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FACULTY OF MECHANICAL ENGINEERING
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Energy Flexibility of Single-family House Located in Region of Central Europe

MASTER THESIS

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MASTER'S THESIS ASSIGNMENT

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Guidelines:

The final project aims to investigate energy flexibility potential of a single-family house with heat-pump system and storage tank using building energy simulation tools (e.g. IDA-ICE or TRNSYS). The analysis should assess the building thermal inertia focusing on various settings of the individual building components (e.i. building structures, storage tank, heat pump etc.). Furthermore, the performance utilizing the energy flexibility will be studied for different energy price tariffs (or grid CO2 intensity) and with respect to thermal comfort. The study assumes the location of the house in the region of central Europe considering relevant boundary conditions (climatic and grid data).

Bibliography / sources:

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Abstract

The paper represents a simulation-based assessment of thermal inertia in family house and its heating system including air-to-water heat HP coupled with the hot water storage tank towards improvement of the building energy flexibility. Building energy flexibility is a relatively new phenomena allowing the users to control their demand upon the dynamically changed grid status often represented by energy price. The hypothesis of current research is that with massive adoption of demand response strategies, it is easy to adapt to intermittent renewable energy in the grid and reduce the carbon footprint. This paper quantifies the flexibility potential of individual building components (building structure, water storage tank, etc.) with respect to electricity use and related operational cost and how it influences the house occupants’ thermal comfort under a demand response strategy. The analyzed building is located in Central Europe (Czech Republic).

Anotace

Tato práce prezentuje simulaci vyhodnocení tepelné setrvačnosti rodinného domu a jeho otopného systému s tepelným čerpadlem ve spojení s akumulační nádrží na teplou vodu pro zlepšení energetické flexibility budovy. Energetická flexibilita budov je relativně nový jev, který uživatelům umožňuje řídit jejich potřebu na základě dynamicky se měnícího stavu sítě, který často ovlivňuje cenu energie. Hypotéza současného výzkumu je taková, že při masivním přijetí strategií reakce na potřebu, je snadné se přizpůsobit přerušované obnovitelné energii v síti a snížit uhlíkovou stopu. Tato práce kvantifikuje potenciál flexibility jednotlivých stavebních prvků (struktura budovy, zásobník vody atd.) s ohledem na spotřebu elektřiny a souvisejících provozních nákladů, a dále jak to ovlivňuje tepelný komfort obyvatel domu podle strategie reakce na potřebu. Analyzovaná budova se nachází ve střední Evropě (Česká republika).

Declaration

I declare that this master thesis entitled " Energy Flexibility of Single-family House Located in Region of Central Europe” is my own work performed under the supervision of Ing. Vojtěch Zavřel, Ph.D. with the use of the literature presented at the end of my diploma thesis in the list of references.

In Prague 31.07.2020 Elizaveta Andreeva

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List of Abbreviations

RES	Renewable Energy Sources
PV	Photovoltaic (solar)
DSM	Demand-Side Management
IEA	International Energy Agency
KPI	Key Performance Indicator
ADR	Active Demand Response
FI	Flexibility Index
DR	Demand Response
UF	Underfloor
HP	Heat pump
HWST	Hot water storage tank
HDO	Mass remote control
HVAC	Heating Ventilation and Air Conditioning
PMV	Predicted Mean Vote
PPD	Percentage of Dissatisfied
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
TRNSYS	Transient Systems Simulation Program
EPS	Expanded Polystyrene
ACH	Air Change Per Hour
COP	Coefficient of Performance

List of Units

q	Thermal load on the body	[W/m^2]
M	Rate of metabolic generation per unit surface area	[W/m^2]
W	Human work per unit surface area	[W/m^2]
Q_{sk}	Heat loss through the skin	[W/m^2]
Q_{res}	Heat loss due to respiration	[W/m^2]
Q_h	Dissipated heat at the condenser (heating)	[W]
Q_c	Removed heat with evaporator (cooling)	[W]
P_{el}	Electric power required for compression	[W]
U_{cyl}	Heat transfer coefficient through cylindrical wall	[W/m^{2}K]
U_{pl}	Heat transfer coefficient through plane wall	[W/m^{2}K]
h_e	Heat transfer coefficient	[W/m^{2}K]
b	Thickness of insulation	[m]
k	Thermal conductivity	[W/mK]
R_1	External radius of water tank	[m]
R_2	Internal radius of water tank	[m]
COP	Coefficient of performance	[-]

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I. Theoretical part

I.1 Introduction

While the world is heading to its third technological revolution bringing the concept of data-driven production and increasing the awareness of humanity in ecological problems, such as global warming, the energy demand continues to grow. Since the all major types of energy sources are fossil fuels, the increased demand leads to higher level of CO2 production worldwide. This, obviously, negatively impacts the ecological situation. The increasing global energy demand and evident negative impact of fossil fuels using during the last years have generated a high interest in renewable energy sources. Despite the fact that the statistical information shows the rapid growth of the penetration of renewable energy sources (RES) all across the globe, the latter is still not enough to cover all the needs of energy. For instance, the total installed capacity for photovoltaic (PV) systems crossed the half of a TW with a 23,5% increase to 100GW from 2016 to 2018 [1]. The 51.3 GW of wind energy of new installations in 2018 brings total cumulative installations up to 591 GW around the world [2]. Nevertheless, the goals of the community are clear – lower the amount of energy produced by fossils, hence decrease the amount of CO2 and hold back the ecological disaster. For this purposes, the political, economic and scientific stimulations are applied. The total amount of funds raised by the renewable energy has reached its historical maximum of share in between other energy sources (becoming 19.5%) in 2018 with a funding rate nearly 13 B$ for the last decade [3]. On the other hand, some government policies and programs tended to have a bigger impact on the RES integration. As an example, the Europe 2020 strategy proposed by European commission includes a target of reaching 20% of gross final energy consumption from renewable sources by 2020, and at least 27% by 2030 [4]. This, definitely does not mean that all the countries which are the part of the European Union are implementing the same strictness. Some of the parties introduces their own governmental strategies on the local level. For instance, Germany intends to provide at least 35% of gross electricity consumption through renewable energy sources by 2020 and 80% by 2050 [5]. Whereas, Denmark aims to achieve an energy supply independent from fossil fuels by 2050 [6]. The importance of the renewable energy sources, the need of changing energy production systems and perspective of the future research of the topics define the scope of the work.

The problem of energy production and renewable energy sources could be seen from a different perspective though. The whole energy supply market does not suit the renewable energy in some important economic aspects. In particular, it's reasonable to say that some renewable energy sources such as solar panels, are less time independent then the traditional ones. In other words, photovoltaic energy sources are generating less energy than the market requires in peak-demand hours, and over generates the remaining time of the day. This effect could be verified by the data, that was published by the California Independent System Operator in 2013 [7] for large-scale deployment of solar photovoltaic (PV) power. The duck curve, which was named after its similarity with a duck, demonstrates the difference in electricity demand and the amount of available solar energy during the day (Figure 1). The curve illustrates a 24-hour period in California during spring time. This is truly the most organic case to demonstrate the described effect, as during the spring time the weather conditions in California are great to use the solar energy, since the activity of the sun is high, while the temperature is not as high as during the summer. Additionally, during the springtime, people in California usually not using the electricity for heating or air-conditioning.

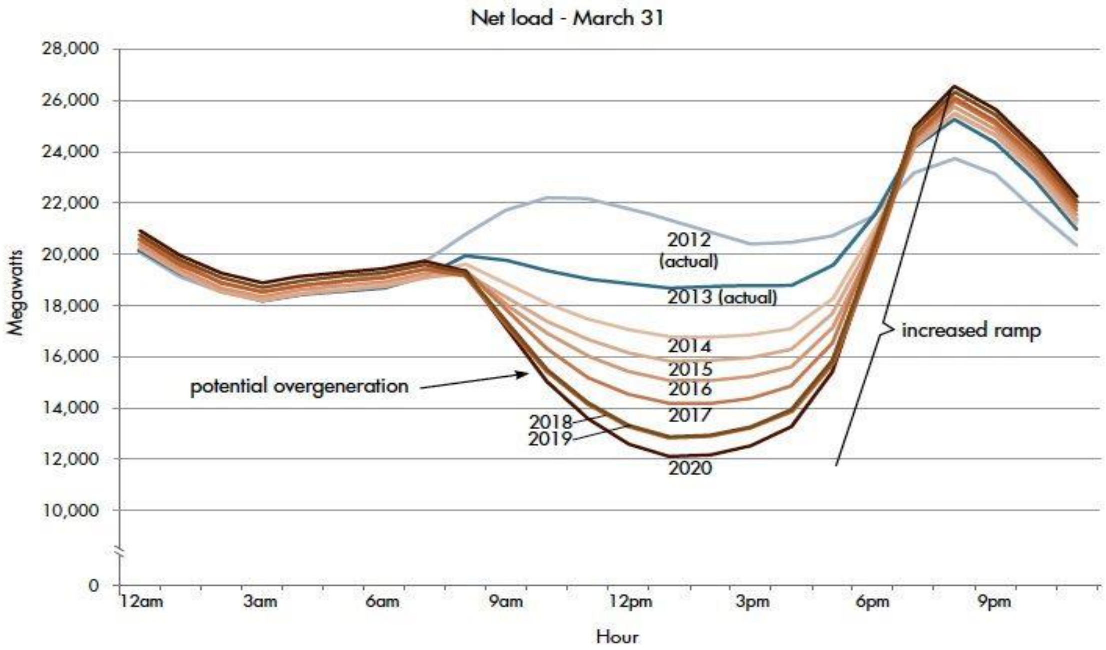

Figure 1: Electricity demand and the amount of available solar energy during the day

Source: [7]

A few dramatically important statements can be formulated as a result of simple analysis of the chart. First of all, the overgeneration of the solar energy at mid-day can force grid operators to curtail PV generation, which would have a negative influence on the economics of solar power generators and grid stability. Another major outcome of high solar power generation and integration is the peak power demand that starts in the evening as the part of the day, when most of the people are at home and utilizes power at the maximum level. This peak demand occurs during 6-10 p.m. when solar generation is completely off the grid and hence, demand must be supported by non-solar power.

Traditionally, the mismatch between local electricity demand and supply is balanced by controlling a limited number of large centralized production facilities, such as coal and gas fired power plants, solar power generation stations, hydro plants, nuclear power stations and other. These sources are connected to the high or medium voltage grids, and keep up with all variations in electricity demand to ensure that the system is balanced [8].

However, as it was stated above, the core goal of the governmental policies is to increase the penetration of the "clean" energy sources to the power supply chain, thus increasing the influence of the renewable energy sources, forcing the traditional electricity system to change rapidly. The next step of the power grids is so called Smart Grids (Figure 2) (or Smart Energy Networks, networks considering other than electricity mean of transferring energy) – an intelligent way of the power consumption optimization. By its nature, the production of solar and wind energy depends on local weather conditions and varies considerably. This instability creates uncertain hourly feed of renewable electricity into the grid, and more flexible operation of power plants is needed to cope with this uncertainty. In addition, the number of small- to medium-scale renewable production facilities that feed decentralized low voltage grids is increasing fast (as a consequence of the continuous trend showing that the renewable energy production systems become more affordable – for example, the solar elements price drop was around 75% for the last 10 years [8]), in opposite to the number of large power stations connected to the high voltage grid. Since, most of the building stock accounted residential and office buildings are connected to the low voltage, the cooperation between the local RES and buildings becomes very desired. Additionally, smart grids integrate real-time communication between actuators on both demand and supply side, that enables demand-side management (DSM) and the use of storage technologies in order to optimize the use of renewable energy sources [9].

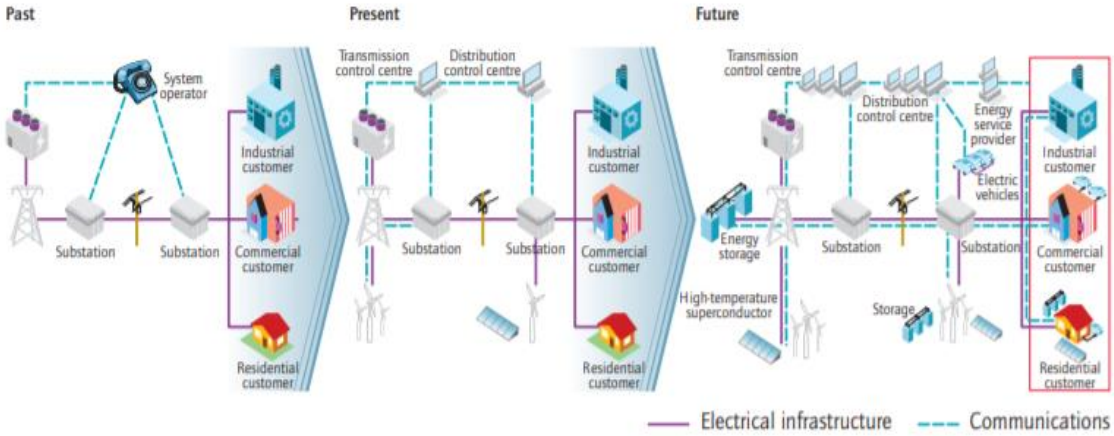

Figure 2: Evolution of the electricity grid

Source: [9]

Considering the smart grids and some similar systems as the future of the energy systems in the world, the impact of the building can be precisely estimated. It appears that all the buildings can account for the 40% share of the global energy use [10]. This energy is used for space heating, heating of domestic hot water, cooling, ventilation, pumps, lighting of rooms and for appliances used by occupants and may deliver considerable flexibility services to the system by smart control of their energy loads. The potential for using a building for demand response is determined as its energy flexibility [11].

I.2 Flexibility as key performance indicator

The question of increasing the energy flexibility of the building has raised discussions all across the scientific and practitioner's communities. This consequently led to arising of several important flexibility indicators as the core assessment criteria. At glance the review process of these quantification methodologies was suggested by Reynders et al [12]. Nevertheless, there is still no common agreement nor standard stating a clear and relatively sustainable description on how to evaluate energy flexibility. This problem occurs because of the fact that the "flexibility" term is understood differently depending on the study context. One of the key objectives of the International Energy Agency in Buildings and Communities program (IEA EBC), Annex 67 [13] is to tackle this issue by providing an overview and recommendations on the subject itself and its matters. According to this project the Energy Flexibility of a building is defined as *the ability to manage its demand and generation according to local climate conditions, user needs and energy networks requirements. Energy Flexibility of buildings will allow for demand side management/load control and thereby demand response based on the requirements of the surrounding energy networks*.

It can be clearly seen from the document [14], the comparison of different flexibility indicators for a single building case study. It, in particular, showed that despite the various focuses and goals in all of the studies three major properties of energy flexibility become can be identified:

i. the time over which energy can be shifted
ii. the amount of energy that can be shifted
iii. the associated cost or efficiency loss at the building level following this flexibility activating.

Nevertheless, the whole majority of researches and studies are prioritizing some virtually main key performance indicators (KPI) and storage types. These are independently indicating the flexibility of the building from relatively different perspective, increasing the accuracy of the most of available for the moment estimates. A range of researches have illustrated that the structural thermal mass can be easily activated and used for flexibility purposes [16-18]. Reynders et al. [18] in their work use the available storage capacity, efficiency of the storage process and power shifting capability as key performance indicators for the active demand response (ADR) potential of structural storage. Additionally, they found out that the median capacities available for storage over a 2 h period differ from 13 kWh to 18 kWh for single family house in Belgium. From the other perspective, Le Dreau et al. [17] offer to use the heating energy to store (when the set-point temperature is increased by 2 K) and the energy to conserve (the set-point is decreased by 2 K) during at a specific period of time for determination of flexibility. In that paper, poorly insulated single-family house from 80's was compared to the modern passive house. For the former one, a large amount of heat can be modulated (e.g. 25 kWh/m2 year) for short periods of time (2-5h), whereas for well-insulated buildings, the amount of heat modulated is relatively small, however the study also illustrates that the periods of modulation can be quite long. Even there, the estimates show that the maximum available time for the heating system to be turned off could arise up to 24 h. Concerning cost, the different scenarios of modulation can result savings arranged from 3 to 10%. The same methodology was used to analyze energy that can be added to or curtailed from a building by Foteinaki et al. as a flexibility indicator. The core of the research was the fact that during the study a clear asymmetry between these two upward and downward events was noticed: for 8 h the heating energy added to the single-family house was 87 Wh/m^2 and the energy curtailed was 36 Wh/m^2 [19]. Additionally, as it could be seen from simulation, the amount of added/curtailed energy during the event is proportional to the event duration. This, therefore, mainly indicates the large heat capacity of buildings.

On the other hand, we can specify another point of view, that was presented by Johra et al. in their work. They, in glance, define energy flexibility as the ability for the building to minimize the heating energy usage during high price periods and maximize it during low price periods [15]. The researches have introduced the energy flexibility index (FI) which demonstrates the change of heating consumption during medium and high price periods when the energy is stored during low price periods with a comparison scenario without any thermal storage strategy. A method of calculation a FI, which evaluates the reaction of building to penalty signals like CO2 intensity or electricity price imposed by the grid, was proposed by Junker [20].

Table 1: Classification of KPI for building energy flexibility

Ref.	Region	Building type	KPI categories			
			Load shifting ability	Cost efficiency	Power adjustment	Energy efficiency
[15]	Denmark	Single-family house	+			
[17]	Denmark	Single-family house	+			+
[18]	Belgium	Single-zone model	+		+	+
[19]	Denmark	Single-family house; Apartment block	+			
[20]	Southern European cities	Single apartment; Double apartment; Passive house		+		

Generally speaking, after the literature review and processing the state-of-the-art research, it can be stated that all of the KPIs are usually related to one of four main categories: 1) load shifting ability, 2) energy efficiency, 3) power adjustment, 4) cost efficiency, whereas the majority of them is based on the energy efficiency or load shifting ability (Table 1). Although the KPIs are set to be independent virtually the most of the research activities was based on the so-called reference scenario. The reference frame is usually the one that has no energy flexibility implemented, which is useful to find the KPI as a ratio of the significative with and without DSM. The use of references scenarios allows to achieve the identical boundary conditions with evaluated real buildings of facilities. As far as an issue of an providing the same boundary conditions for the simulations during the research is indeed complicated and complex, the process of quantifying the energy flexibility becomes vital.

Besides, the most frequently changed and analyzed parameters can be traced based on the studied researches (Table 2).

Table 2 List of varied parameters for determining the EF in literature

Ref.	Region	Building type	Parameters being varied			
			Thermal inertia	Insulation level	Heating/ cooling system	Control strategy
[15]	Denmark	Single-family house	+	+	+	
[17]	Denmark	Single-family house		+	+	
[18]	Belgium	Single-zone model	+			+
[19]	Denmark	Single-family house; Apartment block	+			+
[20]	Southern European cities	Single apartment; Double apartment; Passive house	+	+		+

I.3 Flexibility potential in building structure and systems

Insulation level of buildings appears to have a significant impact on overall energy efficiency as well as its flexibility. Johra et al. in their whitepaper have compared both poorly and highly insulated houses with various thermal mass aiming to determine the dependence of the energy flexibility of the insulation level. The paper claims that "the envelope insulation level is the most important building parameter with respect to the capacity of a dwelling to shift its heating use in time" [15]. In spite the fact, that poorly insulated buildings have lower flexibility index, "the absolute amount of energy they can shift in time is more important than the one of highly insulated houses" according to research of H. Johra, P. Heiselberg, and J. Le Dréau study.

Nevertheless, the impact that thermal inertia has on the different energy flexibility KPIs is unstable and varies in respect to the weather conditions, operation scenarios and specific design characteristics. For instance, theoretically, assuming that the room that the study accounts for has no windows and has an inner mass, the thermal inertia can have large impact on the ultimate heating or cooling demand. According to review made by Verbeke, this influence can reach 40-50 %. Although practically speaking it can't exceed the level of 5%. [21]. The statement can be demonstrated well with an example, taking into account a regular building in Latvia, the experiments show that increasing the thermal mass of the building by 20%, leads to the drop of the cooling load of the building by 1.2% [22]. Buildings with a large amount of thermal mass may exhibit a reduced and delayed reaction to an initial excitation such as a sudden increase of external ambient temperature. This transient activity is called a building's thermal inertia. It is also important to mention in regard to the thermal inertia description that the higher thermal mass is usually related to the better thermal comfort, nevertheless, it cannot be precisely controlled by standard temperature controllers because of the fact that these sensors have high temperature delays. Consequently, advanced control strategies are required to utilize thermal mass either for comfort control or demand response control.

I.4 Demand response strategies

In theory, buildings are able to adjust their way of using energy. This can be achieved by shifting the energy consumption from high-cost to low-cost periods (load shifting), by reducing the demand of energy in peak periods (peak shaving), and by means of increasing the energy use in off-peak periods (valley filling) (Figure 3). This definitely allows to suit the production of RES. From the other perspective, it is also possible to reduce the costs of peak power production unit's operation by storing the electricity. For these purposes the energy storage device, for instance, batteries (e.g. electric vehicles) can be used. In addition to that, buildings have a large potential for short-term thermal storage in hot water tanks (for space heating and/or domestic hot water) [16] and in the thermal mass of building structures referred to aforementioned thermal inertia [15].

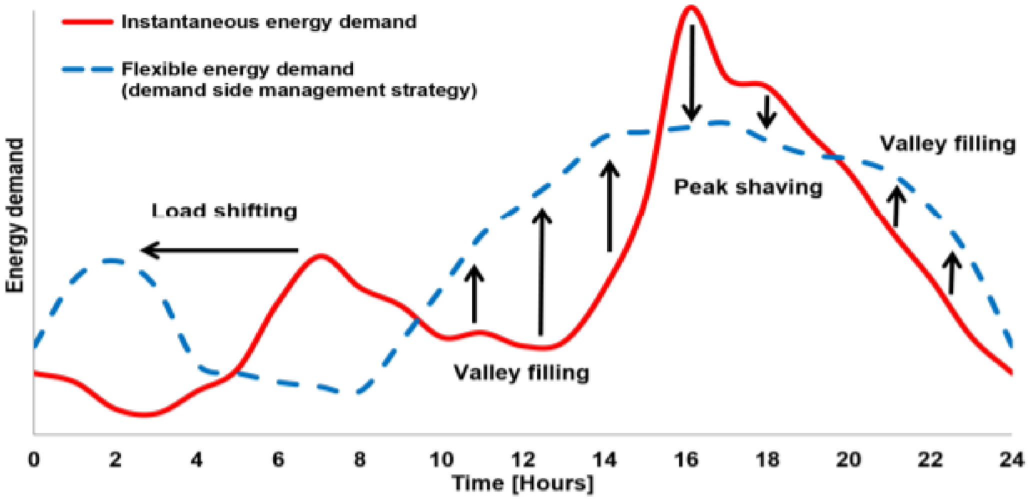

Figure 3: Example of DSM / energy flexibility

Source: [14]

It's fair to state that the DSM is an innovative approach that allows controlling the efficiency of electricity infrastructure. Particularly, a relevant DSM strategy is defined by demand response (DR) mechanism designed to allow end-user consumers to make changes in their regular usage habits in response for changing electricity price over time. According to the study [25], mainly 4 types of components can be used in DSM strategies:

i. energy-efficient end-use devices;
ii. additional equipment, systems and controls to enable load shaping;
iii. standard control systems for turning end-use devices on/off as required;
iv. communication systems between end-users and external parties.

Despite the fact that researches use various control strategies, all of them have achieved significant results of applying DSM (Table 3).

Table 3: Main results of DSM-strategy applying from literature review

Ref.	Region	Building type/ Heating system	Control strategy	Main results
[24]	Nordic countries	Single-family house/ UF heating system + ground source HP	Price based control	"The optimized operating strategy saves 25-35% of the electricity cost"
[25]	Germany	Single thermal zone/ UF heating system + ground source HP + HW tank	Price based control	"The share of surplus energy for space heating is increased by up to 50%, compare to a conventional control system"
[16]	Northern Ireland	Single-family house/ Radiators + UF heating system + HP + HW tank	Energy peak loads control	"Using a DSM achieved no significant reduction in the energy demand for the configurations considered here, but the electricity bill could be cut if a "time of use" tariff and incentives on renewable heat generation were available" "The total energy usage increases on 4%"
[10]	Belgium	Single-family house/ Radiators + UF heating system + air-to-water HP + PV system	Electricity peak demand control	"The use of the structural storage capacity is able to reduce the HP electricity use during peak demand periods significantly (69% - radiators, 88% - UF-heating)" "Activating the structural thermal storage increases the total energy use on 5-8%".

I.5 Mass remote control (HDO)

The electricity demand of the house changes several times during the day. This fact is determined by operation of multiple appliances and devices. Although, at larger scale, accumulation of the household load together with industrial load may exceed the planned production capacity in peak hours, shifting the operation of the major building consumers i.e. electrical boilers, storage heaters, convection electrical heaters and heat pumps, which may be realized by mass remote control allows to prevent the overconsumption during the peak hours. The mass remote control introduces the two-tariff rate pattern (high and low tariff). Tariffs are usually revealed by the electricity distributor. Traditionally the low tariff was applied to the night time period from 22:00 until 06:00, however, the load drop could depend on the season and weather conditions, meaning that the actual value can fluctuate in a wide range. For that reason, it is usually more useful to equip the building with the HDO receivers instead of regular timers. The HDO control signal is transmitted many times during the day leading to a better regulation of the network. In other words, the HDO switch can detect low tariff and turn on connected appliances or turn them off when the high tariff was reached.

The future of the Smart Grids tends to introduce time-dependent tariff system, forcing the distributors to launch the "multi-rate" HDO system, that will include multiple bands according to current electrical grid loading supporting the integration of intermittent RES [27]. A user should have the ability to preset individual appliances into the appropriate bands.

I.6 Flexibility versus thermal comfort

Comfort evaluation is an important factor to be taken into consideration when developing control systems that deal with temperature set-points indoors. Traditionally, temporary adjustment of set-points of the HVAC system is a common method for saving on energy consumption and peak demand. Nevertheless, the degree of the setpoint changes may have a major effect on the building occupants' perception of thermal comfort. During control applying, which utilized the energy flexibility potential of various building components, such as construction thermal mass, hot water storage tank and etc. for demand response purposes, the thermal comfort may be compromised and it became one of the key parameters to investigate. As the energy flexibility strategy being applied, a reduction in energy demand is required over a high price period of electricity. However, or at the same time thermal comfort is a vital and required condition of any energy flexibility event, as it determines the limits of allowable temperature fluctuations and should not be jeopardized. A number of researches use some discomfort metrics for optimization of building. Most of them related to the Fanger Comfort model [26], which implemented 2 indices: *PMV – Predicted Mean Vote* and *PPD – Percentage of Dissatisfied,* and adopted by ASHRAE55 and EN15251. This model is based on the equation of heat balance (1):

$$q = (M - W) - Q_{sk} - Q_{res} \qquad (1)$$

where q – thermal load on the body (W/m^2);
M – rate of metabolic generation per unit DuBois surface area (W/m^2);
W – human work per unit DuBois surface area (W/m^2);
Q_{sk} – heat loss through the skin (W/m^2);
Q_{res} – heat loss due to respiration (W/m^2).

In conformity with European standards, which specify criteria for thermal control and indoor air quality, there are 4 categories of acceptability of the indoor environment representing different levels of expectations (Table 4).

Table 4: Thermal comfort levels

Category of thermal comfort	PPD [%]	PMV	Description
I	<5	-0.2<PMV<+0.2	High level of expectations (For sensitive persons with special requirements)
II	<10	-0.5<PMV<+0.5	Normal level of expectations. (New buildings)
III	<15	-0.7<PMV<+0.7	Acceptable level of expectations. (Existing buildings)
IV	>15	PMV< -0.7 and PMV> +0.7	Values outside the about criteria. (Should be accepted for a limited part of the year)

According to goal of maintaining the comfort level of the building's occupants the key metric of the number of the discomfort hours is presented. This is the most common way in the determination of the comfort levels for different kind of buildings. For instance, Hoes et al [29] minimize overheating in the summer and underheating in the winter to maintain a minimum thermal comfort level described as a constraint on the maximum number of discomfort hours fixed at 200 hours per year.

In this work, discomfort hours, representing the hours, when the actual indoor temperature exceeds the acceptable comfort range, were used for thermal comfort level evaluation. Acceptable comfort temperatures were chosen according to EN Standard 14241 - 2007 for corresponding metabolic activity. The use of the acceptable temperature range, i.e. the range corresponding to the latest (III) comfort category, made it possible to quantify the building's potential for flexibility using minimum amount of energy. Decreasing the energy consumption of the house can lead to shortening the operation costs, as well as CO2 emissions level, which is crucial for the environment.

I.7 Research Question

To summarize the state-of-the-art research and the brief description of the field of study it is fair to state that, it is obvious that the global energy community is on its way to replace fossil fuels with renewable energy sources to reduce CO2 emissions, enabling the green policies to be implemented and Earth atmosphere to start cleaning up. This, in turn, forces traditional electrical systems to change rapidly as the production of alternative energy sources is highly dependent on unstable weather conditions and requires power plants to operate flexible. Modern energy networks (i.e. smart grids) bringing the communication and connection of the demand and the supply side feature to the first place, enabling consumption management. For that reason, term “Energy flexibility” becomes vital as it allows users to control their demand upon the dynamically changing conditions of the grid, represented by the load and price. However, “Energy flexibility” is a fairly new concept, meaning that it is dramatically necessary to find some new key performance indicators or validate the relevance of already existed ones to evaluate the flexibility and assess the state of the modern buildings and constructions. Additionally, as far as the literature review shows, most of the research has been done for the Northern European climate, not taking into account central Europe.

This work represents an analysis of thermal inertia in typical single-family house and its heating system for following evaluation and improvement of the energy flexibility of the building. As long as we find thermal inertia highly dependent on case inputs and crucial for the determination of the energy flexibility, it is important to perform the studies like that for individual cases, since the generalized optimization way, that can be applied to the different types of buildings and climate zones has not been developed yet. As the thermal inertia potential varies within a wide range and depends on the building configuration at first, the only way to justify the energy flexibility strategy is to run a simulation for the specific case inputs (weather conditions and building structure).

II. Practical part

II.1 Description of case study

In order to evaluate flexibility potential of dwelling, single-family house was chosen. The house is equipped with an air-source heat pump system a storage tank, and so-called heat distribution unit representing radiators for space heating. As it already known from the literature review, thermal inertia is supposed to have a major impact on the energy flexibility potential of the building. Consequently, first of all, the thickness of the walls will be varied in this study for flexibility evaluation. Secondly, volume of the storage tank will be changed, as it expected to have a significant influence on flexibility as well. The performance utilizing the energy flexibility will be studied for two different energy price tariffs and with respect to thermal comfort. The house is located in Kladno, Czech Republic and assumes relevant weather conditions and grid data.

II.2 Selected KPI

Since energy flexibility is a relatively new phenomena in ongoing discussion, there are no established or standardized indicators. Researchers still collect information and try various key performance indicators for evaluating of flexibility potential. This work will try to indicate flexibility potential of several building components as time delay of temperature course on the sudden change at the heat source. The delay is mainly given by thermal capacitance of construction thermal mass, coupled both material and insulation, and hot water tank. As it emerged from the literature review, these parameters were the most influential and critical in determining flexibility. First of all, the storage capacity of the building, which represented by the maximum delayed operation time, and related to load shifting ability category from (Table 1), is considered as KPI. A dynamic simulation allows to evaluate the influence of building parameters on buildings storage ability.

Secondly, as energy flexibility allows to speak about applying demand-response strategy, which help significantly reduce load on grid, the electrical use and related operational cost were taken into account.

Due to the significant importance of thermal comfort for such studies, temperature will be observed as a defining parameter in this work. Consequently, an uncomfortable watch can be evaluated and used as an indicator of thermal comfort. Typically, family-houses residents are considered to have sedentary activity of 1.2 met in living spaces. According to EN Standard 14241 2007 – *Indoor environmental input parameters and assessment of energy performance of buildings*, the following temperatures should be kept in the indoor environment during heating and cooling season (Table 5). Categories from the following table were described in the chapter *I.6.*

Table 5: Recommended values of indoor temperatures for living spaces

Type of building/space	Category	Minimum temperature for heating season	Maximum temperature for cooling season
Living spaces of residential building	I	21	25
	II	20	26
	III	18	27

Since room temperature control is based on the temperature of the living room, these values were chosen for experiments providing. Consequently, all the time, when temperature in the living room is less than the minimum recommended temperature or higher than the maximum one for various categories of thermal comfort, can be considered as discomfort hours.

In this work, DSM responding to the price of electricity is implemented and its impact is evaluated. Control strategy requires comfort restrictions so as not to let the goal of flexibility jeopardize the comfort of the occupants of the building. For this reason, it becomes crucial to determine comfort (or discomfort) in such a scenario. After demand-side management applying, discomfort hours have to be as low as possible with respect to HDO signal.

II.3 Simulation tools

Taking into account system's dynamic behavior, the solution of this non-trivial multi-criterial task requires advanced simulation tools. The transient simulation of the system, which includes the building itself and HP coupled with the HW tank, was performed using TRNSYS, a simulation environment for dynamic analysis.

For making a simulation of the system, the model should be produced at first. Model is a similar but simpler representation of the system. From one side, model has to be close approximation of the reality and answer all of the research questions, however at the same time it should be as simple as possible to be able to understand the results and work with them. Energy simulation tools help to designers in evaluation of the energy performance of building before it was constructed or in simulation of the energy cost in already existing dwelling. A lot of questions concerning heating, cooling, lighting, ventilation needs of the occupants and their interior comfort can be solved with the help of the simulation software. That is the reason of significance of the proper energy simulation tool selection.

Nowadays, a lot of software tools available for building performance simulation. The well-established and trustworthy are TRNSYS, IDA, Energy+ and ESP-r. In this work, the transient simulation of the system, which includes the building itself and HP coupled with the HW tank, was performed using TRNSYS, a simulation environment for dynamic analysis with a modular structure.

The latter allows to outline the problem in a number of smaller components ("Types"), ranging from simple models as pumps to complicated multi-zone buildings. All the components can be changed or created by users. TRNSYS has 2 levels of modeler applications. The upper level is a Simulation studio – graphical interface where all of the components are presented, and the lower one – TRNBuild with TRNSYS open-studio plugin for Sketchup, which can define a building construction, schedules, geometry and etc., and can be controlled from the upper level [30].

II.4 Numerical model development

II.4.1 Building model

The case-study house has 2 floors and the total floor area 180 m^2. It was built in 50s with following full renovation in 2003. The complexity of the building model is limited by 9 thermal zones. On the first floor, kitchen, bathroom, living room, the staircase with the corridor and small entrance are located. Three bedrooms (two of them are form one thermal zone), bathroom and the corridor are located on the second floor. Interior doors are considered to be permanently closed, consequently there will be no direct air exchange between the thermal zones. The floor plan of the building can be found in Appendix A. Taking into account the fact that there is no need for heating in entrance, the heated floor area of the building amounts 174 m^2 and the windows surface comprise 11.5 % from entire external wall area.

The 3-D model of the house for following simulation was made in in TRNSYS open-studio plugin for Google SketchUp. Table 6 demonstrates the thermal properties of the envelope. During the renovation expanded polystyrene (EPS) was used as insulation material. Cement blocks filled with concrete was introduced as inner material of the external walls.

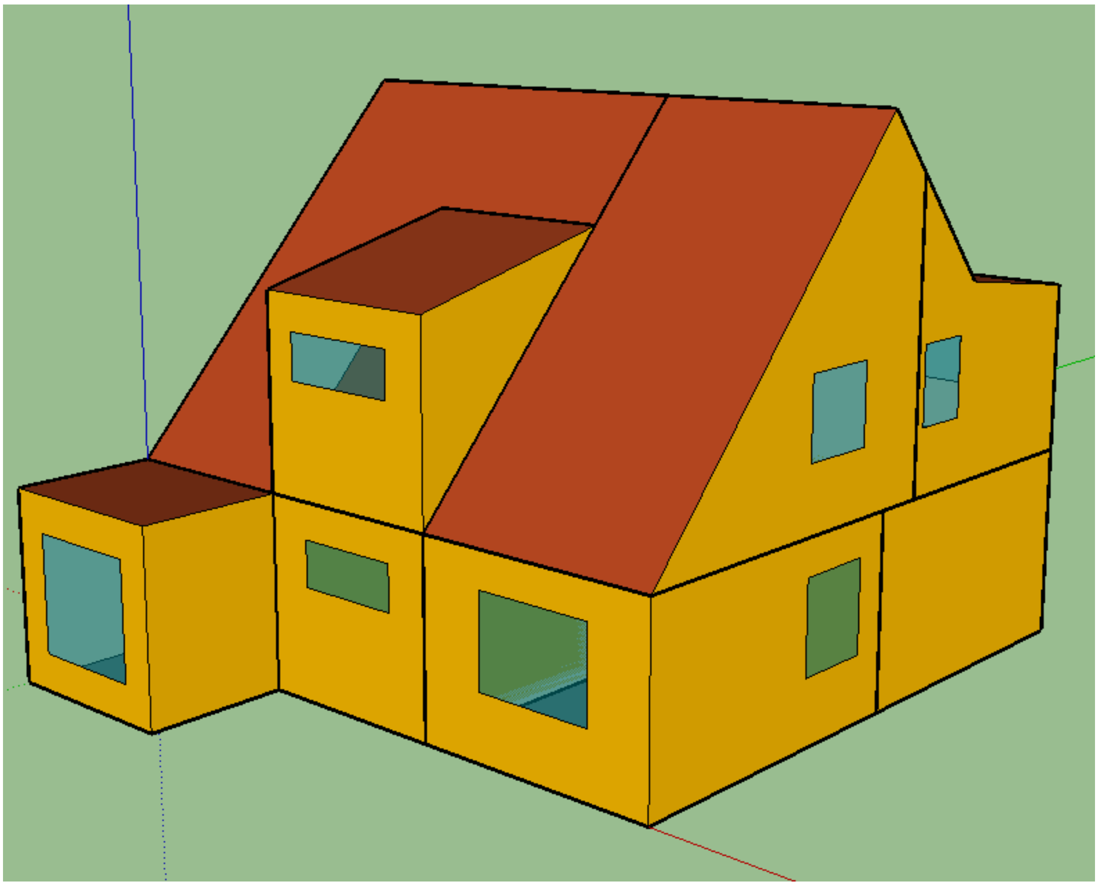

Figure 4: 3-D model of the building

Since there were limited information concerning exact materials of which consist all of the surfaces and their thicknesses, an assumption was done based on recommended U-values for old buildings [28] and taking into account the full renovation and new standard values according to ČSN 73 0540-2.

Table 6: Thermal properties of building's construction

Surface	Thickness, m	U-value, W/m²K	Recommended U-value, W/m²K	Old standard U-value, W/m²K
External wall	0.59	0.234	0.25	1.7
Roof	0.4	0.273	0.16	1.5
Cellar ceiling	0.43	0.368	0.4	-
Top floor ceiling	0.3	0.311	0.4	0.68
Window	Double glazing	1.6	1	4.8

In this study, Type 56 (multi-zone building) was used for determining properties of the building structure with following evaluation of flexibility potential.

II.4.2 Heating system

The heating system of the house includes an air-to-water heat pump for heat production coupled with low temperature system for heat generation. Domestic hot water was not taken into consideration. Heat load for each of the rooms were obtained by TRNSYS, including influence of infiltration and internal gains.

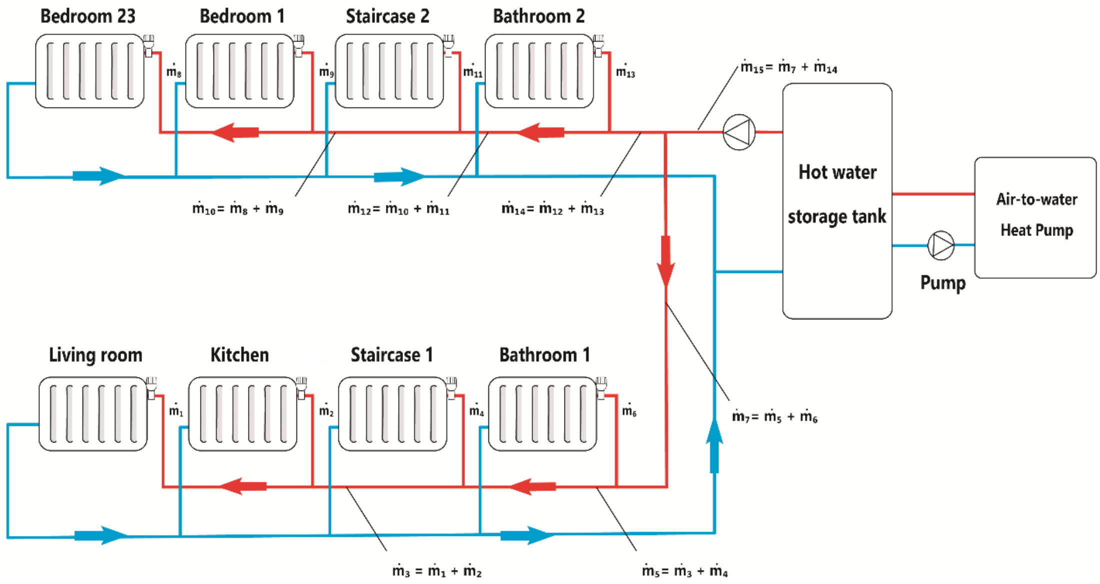

Figure 5: Heating system

II.4.2.1Heat emission

It was decided in this work to use contemporary low-temperature radiators, that can be supplied with hot water at temperature ranging from 45°C to 55°C, comprising 10°C the design temperature difference. In simulation studio Type 1231 was used for radiators representation. This model is based on the information in the ASHRAE Handbook – HVAC Systems and Equipment [ASHRAE 2004]

Design heat load was calculated based on EN12831 (Table 7). Assuming that even after the total renovation the residential building cannot be considered as tightly constructed one, infiltration rate amounting 0.6 ACH (air change per hour) was providing according to ASHRAE recommendations. That value can guarantee sufficient air renewal. Internal heat gains are included in total heat load calculation. More detailed description of the former can be found in the chapter II.4.2.2.

Table 7: Heat load of the building

Room	**Heat load, W**
Bedroom 1	1217.6
Bedroom 23	2455.0
Staircase 1	359.3
Staircase 23	465.6
Living room	2094.4
Kitchen	991.8
Bathroom1	974.6
Bathroom 2	1581.1
Total	10139.5

II.4.2.2 Internal heat gains

Internal heat gains include the sensible and latent heat generated by any source that is to be eliminated by air conditioning or ventilation within an enclosed room, and/or resulting in a rise in temperature and humidity within the room. They can be produced by occupant's activity, use of electrical equipment or emissive heat of artificial lightning.

a) Occupants

All the people lose heat to the surrounding because of their metabolic activity. Total rate of heat emission, including both sensible and latent heat, can significantly varies depending on the type of performed activity. Thereby, for this residential building a third level of activity was selected according to ASHRAE classification, which corresponds to sitting or doing some very light work and producing 115W of energy. Moreover, the assumption concerning weekly and annual house's occupancy has been done. Table 8 demonstrates the obtained possible schedule of the family.

Table 8: Weekly and annual schedule of the house

Room	**Temperature**	**Weekdays occupancy**	**Weekends occupancy**	**Yearly occupancy**
Living room, Kitchen, Bedrooms	20	06:00-08:00 15:00-18:00 (1/2) 18:00-06:00	08:00-13:00 15:00-08:00	2 weeks in July, 2 weeks in December are off
Bathrooms	24			
Staircases	15			

b) Equipment

Personal computers, TV's and other electrical devices give the house heat gains equal to the total power input. Equipment heat gain was chosen from library of TRNbuild and considered in this work as area related one, based on SIA 2024(2015) standard for residential building category. Calculation of electrical equipment heat gain was applied for living room, bedrooms and kitchen. Convective power by standard comprises 23 kJ/h·m^2, while radiative power is 5.76 kJ/h·m^2.

c) Lighting

In the end all the electrical energy lamps use is emitted as heat as well. This area-related heat gain was also evaluated by means of TRNbuild. According to SIA 2024 standard for residential building, convective power amounts 2.916 kJ/ h·m^2, and radiative – 6.804 kJ/ h·m^2.

II.4.2.3 Heat production

An air-to-water heat pump was introduced as a heat source for the family house. The operation principle is demonstrated on the picture below (Fig.6), where all the main components can be observed.

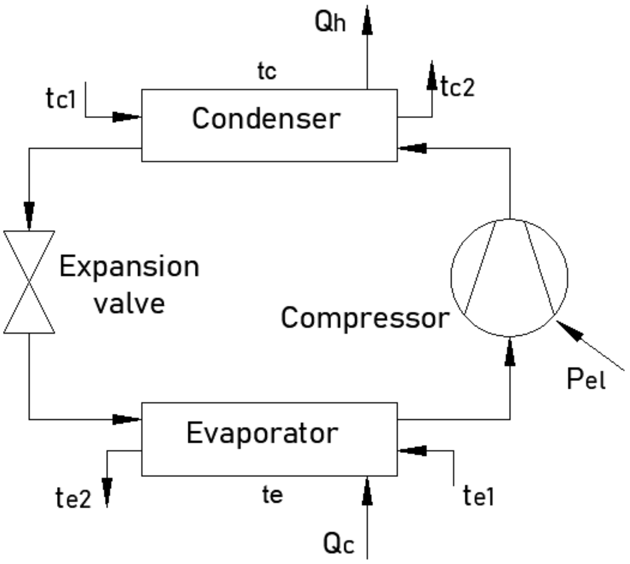

Figure 6: Principal scheme of the heat pump

On the picture:

Q_h – dissipated heat at the condenser (heating);

Q_c – removed heat with evaporator (cooling);

P_{el} – electric power required for compression.

As a reference device heat pump VITOCAL 200-S by Viessmann company was chosen. The overall list of technical parameters can be found in Appendix B. The annual coefficient of performance (COP) is illustrated on the Fig. 7. As it can be seen from the graph, the averaged COP level amounts approximately 3.5 in winter and 4 in summer, which corresponds to ongoing COP of the modern heat pumps. In TRNSYS Simulation studio Type 941 represents the heat pump.

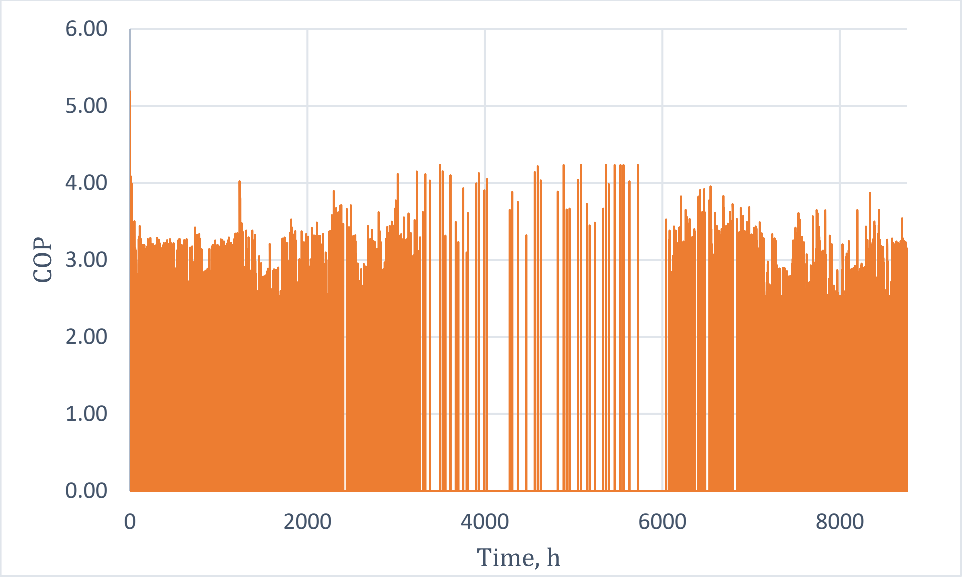

Figure 7: COP of the heat pump

II.4.2.4 Storage tank

As it already known from the literature review, the hot water tanks can offer good potential for a short-term energy storage, that can be utilized for DSM. Therefore, storage tank is a key element for the evaluation of building's flexibility potential. Type 158 represents constant-volume cylindrical hot water storage tank with vertical configuration in TRNSYS. The temperature of the tank is controlled and it can vary in the range between 45°C - 55°C based on the actual heating load. As a reference from the market, R0BC 500 Hot Water Storage Tank on 500l by Regulus was selected. The technical data sheet can be found in Appendix C. The storage tank is supposed to be in the technical room, which is located on the ground floor. For that reason, bottom, edge and loss temperature were evaluated as soil temperature +10°C. Heat transfer coefficient through both plane and cylindrical walls of the tank can be calculated according to equations (2)-(3):

$$U_{cyl} = \frac{1}{\frac{1}{h_e}+\frac{b}{k}} = 1.004\frac{W}{m^2K}, \tag{2}$$

$$U_{pl} = \frac{1}{\frac{1}{2\pi h_e R_2}+\frac{1}{2\pi k}ln\frac{R_2}{R_1}} = 0.435\ \frac{W}{m^2K} \tag{3}$$

Where b – thickness of the insulation, k – thermal conductivity, R_1, R_2 – external and internal radiuses (see Appendix C).

$h_e = 10\frac{W}{m^2K}$ – heat transfer coefficient.

II.4.3 Control

The air temperature in the living room is controlled by means of 5-stage room thermostat (Type108). Temperatures in other thermal zones are adapted to behavior of the living room temperature selected as representative temperature for entire building (i.e. assumed location for thermostat). The setpoint temperature was assumed at 20°C. As soon as the temperature fell below the set point, the 1st stage heating is commanded. When it reduced one degree more, the second heating stage turned on. The same principle applies for the third stage.

Similar thermostat controls temperature of the hot water storage tank. The first stage heating is turned on when the temperature of the tank falls below than 55°C.

II.5 Simulation-based assessment

II.5.1 Simulation scenarios

For answering the research question, two experiments were executed and presented in the thesis (Table 9). First of all, the reference simulation scenario without any activation of energy flexibility was introduced for following comparison with the cases with applied demand side management. The reference case was designed according to the original data on the building and heating system. The scheme of the model, which was built in Simulation Studio, can be found in Appendix D. After simulation, heat load (Table 7), temperatures of the room (Fig. 9), coefficient of performance of the HP (Fig.7) and other system parameters were obtained.

The next step was to conduct experiments, which focus on the cooling-down period of the thermal zones with respect to various settings of the wall construction and size of the hot water storage tank, for investigation of temperature course after sudden switch.

Table 9: Description of the carried-out experiments

	1st experiment	**2nd experiment**
Weather conditions	Zero outside temperature and radiation	Dynamic change
Duration	3 weeks	1 year
Main point of the experiment	Time-response evaluation	Evaluation of the discomfort hours in accordance with the HDO signal profile

II.5.1.2 First experiment

The purpose of the first theoretical experiment is to evaluate the delay of the temperature drop, that indicates the flexibility potential for the heat pump operation as the heating source. The delay in temperature course is given by various storage capacities of building configuration. During this experiment, a sudden step was applied to the supply side of the heating system.

The experiment begins in steady-state situation, when the HP is operated to keep the desired temperature in the room. At defined time-step, the space heating is turned off and the step-response of the air temperature is observed. The simulation time step is selected to be 1 minute, to captured the response in higher detail. The whole simulation lasts 3 weeks.

Static boundary conditions were set for this experiment. Temperature, solar radiation and internal gain equal to zero.

The limits for the observation start at 25°C and finish at 20°C, that satisfy II category of thermal comfort limits according to EN15251. The result will give an indication of the load shifting ability and finally energy flexibility potential.

Also, heat pump was replaced by an ideal heater with the same heat load. The modified scheme of the model can be found in Appendix E.

In the first experiment, PID controller is used for the room temperature control. The on/off variable is changed depending on difference between tank and living room temperatures. When difference become more than 8°C, PID controller is on. This allows to describe useful energy of the tank and see in more detailed way the contribution of the tank to the overall shifting ability.

During experiment building thermal mass, insulation level and volume of the water storage tank have been varied to determine the most significant parameter and evaluate load shifting ability in general. The simulation plan can be found in chapter II.5.2.2.

II.5.1.3 Second experiment

In the course of the second experiment, a year-round simulation was conducted to evaluate the energy flexibility of a building. In this case, dynamically changed weather conditions were taken into account during simulation. Weather file for Prague city was used in the work. The TRNSYS simulation model for the second experiment can be found in the Appendix F.

The main purpose of the experiment is to determine discomfort hours considering 2 tariff profiles of electricity price. As it already known from the chapter I.5, using HDO signal transmitted several times per day allows to regulate the network in better way. The HDO switch will sense low tariffs and switching on attached devices, or shut them off when hitting the high tariff. Consequently, there is 3 possible scenarios can be observed in this experiment. First of all, the whole-year simulation of the system without HDO switching use. The second is the one including the HDO influence. And the last scenario describes applying the mass remote control but with temperature regulation for decreasing the discomfort hours. As in the previous experiment, the influence of all: size of the hot water storage tank, insulation level and thickness of the concrete would be observed to compare their contribution to the possible load shifting ability and cost saving.

Figure 8 demonstrates the one-day averaged HDO signal profile, where 1 means high tariff and 0 – the low one.

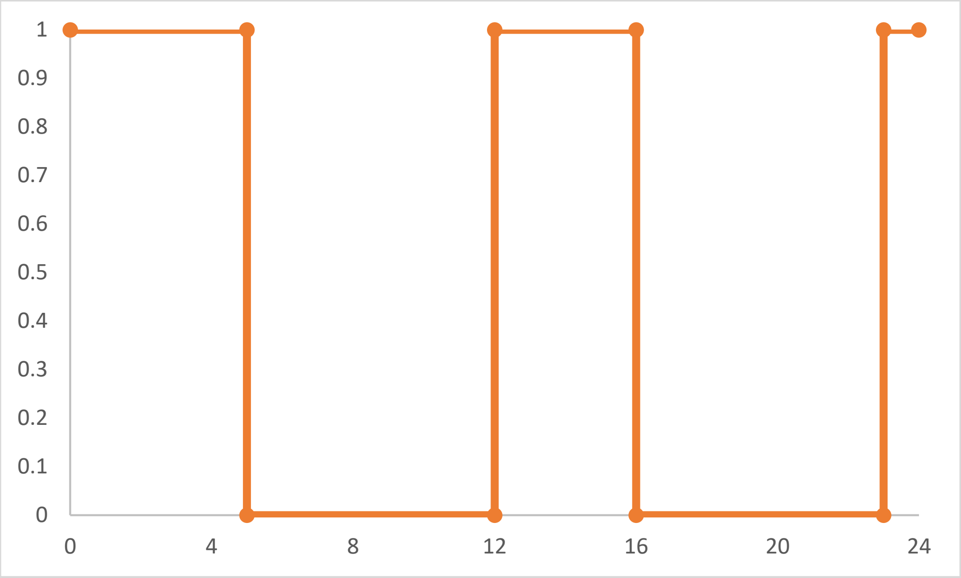

Figure 8: HDO signal profile

For the second experiment, discomfort hours are determined according to EN Standard 14241 2007, which says that comfort level with +0.7<PMV< -0.7 and more than 15% of dissatisfied can be deemed a discomfort one. In other words, temperature range from 18 to 27 degrees, which corresponds to III comfort level for residential buildings and sedentary activity, can be considered as still acceptable room temperature. Such an approach allows to reduce maximally energy consumption with still acceptable comfort level.

Besides the discomfort hours, electricity bill is evaluated for various simulation scenarios and it also can be used as a performance indicator. Electricity price comprises 0.044 Euro/KWh for high tariff and 0.032 Euro/KWh for the low one. Electricity provided by the Stabil energy supplier for heat pump rate D56d for Prague region. Also, a distribution fee amounting should be included into price by adding 0.095 Euro to the high tariff and subtracting 0.0038 of the lower tariff.

II.5.2 Simulation results

II.5.2.1 Zero simulation scenario

It can be clearly seen in the Figure 9 how internal environment respond to turning off the heating. On the graph influence of both building envelope and hot water tank can be observed.

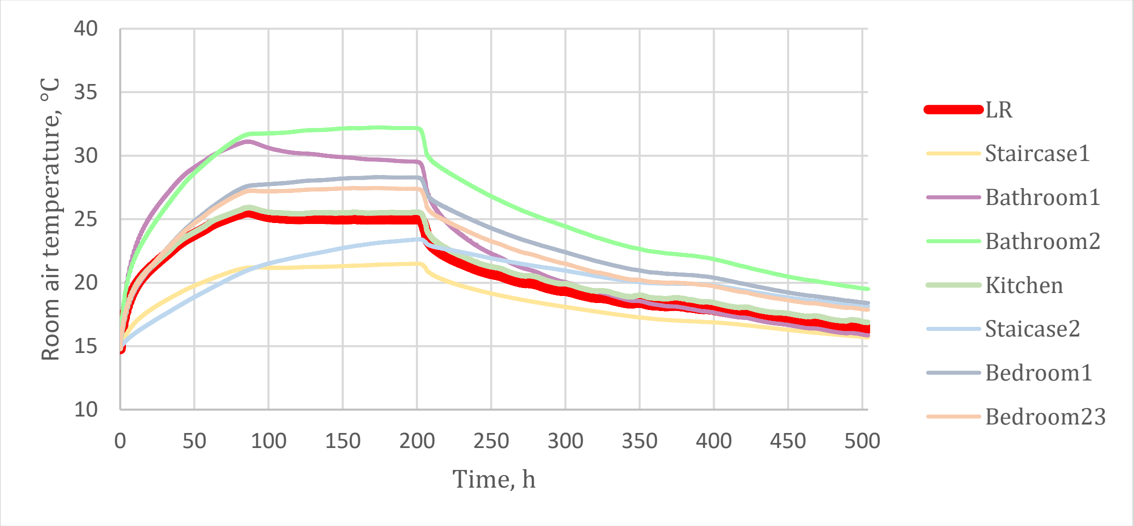

Figure 9: Temperature course in rooms during the experiment

As follows from the plot, it takes some tangible time for the house to reduce the temperature to 20°C. Next, only the living room will be considered in the simulations as it is the basis for air temperature control.

II.5.2.2 First experiment

Experiment was provided in accordance with the simulation plan (Table 10), where the obtained results can be found as well. The following 3 variable parameters are considered, which have a maximum impact on the flexibility potential.

a) Variable size of the hot water tank

A number of water tanks from the same manufacturer REGULUS was considered for this case. For each tank, volume, height and heat loss coefficient was set in the simulation studio.

Table 10: Simulation plan of the first experiment

Simulation	**Description**	**Tank volume, l**	**Insulation thickness, m**	**U-value, Wm2/K**	**Concrete thickness, m**	**Time delay, Δt, h**
Reference	Simulation for defined tank volume, defined U-value, 1 tariff profile	500	0,14	0,234	0,45	73
1	Delayed operation during cooling-down with the different tank volumes, ref. U-value	170	0,14	0,234	0,45	68
2		300	0,14	0,234	0,45	69
3		750	0,14	0,234	0,45	79
4		1000	0,14	0,234	0,45	82
5		1500	0,14	0,234	0,45	86
6		2000	0,14	0,234	0,45	91
7	Delayed operation during cooling-down with the ref tank volume, different insulation thickness	500	0,08	0,368	0,45	109
8		500	0,10	0,309	0,45	90
9		500	0,12	0,267	0,45	82
10		500	0,16	0,209	0,45	67
11		500	0,18	0,189	0,45	64
12		500	0,20	0,172	0,45	62
13	Delayed operation during cooling-down with the ref tank volume, different material thickness	500	0,14	0,261	0,05	35
14		500	0,14	0,254	0,15	49
15		500	0,14	0,247	0,25	63
16		500	0,14	0,24	0,35	71
17		500	0,14	0,231	0,5	69

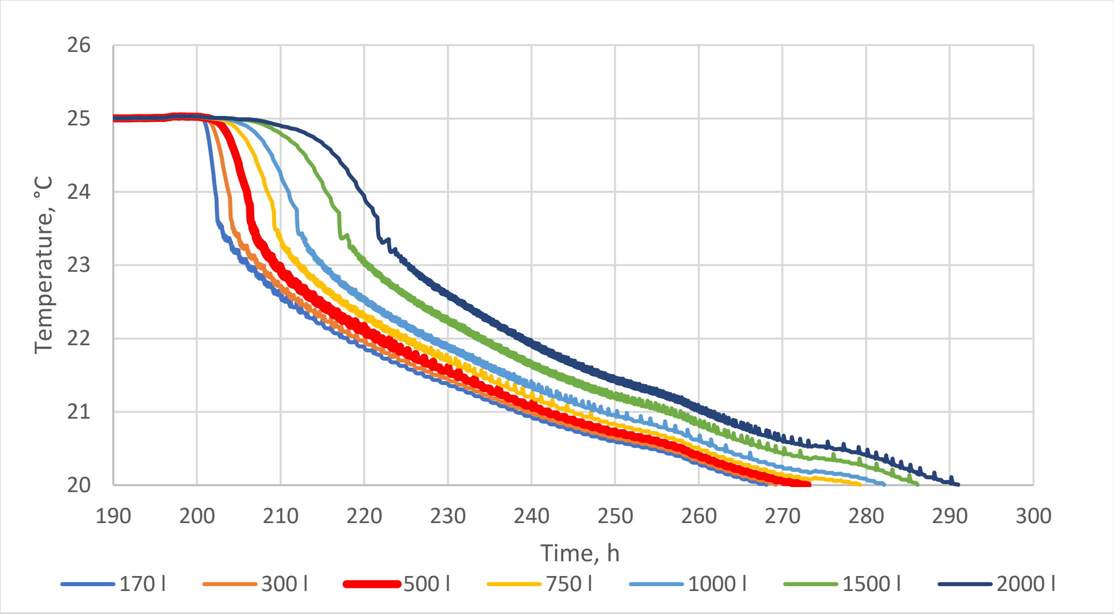

Figure 10: Step-response of the representative room temperature with respect varied HWST size

It is in clear view, that the bigger the size of the tank, the longer it takes the room temperature to cool down (Fig.10). Using a designed 500-liter storage tank, 20°C can be reached within 73 hours after switching off the space heating. Comparing two extremes – 170-liter tank and 2000-l tank, delayed operation time is 23 hours less for the former one. Moreover, noticeably that the low size of the tank leads to a sharper drop of the air temperature.

The contribution of the hot water tank to a building's flexibility potential can be assessed using the following graph (Figure 11). It represents difference between living room and tank temperatures. Once the heating is switched off, the tank is being discharged until the temperature difference is zero. The discharging time depends on the size of the tank.

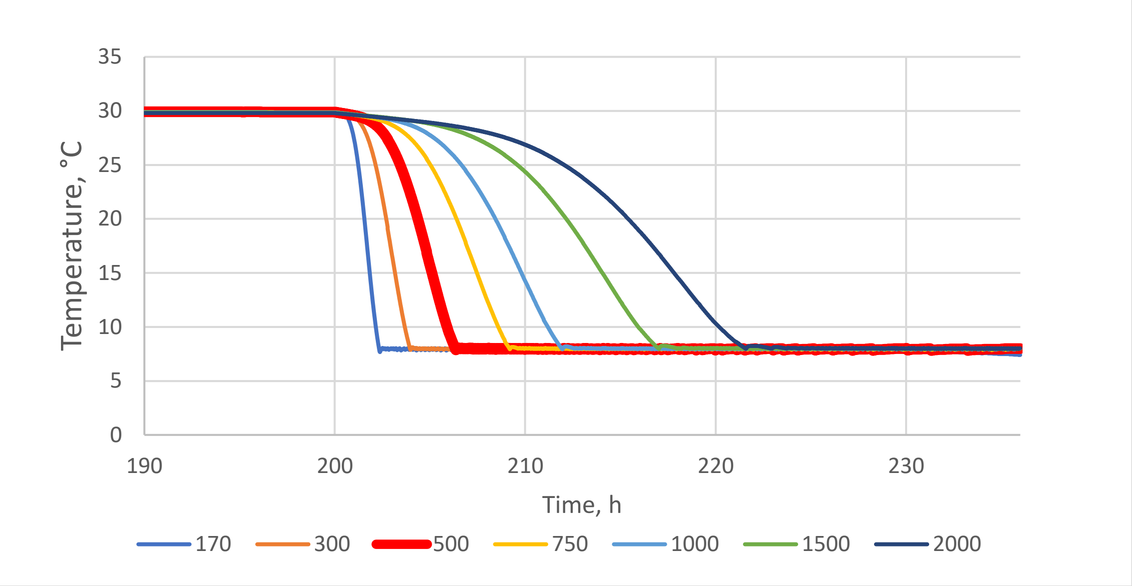

Figure 11: Step-response of the temperature difference between tank and room temperature with varied HWST size

Repeatedly, the trend looks the same. Using huge 2000-liter water tank requires 7 times longer period for cooling-down in comparison with a smallest one. Besides, curve behavior changes much more smoothly for the former one. Concerning designed 500-liter storage tank, it's contribution to overall delayed operation time comprises 7 hours.

b) *Variable thickness of the insulation level*

Originally, 14-cm insulation layer was used in building construction. After providing the building simulation with the inner construction layer and HWST set based on the reference value and variable insulation thickness in increments of 2 cm from 8 cm to 20 cm, the following figure was received (Fig.12).

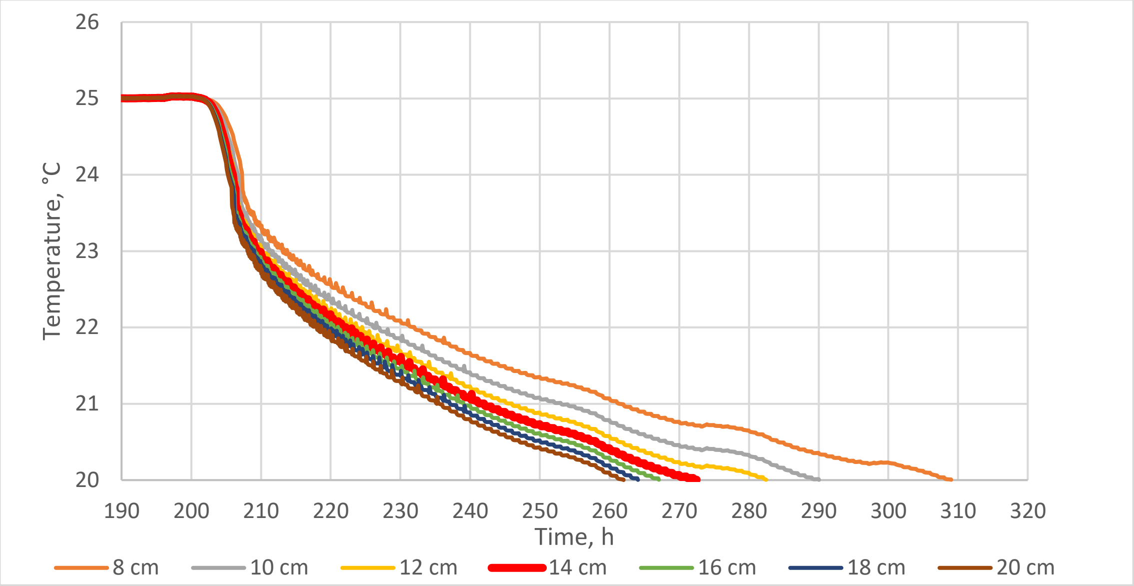

Figure 12: Dependence of the insulation thickness on the cooling-down time of the room

Compared to Figure 10, in the left part of the chart all curves begin to fall at the same speed and tilt angle, which can be explained by the presence of the same hot water storage tank. The use of insulation material 8 cm leads to a 33% increase in time, while the increase the thickness of insulation at 20 cm reduces the duration by 15% from reference value.

c) *Variable thickness of the inner material*

In order to assess the dependence of the thickness of the external wall inner material on the load shifting ability, the figure below was obtained in Simulation Studio (Figure 13).

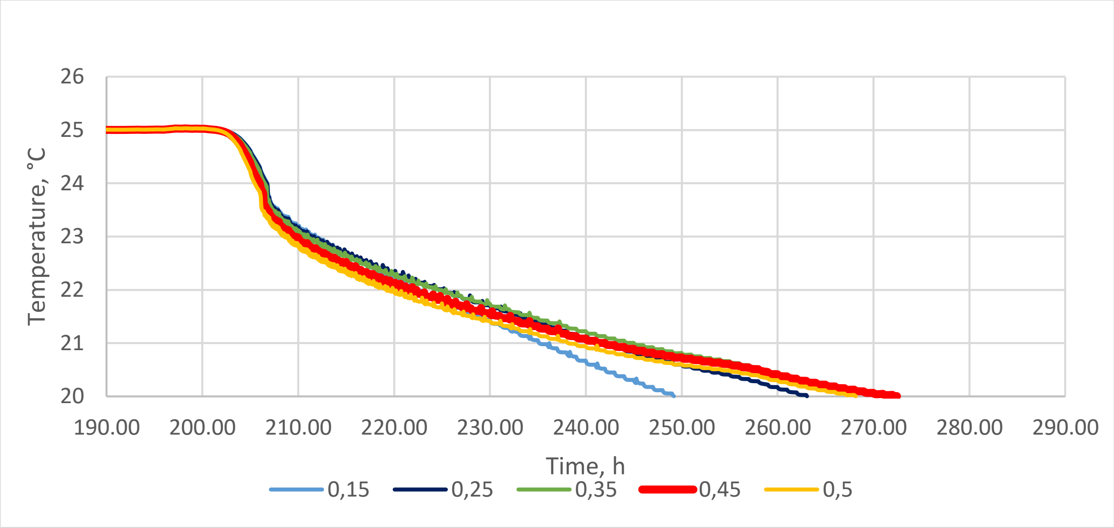

Figure 13 Dependence of the inner material thickness on the cooling-down time of the room

As it can be seen from the graph, longer period of cooling-down time can be observed for building with higher thickness of the inner material of external walls. Minimal difference can be seen for thicknesses above 0.25m. This can be explained by the fact that only limited so-called effective thermal capacity of the inner wall is able to interact with the air in zone. Increasing the thickness of the wall above certain limit does not improve the storage capability. As the thickness of the wall decreases, the duration drops faster and faster.

II.5.2.3 Second experiment

The need to consider the impact of the hot water tank size, insulation thickness and wall internal material for all 3 scenarios leads to 21 necessary simulations. Compared to the reference designed values of the basic parameters, the values in both directions - greater and lesser - were considered in this experiment. The simulation plan for the second experiment can be seen on the Table 11. For all of the three scenarios with or without HDO signal applying discomfort hours were calculated for 3 different variants of variable parameter. Likewise, since comfort level is important only while residents are in the house, non-occupied hours were calculated and subtracted from the total discomfort hours. Moreover, for each case bill was calculated depending on the total energy demand.

Table 11: Simulation plan of the second experiment

Case	Varied Parameter	Total discomfort hours, h	Non-occupied hours, h	Final discomfort hours, h	Bill, Euro
TEMP	170	2	0	2	990
	500	3	0	3	979
	1000	5	0	5	1024
HDO	170	1498	555	943	717
	500	1605	588	1017	752
	1000	1645	604	1041	719
HDO + TEMP	170	165	81	84	713
	500	220	86	134	722
	1000	216	91	125	738
TEMP	8cm	18	0	18	1091
	14cm	3	0	3	979
	18cm	3	0	3	987
HDO	8cm	2159	740	1419	770
	14cm	1605	588	1017	753
	18cm	1305	477	828	719
HDO + TEMP	8cm	342	139	203	784
	14cm	220	86	134	722
	18cm	160	79	81	726
TEMP	0,15m	3	0	3	1024
	0,25m	3	0	3	1023
	0,45m	3	0	3	979
HDO	0,15m	1671	611	1060	752
	0,25m	1658	615	1043	744
	0,45m	1605	588	1017	753
HDO + TEMP	0,15m	223	100	123	748
	0,25m	220	90	130	749
	0,45m	220	86	134	722

a) Variable size of the hot water tank

It was decided to use the smallest hot storage tank from the range suggested by manufacture and the tank 2 times bigger then the reference one. The results of simulation of the system with variable volume of the hot water storage tank is presented in the figure 14, where bar-charts demonstrates electricity bill and lines illustrates the discomfort hours.

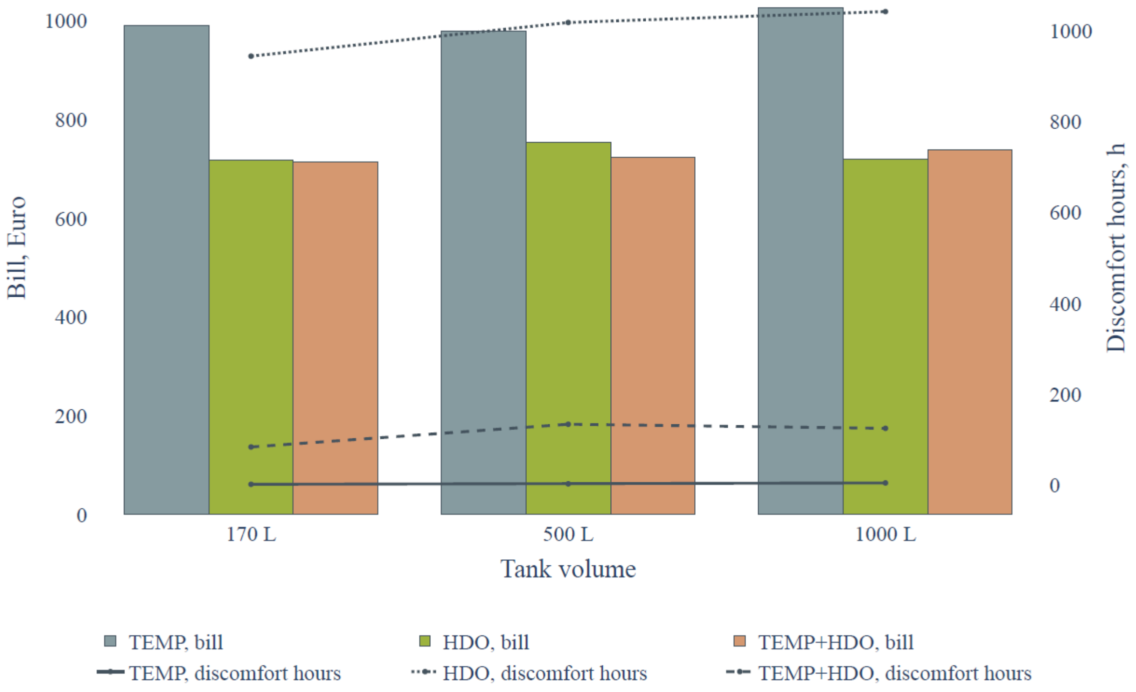

Figure 14: Second experiment result for varied size of the tank

As it can be seen from the graph, discomfort hours using HDO is vastly exceeds the value of the case when the temperature control only is applied, amounting slightly more than thousand hours over the year for the former in contrast to the latter one. Consequently, the need for temperature regulation is obvious when using the HDO. Applying of the temperature regulation allows to decrease the amount of discomfort hours on approximately 90% for each of the tank sizes. Three discomfort hours for TEMP case can be explained by using of 15 degrees initial temperature.

Regarding the electricity bill, the bar-chart shows the opposite trend. For 500-l water tank difference between the cases with and without HDO amounts 23%. Using mass remote control with 1000l tank allows to save about 30% of the electricity cost. Bill of both HDO cases: with or without temperature regulation demonstrates almost the same results for each size of the tank.

b) Variable thickness of the insulation

The next varied parameter is insulation level. It can be seen on the following Fig. 15, that thickness of the insulation influence more on the discomfort hours in comparison with the scenario a), accounting 828 discomfort hours for 18-cm insulation and 1419 for the 8-cm one. Decreasing of the insulation from 14 to 8 cm leads to increase of amount of discomfort hours an almost 1.5 times, using the HDO switch. At the same time, the significant difference can be observed for 8-cm insulation case in electricity bill. Applying HDO allows to save about 30% of cost comparing to 23% for the designed 14 cm.

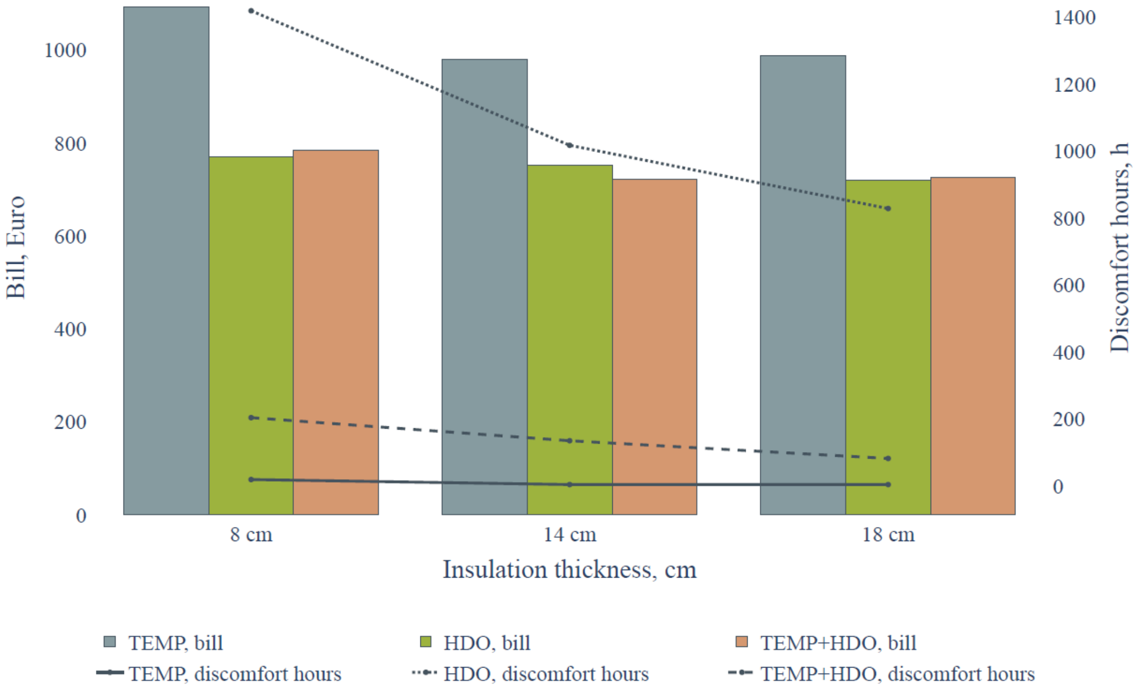

Figure 15: Second experiment result for varied thickness of insulation

In general, the need for HDO temperature regulation is obvious as well. Applying this regulation allows to tend the amount of discomfort hours for 18-cm EPS insulation case to almost the reference value of comfort.

c) Variable thickness of the inner material

Since according to the first experiment, thickness of the concrete layer comprising more than 0.45 m does not have a great influence on the flexibility potential, two sized less than designed one were taken into consideration. Anyway, there is almost no impact on the discomfort hours depending on concrete thickness (Fig.16). The amount of the discomfort hours using the mass remote control amounts roughly 1000 h and it can be decreased up to 120-130 h by using the temperature regulation as well. Increasing of the wall thickness leads to less spending however the savings by applying the HDO control is 4% more for the thinner wall.

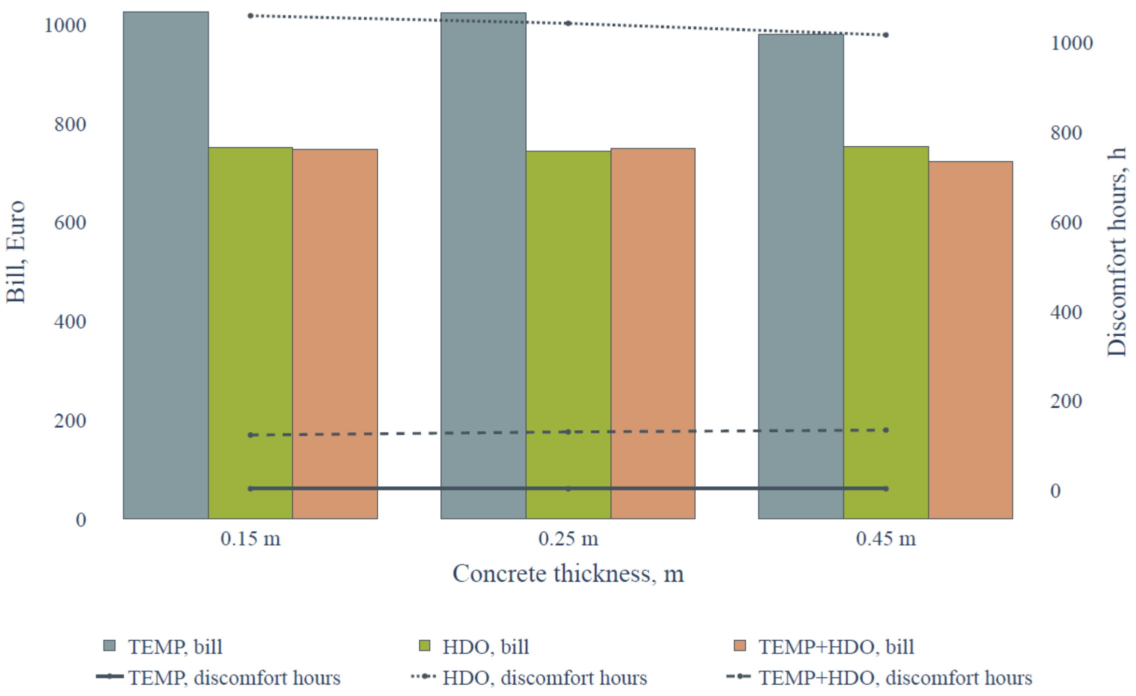

Figure 16 Second experiment result for varied thickness of inner material of the wall

After the second experiment, the benefits of using mass remote control with temperature regulation for thermal comfort ensuring became apparent. The following 3 graphs show the changes in comfort hours and electricity costs for all 3 variable parameters, but for the second category of thermal comfort according to EN Standard 14241 2007, which means room temperature in the range from 20 to 26 degrees.

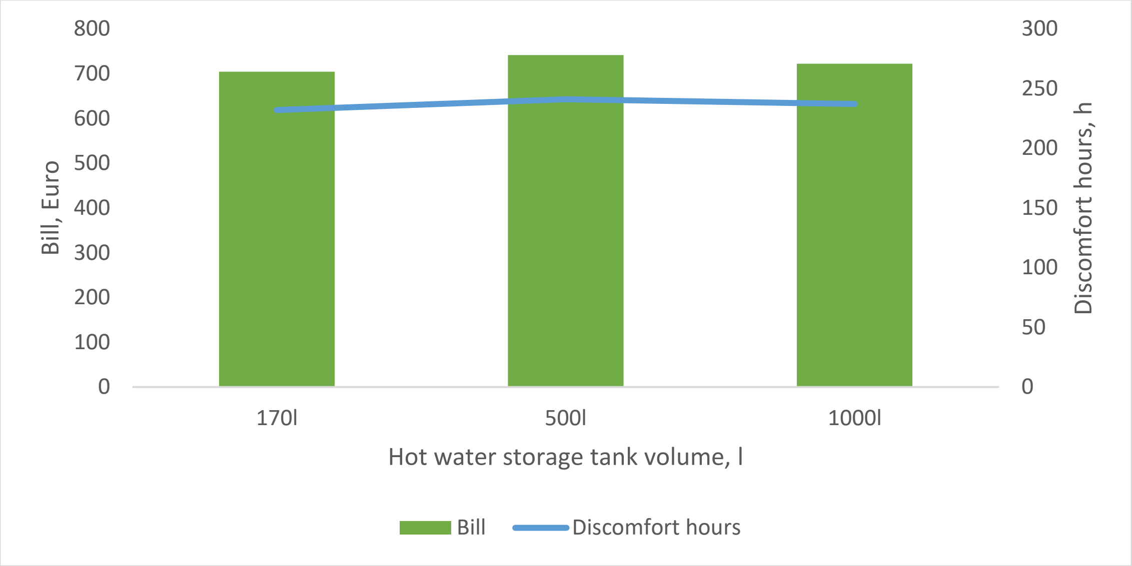

Figure 17: HDO + Temperature regulation control for varied size of the tank and II category of thermal comfort

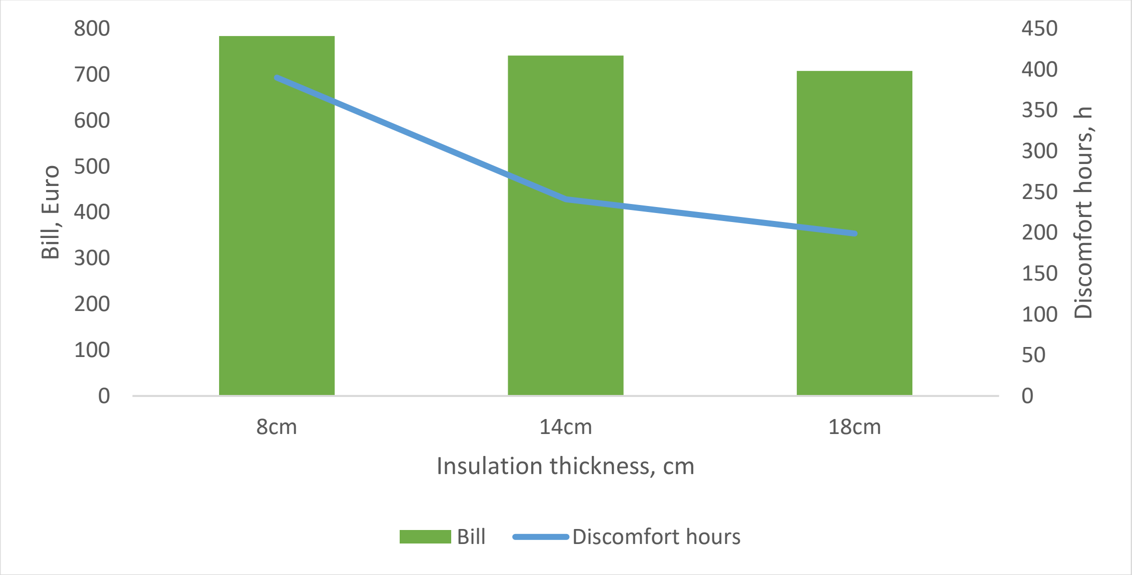

Figure 18: HDO + Temperature regulation control for varied insulation thickness and II category of thermal comfort

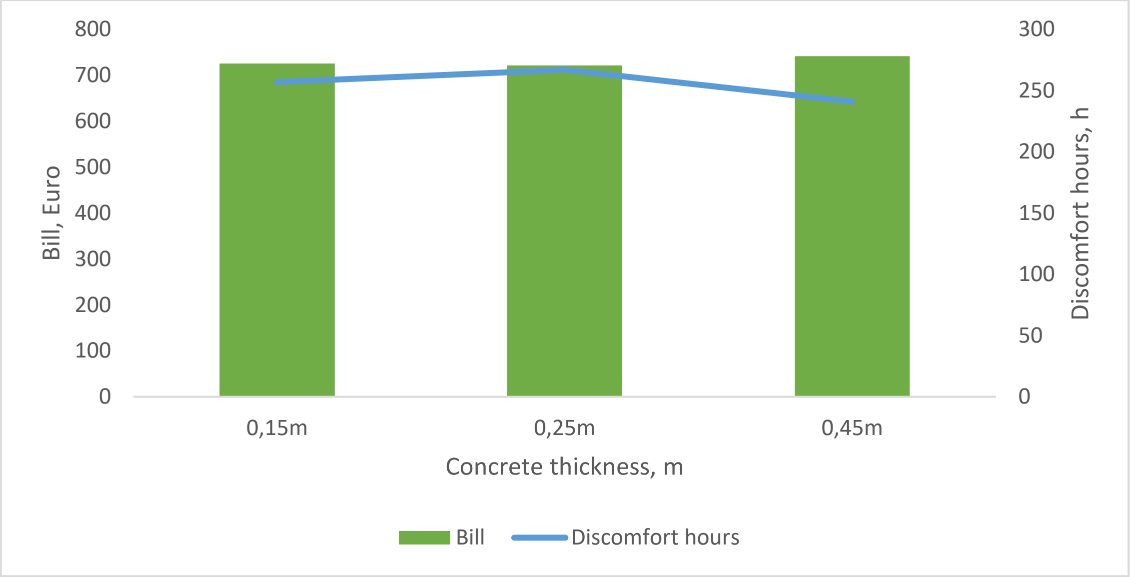

Figure 19: HDO + Temperature regulation control for varied inner material thickness and II category of thermal comfort

According to obtained charts, if it is necessary to maintain the temperature in the living room at least 20 degrees Celsius, there is approximately 2 times more discomfort hours than in the previous case with the lower limit of the acceptable temperature range - 18 degrees. Again, the poor insulation of the house leads to the longest uncomfortable occupied period and the to the highest total demand, which means the highest electricity cost as well. However, in general, electricity bill comprises 1-3% less than when III category of thermal comfort is met.

II.6 Discussion

To determine the energy flexibility potential for a 2-storey residential building located in Czech Republic, two experiments were conducted. The purpose of the first of them was to find out the building capacity without disturbing the thermal comfort conditions, taking into consideration zero ambient temperature, radiation and internal gains. During this experiment the step function was applied to the supply side of the heating system, and the cooling-down time for the range from 25 to 20 degrees in the room was determined for 3 different variable parameters: the size of the hot water tank, thickness of the insulation material and the inner material of the wall.

The result shows for the first theoretical experiment that using the water storage tank allows to stay within the range of thermal comfort after turning off the heating from 68 hours for small devices to 91 hours for huge tanks. At the same time, the contribution of the tank in this delayed operation time varies from 3 to 21 hours respectively. However, in practice, storage tanks of more than 1000 liters are rarely used for residential buildings, so the cooling time can be expected to be no longer than 12 hours.

The results of simulations with varying insulation levels show that reduction of the thickness of the insulation material leads to significant rise of the time constant. This can be explained by the fact that as the insulation thickness decreases, the thermal resistance decreases as well, which means increasing of the heat flux and consequently more heat can be stored in the inner walls. Otherwise, increasing the insulation level reduces heat loss and thus the potential for energy storage. Thus, a well-insulated building with 20 cm EPS can provide about 50 hours shorter cooling time than the same building with 8 cm insulation material, which amounts to as much as 109 hours.

With an increase in effective thermal capacity or in other words, the thickness of the inner material of the house structure, there can be observed a longer cooling period. In this experiment, different thicknesses of concrete external walls in the range from 0.05m to 0.5m were compared. As it follows from the obtained graph (Fig. 13), starting with a concrete thickness of 0.035 m and more, the time constant is almost the same, as only a fraction of the thickness of such a large wall can be used for an effective thermal storage. Therefore, for further experiments the wall dimensions of 0.15 m and 0.25 m were chosen, as the entire thickness can be effectively used as a thermal capacity in this case, and such dimensions meet the standards of modern buildings.

In general, as a result of the first theoretical experiment at a constant zero ambient temperature, it became clear that the developed house with a heating system connected to the hot water storage tank can demonstrate an average of 3 days of operation without disturbing the comfort range of temperatures after turning off the heating, if the storage tank and inner mass is charged at level 55°C and 25°C, respectively. A reduction in insulation material thickness can provide the longest cooling time, while a reduction in concrete thickness results in the shortest cooling-down duration. Despite the fact that the water tank itself can ensure only short-term accumulation of the heat it is important to install this storage unit to avoid the undue heat pump on/off cycling.

The purpose of the second experiment was to determine how the application of the demand response strategy will affect the level of comfort of the inhabitants of the house, taking into account internal gains and dynamically changing weather conditions. To evaluate the results obtained using HDO signal, year-round system simulations without DSM were also performed. The use of HDO can reduce the cost of electricity by an average of 20-25%. This value of the saved electric cost is consistent with another result of a study by R. Halygaard et al. [24], which states that the optimized operating strategy has saved 25-35% of the electric cost compared to operation at a constant price for electricity. However, about 12% of the time per year thermal comfort will be impaired and the room air temperature will be unacceptable. The poorly-insulated building demonstrates the largest number of uncomfortable hours, counting 1419 h in comparison with 828 h for well-insulated house. For buildings with different inner material thicknesses or various hot water tank sizes, no significant difference was observed, accounting on average about 1000 discomfort hours. Consequently, additional thermal regulation has been provided to reduce such an enormous discomfort level without compromising with the electricity bill. Buildings with higher thermal inertia better maintain comfort level.

III. Conclusion

The work, as it was stated earlier, conducted the analysis of an energy flexibility of the regular family house equipped with an air-to-water heat pump and storage tank. The assessment of the potential was made based on the analysis of the simulation made in TRNSYS software in regard to the climate conditions of the Czech Republic. The influence of an individual building components such as building structure and storage tank was estimated by analyzing 18 different cases for time constant boundary conditions, including variating storage tank volume, insulation thickness, inner material thickness and a reference frame. The results have shown a significant impact of the thermal inertia on building time constant. The higher the thermal mass, the more heat can be stored by the wall and thus the greater the load shifting ability. However, after a thickness of the concrete slub of 0.45m, the increase in cooling time stops as only a fraction of the thickness of the inner material works for efficient heat storage. The increase in the insulation material level had the most significant effect on the duration of cooling down process, reaching almost 5 days of operation in a comfortable heat range after the heat pump is switched off. Nevertheless, in average, it was required about 72 hours for system to reach the set 20 degrees.

The aim of the provided analysis with dynamically changed weather conditions was to determine the influence of a demand response strategy applied for shifting the energy consumption from high-cost to low-cost periods by switching off the heat pump according to HDO signal on the performance of the heating system and thermal comfort of the inhabitants. According to the results, using HDO switching allows to reduce electricity demand of the HP on 25% in average. However, since switching the heat source on and off with a price as the main driver leads to a significant disturbance in thermal comfort, the temperature feedback had to be set. The control based on HDO with temperature feedback does not limit the savings potential but can reduce significantly the number of discomfort hours.

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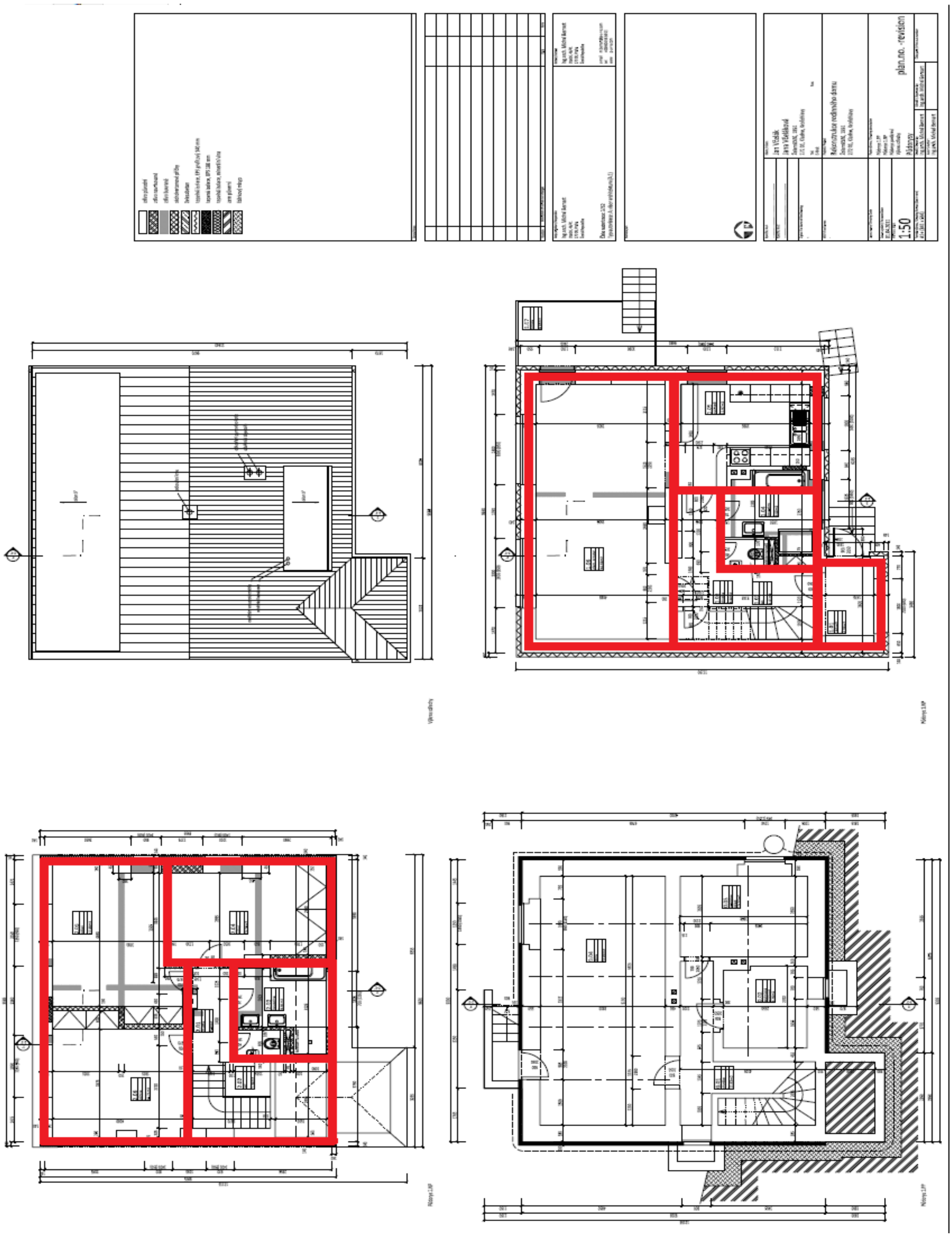
Appendices

Appendix A



Appendix B

Splitové tepelné čerpadlo vzduch/voda

VITOCAL 200-S

Vitocal 200-S	Typ	AWB-M / AWB-M-E-AC				AWB / AWB-E-AC		
		201.D04	201.D06	201.D8	201.D010	201.D10	201.D13	201.D16
Napětí	V	230	230	230	230	400	400	400
Údaje o výkonu k vytápění								
(podle ČSN EN 14511, A2/W35)	kW	2,6	3,1	4,0	5,0	5,9	6,3	7,0
Výkonové číslo ε (COP) topný provoz		3,6	3,7	4,0	4,0	4,1	4,0	3,9
Regulace výkonu	kW	2,0–4,1	2,4–5,5	2,8–7,0	4,4–9,6	4,4–10,1	4,8–10,6	5,2–11,2
Údaje o výkonu k vytápění								
(podle ČSN EN 14511, A7/W35, tepl. rozpětí 5 K)	kW	4,0	4,8	5,6	7,0	7,6	8,6	10,1
Výkonové číslo ε (COP) topný provoz		4,6	4,6	4,7	4,7	5,0	4,9	5,0
Regulace výkonu	kW	2,4–4,2	3,0–6,3	3,5–7,5	5,5–12,6	5,5–12,6	5,9–13,7	6,4–14,7
Údaje o výkonu k vytápění								
(podle ČSN EN 14511, A–7/W35, tepl. rozpětí 5 K)	kW	3,8	5,5	6,7	8,7	10,1	10,7	11,6
Výkonové číslo ε (COP) topný provoz		2,9	2,8	2,9	3,1	3,2	3,0	3,0
Údaje o výkonu k chlazení								
(podle ČSN EN 14511, A35/W18)								
Jmenovitý chladicí výkon	kW	4,0	5,0	6,0	7,0	7,0	8,2	9,2
Výkonové číslo (EER) chladicí provoz		4,2	4,2	4,1	4,2	4,0	3,9	3,8
Chladicí okruh								
Chladivo		R410A	R410A	R410A	R410A	R410A	R410A	R410A
– plnicí množství	kg	1,8	1,8	2,39	3,6	3,6	3,6	3,6
– skleníkový potenciál (GWP) [1]		1924	1924	1924	1924	1924	1924	1924
– CO_2 ekvivalent	t	3,5	3,5	4,6	6,9	6,9	6,9	6,9
Rozměry vnitřní jednotky								
délka (hloubka) x šířka x výška	mm	370 x 450 x 880						
Rozměry venkovní jednotky								
délka (hloubka)	mm	546	546	546	546	546	546	546
šířka	mm	1109	1109	1109	1109	1109	1109	1109
výška	mm	753	753	753	1377	1377	1377	1377
Hmotnost vnitřní jednotky	kg	44	44	44	45	45	45	45
Hmotnost venkovní jednotky	kg	94	94	99	137	148	148	148
Třída energetické účinnosti*	▮	A^{++} / A^{+}	A^{++} / A^{++}	A^{++} / A^{++}	A^{++} / A^{++}	A^{++} / A^{++}	A^{++} / A^{++}	A^{++} / A^{++}

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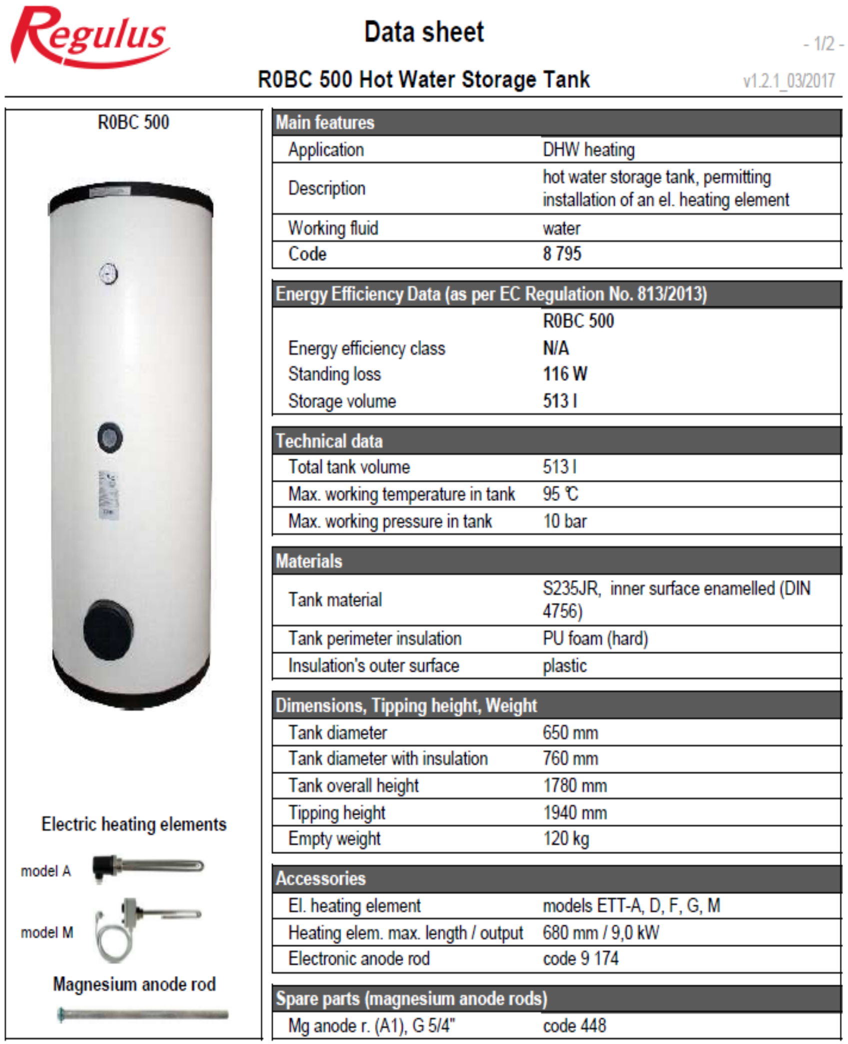
[1] Třída energetické účinnosti podle zařízení EU č. 813/2013 vytápění, průměrné klimatické poměry – Použití nízké teploty (W35)/ použití průměrné teploty (W55).

* Vychází z 5. znalecké zprávy mezistátního výboru pro klimatické změny (IPCC). V ČR zatím platí hodnota 2088.

Appendix C



Regulus

Data sheet

- 1/2 -

R0BC 500 Hot Water Storage Tank

v1.2.1_03/2017

R0BC 500

Main features	
Application	DHW heating
Description	hot water storage tank, permitting installation of an el. heating element
Working fluid	water
Code	8 795

Energy Efficiency Data (as per EC Regulation No. 813/2013)	
	R0BC 500
Energy efficiency class	N/A
Standing loss	116 W
Storage volume	513 l

Technical data	
Total tank volume	513 l
Max. working temperature in tank	95 °C
Max. working pressure in tank	10 bar

Materials	
Tank material	S235JR, inner surface enamelled (DIN 4756)
Tank perimeter insulation	PU foam (hard)
Insulation's outer surface	plastic

Dimensions, Tipping height, Weight	
Tank diameter	650 mm
Tank diameter with insulation	760 mm
Tank overall height	1780 mm
Tipping height	1940 mm
Empty weight	120 kg

Accessories	
El. heating element	models ETT-A, D, F, G, M
Heating elem. max. length / output	680 mm / 9,0 kW
Electronic anode rod	code 9 174

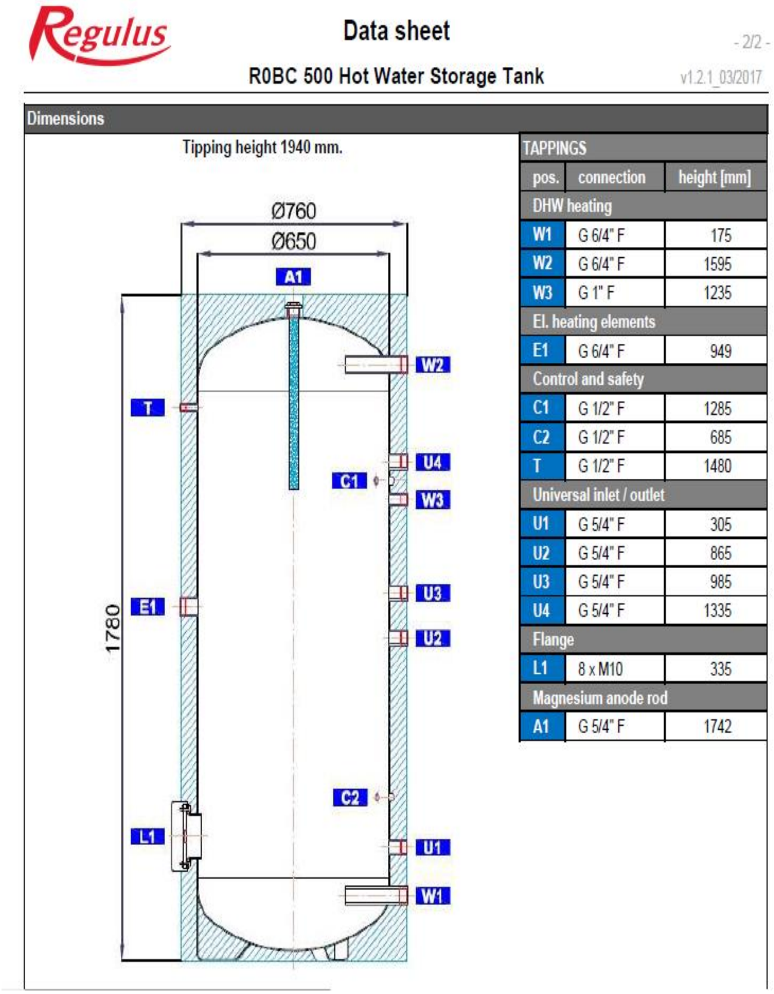
Spare parts (magnesium anode rods)	
Mg anode r. (A1), G 5/4"	code 448

Electric heating elements

model A

model M

Magnesium anode rod



Regulus

Data sheet

- 2/2 -

R0BC 500 Hot Water Storage Tank

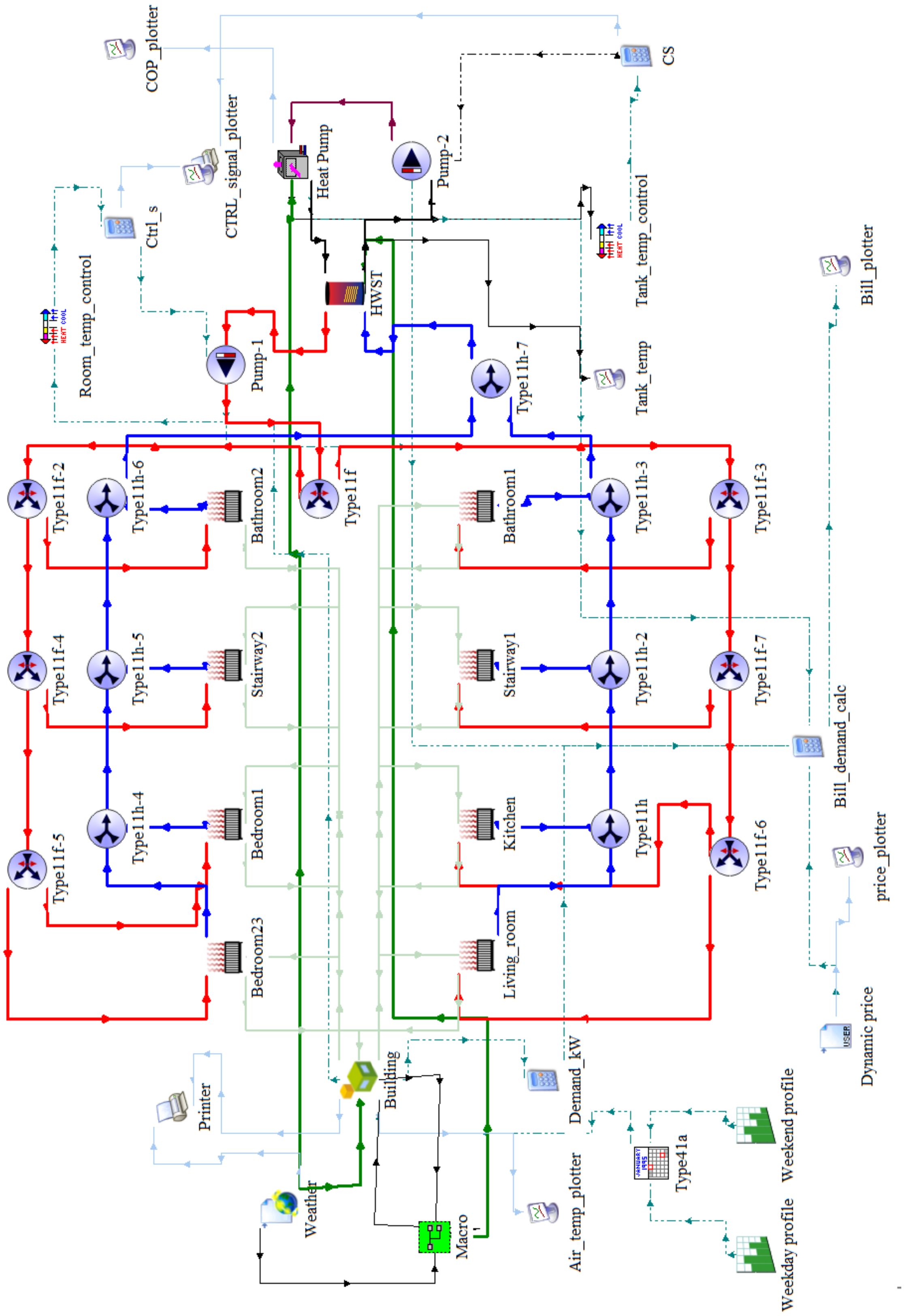
v1.2.1_03/2017

Dimensions

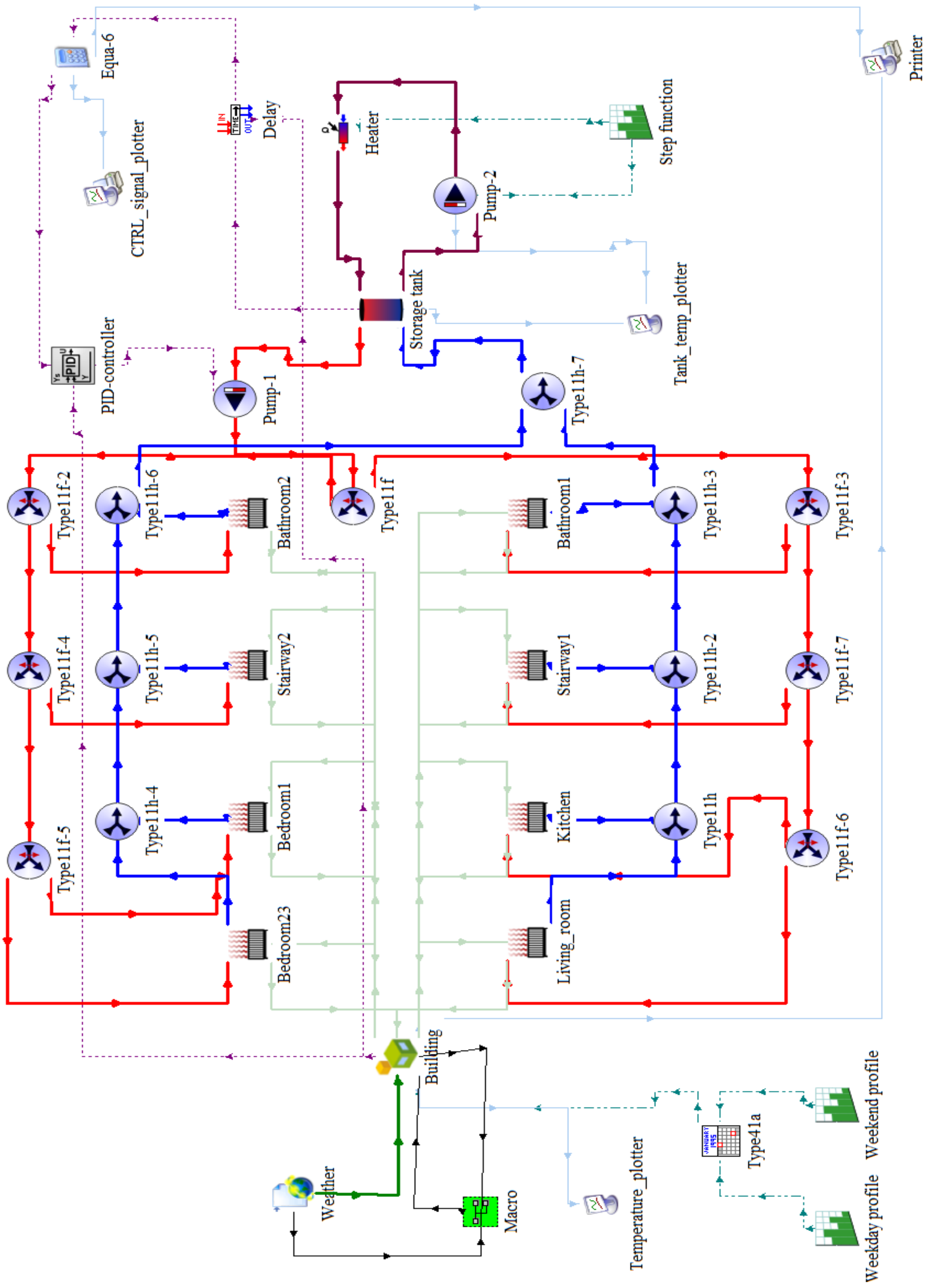
Tipping height 1940 mm.

TAPPINGS		
pos.	connection	height [mm]
DHW heating		
W1	G 6/4" F	175
W2	G 6/4" F	1595
W3	G 1" F	1235
El. heating elements		
E1	G 6/4" F	949
Control and safety		
C1	G 1/2" F	1285
C2	G 1/2" F	685
T	G 1/2" F	1480
Universal inlet / outlet		
U1	G 5/4" F	305
U2	G 5/4" F	865
U3	G 5/4" F	985
U4	G 5/4" F	1335
Flange		
L1	8 x M10	335
Magnesium anode rod		
A1	G 5/4" F	1742

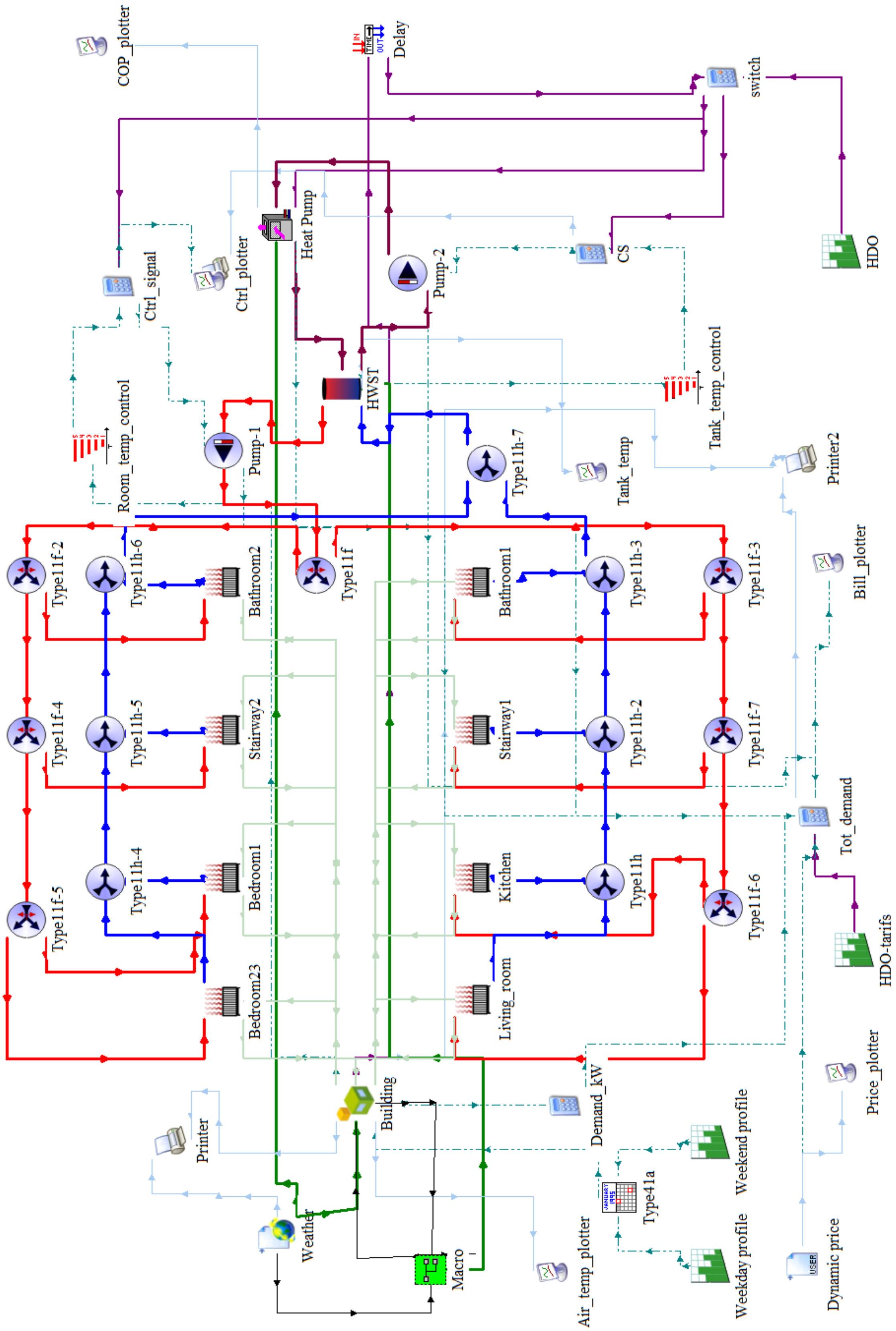
Appendix D


COP_plotter
CTRL_signal_plotter
Heat Pump
Pump-2
CS
Ctrl_s
Room_temp_control
HEAT COOL
Pump-1
HWST
Tank_temp_control
HEAT COOL
Type11h-7
Tank_temp
Bill_plotter
Type11f-2
Type11h-6
Bathroom2
Type11f
Bathroom1
Type11h-3
Type11f-3
Type11f-4
Type11h-5
Stairway2
Stairway1
Type11h-2
Type11f-7
Bill_demand_calc
Type11f-5
Type11h-4
Bedroom1
Kitchen
Type11h
Type11f-6
price_plotter
Bedroom23
Living_room
Dynamic price
Printer
Building
Demand_kW
Weekend profile
Weather
Macro
Air_temp_plotter
Type41a
Weekday profile

Appendix E


Equa-6
CTRL_signal_plotter
Delay
Heater
Step function
Printer
Pump-2
Storage tank
Tank_temp_plotter
PID-controller
Pump-1
Type11h-7
Type11f-2
Type11h-6
Bathroom2
Type11f
Bathroom1
Type11h-3
Type11f-3
Type11f-4
Type11h-5
Stairway2
Stairway1
Type11h-2
Type11f-7
Type11f-5
Type11h-4
Bedroom1
Kitchen
Type11h
Type11f-6
Bedroom23
Living_room
Building
Weather
Macro
Temperature_plotter
Type41a
Weekend profile
Weekday profile

Appendix F


COP_plotter
Delay
switch
Heat Pump
Ctrl_signal
Ctrl_plotter
Pump-2
CS
HDO
Room_temp_control
Pump-1
HWST
Tank_temp_control
Type11h-7
Tank_temp
Printer2
Type11f-2
Type11h-6
Bathroom2
Type11f
Bathroom1
Type11h-3
Type11f-3
Bill_plotter
Type11f-4
Type11h-5
Stairway2
Stairway1
Type11h-2
Type11f-7
Tot_demand
Type11f-5
Type11h-4
Bedroom1
Kitchen
Type11h
Type11f-6
HDO-tarifs
Bedroom23
Living_room
Price_plotter
Printer
Building
Demand_kW
Weekend profile
Type41a
Weather
Macro
Air_temp_plotter
Weekday profile
Dynamic price