devices weren't considered. For development of more accurate model that could be used in other application (e.g. cooling) this would be more important. But since the aim is to study the heating system, the focus is solely on winter months.

Another important indicator is heat load or more specifically annual heat demand. Annual heat load profile is plotted in Figure 8.

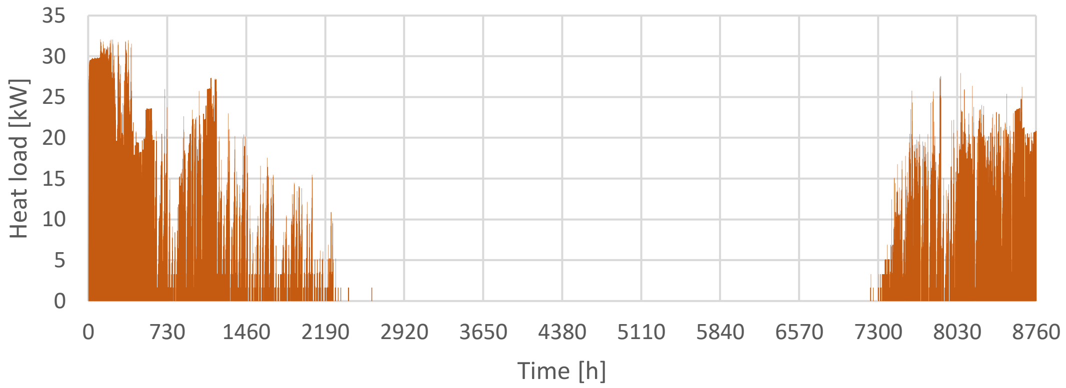


Figure 8 - Heat load profile

Annual heat demand is obtained as a sum of heat load during the year, with consideration of 30 minutes simulation timestep. Resulting heat demand is **38 055 kWh/year**, while the real building has demand of **33 045 kWh/year**. To explain the difference, we have to take into account simplified geometry, assumed internal gains and infiltration, which hasn't been considered in the calculations of the real building. A higher demand was expected, since the model has more elements, which can describe losses. Also, the results obtained from the simulation have finer time step than the calculation from the project documentation, which uses degree-day method based on average daily values not hourly.

In summary, the level of accuracy of the model is considered as satisfactory. When comparing the ratio of annual heat demand to heated floor area both building satisfy the criteria for nZEB buildings, which has to be less than **50 kWh/m^2.year** [28]. Values for real and model case are **18** and **20 kWh/m^2.year** respectively, which is in compliance.

6. Evaluation of building energy flexibility

Goal of this work is to evaluate energy flexibility potential of a residential building. The potential lies in exploiting thermal storage, both in building systems and thermal mass to delay of force operation without disrupting the user's thermal comfort. It is evaluated with the aid of simulation software described in section 5. The experiment is also meant to compare influence of different combinations of source heating capacity / storage tank volume, along with a changing outside temperature on energy flexibility.

6.1. Experiment settings

The experiment uses building model that was developed in section 5. The experiment is designed as a step response analysis, where the initiator is heating sources ON/OFF signal. Time step for simulation is set to 15 minutes to capture enough detail, but without slowing the computational time. Length of simulation varies with outside air temperature, which is kept constant throughout the whole simulation run. Also, the weather is set that the received solar radiation is equal to zero, essentially making the simulation for nighttime. This helps to reduce "noise" in the temperature course due to significant heat gains. Three different temperatures are evaluated.

- $-4\,°C$
- $+1\,°C$
- $+6\,°C$

All temperatures were taken from average monthly temperatures and each represents a different season. Extremely cold winter in Czech climate has average monthly temperature around – 4 °C. Temperature of +1 °C represents transitional period around November and February. And lastly start or end of heating season for modern buildings is October and March respectively, which corresponds to average monthly temperature of +6 °C. This is also the limit in which studied building needs to use the heat source, see Figure 8 for reference. Data about outdoor temperatures were adopted from Czech Hydrometeorological Institute found in [29].

The typical definition of control signals during the experiment is explained on example for outside air temperature of 1 °C in Figure 9. The simulation is run for two scenarios – reference and flexible.

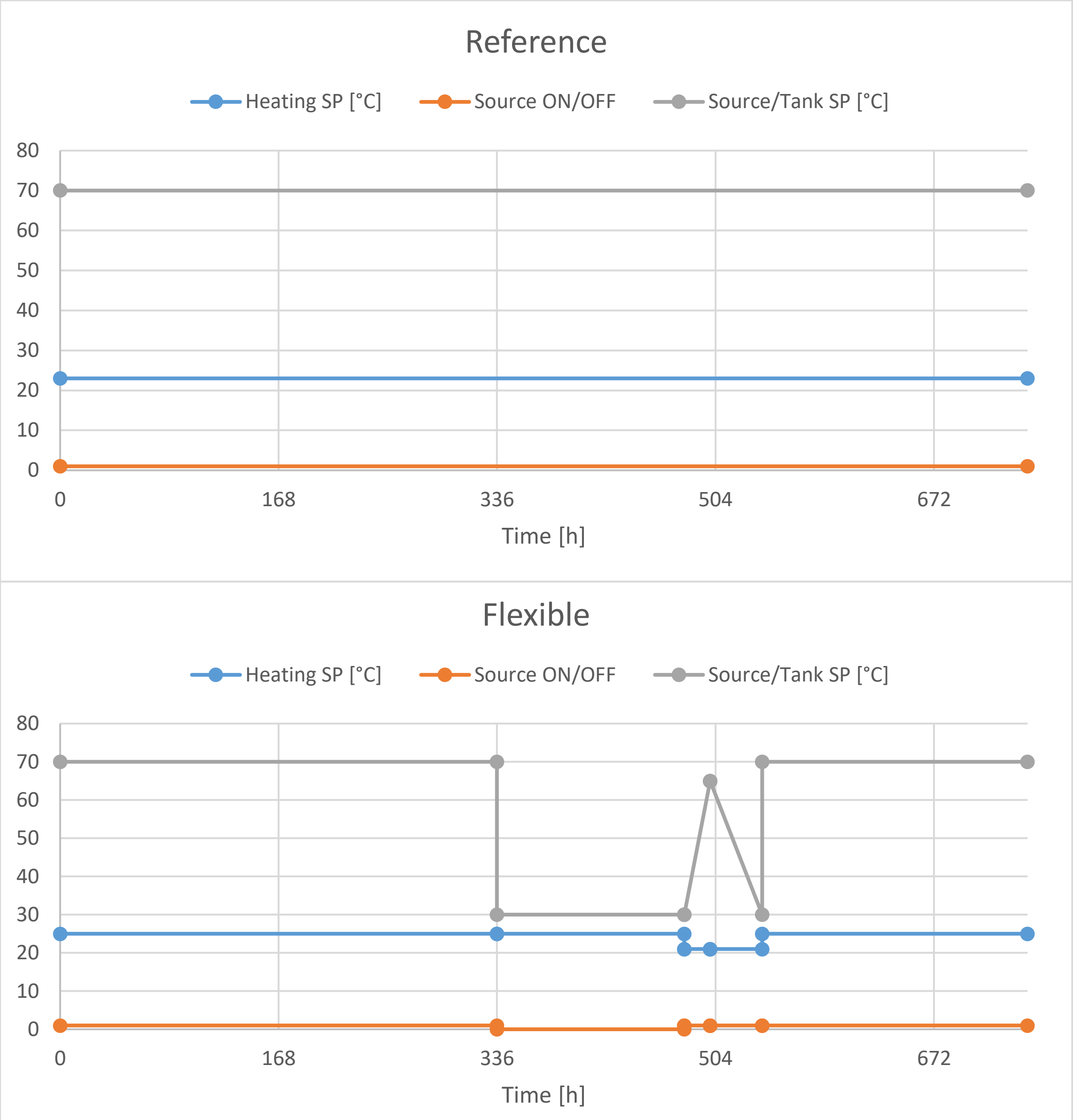


Figure 9 – Control signals setup

For reference case, the temperature is set on 23 °C for the whole simulation, source is ON and tank setpoint is 70 °C. Tank setting comes from the design of heating system and heating setpoint is chosen 23 °C to allow for the flexible scenario to have a range of $\pm 2\ °C$.

In flexible scenario, there are two states: charged and discharged. Charged state is defined as having heating setpoint of 25 °C and tank setpoint of 70 °C. This means that, storage tank is charged, and the building construction has accumulated heat. Discharged state is analogically described with heating setpoint of 21 °C and tank temperature of 30 °C. In regard to time, the first part is initial period to reach charged state. This part is not evaluated. When charged state is reached, the source is turned off and the system is delivering heat only from the storage. The evaluation period ends when the zone temperature reaches 21 °C. After that follows an initialization of discharged state before the charging phase. This period isn't subject of evaluation. Lastly a charging occurs, starting from depleted state of charge and ending when the zone temperature reaches 25 °C. Length of each stage is different depending on the outside temperature. However, it is set that the evaluated parts start in as close conditions as possible.

Heating setpoint limits selection has two reasons. First was mentioned in previous paragraph and has to deal with providing range for flexible behavior. Second, it is tied to the user's thermal comfort. Detailed overview is in Table 4. Assumption, that air temperature is almost equal to operative temperature was made. In reality this is not the case and is only valid if MRT (Mean Radiant Temperature) is the same. With increasing MRT the operative temperature would also be higher and vice versa. Indicators were calculated using CBE thermal comfort tool [30] based on EN-16798. Other parameters for calculation are air speed of 0,1 m/s, relative humidity 50% and metabolic rate of 1 met. Compliance with EN-16798 is given by condition $-0{,}7 < PMV < 0{,}7$. [31]

Table 4 - Comfort assessment

Metabolic rate	**1 met**								
Clothing level [clo]	**1**			**0,75**			**0,6**		
Operative temperature [°C]	25	23	21	25	23	21	25	23	21
PMV [-]	0,47	-0,08	-0,61	0,11	-0,52	-1,13	-0,18	-0,86	-1,55
PPD [%]	10	5	13	5	11	32	6	21	54
Complies with EN-16798	YES	YES	YES	YES	YES	NO	YES	NO	NO

Indicators were calculated for three different clothing options. First a typical winter indoor clothing with value 1 clo, sweatpants and long sleeve sweatshirt with value of 0,75 clo and trousers with long sleeve shirt with value of 0,6. Results for typical winter clothing satisfy comfort requirements even for operative temperature of 21 °C, however with decreasing clothing level thermal discomfort can be felt in lower temperatures. State where the zone operative temperature drops under 21 °C is just for purposes of finding the limits for flexibility. In reality this state is undesirable for the occupants. Perception of thermal comfort is subjective matter and would depend on the users. Also, the simulation represents dynamic processes, while this method of evaluating thermal comfort is designed for steady state environment. Results from the analysis serve just as an approximation of the indoor environment in boundary conditions of the experiment.

Parametric study

Next step of the experiment is a parametric study, where different combinations of source heating capacity and storage tank volume are tested. Combination with which the model was verified is 30 kW source heating capacity and 1000 l storage tank. Three source heating capacity variants and five storage tank volumes were tested. Source heating capacity was chosen to be 30, 40, and 50 kW.

Table 5 - Storage tank options

Tank volume [l]	**750**	**1000**	**1500**	**3000**	**5000**
Height [m]	1,53	2,04	1,91	2,98	2,68
Static heat loss [W]	113	121	153	354	658

Considered heat source is ideal fluid heater and storage tanks are taken from RBC series by Regulus. Documentation for storage tanks can be found at [32]. Tank with volume of 5000 l is assumed to be one tank in the model, but in reality, would be two 2500 l tanks. Technical parameters used in simulation are in Table 5.

Selected key performance indicators

To evaluate energy flexibility the following indicators were chosen. Discharge time T_{dis}, which represents the time of system going from charged state to discharged. Next indicator is charging time T_{char} describing the time the system needs to go back from discharged state to charged state. Both time indicators were described in section 3. Lastly an energy indicator is selected in ΔE defined by equations (1)(2)(3). This captures the energy requirements of flexible behavior, compared to the reference scenario.

$$\Delta E = E_{ref} - E_{flex} \tag{1}$$

where

$$E_{ref} = \int_{T_{Dis,start}}^{T_{Dis}} Q_{source,ref}\, dt + \int_{T_{Char,start}}^{T_{Char}} Q_{source,ref}\, dt \tag{2}$$

and

$$E_{flex} = \int_{T_{Dis,start}}^{T_{Dis}} Q_{source,flex}\, dt + \int_{T_{Char,start}}^{T_{Char}} Q_{source,flex}\, dt \tag{3}$$

Energy based indicators were adopted from [19], previously mentioned in section 3, and expanded to include buildings thermal mass. As the original method works only with storage tank capacity.

6.2. Experiment results

Results for all combinations of source heating capacity, tank volume and outside temperature give overwhelming amount of data, so for better explanation two of the three variables will be fixed to illustrate the impact of the remaining one. Insight about behavior during discharging is given, followed by charging. Evaluation regarding all combinations is given at the end of this section.

6.2.1. Discharge (Delayed operation)

First a look into discharge characteristic with source heating capacity 30 kW and outside temperature of 1 °C. The plot is shown on Figure 10.

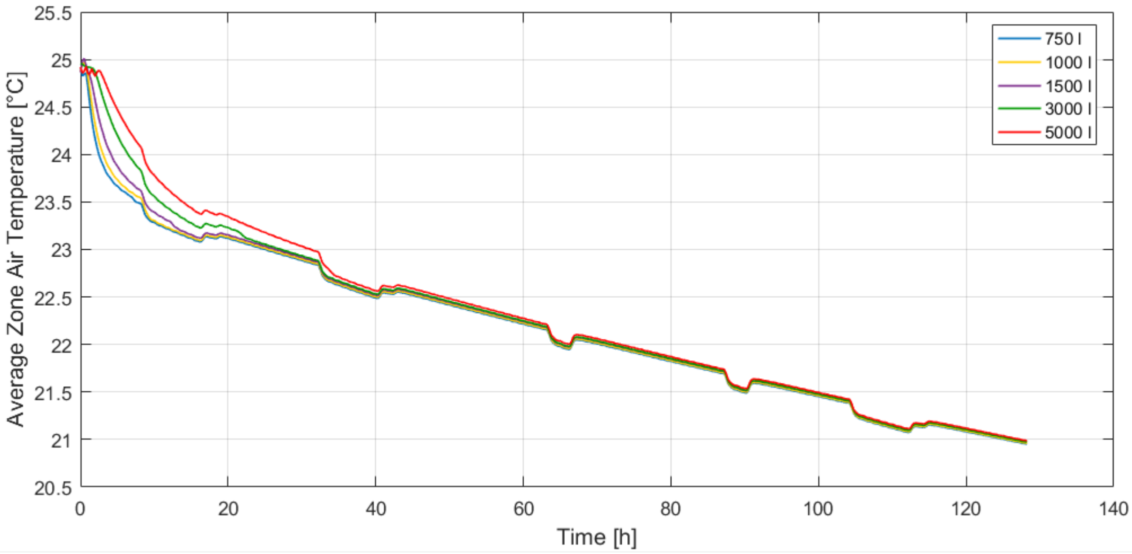


Figure 10 - Discharge characteristic for varying tank volume

Dips in average zone temperature are caused by internal gains schedule. Impact on total discharge time is negligible, 126 hours for 750l and 128 hours for 5000l, however difference can be spotted in the beginning phase of discharge. Detailed look into the start of discharge is revealed on Figure 11.

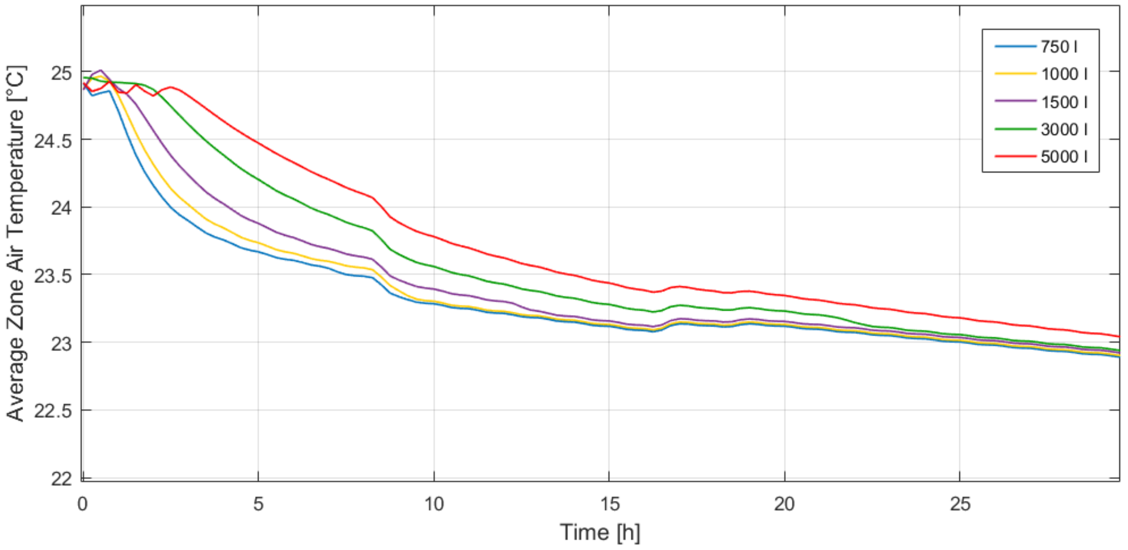


Figure 11 - Discharge characteristic for varying tank volume, beginning phase

In Figure 11 we can see, that with bigger tank the cooling of the zones slows down. For example, if we look at time to reach 24 °C. Smallest tank (750 l) reaches that temperature in 3 hours, compared to the biggest tank (5000 l) for which it takes 8 hours. This is caused by the energy stored in the tank. With increasing capacity rises capability to cover heat losses of the building without the heat source. Largest tank has enough capacity to even allow the regulation to oscillate and hold the zone at desired temperature level for 3 hours. The initial phase where the tank depletes ranges from 8 hours for tank with volume 750 l to 40 hours for 5000 l tank. After the tank was depleted and can no longer supply energy into the radiators, the rate of cooling is dependent on thermal capacity of the buildings constructions and the tank has no influence.

To see impact of different source heating capacity a characteristic with fixed tank volume of 1000 l and fixed outside temperature 1 °C is presented in Figure 12.

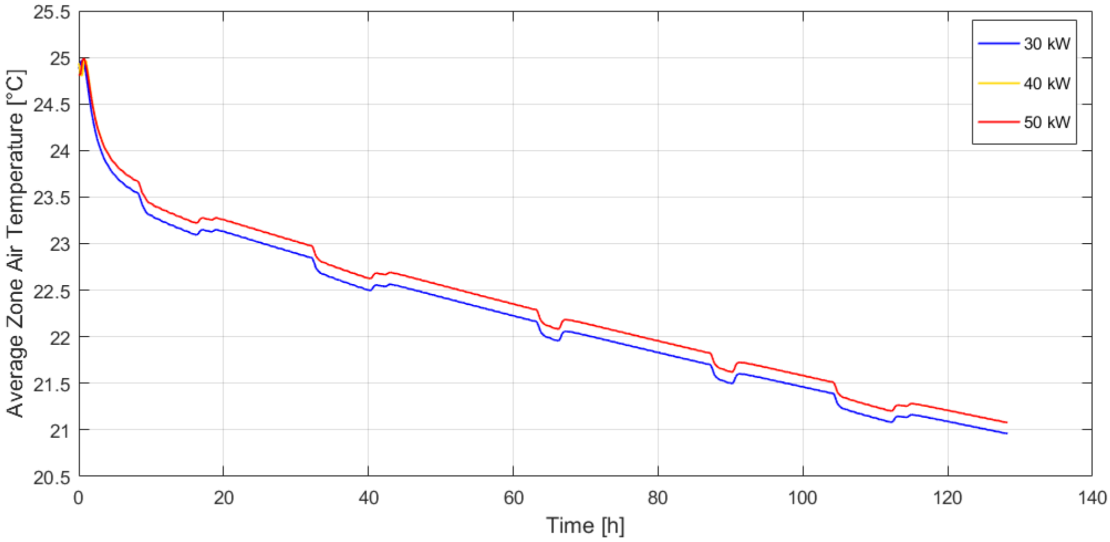


Figure 12 - Discharge characteristic with varying source heating capacity

Impact of source heating capacity has very limited impact on discharging phase. No difference between 40 and 50 kW was observed. Source with heating capacity of 30 kW seems to cool down faster, but in the end the discharge time is 2 hours less.

Lastly an impact of changing outside temperature is evaluated. Plotted characteristic is displayed on Fig. 13. Fixed parameters are source power 30 kW and tank volume 1000 l.

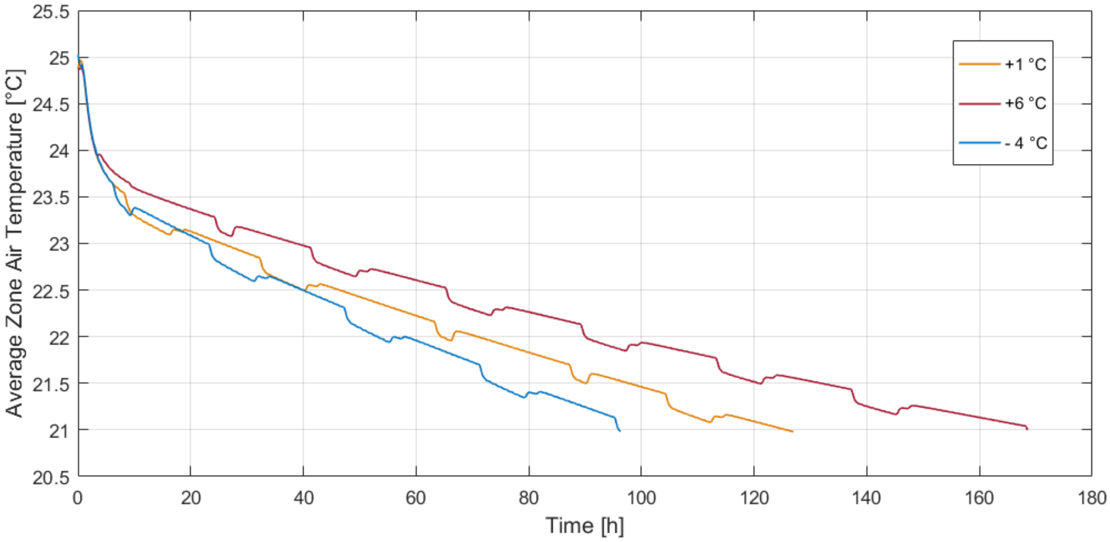


Figure 13 – Discharge characteristic with varying outside temperature

Here, we can observe that the dips caused by internal gains are uneven. Due to different outside temperatures, resulting in different heat demand, the time to get the system to initial charged state is longer for colder temperature, thus shifting the dips. From the plot it is obvious, that with increasing outside temperature, the rate of temperature drop will be slower. Values of KPI are in Table 6 in section 6.2.3.

6.2.2. Charging (Rebound)

Another studied part of flexible event is charging the system back to original state after the heat source has been turned OFF. Similarly, to discharge, first an impact of varying tank volume is presented in Figure 14. Characteristic is for source heating capacity 30 kW and ambient air temperature 1 °C.

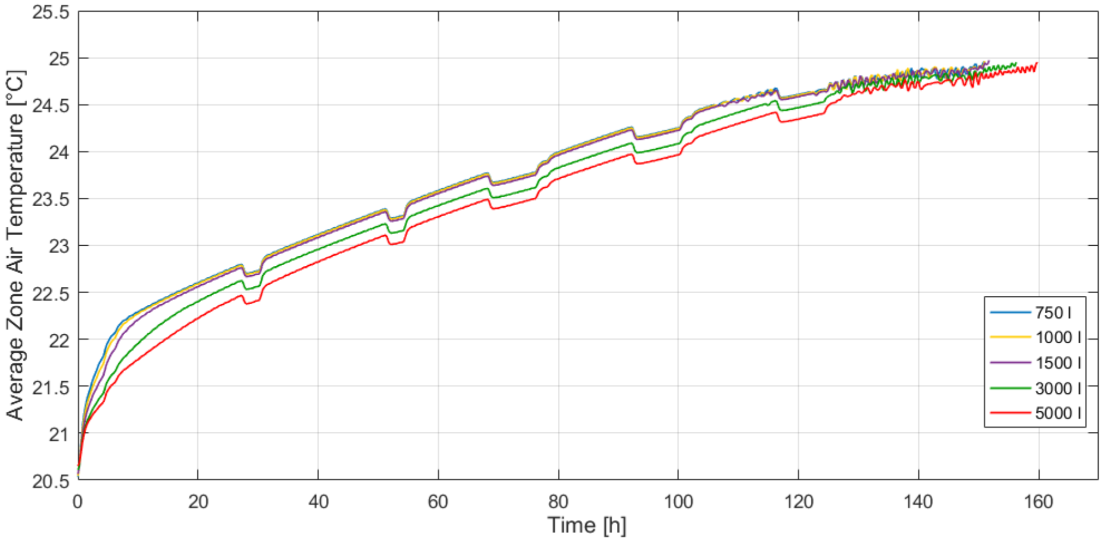


Figure 14 – Charging characteristic with varying tank volume

Charging time is practically similar for the smaller three storage tanks (151 hours) and increases for the bigger two – 156 and 160 hours respectively. Possible explanation is that the heat delivered into the tank can be divided into heat covering the heat loss in the building and heat that is used to warm up water in the storage tank. Also, due to regulation the supply pump draws water from the tank even if it has not reached the desired tank setpoint. Combining these two factors, if the source does not have enough capacity to cover both losses and accumulation, the tank will take longer to heat up. Resulting into zones being heated with lower temperature water, which means lower delivered power to zones and the charging of thermal mass will take longer.

Next figure (Figure 15) describes the change in charging time with varying heating capacity of the source. Tank size is fixed at 1000 l and outside temperature at 1 °C.

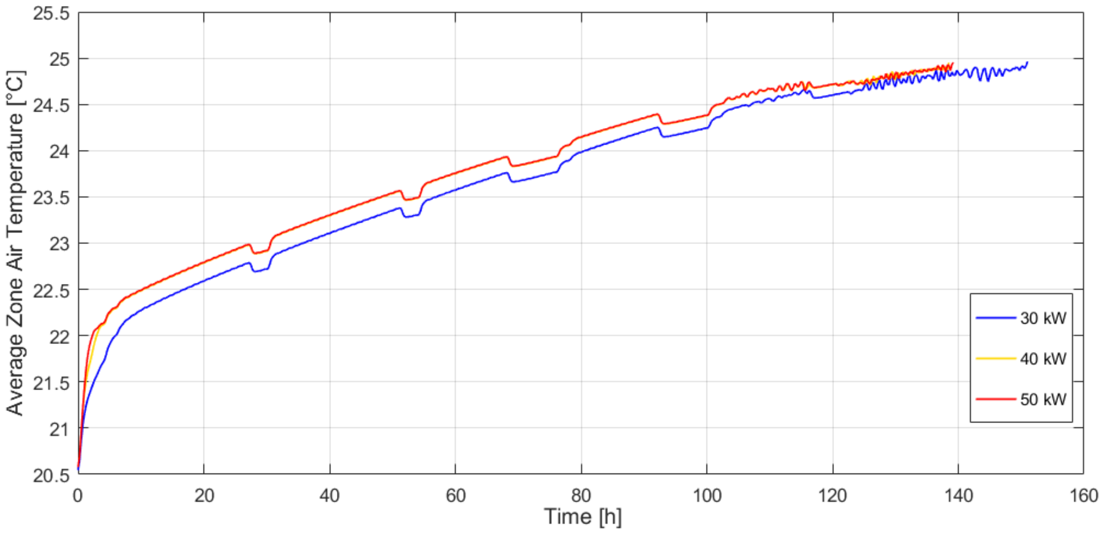


Figure 15 – Charging characteristic with varying source heating capacity

Contrary to intuition, there is no difference between sources with 40, and 50 kW heating capacity. Difference between charging times is 12 hours (139 h for 50 kW and 151 for 30 kW). Explanation could be, that the only variable is changing the source heating capacity, which has impact on faster charging the storage tank. But the heating system on the demand side (supply pump and radiators) is still the same and designed in this case for the buildings heat loss of 32 kW. So, increase in source heating capacity has no impact on the rate with which the heat is delivered from the tank to the zone. Longer charging time for 30 kW source is suspected to be caused by undersized heating capacity of the source, that is lower than the 32 kW of heat loss.

Lastly the effect of different ambient temperature on charging time was studied. Plotted characteristic is depicted on Figure 16. Same as discharge, fixed parameters are source heating capacity 30 kW and tank volume 1000 l.

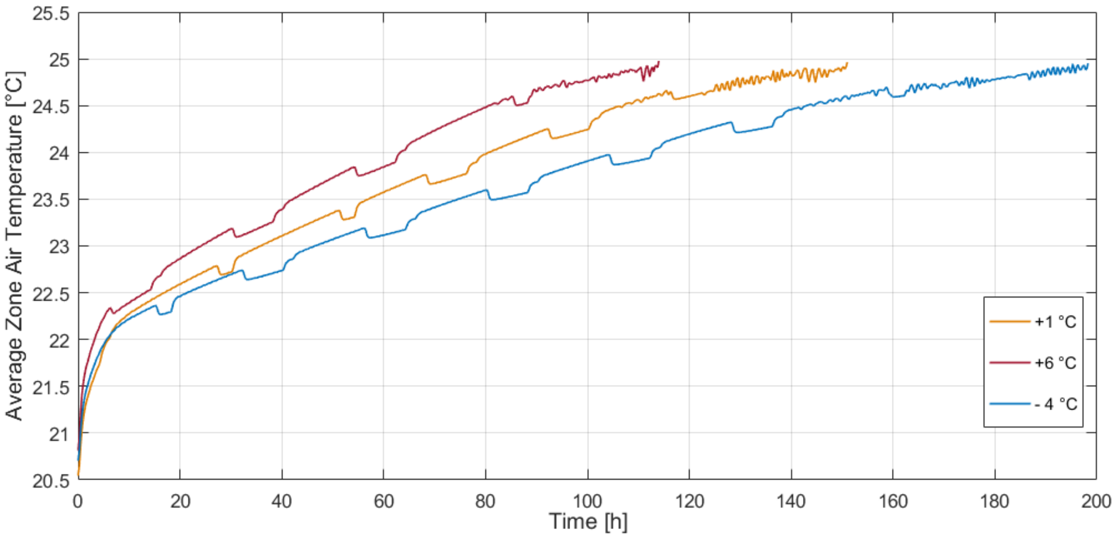


Figure 16 – Charging characteristic with varying ambient temperature

Similar to discharging characteristic, due to different ambient temperature each line is shifted. Even though the plot is jagged thanks to internal gains scheduling, the impact of ambient temperature on charging time can be clearly seen. With warmer outside temperature the time is shorter and with cooler temperatures will increase. Change in charging time can be explained by different heat demand. For this combination of source/tank the results are 114 h for ambient temperature of 6 °C, 151 h for 1 °C and 198 h for -4 °C. So, depending on the season the charging time can differ by 90 hours, which can be significant.

6.2.3. Summary of results

Step response characteristics provide information about the time aspect of flexible behavior, but don’t give insight into the energy used or saved. Results with all combinations and their KPIs are in Table 6.

Table 6 – Results of key performance indicators

	Discharge Time [h]			Charge Time [h]			Total (Ref - Flex) ΔE [kWh]		
Tamb [°C]	-4	1	6	-4	1	6	-4	1	6
30kW / 750l	96,0	126,3	168,5	195,3	151,0	113,8	-439	-237	77
40kW / 750l	97,3	128,5	180,5	189,3	138,5	107,5	-456	-165	231
50kW / 750l	97,3	128,5	180,5	189,3	145,0	107,0	-464	-230	235
30kW / 1000l	96,3	127,0	168,5	198,3	151,0	114,0	-475	-223	72
40kW / 1000l	98,0	128,5	181,3	189,3	138,5	107,5	-442	-166	236
50kW / 1000l	98,0	128,5	181,3	189,3	139,3	108,5	-429	-186	216
30kW / 1500l	96,8	127,5	173,0	199,3	151,8	115,3	-472	-232	113
40kW / 1500l	99,0	128,8	183,0	189,3	145,0	107,5	-425	-243	243
50kW / 1500l	99,0	128,8	183,3	189,3	139,3	108,5	-426	-196	227
30kW / 3000l	98,0	127,5	174,3	210,5	156,3	118,5	-460	-171	181
40kW / 3000l	107,3	130,0	187,5	193,0	149,0	108,0	-268	-213	348
50kW / 3000l	107,5	130,3	188,0	189,5	144,0	108,0	-254	-197	339
30kW / 5000l	99,5	128,3	177,0	222,5	159,8	123,0	-481	-147	210
40kW / 5000l	112,0	141,5	190,8	193,8	142,8	106,5	-216	27	410
50kW / 5000l	112,0	142,0	190,8	189,3	141,3	106,5	-191	18	390

Looking at the times for discharge, there is no difference between 40- and 50-kW sources regardless of tank volume or ambient temperature. Source with heating capacity of 30 kW has shorter discharge times and the difference is more pronounced with increasing ambient temperature, meaning the warmer it is, the less flexibility is offered compared with bigger sources.

If we focus on charging time, again there is no difference between 40 and 50 kW. Only inconsistency is in combinations with 750, 1500 and 3000 l tanks. This can be explained such as that the zone temperature of 25 °C was reached in a dip caused by internal gains, which could be lacking in that time.

In regard to energy, red fields mean that the flexible behavior requires more energy than reference scenario and green indicates the opposite, flexible behavior consumes less energy than reference. For ambient temperature – 4 °C every case needs more energy to be flexible. However, for source power 30 kW ΔE represents more demand for flexible behavior with increasing tank size. But for bigger sources it is the opposite. For tank sizes up to 1500 l the difference is small (10-30 kWh), but for 5000 l can be almost 300 kWh. This can be explained by behavior during charging (Figure 14). For larger tank, the small 30 kW source is not enough to simultaneously cover heat losses and warm the tank with enough speed, while for sources 40 and 50 kW the remaining power left to heat up the tank is larger. Faster charging time then leads to less energy consumed for that period. Same effect is observed with increasing ambient temperature. For 1 °C there is a breaking point for combination of 40kW/5000l, which shows positive balance meaning flexible behavior costs less energy.

6.3. Discussion

From available data, the building is capable of delaying heat delivery for 96 hours and up to 168 h even for the smallest source/storage tank combinations depending on ambient outside temperature. After conversion this means that the building cools down for 4 to 7 days without impact on user comfort if we take into account typical winter clothing with value of 1 clo as discussed in table 6. Compared to the flexibility window provided by grid analysis, where shifting demand is favorable for 8 to 24 hours, the flexibility potential of this building can be used to exploit the dynamic electricity price and help balance the grid.

Charging to original so-called rebound effect was also part of the study. Charging time is longer than discharge time for colder temperatures for all combinations. Balance point, where reference and flexible scenario require the same amount of energy seems to be around 1 °C for sources 40 kW and above paired with 5000 l storage tank. To find these points for smaller tanks, more simulations with smaller step in ambient temperature would be necessary. Also, from the data it seems, that length of charging time vs. discharge time can be corelated to the difference in energy requirements.

Another finding is, that small oversizing in source heating capacity offers additional flexibility in time and with lower energy requirements if paired with big enough storage tank. Additionally, radical oversizing doesn't bring any benefits either to flexibility in time or in energy. On the other hand, undersizing the heat source lowers the flexibility potential as charging times increase by 6 to 30 hours for ambient temperature – 4 °C, based on size of the storage tank. Smaller tank leading to less drastic increase in charging time. Also, the upper limit of 30 hours gets lower with increasing outside temperature, being 17 hours for ambient temperature 6 °C.

7. Conclusion

The goal of this work was to evaluate energy flexibility potential of a modern 6-storey residential building. To achieve that, a step response experiment using building simulation software (namely TRNSYS) was designed. The experiment was repeated for various settings in a parametric study. Parametric study aimed at the impact of different combinations of heating capacity and size of storage tank. In addition, influence of changing ambient air temperature was investigated.

From total of 45 simulated cases the results show that even for the smallest combination of source heating capacity and storage tank volume, the building is able to operate within comfort range for 4 to 7 days with the source turned OFF depending on ambient air temperature. Similarly, it takes 4,5 to 8 days to get the system back to charged state, based on ambient air temperature and selected combination of source heating capacity and storage tank volume. From energy perspective, with ambient temperature of 6 °C all combinations required less energy using flexible behavior than in reference without flexibility. For smallest tank size the saving were 70 kWh up to 400 kWh for the largest tank. However, for ambient air temperature of – 4 °C, flexible behavior needed more energy than reference. Again, depending on tank size energy requirements were 200 to 460 kWh from largest to smallest.

To evaluate possible flexibility from the grid’s perspective, an analysis of day ahead electricity market was conducted. Daily patters in electricity price give opportunity to shift loads. Window to delay consumption was found to be favorable in range of 8 to 24 hours. Potential in buildings energy flexibility is thus enough to support flexibility required from the grid side. However, realizing the buildings potential requires smart control strategy and incentive from the grid via dynamic pricing of electricity.

Further work with this model could include more variations by adding another ambient temperatures and heat sources. Doing so would allow to find the balance point, where flexible behavior has the same energy requirements as normal operation without flexibility.

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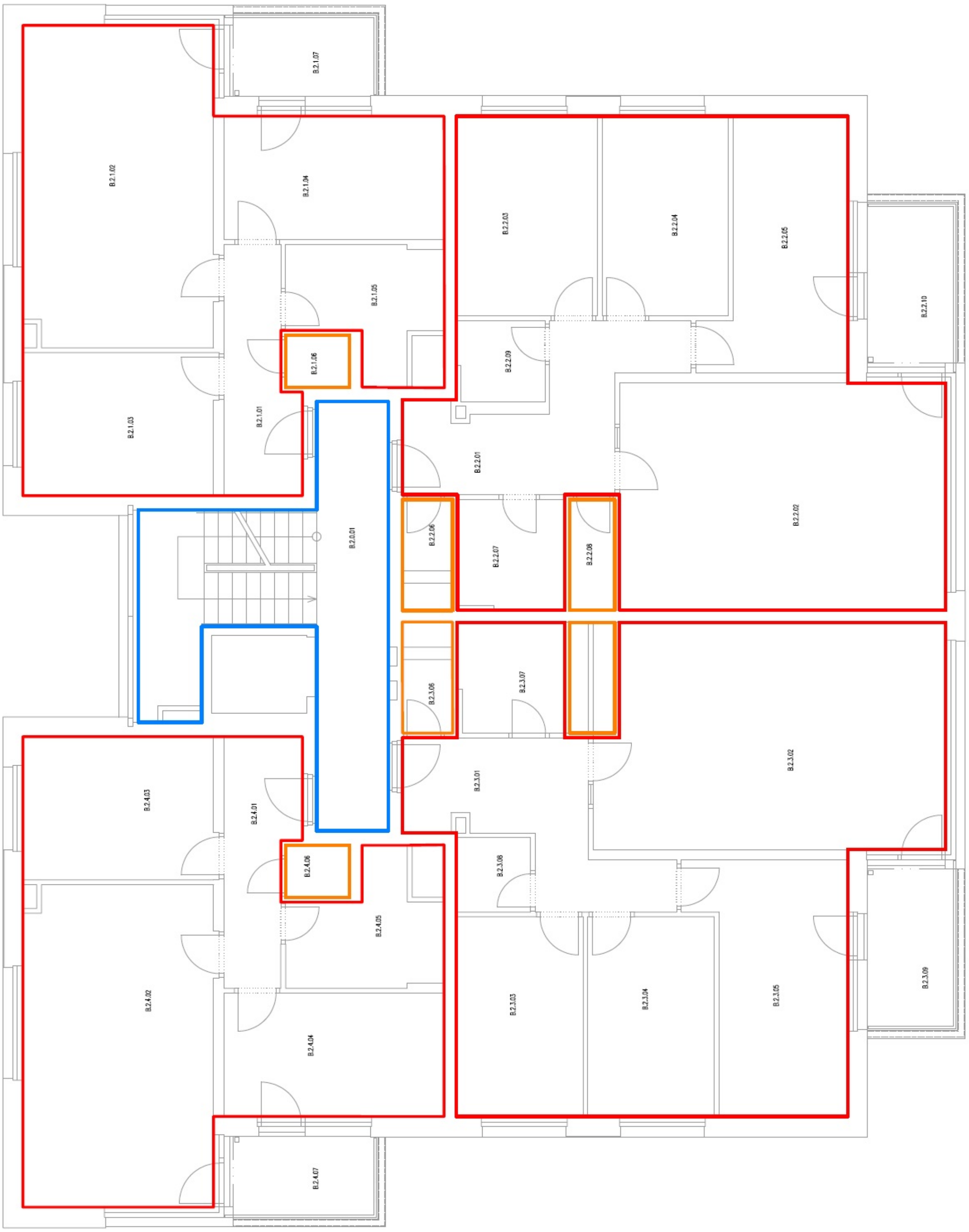
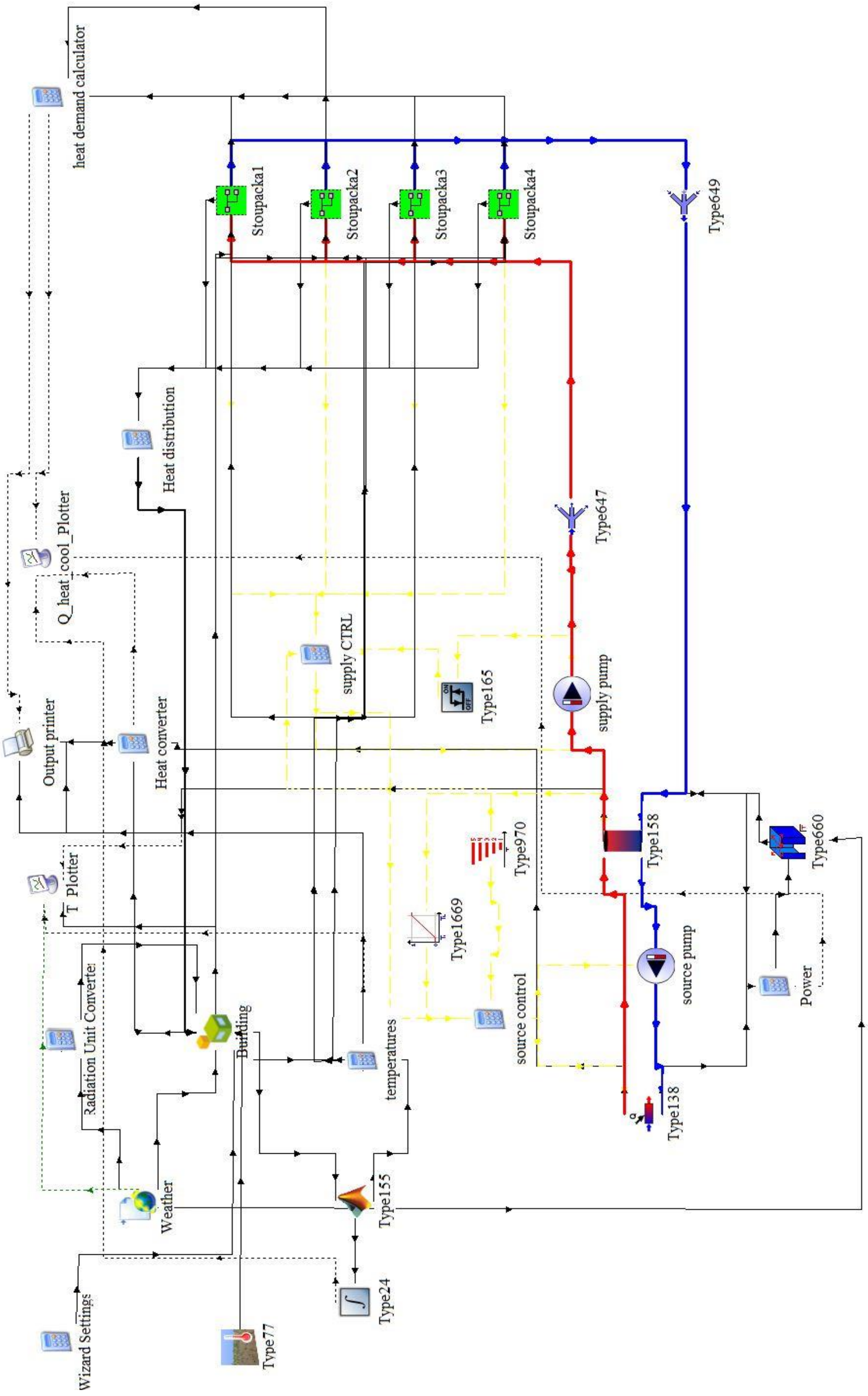
Appendix 1a – Zoning layout of floors 1-5

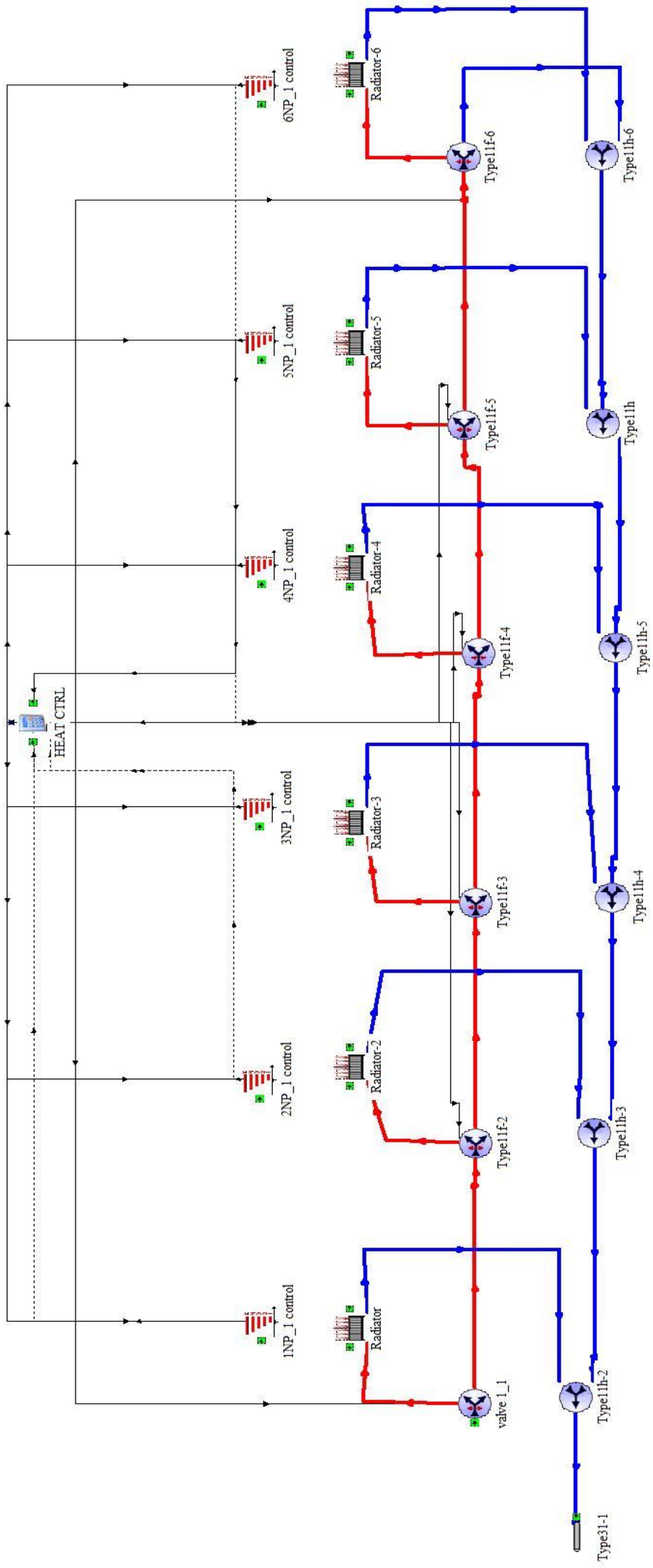


Appendix 1b – Zoning layout of 6th floor

Appendix 2 – TRNSYS model of the system



Detail of Stoupacka1



Appendix 3 – Building design heat load

Zone/Flat	Heat load (W)
1 01	1665
1 02	1802
1 03	1762
1 04	1652
2 01	1251
2 02	1264
2 03	1186
2 04	1277
3 01	1251
3 02	1264
3 03	1186
3 04	1277
4 01	1251
4 02	1264
4 03	1186
4 04	1277
5 01	1387
5 02	1350
5 03	1330
5 04	1400
6 01	2376
6 02	2361
TOTAL	**32019**