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RESIDENTIAL DEMAND RESPONSE STRATEGIES

Master of Science thesis

Examiner: Prof. Sami Repo
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ABSTRACT

KONSTANTIN PANDAKOV: Residential Demand Response strategies
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Nowadays Demand Response (DR) in Finland is market based, and such approach as controlling of domestic loads by a special type of a controller is developing. It would allow excluding of a human segment from a connection between the system operator and loads, as well as to perform automation processes in the fastest and the most efficient way. Hence, one of the possible implementations of DR is becoming direct control of domestic loads.

Thus, the primary aim of this thesis is studying of DR opportunities for a conventional detached house. Another important purpose is to find ways of power consumption peaks clipping that have negative impact on a power network. It is also necessary to reveal actions for decreasing of pay - back energy consumption peaks. Finally, intention behind the paper is to provide information for future works.

In this work efficiency of DR actions is measured in terms of saved energy harvested from a specific DR event. For these aims a thermodynamic model of a house and models of electrical appliances have been built. Further, various DR programs (shut off, preheating, temperature settings diversification) and strategies associated with them are probated by the means of these models. The main limitation here is preserving comfort living conditions inside the house.

The results of the research method above allow to obtain necessary values of saved energy and power for different tests. Moreover, the most suitable strategies of equipment controlling have been detected, especially in minimization of pay - back power peaks point of view. Finally, utilization of such models in energy management has been determined.

In conclusion the main findings of the given thesis and their meanings are presented. Furthermore, points for further application of the achieved results have been given.

PREFACE

DR is an essential part of Smart Grid solution because it gives many benefits and for a customer of electrical energy and for a supplier. This strategy implies managing of customer consumption according to supply circumstances in order to use electrical energy more efficiently and to utilize existing power networks with higher coefficients of performance. Primarily it helps to decrease expenditures of power production and negative influence on the environment.

In this study the potentials of DR strategies applied for a detached house has been investigated. DR programs are implemented through various actions applied for domestic equipment, namely cooling and heating appliances as the most energy demanding electrical loads inside the house and the most suitable for direct control, results of which do not affect too much inhabitants.

I would like to start with acknowledging my supervisor Sami Repo who gave me opportunity to start this work as the Master Thesis job. Moreover, he made this thesis possible and has also given me much support. Additionally, I thank so much for help of Doctoral Student of the Electrical Engineering Department Antti Rautiainen who provided me necessary information for modeling. Further, I would like to thank all people working in the Department of Electrical Engineering in TUT who interacted with me and created encouraging environment.

Tampere, 3.12.2014

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LIST OF ABBREVIATIONS AND SYMBOLS

AH	Air Heater
AHP	Air Heat Pump
C	Cost
CHEX	Coil Heat Exchanger
CHS	Central Heating System
COP	Coefficient of Performance
DHW	Domestic Hot water
DR	Demand Response
GHP	Ground Heat Pump
HA	Home Automation
HAN	Home Area Network
HEMS	Home Energy Management System
MP	Microprocessor
NAN	Neighborhood Area Network
SC	Solar collector
WAC	Water Accumulator Tank
WAN	Wide Area Network

α	absorptivity, unitless
δ	width, m
η	coefficient of efficiency, unitless
λ	coefficient of heat conductivity, $\frac{\mathrm{W}}{\mathrm{m \cdot K}}$
ρ	density, $\frac{\mathrm{kg}}{\mathrm{m}^3}$
τ	transmittance, unitless
A	area, m^2
C	thermal capacitance, $\frac{\mathrm{J}}{\mathrm{m^2 \cdot K}}$
c	specific heat capacity, $\frac{\mathrm{J}}{\mathrm{kg \cdot K}}$
D	diameter, m
E	electrical energy, Wh
$\dot{E}$	electrical power, W
F	heat removal factor, unitless
G	global incident solar irradiation, $\frac{\mathrm{W}}{\mathrm{m}^2}$
h	enthalpy, $\frac{\mathrm{J}}{\mathrm{kg}}$
$\mathbb{K}$	matrix of coefficients
K	coefficient, unitless
$\dot{m}$	flow, $\frac{\mathrm{kg}}{\mathrm{s}}$

N	amount, unitless
P	heat or electrical power, W
Q	heat flow, $\frac{\mathrm{W}}{\mathrm{m}^2}$
q	flow, $\frac{\mathrm{m}^3}{\mathrm{s}}$
R	thermal resistance, $\frac{\mathrm{m}^2\cdot\mathrm{K}}{\mathrm{W}}$
T	temperature, ^{0}C
U	heat loss coefficient, $\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}$
V	volume, m^3
$\mathbb{W}$	matrix of input variables
w	input variable
x	linear dimension, m
$\mathbb{Y}$	matrix of output variables
y	output variable

1. INTRODUCTION

Nowadays energy used by mankind is gradually rising, cost of production increases and unsustainable usage affects the environment. It is obvious that the most appropriate solution is saving in any field which able to minimize useless losses of energy. Efficient use of electric energy causes decreasing of fuel consumption and costs for its delivery, reduction of investments needed for electricity production and distribution, shrinkage of building new power grids and other consequences that have positive influence on maintaining of necessary environmental equilibrium. Moreover, this concept helps to increase quality of electrical energy and safety of its consumption.

Modern energy efficient technologies are improved or completely new processes, and one of these actions is Demand Response (DR). DR is not directly an energy efficient measure because it depicts mechanisms to manage a demand of electrical energy in compliance with the power system constraints and supply conditions [1]. In other words, DR changes a shape of a demand curve (Figure 1.1 [1]) providing different services such as load shifting, valley filling and peak clipping.

The main benefits of these actions are [2]:

- Facilitating of consumer choice by the means of creating a wide set of electrical products and services;
- Management of consumer loading allowing to remain total consumption with connection of new appliances within existing household capacity;
- Optimization of investments in power grids;
- Avoiding regional and national network congestion, and providing fault based network services;
- Balance generation at national level through reserve or response services;
- Balance the trading position of energy suppliers;
- Future flexibility allowing covering of forthcoming demands;

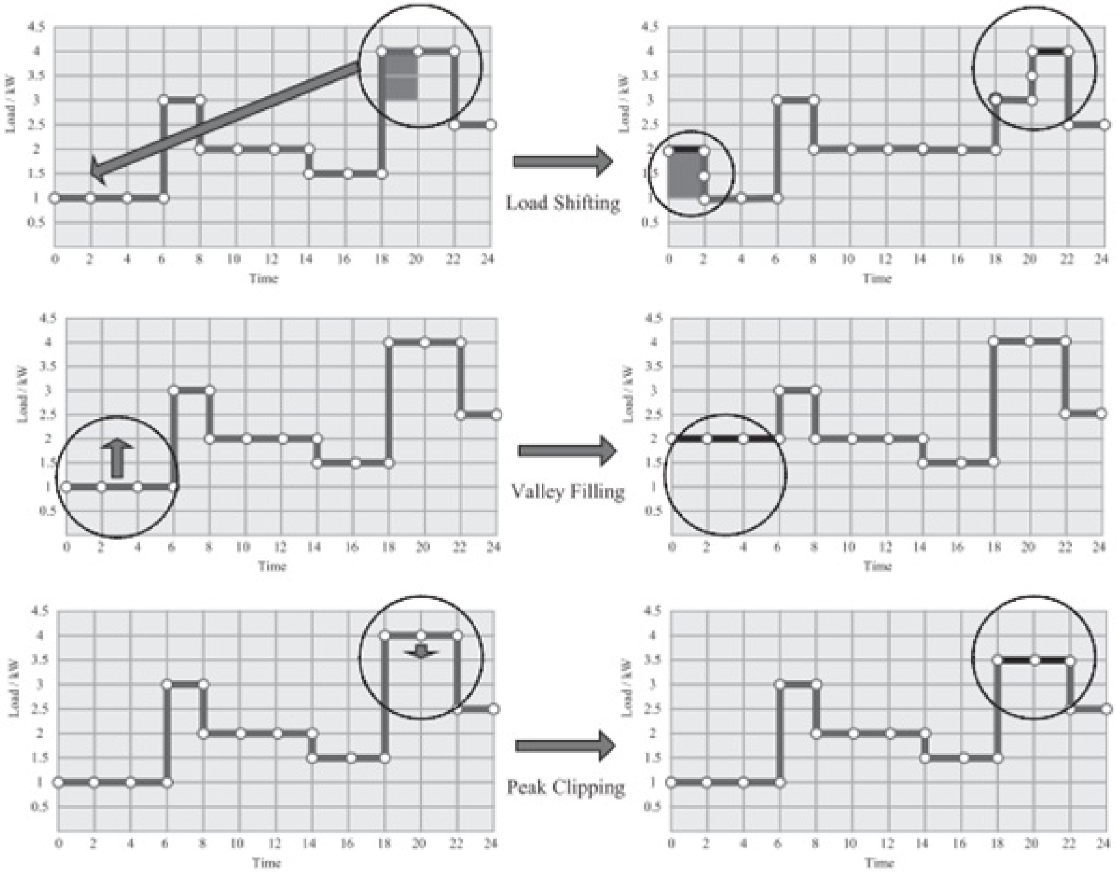

Figure 1.1 *The DR services.*

- Foregoing environmental and efficiency issues.

There are several approaches to implement DR based on retail energy pricing and/or incentive structure [1]:

- Price - Based Demand Response: Time of Use, Real - Time Pricing and Critical Peak Pricing;
- Incentive - Based Demand Response: Direct load control, Interruptible service, Buy - back programs, Emergency and Capacity market programs, Ancillary services market program.

Much research work on almost all of these methods has been done and currently they function in real life; therefore, their study is out of the scope of the present paper and they are not considered explicitly. For several years great effort has been devoted to the study of possibilities of DR for households. Nowadays it is possible to find great opportunities in this field for demand response programs because level of electrical energy consumption, among other energy sources as can be seen from Table 1.1 [3], is more than 30%. Without doubt it is the most spread consumer of electrical energy.

Table 1.1 *Energy consumption (GWh) in households by energy source in Finland 2012.*

Wood	**Peat, Coal**	**Heavy, Light fuel oil**	**Natural gas**	**Ambient energy**[1]	**District heat**	**Electricity**	**Total**
15462	62	5047	387	4138	19346	22240	66682

1. Ambient energy is delivered through special types of heat pumps.

Typically the following domestic appliances are considered as the most appropriate loads for demand response programs:

- Electric space heating (electric radiators, supplementary heaters);
- Electric water heaters (boilers);
- Electric floor heating;
- Heat pumps (air/air, air/water, ground/water);
- Ventilation systems with electric heaters;
- Fridges/freezers;
- Electrical vehicles;
- Car preheating system;
- Washing machines;
- Drying appliances;
- Electric stoves (saunas).

These appliances are of interest because some of them have variable speed drives (washers and dryers) and are capable of adjusting their power consumption levels. Other do not require power immediately (stoves) and can have their operation shifted to off - peak hours when a power demand is at the lowest level. Loads that provide hot water in dwellings and maintain desired temperature (boilers, heat pumps, ventilation systems and cooling appliances) can be shut down for extended periods of time while having minimal impact on comfort of inhabitants. Furthermore, power consumption of these appliances in detached houses with electric heating according

Table 1.2 *Power consumption of domestic appliances in Finland 2006.*

Appliance	**Power consumption, GWh**	**Percentage from total**	**Importance for DR**
Indoor lighting	761	9.4%	Low
Cold appliances	335	4.1%	Medium
Entertainment appliances	190	2.4%	Low
Electric sauna	303	3.7%	Medium
Cooking appliances	141	1.7%	Low
Computers and related	77	1%	Low
Heating and air cooling	110	1.4%	High
Washing machines	105	1.3%	High
Floor heating	198	2.5%	High
Dish washers	77	1%	Medium
Car heating	96	1.2%	Medium
Outdoor lighting	29	0.4%	Low
Others	224	2.8%	
Electric heating of hot water	5435	67.3%	Very high
TOTAL	8081	100%	

to Table 1.2 [4] is comparatively high that gives solid opportunity for DR, especially in case of aggregation of dwellings.

The literature on DR in the residential sector (for example, [5], [6], [7], [8]) shows a variety of approaches to implement forming of desired load shaping affecting this equipment. Most of the work, such as [5] and [6], have the results obtained using the predicted and experimentally delivered load curves. Besides, efforts to describe customer behavior are done in order to find the best ways for DR programs realizations. Another approach is modeling of domestic equipment with thermodynamics of a house for the sake of delivering real - world scenarios of customer reaction on DR actions (see, for instance, [7], [8]).

In spite of this, limited attention has been given to the study of the appliances affecting indoor air and water temperature in multi room houses for different seasons of the year. Thus, for example, in [7] it is described only the water heater and the air cooling systems in the simple model of the house, whereas the air heating system was not considered. Work [8] showed a variety of equipment, and the model of power consumption prediction is studied. Nevertheless, heating and air cooling opportunities are described through the coefficient of performance which is deduced by empirical means.

State of the facts allows concluding that necessity in a simple and accurate model of a typical living house with heating/cooling systems is quite significant because it will help to solve the important task - analysis of DR opportunities for long term periods (the day - ahead market), and especially understanding how much energy can be unconsumed in a house in order to use it later to cover peaks or to fill valleys in a power demand profile. The main idea here is to detect thermodynamic behavior of a dwelling during DR actions and find limitations (time duration of a specific DR program) of these processes based on comfort conditions for inhabitants. The model gives also possibility to find means of governing of equipment by a DR - controller, response times and reaction of the object (a house). Furthermore, a sustainable model is a practical and safety tool which allows managing experiments in a fast and effortless way and to detect the most appropriate approaches for DR realizations.

To sum up the foregoing, the goal of this thesis is to analyze demand response potentials of typical residential loads in a dwelling. The main objectives of the study are the followings:

- Building the model of a house with air/water heating/cooling appliances in Matlab;
- The model validation;
- Studying of DR scenarios by the mean of the model;
- Finding the most appropriate cases and limitations;
- Determination an amount of energy which can be saved due to these actions.

The remainder of the paper is organized as follows sections: chapter 2 outlines theoretical basics of DR strategies, namely means of measurement of its efficiency; chapter 3 describes the thermodynamic model of a detached house and the models of electrical loads inside this house, as well as in this chapter verification of the proposed models is performed; experimental results of different DR actions are presented in chapter 4 that also contains analyses of them; possible application of the described model in energy management is considered in chapter 5; chapter 6 concludes the paper.

2. THEORETICAL BACKGROUND

Nowadays in Finland DR programs are basically based on the tariffs of electrical energy. At the same time, among different types of DR programs, the most promising and currently developing for residential and small commercial customers is the approach foreseeing combination of demand scheduling of controllable loads with home energy management. The last one is accomplished through so called HEMS (home energy management system) devices that control domestic electrical appliances (for example, an air conditioner, a water heater, space heating) according to predefined scenarios based on the tariffs changing a power consumption profile (Fig. 1.1).

During this initiative results of DR actions can be measured as a load reduction in quantity of power. Figure 2.1 illustrates this method as well as explains the term duration of a DR event. It is observable from Fig. 2.1 that a load reduction is subtraction of the baseline (an amount of energy which would be consumed without a DR action) and the actual use line (actually consumed energy in presence of a DR event) [9]. This approach of determination of saved energy (a subtraction is positive) is broadly used in chapter 4 with results as a measure of effectiveness of a DR event.

Event durations are determined with the help of the thermodynamic model of a house on the ground of a temperature drop (water or inner air) that determines comfort conditions inside a house for inhabitants. Temperature thresholds, determining a duration of a DR event, are governed by the air/water quality standards described in [10]. This time is split into the ramp period (decreasing of energy consumption right up to the actual level), the sustainable response period (shedding, curtailment or other regulating processes) and the recovery period (returning to the usual consumption level).

Here it is worth noting that power required for restoration of thermal characteristics might be even higher than power in absence of DR programs. This period is referred to as a pay - back period, and usually it takes place in the recovery period; during this event energy is consumed from a power network, that is subtraction of the curves in Fig. 2.1 will give a negative value. One of the minor objectives of this thesis is to find ways of minimization of energy consumption during the recovery

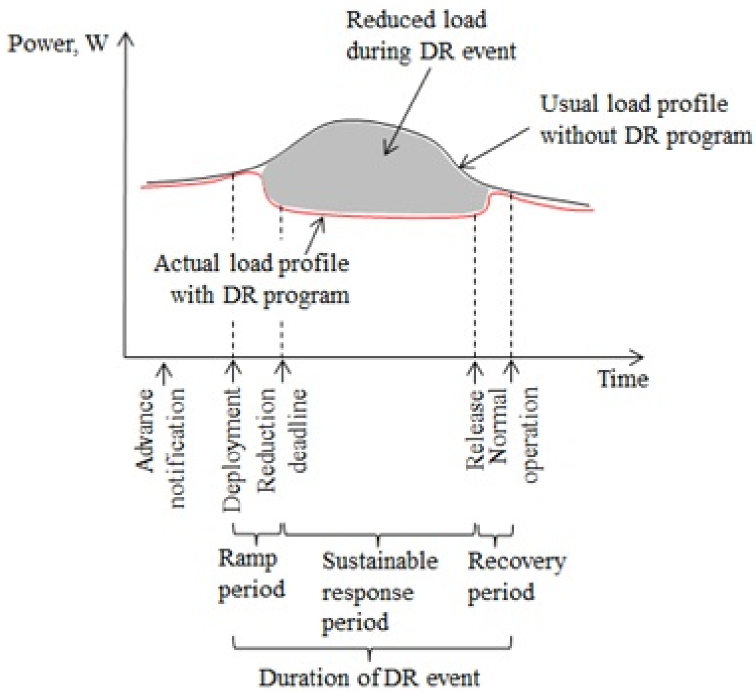

Figure 2.1 *DR measure and duration.*

period, and especially revealing strategies of its power peaks clipping.

Traditionally DR actions take place during a peak or off - peak of power consumption for the purpose of flattening of a load profile. The main tools for that are a shifting and curtailment algorithm the goal of which to minimize difference between the actual load profile and the objective curve set by the response program operator on the ground of price optimization. The current work does not concentrate attention on study of implementation of these algorithms (it can be found, for instance, in [5]), whereas determination of a DR potential of domestic appliances is of interest.

DR events managed during (off -) peaks are governed by different scenarios. One of examples is presented in [11] and includes: the setback strategy (only during peak hours), the preheat strategy (off - peak hours) and the power limitation strategy. All these strategies are applied for different places inside a house, times and settings of equipment. In this paper the similar scenarios are considered with extension of model possibilities: separate and collective participation of domestic appliances in DR events, a specific room control program, diversification of temperature settings, considering of ambient temperature and season changing, and other DR actions. In order to illustrate possible DR actions, the most typical heating/cooling equipment is considered and combined into the two groups - air heating/cooling and water heating as presented in Table 2.1. More detailed they are discussed in section 3.2

with modeling of heating/cooling equipment.

Table 2.1 *Equipment types.*

<table>
<tr><th>Type</th><th>Equipment</th><th>DR action</th><th>Season</th></tr>
<tr><td rowspan="4">Air heating/cooling</td><td>Electric or water based radiator</td><td rowspan="2">Shut off, diversification of temperature settings and preheating (or pre - cooling) for one, several (with different combinations, such as one by one, together etc.), all rooms</td><td>H[1]</td></tr>
<tr><td>Air/air heat pump (basically for cooling)</td><td>UH[2]</td></tr>
<tr><td>Floor heater (electric, water based)</td><td>The same for the places where the system is situated</td><td>All</td></tr>
<tr><td>Ventilation (electric or water based heating)</td><td>Shut off, changing of temperature settings affect all rooms inside the house</td><td>H</td></tr>
<tr><td rowspan="3">Water heating</td><td>WAC[3] with electric heaters</td><td rowspan="3">Shut off, diversification of temperature settings</td><td rowspan="3">All</td></tr>
<tr><td>WAC with water heat sources (ground heat pump, boiler etc.)</td></tr>
<tr><td>WAC with additional heat sources</td></tr>
</table>

1. Heating season. 2. Unheated season. 3. Water Accumulator.

As it is described in the table, the first group is assigned for air heating or cooling allowing to implement all types of DR actions for different places inside a house during the various seasons. Here shut off actions imply disconnection of equipment from an electric (or heat by the mean of closing a water valve) source. Preheating is a method to increase temperature within the given limits in advance in order to keep shut off state as long as possible. Usually diversification of temperature settings can be applied for different kind of places - occupied and free areas inside a house what means controlling of temperatures of an each place individually.

The second type of appliances is equipment controlling temperature of domestic hot water for inhabitants. Such equipment as a water accumulator (WAC) tank, that stores hot water for the domestic and heating purposes, can have an electric heater inside, and therefore, it can be subjected to the all before mentioned actions. Though, nowadays it is more popular to exclude electrical heaters because they require a considerable amount of energy, and to use instead of them different types of heat pumps (water heat source in Table 2.1). It limits possible DR actions (provided that a WAC is not equipped by additional electric heaters) because the output hot water (or other heat carriers, for instance, glycol) flow of these heat sources has a certain temperature and it can be adjusted quite rare. With the exception of an electric boiler that has such possibility. It is also concerned with additional heat sources such as water solar collectors (it is performed later) that are getting more ubiquitous. Hence, in this paper the WAC with the ground heat pump is considered, and only shut off actions are applied.

It is worth mentioning that the water tank and water based equipment (central heating and floor heating systems) are connected and switching off actions have influence on each other. Changing of water consumption, for example, in radiators will lead to dynamic in heat demand of the WAC; shutting off of the water heaters in the WAC causes falling of water temperature in a central heating system and consequently, air temperature inside a house. However, a switch on signal will be based on water temperature rather than air (especially domestic hot water temperature is crucial); therefore, presence of additional heat sources inside the tank (for instance, a heat exchanger of a solar collector as it is considered in this paper) has positive effect in this point of view.

Thus, DR scenarios depend on the specific equipment and their possible combination. In this work the most typical approaches of DR implementation are presented ([11]), such as shut off actions taking place during peaks of power consumption, preheating during off - peaks, and setting changes for the both cases are valid. More particular description of these DR actions is given in the chapter with results 4. Efficiency of a specific program is measured in the term of saved and pay - back energy as well as power.

3. RESEARCH METHODOLOGY AND MATERIALS

The main steps of the research methods applied in this paper are:

1. Choice of a typical dwelling and construction of its thermodynamic model using a variety of simplifications. The research materials here are a plan of the dwelling, geometric and thermophysics data;

2. Studying the most spread heat solutions for the chosen object and building math models of constituent components of hydronic and ventilation systems. Accompany information is also necessary;

3. Verification of the achieved models in order to estimate correctness of the applied assumptions, and using it for the following investigations. The research materials here are measurements of electric power consumption of different appliances situated in the house;

4. Subjecting the model to different DR scenarios (partially presented in Table 2.1) with the purpose of studying opportunities of household customers in delivering of deficient energy potential (the reduced load in Fig. 2.1). The research materials here are the described math model and the air/water quality standards [10] restricting time (it impacts on an amount of energy) of a DR action.

On the ground of the presented work recommendations about possible strategies of DR actions can be given. Below steps 1 - 3 are performed. Step 4 is given as the separate chapter with the results and their analyses.

3.1 Description of thermodynamic model of house

First of all, the house presented in Figure 3.1 (a) is chosen as an object for math modeling. This dwelling is a quite typical detached house in Finland that is oriented

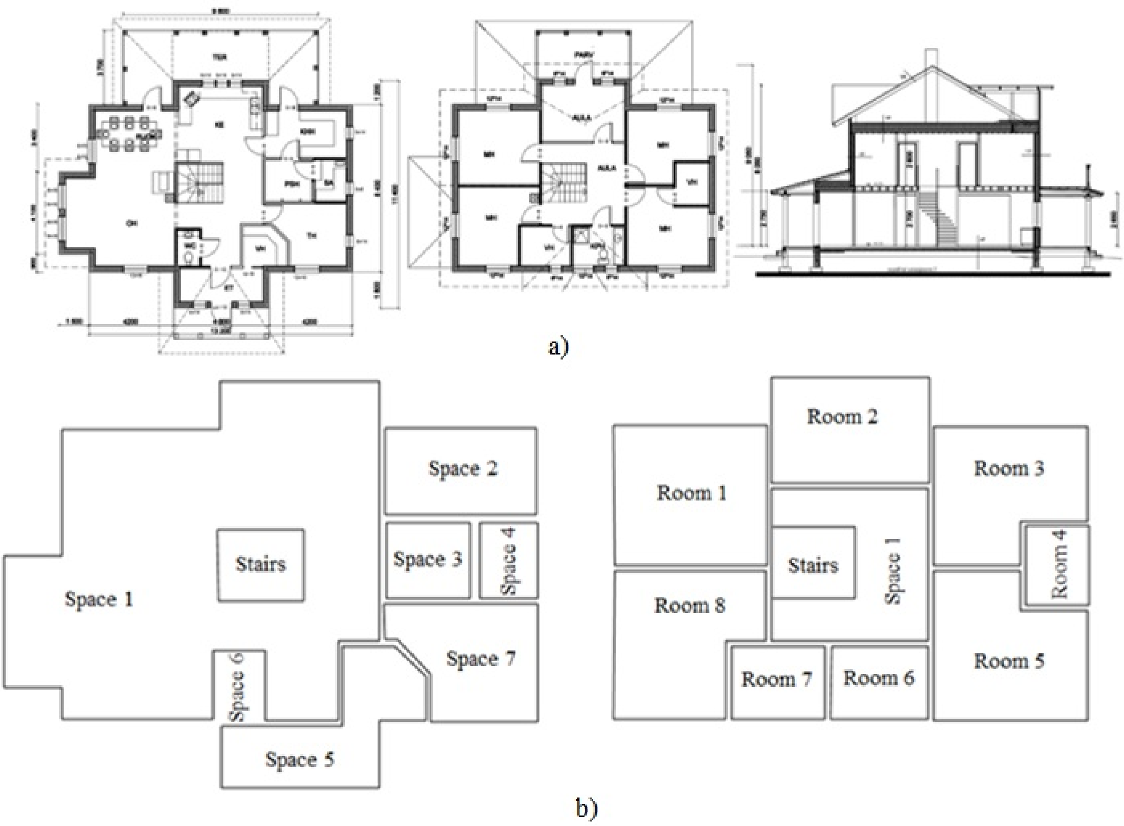

Figure 3.1 *The modeled dwelling.*

for one family, and it has all necessary equipment for its heating and cooling described in section 3.2. According to the layout of this dwelling, it has been decomposed into spaces 1 - 7 which are related to the first floor and rooms 1 - 8 for the second floor as it is presented in Fig. 3.1 (b). It is needed to decrease a number of parameters and to simplify the final model because it will perform heat exchange between the adjacent spaces and rooms.

The geometric parameters used for construction of the thermodynamic model of the given house are listed in Appendix A. In order to make the model as close to the real object as possible, the same construction materials of the walls (outer and inner), the floors (including the attic floor) and the ceiling were utilized. Information about the structure of these house components are gathered into Table 3.1 as inner order of different materials. The geometric and physical parameters of the each layer can be found in Appendix B.

Thermodynamics processes in the multilayer structure can be described as an electric circuit on the ground of electrical analogy. Hence, all these house components are modeled in the same fashion as described in [12], and Figure 3.2 illustrates this approach. According to this method, a heat flow is an electric current in this circuit;

Table 3.1 *The house component and its construction materials.*

Component	**Materials**
Outer wall	gypsum (interior layer) - air gap - fibre - concrete - wool - concrete - wool - gypsum (exterior layer)
Inner wall	cement chipboard - air gap - cement chipboard
Inner (bearing) wall	plaster - concrete - plaster
Floor	timber (upper layer) - concrete - expanded polystyrene - air gap - infinite ground (lower layer)
Attic floor	wool (upper layer) - air gap - concrete (lower layer)
Ceiling	timber (upper layer) - air gap - concrete (lower layer)

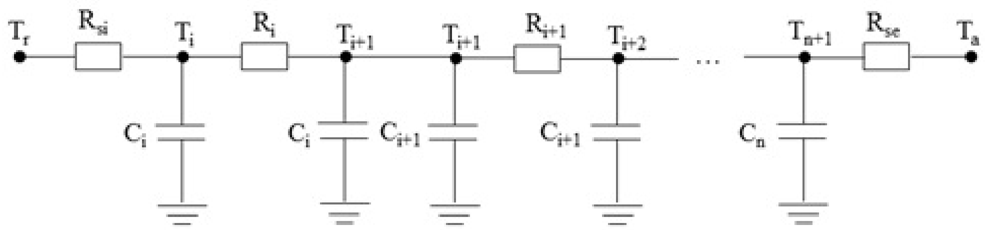

Figure 3.2 *The electric circuit describing thermodynamic behavior of the multilayer structure.*

electrical potentials are the temperatures of the layer surfaces T_i ($i = 1...n$, n - a number of layers); the heat resistance R_i and the capacitance C_i are similar to electric resistance and capacitance. In Fig. 3.2 T_r is the room temperature; T_a is ambient temperature; R_{si} and R_{se} are the internal and external heat resistances of air correspondingly that are determined experimentally and given, for instance, in [13]; the values can be found in Appendix B. The system in Fig. 3.2 can be described through Kirchhoff's laws as follows:

$$\begin{aligned}
\frac{1}{R_{si}}(T_r - T_i) &= C_i\frac{dT_i}{dt} + \frac{1}{R_i}(T_i - T_{i+1}) \\
\frac{1}{R_i}(T_i - T_{i+1}) &= (C_i + C_{i+1})\frac{dT_{i+1}}{dt} + \frac{1}{R_{i+1}}(T_{i+1} - T_{i+2}) \\
&\cdots \\
\frac{1}{R_n}(T_n - T_{n+1}) &= C_n\frac{dT_{n+1}}{dt} + \frac{1}{R_{se}}(T_{n+1} - T_a),
\end{aligned} \tag{3.1}$$

where the heat flow (as an electric current) through the heat capacitance is:

$$Q_C = C_i \frac{dT_i}{dt}, \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{3.2}$$

and through the heat resistance is

$$Q_R = \frac{1}{R_i}(T_i - T_{i+1}), \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{3.3}$$

Here the heat capacitance of the i - layer can be calculated as:

$$C_i = 0.5 c_i \rho_i \delta_i, \quad \left[\frac{\mathrm{J}}{\mathrm{K} \cdot \mathrm{m}^2}\right], \tag{3.4}$$

where c_i - the specific heat capacity of the i - layer material, [J/kg·K]; ρ_i - the density, [kg/m^3]; δ_i - the layer width, [m].

The heat resistance of the i - layer is

$$R_i = \frac{\delta_i}{\lambda_i}, \quad \left[\frac{\mathrm{K} \cdot \mathrm{m}^2}{\mathrm{W}}\right], \tag{3.5}$$

where λ_i - the coefficient of heat conductivity of the material, [W/m·K].

These expressions after rearranging yield a set of equations suitable for dynamic modeling in Matlab:

$$\begin{aligned}
\frac{dT_i}{dt} &= \frac{1}{C_i}\left[\frac{1}{R_{si}}(T_r - T_i) - \frac{1}{R_i}(T_i - T_{i+1})\right] \\
\frac{dT_{i+1}}{dt} &= \frac{1}{C_i + C_{i+1}}\left[\frac{1}{R_i}(T_i - T_{i+1}) - \frac{1}{R_{i+1}}(T_{i+1} - T_{i+2})\right] \\
&\cdots \\
\frac{dT_{n+1}}{dt} &= \frac{1}{C_n}\left[\frac{1}{R_n}(T_n - T_{n+1}) - \frac{1}{R_{se}}(T_{n+1} - T_a)\right]
\end{aligned} \tag{3.6}$$

The main assumptions made for the model of the structures are:

- The physical parameters do not depend on neither temperature nor space coordinates of the material;

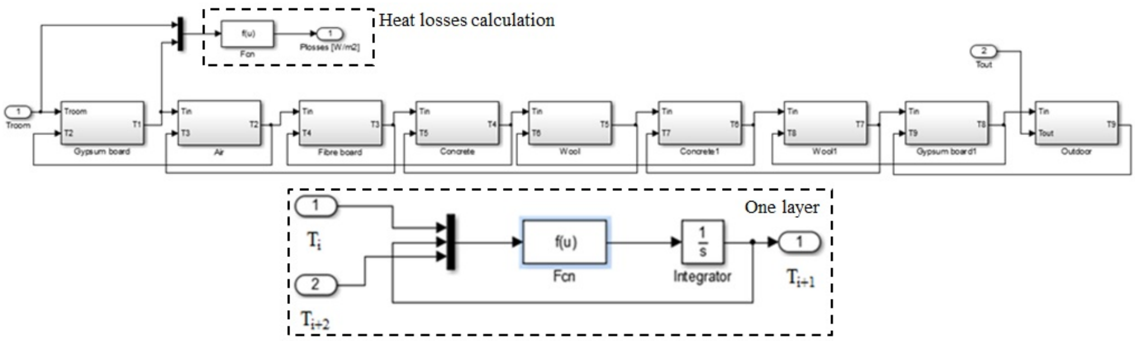

Figure 3.3 *The model of the outer wall in Matlab.*

- R_{si} and R_{se} are chosen according to the recommendations of [13], and they are the constant values;
- The heat flow from a room to the environment is homogeneous and equal for all directions;
- Surfaces are isothermal (temperatures of points of the same surface in different locations are equal);
- Edge effects are neglected;
- All structures are infinite plates.

Finally, the model of the multilayer structure (the outer wall as an example) has the appearance in Matlab presented in Figure 3.3. It looks like the chain of the sub - blocks, and the each sub - block represents a model of one layer Basically, this wall model is needed to find heat losses through the wall using (3.3) in which $R_i = R_{si}$, $T_i = T_r$ and $T_{i+1} = T_1$ (a surface temperature of the first layer). The corresponding block implementing this calculation can be found in Fig. 3.3). Moreover, the same approach is used for heat losses calculation for the floor and the roof as well as for performance of heat exchange between the inner spaces and rooms.

Looking at the model of the layer in Fig. 3.3), it can be noted that the block "Fcn"contains one of expressions (3.6) and the depicted model calculates the temperature T_{i+1} on the ground of the T_i and T_{i+2} in compliance with Fig. 3.2. Applying the described method, all structures are composed into the house model. In addition, blocks for description of heat exchange among the rooms are used; they consist of the inner walls and ceiling models. The main equation expressing thermodynamics of a room or T_r is

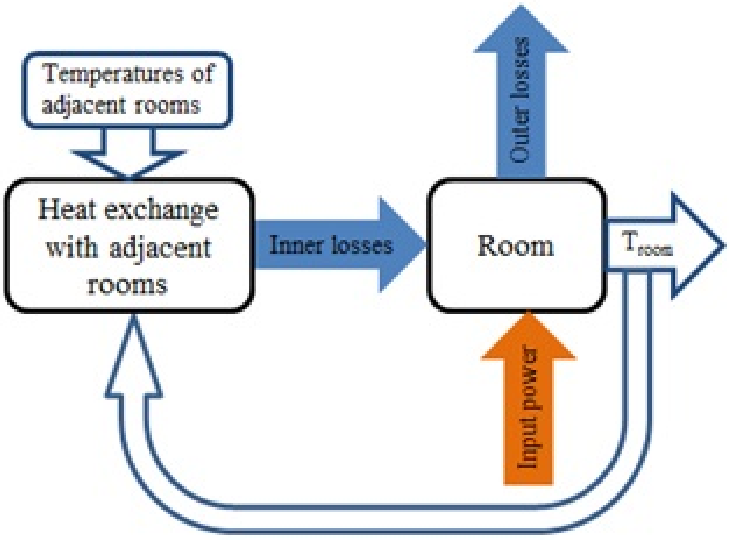

Figure 3.4 *The block - diagram of the room model.*

$$\frac{dT_r}{dt} = \frac{1}{c_{air}\rho_{air}V_r}\left[P_{in} - P_{out}\right], \tag{3.7}$$

where c_{air} - the specific heat capacity of air in the room, [J/kg·K]; ρ_{air} - the air density, [kg/m^3]; V_r - the room volume, [m^3]; P_{in} - the input power. This power can be either heat produced by appliances, humans or heat delivered from the adjacent rooms. For the more developed model solar irradiance is also the input heat power, and its consideration is performed in section 3.2.7. P_{out} - is accordingly the output heat of losses into the environment or other rooms through the walls, windows and doors. The method of heat losses calculation is described above.

It is worth mentioning that in the model additional heat losses through various cracks and air infiltrations are taken into account by the coefficient of uncounted heat losses K_{ul} (see Appendix B). Using in the model expression (3.7), it is supposed that the air physical characteristics are constant. Such approach with the applied assumptions will give the idealized model of the house that causes underestimating of heat losses (the correction factor K_{ul} is provided) and uniformity of temperature fields.

Thus, the thermodynamic model of the house has been obtained. Figure 3.4 illustrates, with the help of the block - diagram, the model of the room inside the house. In this model heat losses into the adjacent rooms (inner losses) are determined on the ground of the room temperatures (the input parameters), and they can be positive

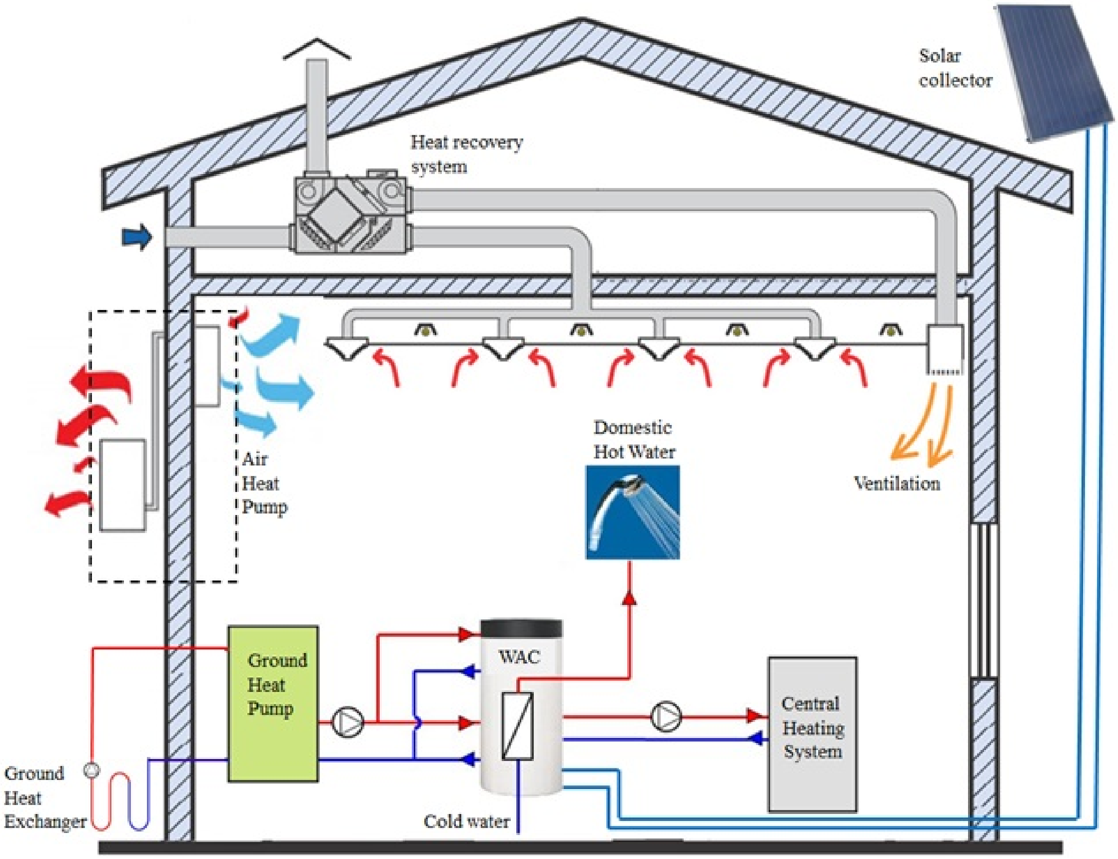

Figure 3.5 The typical domestic equipment for the heating purposes.

or negative; outer losses are calculated using outside and the ground temperatures. For the both cases equation (3.3) can be applied. These losses constitute the value P_{out} in expression (3.7). The performed model contains also the doors and windows that can be open or closed. In case of open state, the heat resistance and capacitance of a window or a door are assumed to be zero. Heat losses through closed windows are calculated on the ground of the heat loss coefficient $U_{wd} = 1$ [W/K $\cdot$ m^2] which is simply the reciprocal value of the heat resistance in (3.5); therefore, heat losses are determined through equation (3.3).

3.2 Description of models of heating/cooling equipment

Further development of the model demands including heat sources to determine the value P_{in} in (3.7). In this work the most typical solutions for heating/cooling of a house in Finland are considered (in compliance with Table 2.1) and shown in Figure 3.5.

According to Fig. 3.5, the following equipment is supposed to be performed:

- Water heaters: heat pumps (ground/water, air/water, water/water). Usually the maximum temperature of output water of such equipment is around 60^0C. A part of heat delivered by a pump is wasted for domestic hot water (DHW) demands temperature of which should be, according to the hygienic norms, 55-60^0C. Very often, instead of a heat pump, a boiler (electric, gas) is used with output water temperature 70-90^0C, and it can be equipped by radiators. A ground heat pump (GHP) is considered more detail because it is realized in the real object of modeling (Fig. 3.1);
- Central heating system (CHS) including water floor heating pipes according to situation in the real house performed in Fig. 3.1; These pipes require only 35-40^0C temperature of an input water flow;
- A solar water collector. There is not in the real house, but it is modeled for studying of summer DR actions;
- Ventilation with heat recovery system;
- An air heat pump in heating and cooling modes;

Below description of a math model or modeling approach for the described equipment is performed.

3.2.1 Electric boiler

This equipment is considered as a water heater source (Table 2.1). Many research works are dedicated to modeling of an electric boiler. It is not used, however, in the model of the house, whereof it is absent in the real object (Fig. 3.1). Nevertheless, the approach and corresponding equations are used in the further models; therefore, there is point to consider it. In this paper the simplified approach is shown with the following assumptions:

- The temperature field of water inside a boiler is uniform on the ground of small dimensions and high input electric power. Hereinafter, the corresponding parameters for all models can be found in Appendix C;
- Heat losses are constant and described through the coefficient of efficiency;
- The coefficient of efficiency of a water heater is 100%;
- Hereinafter, it is assumed that water properties do not depend on temperature.

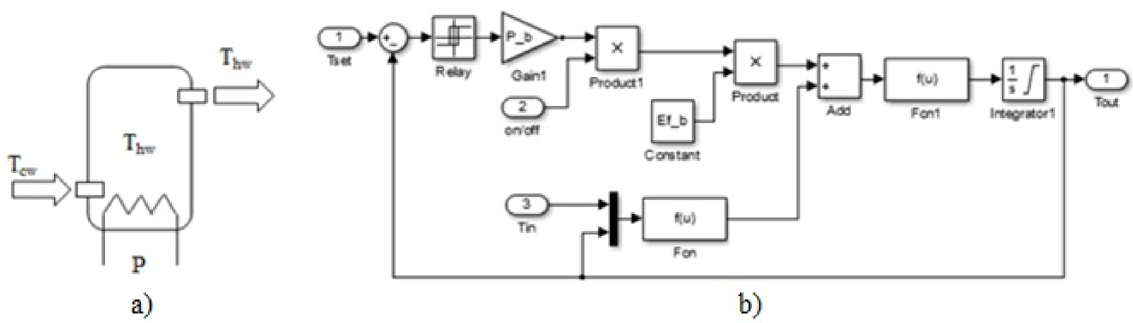

Figure 3.6 *The electric boiler and its model in Matlab.*

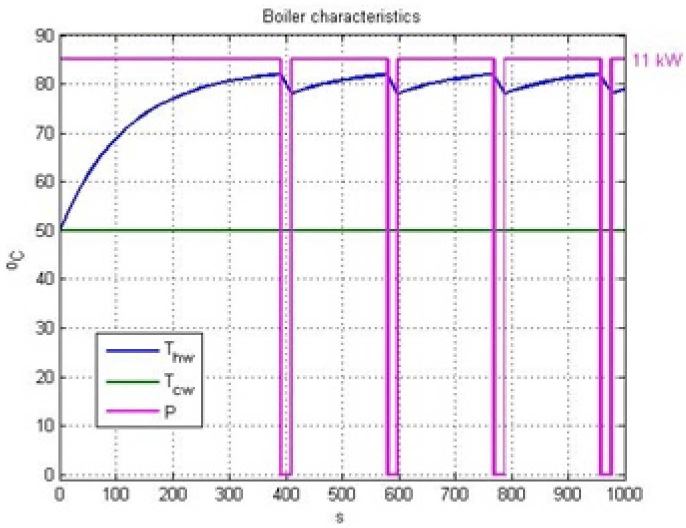

Figure 3.7 *The temperatures and consumed electric power of the boiler.*

Such assumptions do not affect too much calculated values (output temperature), with the exception of the fact that output temperature will be constant in absence of input power (due to the second assumption above). Figure 3.6 (a) presents the modeled physical object. It can be mathematically described by expression (3.8) [14]:

$$\frac{dT_{hw}}{dt} = \frac{1}{c_{wtr}\rho_{wtr}V_b}\left[c_{wtr}\dot{m}(T_{cw} - T_{hw}) + \eta P\right] \tag{3.8}$$

Here T_{cw} and T_{hw} are the temperatures of cold and hot water correspondingly; c_{wtr} - the specific heat capacity of water, [J/kg·K]; ρ_{wtr} - the water density, [kg/m^3]; V_b - the boiler volume, [m^3]; P - the input heating power without considering of heat losses, η - the coefficient of efficiency; $\dot{m}$ - the water flow, [kg/s]. Fig. 3.6 (b) presents the boiler model in Matlab.

The performed model has the relay element for temperature control and an on/off signal for a DR - controller (considered later). The input parameters are the set temperature and the input water temperature. Figure 3.7 shows the graphs of the set temperature 80^0C and input electric power. Other parameters can be found in Appendix C.

3.2.2 Water radiator

The model of a water room radiator is also described in [12]. In this paper the simplified version is used with the purpose of calculation time reduction of the program. In the real house (Fig. 3.1) there are not radiators; however, their model will be needed later for calculating temperature of a return water flow of a water floor heating system. The model of a radiator has the same structure as the boiler, (Figure 3.6 (a)) with the exception of that it emits heat, and therefore it can be described as:

$$\frac{dT_{cw}}{dt} = \frac{1}{c_{wtr}\rho_{wtr}V_{rad}}\left[c_{wtr}\dot{m}(T_{hw} - T_{cw}) - P_{rad}\right], \tag{3.9}$$

where V_{rad} - the radiator volume, [m^3]. Unlike the boiler, temperature of the output water flow is less than the input. P_{rad} is the heat power emitting into a room by the radiator, and it can be calculated as (similarly to (3.5)):

$$P_{rad} = \frac{A_{rad}}{R_{rad}}(T_{cw} - T_{room}), \tag{3.10}$$

where A_{rad} - the radiator emitting area, [m^2]; R_{rad} - the overall heat resistance between the output water flow and a room temperature, chosen according to [15]. Here the following assumptions have been made:

- Instead of advised by [12] the log mean temperature, the simple difference of temperatures is used;
- This model does not take into account place of a radiator in a room and heat delivered by water supply pipes;
- Hereinafter, R_{rad} (or for another equipment) is not function of the water flow velocity.

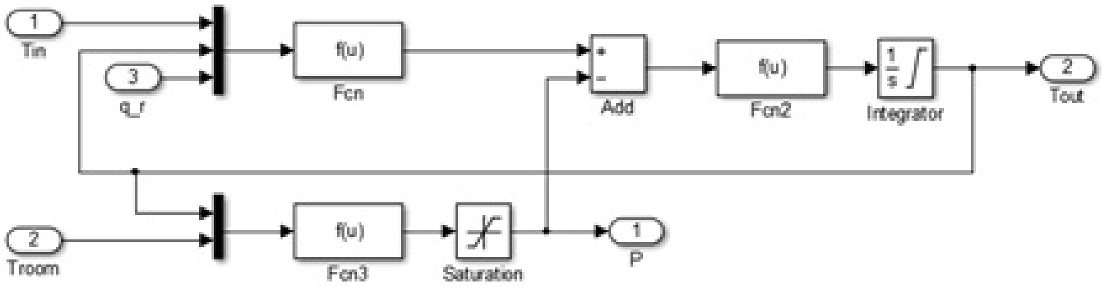

Figure 3.8 *The radiator model in Matlab.*

These assumptions lead to better and faster heat exchanging between a radiator and room air than in reality that causes more significant cooling of the water flow in a central heating system. The model of the radiator in Matlab is presented in Figure 3.8. The blocks "Fcn"and "Fcn2"contain expressions from equation (3.9), "Fcn3"presents (3.10). The input parameters are the input water flow temperature (from a coil heat exchanger situated inside the WAC in Fig. 3.5), the water flow consumption q in [m^3/s] (according to (3.9), $q = \dot{m}/\rho_{wtr}$) and the room temperature. The output parameters are the output water flow temperature and the emitted heat power, which is considered as a part of the value P_{in} in (3.7). As the house has several radiators, the common return water flow temperature T_r^{rad} can be calculated as the averaged value:

$$T_r^{rad} = \sum_i \left(q_i T_{cw}^i\right) \Big/ \sum_i q_i \tag{3.11}$$

The each radiator in the house is equipped with a valve which allows changing of the water flow q_i in order to regulate emitting heat power from the radiator. This thermostatic valve presents by itself a P - regulator. The tests with the central heating system (including only floor heating as it is in the modeled object) will be presented later together with the water accumulator tank and another equipment in the section with the total model validation 3.3.

3.2.3 Floor heating

In order to implement floor heating systems, the same approach is used as for description of heat losses through the walls (Fig. 3.2). The exception is fact of presence of an interior heat source, electric or water type. Such task can be presented as shown in Figure 3.9. This system can be described by expressions (3.6), with the exception of the node $i+1$ which is split into the two points. For them the following

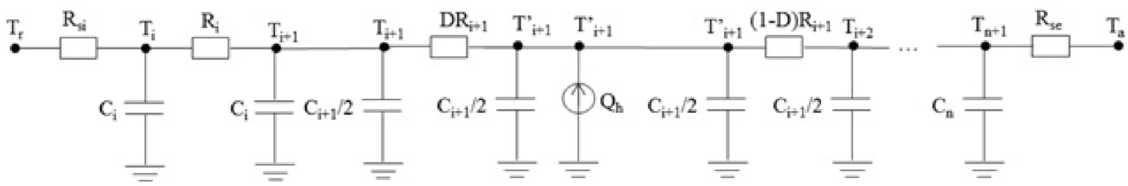

Figure 3.9 *The multilayer structure with the interior heat source.*

equations can be derived:

$$\frac{1}{R_i}(T_i - T_{i+1}) = (C_i + \frac{C_{i+1}}{2})\frac{dT_{i+1}}{dt} + \frac{1}{K_D R_{i+1}}(T_{i+1} - T'_{i+1}) \quad (3.12)$$

$$\frac{1}{K_D R_{i+1}}(T_{i+1} - T'_{i+1}) + Q_h = C_{i+1}\frac{dT'_{i+1}}{dt} + \frac{1}{(1-K_D)R_{i+1}}(T'_{i+1} - T_{i+2}) \quad (3.13)$$

that yield:

$$\frac{dT_{i+1}}{dt} = \frac{1}{C_i + \frac{C_{i+1}}{2}}\left[\frac{1}{R_i}(T_i - T_{i+1}) - \frac{1}{K_D R_{i+1}}(T_{i+1} - T'_{i+1})\right] \quad (3.14)$$

$$\frac{dT'_{i+1}}{dt} = \frac{1}{C_{i+1}}\left[\frac{1}{K_D R_{i+1}}(T_{i+1} - T'_{i+1}) + Q_h - \frac{1}{(1-K_D)R_{i+1}}(T'_{i+1} - T_{i+2})\right] \quad (3.15)$$

$$K_D = \frac{x}{\delta_{i+1}}, \quad (3.16)$$

where x - the depth of the heat source place, [m]; Q_h - the heat power density of the source, [W/m^2].

In case of electric floor heating, the heat power density Q_h is limited and determined by a producer of a heat cable (usually about 80 W/m^2). It is controlled through a thermo sensor situated in a room and a P - controller (or PI) with a relay element for input electric power.

The model of water floor heating is completely similar to the radiator model, and it uses a hot water flow from a coil heat exchanger in the water accumulator tank, Fig. 3.5. A control system is also built with the help of a thermostatic valve and data of a thermo sensor measuring a room temperature. In the model a heating pipe of U - form is situated in the floor in the layer of concrete (Table 3.1), see the parameters in Appendix C. Such approach of modeling of additional heat sources (Fig. 3.9) is useful for taking into account solar irradiance (performed in section 3.2.7) that has impact on interior temperature due to not only energy transmitted through the windows, but also through heating up of the outer walls. The tests with the water floor heating system, which is really situated in the considered house (Fig. 3.1), is performed in the section with the total model validation 3.3.

3.2.4 Water accumulator tank

Recently, several authors [16], [17] have proposed the same approach for modeling of the hot water accumulator tank. As it was advised, for example, in [17], a large volume with water can be split into several layers in order to describe a temperature gradient inside a vertical tank as accurate as possible. This model contains also a coil heat exchangers (CHEX) inside the tank for heating water in the CHS, illustrated in Figure 3.5. The following assumptions for the WAC model in this thesis are applied:

- The water tank and its heat insulation (one layer of wool material) have the right cylindrical form;
- All physical parameters do not depend on temperature and water flow velocity;
- The coil heat exchanger in the each layer has the form of a ring;
- The overall heat resistance between water inside the CHEX and water of the tank is constant;
- Widths of the layers are equal as well as the water flows in them;
- There is no mixing;
- Heat exchange between the layers takes place, and it is described through the coefficient of heat conductivity of water and the tank cross section for the each layer;
- The metallic walls of the tank are ignored.

Such assumptions allow to simplify the model of the real object; however, temperature difference between the layers will be more than in reality. Heat exchange in the modeled CHEXs will be also better comparing with real situation. The modeling system presented in Figure 3.10 is considered.

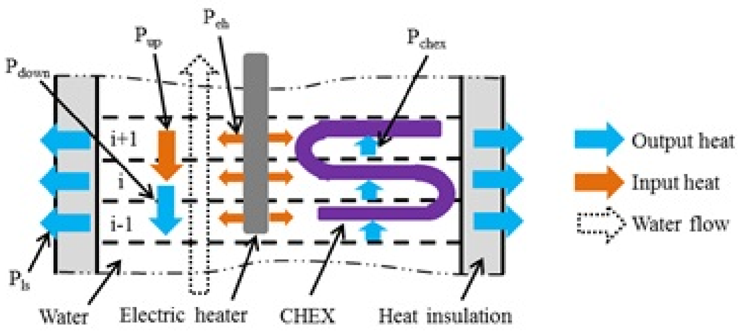

Figure 3.10 *Heat propagation inside the tank.*

Math description of the i - layer temperature T_i is similar to 3.8, where ηP performs heat balance between input and output powers (shown in picture) for one layer. Thus, the following expression can be written:

$$c_{wtr}\rho_{wtr}V_{lr}\frac{dT_i}{dt} = c_{wtr}\dot{m}_{wf}(T_{i-1} - T_i) + P_{up} - P_{down} + P_{eh} - P_{chex} - P_{ls}, \qquad (3.17)$$

where V_{lr} - the water volume of one layer; $\dot{m}_{wf}$ - the water flow from a water heater (a boiler or a heat pump); P_{up} - the heat delivered from the adjacent upper layer; P_{down} - the heat delivered to the adjacent lower layer; P_{eh} - the heat delivered from an electric heater; P_{chex} - the heat delivered to water inside the pipe of the coil heat exchanger; P_{ls} - the heat delivered into space (losses). Eventually, the water accumulator tank is divided into the fifteen layers, and the following corrections for (3.17) are made (with compliance to Fig. 3.5):

1. $i = 1$: T_{i-1} is equal to the input cold water temperature; $P_{down} = 0$, P_{ls} is increased by P'_{ls} - the heat losses through the bottom of the tank;

2. $i = 15$: $P_{up} = 0$, P_{ls} is increased by P'_{ls} - the heat losses through the closure of the tank;

3. A layer without the water flow or the electric heater, or the CHEX (or their combination) is modeled assuming that $\dot{m}_{wf} = 0$ or $P_{eh} = 0$, or $P_{chex} = 0$ (or corresponding combination excluding the appropriate equipment in (3.17)).

Domestic hot water tanks can be also equipped by an additional electric heater to support temperature of the upper part at the set level, when heat produced by a GHP is not enough [18]. In the tank model power from the electric heater P_{eh}, injected into the i - layer, divided by a number of the layers where this heater is situated. For the control aims a heater is usually equipped by a P - regulator and a temperature feedback signal from the upper layer. However, in the considered model there is not an electric heater.

Heat exchange between the adjacent layers is expressed as:

$$P_{up} = \frac{A_{lr}}{R_{lr}}(T_{i+1} - T_i), \; P_{down} = \frac{A_{lr}}{R_{lr}}(T_i - T_{i-1}) \tag{3.18}$$

Here A_{lr} - the area of the cross section of one layer, and R_{lr} - the heat resistance between the two adjacent water layers inside the tank chosen on the ground of the modeled experiments and recommendations of [15].

As it was stated before, the WAC contains at least the two heat exchangers: one (the upper) is for heating of water inside the tank (it is associated with water heaters such as a GHP or a boiler) and another (the lower) consumes stored heat, that is it decreases temperature of the tank water (it is associated with the CHS). For description of heating process of water inside the last mentioned coil heat exchanger, the following equation are applied:

$$P_{chex} = \frac{N_{tn}A_{rg}}{R_{chex}}(T_i - T_{chex-i}) \tag{3.19}$$

$$c_{wtr}\rho_{wtr}N_{tn}V_{rg}\frac{dT_{chex-i}}{dt} = c_{wtr}\dot{m}_{chex}(T_{chex-(i-1)} - T_{chex-i}) + P_{chex}, \tag{3.20}$$

where N_{tn} - the number of the CHEX turns per layer; A_{rg} - the area of one ring of the CHEX, and R_{chex} - the overall heat resistance between the CHEX and the tank water, chosen according to [15]; T_{chex-i} - the temperatures in the rings of the coil heat exchanger; V_{rg} - the volume of one ring of the CHEX; $\dot{m}_{chex}$ - the water flow in the CHEX; Thus, P_{chex} is changed from one layer to another, and for $i = 1$ $T_{chex-(i-1)}$ is equal to temperature of the return water flow from a corresponding system (for instance, the CHS or a solar collector).

Heat losses into the environment are calculated as:

$$P_{ls} = \frac{\Delta A_{tank}}{R_{t-a}}(T_i - T_{room}) \tag{3.21}$$

$$R_{t-a} = \frac{\Delta x_{tank} \ln \frac{D_{tank}+2\delta_w}{D_{tank}}}{2\lambda_w} + R_{si}, \tag{3.22}$$

where ΔA_{tank} - the area of the outer surface (considering the heat insulation) of one layer; Δx_{tank} - the height of one layer; D_{tank} - the inner diameter of the tank; δ_w - the width of the wool heat insulation; λ_w - the coefficient of wool heat conductivity; R_{si} - the heat resistance between the heat insulation and ambient air [13]. The before mentioned heat losses through the bottom and closure of the tank P'_{ls} can be derived using heat resistance calculation (3.5) and the difference of the corresponding temperatures.

As it was noticed before (it is possible to observe in Fig. 3.5) besides the lower CHEX of the CHS, the tank contains also the upper coil heat exchanger that delivers heat from the primer heat source such as a boiler or a heat pump. Sometimes the lowest part of the tank can be additionally equipped by one more CHEX which is connected to the secondary heat source such as a water solar collector (performed below) or a fire place. Modeling of such type of the CHEX is the same as described above in (3.19) and (3.20), except for one difference: as it is a heat source, then in equation (3.17) P_{chex} has opposite sign, that is positive because heat is delivered from the CHEX to the tank water. For calculation of water cooling inside the CHEX, expressions (3.19) and (3.20) are used with negative sign of P_{chex} for the both equations.

Recently a new way to save expenditures for water heating has been appeared - applying a solar collector as an additional heat source; this method is studied, for example, in [16]. The main idea is heating of a transfer liquid (generally glycol) in the primary contour of the solar collector and transmitting it to the heat exchangers (as it is performed in Fig. 3.5, the tank contains also the heat exchanger connected with the solar water collector).

In this paper the glazed liquid flat - plate collector is considered [19]. Though in the real house it is not implemented, but the model can be used for studying summer DR actions. The idealized version of the model can be presented through the expression similar to (3.8):

$$\frac{dT_{hg}}{dt} = \frac{1}{c_{gl}\rho_{gl}V_{sc}} \left[c_{gl}\dot{m}_{gl}(T_{cg} - T_{hg}) + P_{sc} \right], \tag{3.23}$$

where T_{cg} and T_{hg} are the temperatures of the cold and hot glycol flow correspondingly; c_{gl} - the specific heat capacity of glycol, [J/kg·K]; $\dot{m}_{gl}$ - the glycol flow in the collector; ρ_{gl} - the glycol density, [kg/m^3]; V_{sc} - the solar collector volume, [m^3]; P_{sc} - the collected solar energy per time, [W]. This power for the glazed collector can be calculated as [19]:

$$P_{sc} = \Big(F_R \tau \alpha G - F_R U_L \Delta T\Big) A_{sc}, \tag{3.24}$$

where F_R - the collector's heat removal factor; τ - the transmittance of the cover; α - the shortwave absorptivity of the absorber; G - the global incident solar radiation on the collector, [W/m^2]; U_L - the overall heat loss coefficient of the collector, [W/K·m^2]; ΔT - the temperature difference between glycol and ambient air; A_{sc} - the area of the solar collector. F_R and U_L are independent of wind due to the glazed collector surface.

As it is possible to see, the model of the water accumulator tank is quite complex. It is based on the real tank situated inside the house, with the exception of including the solar collector (in validation process it will be excluded as may be necessary). Thus, the input parameters of the model will be: the temperatures and discharges of the input water flow from the water heater (the GHP) and the solar collector, the return temperature and discharge from the CHS, the inlet domestic cold water temperature and its discharge rate, ambient temperature (a room temperature). The outputs are: the temperatures of the return flows of the water heater and the solar collector (cooled water and glycol in cold state are delivered to the corresponding systems), the output flows of hot water delivered from the tank to the CHS and for the DHW purposes. Most of these characteristics can be found in the tests performed in validation section 3.3. Other numerical parameters used in modeling can be found in Appendix C.

3.2.5 Ventilation with heat recovery system

Buildings shall be designed and constructed in such way that indoor air does not contain any gases, particles or microbes in such quantities that will be harmful to health, or any odours that would reduce comfort [20]. Ventilation solves these tasks; moreover, it reduces costs associated with heating of buildings.

Basically an air ventilation system (Fig. 3.5) consists of supply - exhaust ventilators, air ducts, a heating equipment and an air recuperator. The main aim of the last is heat recovery, that is transmitting of heat from warm exhaust air from a room

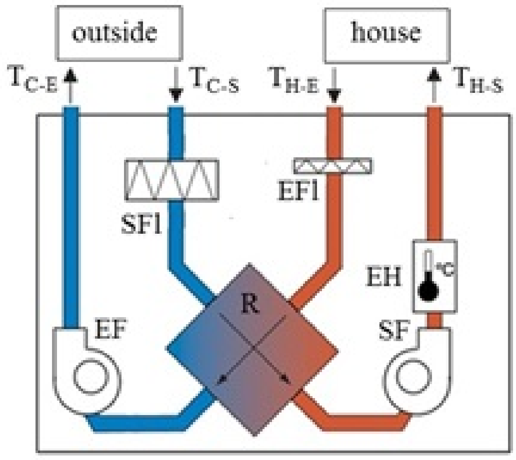

Figure 3.11 *The ventilation system.*

to incoming cold air (or vice versa in case of cooling). Besides the recuperator, in the ventilation system there is the heating equipment to increase temperature of incoming air (even after heat the recovery process); usually it can be a water coil, an electric heater or an air/air heat pump. In our model an electric heater (math description is equal to the boiler equation (3.8)) is applied as it is shown in Figure 3.11. In this figure: "EF" - the exhaust air fan, "SFl" - the supply air filter, "EFl" - the exhaust air filter, "SF" - the supply air fan, "EH" - the electric heater, "R" - the recuperator.

The model of the air heat recovery system is constructed on the ground of three equations (3.25)-(3.27) with the following simplifications:

- Due to small temperature differences, heat losses are neglected;
- Heat transferred from the exhausted to supply air flow depends on only temperature difference;
- All parameters are not functions of air flow velocity or quality;
- The temperature fields are uniform.

These assumptions give the idealized and simple model (it causes discrepancy in power consumption of the electric heater between the real and simulated situations) which is described by:

$$\frac{dT_{C-E}}{dt} = \frac{1}{c_{air}\rho_{air}V_{rec}}\Bigg[c_{air}\rho_{air}q_{air}(T_{H-E} - T_{C-E}) - P_{E-S}\Bigg] \tag{3.25}$$

$$\frac{dT_{H-S}}{dt} = \frac{1}{c_{air}\rho_{air}V_{rec}}\Bigg[c_{air}\rho_{air}q_{air}(T_{C-S} - T_{H-S}) + P_{E-S} + P_{eh}\Bigg] \tag{3.26}$$

$$P_{E-S} = \frac{A_{rec}}{R_{rec}}(T_{H-E} - T_{C-S}), \tag{3.27}$$

where q_{air} - the air flow in the recovery system calculated as the sum of the air flows of an each room, [m^3/s]; T_{C-E} - the temperature of the cold exhausted air flow going outside from the recuperator; T_{H-E} - the temperature of the hot exhausted air flow going from the house to the recuperator; T_{H-S} - the temperature of the hot supply air flow going into the house from the recuperator, and it is preliminary heated by the electric heater with the power P_{eh} regulated by a P - regulator; T_{C-S} - the temperature of the cold supply air flow going into the recuperator from outside (fresh air); P_{E-S} - the power delivered from the exhausted to the supply air flow inside the recuperator; A_{rec} and V_{rec} - the area and volume of the recuperator correspondingly; R_{rec} - the overall heat resistance between the two air flows chosen according to [15]. Other numerical values for modeling can be found in Appendix C.Thus, the input parameters of this model are: ambient air and the room temperatures; the output is temperature of the air flow going into the rooms inside the house. With moving of air mass inside a room equation (3.7) is transformed into:

$$\frac{dT_r}{dt} = \frac{1}{c_{air}\rho_{air}V_r}\Bigg[P_{in} - P_{out} + c_{air}\rho_{air}q^r_{air}(T_{H-S} - T_{room})\Bigg], \tag{3.28}$$

where q^r_{air} - the air flow of one specific room calculated through the standard value of the air flow rate according to [20] and the room volume, [m^3/s]. T_{H-E} in (3.25) can be calculated in the same manner as the temperature of the return water flow in the central heating system expressed through (3.11). It is obviously that during a warm period of the year, the recovery system works in reverse direction - it cools down incoming warm fresh air transmitting power from it to the chill exhausted flow. Illustration of contribution of the recovery system into heating process is also performed in validation section 3.3.

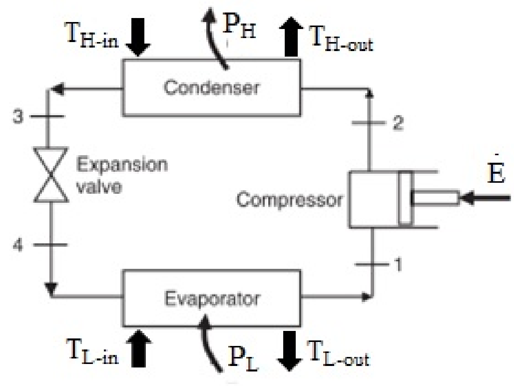

Figure 3.12 *The structure of heat pumps.*

3.2.6 Heat pumps

A conventional heat pump using any medium for work has the structure presented in Figure 3.12. The work process is the following [21]: a refrigerant as a gas is compressed by a compressor such that enthalpy is changed from h_1 to h_2, [J/kg]; temperature of the gas is increased, and it is described as $\dot{m}(h_2 - h_1) = \dot{E}$, where $\dot{m}$ denotes the discharge of the refrigerant flow, h - its enthalpy in the different points of the system in Fig. 3.12 and E is the electric energy consumed by the compressor; then the refrigerant gives away heat in a condenser, that is $\dot{m}(h_2 - h_3) = P_H$, and it turns into a liquid state going through a valve where $h_3 = h_4$; in the condenser the heat power P_H increases temperature of the medium in the second contour from T_{H-in} to T_{H-out} (or decreases in case of cooling mode); typically this medium is domestic water or air; in an evaporator due to the incoming heat power P_L the hot liquid becomes the gas again, and here equation $\dot{m}(h_1 - h_4) = P_L$ is valid; in turn, the heat power P_L cools down a heat carrier in the second contour of the evaporator from T_{L-in} to T_{L-out} (or heats up in case of cooling mode). Hence, in Fig. 3.12 the index "L"denotes the low temperature side, "H" - the high temperature side.

Quite often this heat carrier in the evaporator is glycol (in water/water or ground/water types) or just air (air/air type). For the first type an additional heat exchanger is needed - the ground, a water pound, ground water and other sources [21] in order to achieve the desired level of T_{L-in}. Sometimes heat delivered by the evaporator is not sufficient to increase the enthalpy from h_4 to h_1, and then an additional electric heater (or even heat from the compressor) before the compressor is used. As power consumption of this heater is low - from 20 to 80 W, then it is not included into the final model.

Here the power balance for heating mode is $P_L + \dot{E} = P_H$, and cooling is $P_L - \dot{E} =$

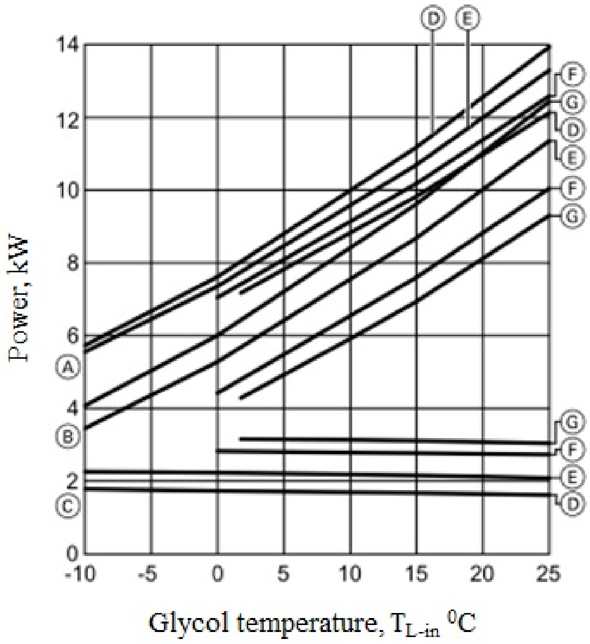

Figure 3.13 *Characteristic of the ground heat pump "Vitocal 200-G".*

P_H. Separate modeling of the each component (the evaporator, the compressor, the condenser, and the valve) and detection of the coefficient of performance (COP) is out of the scope of this work since the complete model, described for example in [22], is quite bulky and wastes much time for getting results (computationally demanding). The particular study of these types of equipment is also well known and can be found, for instance, in [21]; therefore, in this thesis the simplified approach for modeling is used. The main idea is a dependence of the evaporator power P_L (and consequently the consumed electrical power $\dot{E}$, the COP and the condenser power P_H) on the temperature of the working medium - T_{L-in}. Below the most spread types of heat pumps are considered that are included into the final model.

Ground/water heat pumps

As it was stated above, the main approach applied in modeling of such type of equipment is performance of a dependency of the heat flow in the evaporator on temperature of the working medium. In most cases this information is provided directly by a producer as it is shown in Figure 3.13 for the model "Vitocal 200-G"situated inside the real house.

This figure presents the connection of the consumed by the compressor electrical power $\dot{E}$ (in Fig. 3.13 the group of the curves denoted by the letter "C"), the

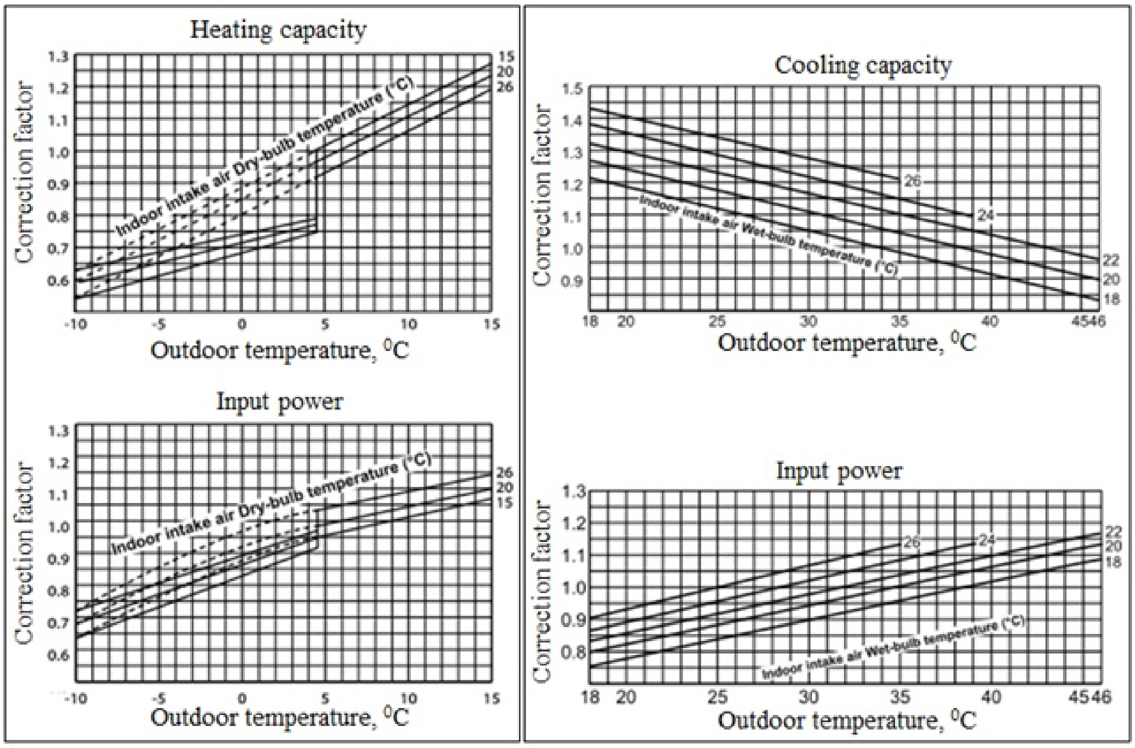

Figure 3.14 *Characteristic of the air heat pump "Onnline N09".*

condenser P_H (the group "A") and the evaporator heat powers P_L (the group "B") with the glycol temperature T_{L-in} (the horizontal axis) for the different temperatures of the output hot water T_{H-out}: the curves denoted by "D" are for $T_{H-out} = 35^0$C, "E" - $T_{H-out} = 45^0$C, "F" - $T_{H-out} = 55^0$C, "G" - $T_{H-out} = 60^0$C. In the model the presented graphs are simulated by the means of a cubic polynomial. Usually the temperature of the working medium T_{L-in} is in the range of $-4...+6^0$C during the year, and it can be described through the sine function as it is proposed in [23]. The condenser model is also equal to the boiler, equation (3.8), with the only difference that, instead of input electric power, heat from the refrigerant is used (see the parameters in Appendix C). The input signals for the model are - the input water temperature (the output after the water accumulator tank) and time of the year; the outputs are the power consumption of the compressor and the outlet water temperature (the input for the water accumulator tank). The test with the GHP is presented in section 3.3.

Air/air heat pumps in heating and cooling modes

This type of equipment is modeled using the same method as for the described above ground heat pump. Usually air/air heat pumps (AHP) are used for a dwelling heating in a cold time of the year and for cooling in a warm; therefore, it is presented by the two types of the characteristics - heating and cooling mode, Figure 3.14. The dashed lines on the plots are performing characteristics of the pump without any frost and defrost operation; however, such operations are not considered in this thesis.

These characteristics depend on both temperatures - indoor and outdoor (the input parameters of the model); therefore, in the model they are presented as the standard blocks from the Matlab library "2-D Lookup Table". Temperatures differed from the listed on the plots are interpolated by the first - order polynomial. In the model heating or cooling capacity is multiplied by the correction factor which is a ratio between the actual power produced (in case of heating mode) or consumed (cooling mode) by the condenser P_H and the base value given by a producer for the normal condition. Power of the condenser (the output parameter of the model) is the input heat included in (3.28). The corresponding parameters can be found in Appendix C, and simulations of the AHP are performed in the section with model validation 3.3.

3.2.7 Solar radiation calculation

The sun is a natural heat source for the house therefore its influence has to be taken into account. Nevertheless, the model demands including of solar radiation impact in order to compare season DR actions. For simplicity the following assumptions have been done:

- The attic floor does not grasp solar radiation because of the roof;
- The global incident solar radiation G in [W/m^2] for the house is averaged for the four sides (north, east, south and west side) of the house and added as it is shown in Fig. 3.9, that is there is the additional heat source Q_h [W/m^2] situated in the node $n+1$ (the outer surface of the wall subjected to the sun radiation);
- All windows are open, that is there is no curtains, and solar gain through the doors is neglected;
- Partially solar radiation is absorbed by the walls and windows that are taken into account as the coefficients of absorptivity α_w and α_{wd} correspondingly. Transfer of energy through the window is expressed as the transmittance coefficient τ_{wd}.

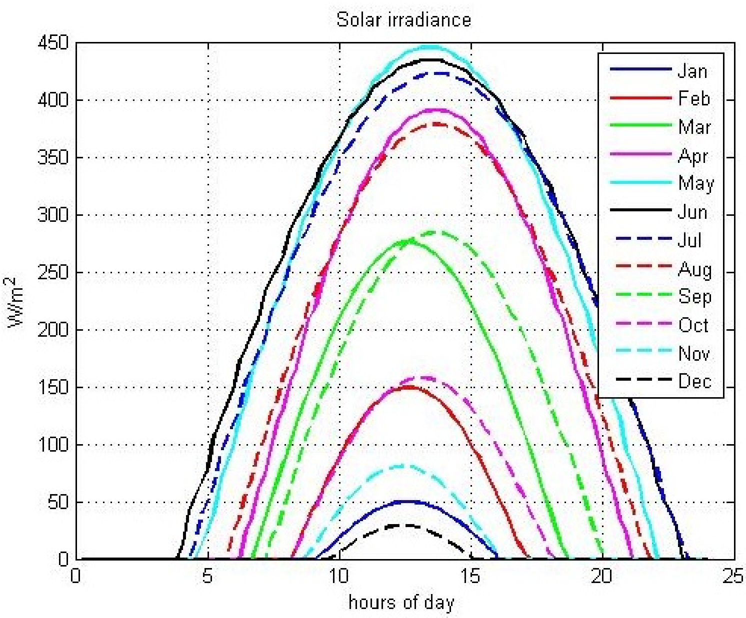

Figure 3.15 *The monthly solar irradiance patterns.*

Thus for the walls it is possible to write:

$$Q_h = \alpha_w G \tag{3.29}$$

The solar gain through the windows is taken as a part of the value P_{in} in (3.28) and expressed as:

$$P_{in} = \alpha_{wd} \tau_{wd} G A_{wd}, \tag{3.30}$$

where A_{wd} is the area of the window. In the model the parameters Q_h and P_{in} are multiplied by coefficient 0.25 (4 sides) to average total irradiance affecting the house. The global irradiance is presented in the model for each month (with changing of the time of sunset and sunrise), and it is approximated by the sine function. The average values and the corresponding times are taken from [24] for the Tampere region. Figure 3.15 illustrates these patterns for a vertical plane, and influence of solar energy on the indoor temperatures is shown in the section below.

3.3 The total model validation

The model validation process is accomplished on the basis of adequate behavior of the simulated curves and the obtained values of energy, power, temperatures and other parameters (the model's output parameters). Moreover, for verification of the complete model of the given house (the initial object) and estimation of its accuracy, a set of measurements were carried out in order to compare them with the simulated results. The following equipment is included in the final model of the house:

- The central heating system consisting of the water floor heating pipes. Here the simplification has been made: in the model the floor heating presented in Fig. 3.9 is not used in order to reduce time of calculation (as much as 2 times) and to simplify the model. Another way is to reduce the number of the layers in the wall model, but it will lead to deterioration of the model performance. Instead of it, the needing heat power is calculated (P_{in} in (3.28) to ensure T_r = 22^{0}C) for the each room, and after that these values are used in (3.9) to determine the cold water flow temperature T_{cw} transmitting to the water tank for further heating again. Such approach allows also avoiding needing for modeling of a further hydronic system, and especially the mixing valves (more detailed it is explained in simulation test 3, Fig. 3.18);
- The hot water accumulator tank with the ground heat pump and the solar collector;
- The air heat pump in space 1 (basically it is used for cooling aims);
- The ventilation system (the recuperator with the electric heater).

The verification process is performed through the several simulations tests for different cases described below with further analysis and comparison with each other and/or with real measurements. All geometric and thermal parameters for the above-listed models are collected in Appendix C.

Simulation test 1. Heating demand of the house. This experiment shows the results of the heating (the floor pipes) and electric (the air heater in ventilation) power for the whole house required to support the room's temperatures at +22^{0}C (for other simulations this level is the same) for different ambient temperatures: +3^{0}C (October) and -24^0C (January). Ambient temperature is chosen with accordance to the meteorological records (the measured data). The duration of the each simulation is 4 days in order to achieve steady - state modes (for other simulations this time is the same). Solar irradiance is neglected for these periods of the year. The most interesting results are performed in Figure 3.16.

The first plot (counting from left to right) demonstrates the heating demand (power produced by the water floor pipes) for the different ambient temperatures. It is

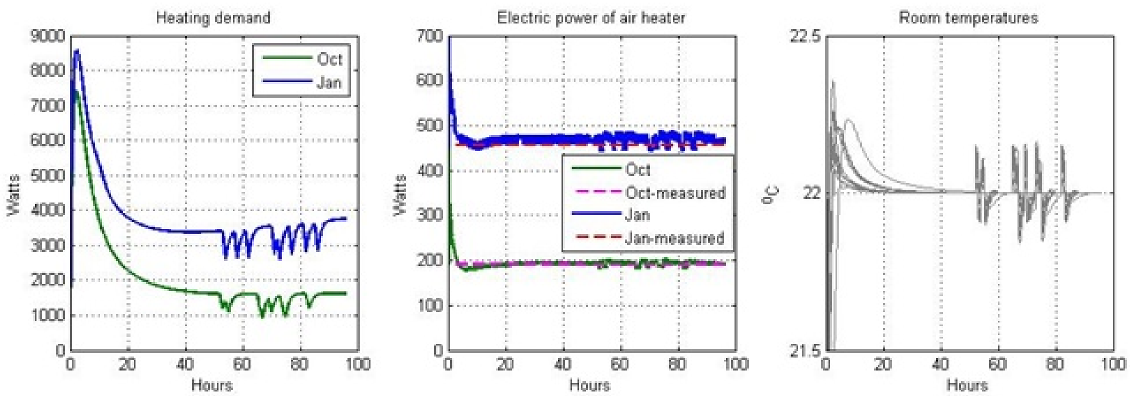

Figure 3.16 *The results of simulation test 1.*

possible to observe the rise of the power (the blue and green lines) due to the falling of the ambient temperature that conforms to expectations. Consequently, it will lead to increasing of power consumption of the GHP in order to heat up the WAC. On the both plots there are the quite long accelerating periods due to the big time constant of the house. The high overshoot of the power is the result of summation of the transient characteristics of the heating power of the each room; furthermore, the coefficients of the corresponding P - regulators are not adjusted. The small peaks and pits in the steady - state mode are the consequences of human presence inside the house; namely, the peaks are connected with sudden heat losses (opening of the windows, the doors), whereas the pits - with additional heat sources such as: human heat, the lightning, the cooking and other appliances. These additional heat and losses sources are fitted on the ground of approaching the simulated curves of power consumption of the GHP to the measured values which have the hardly predictable small peaks and pits due to human behavior (the upper plots in Figure 3.18 showing the power consumption of the GHP).

The variations in the heating power cause changing of the indoor air temperature illustrated in the third plot. Because of the graph scale, the temperature rise and fall have instant character (the steep slope), in fact, it is not true and it can take several hours. In the accelerating period the small overshoots of the temperature curves are observed as well.

The second plot shows comparison of the consumed electric powers of the air heater inside the ventilation system. The measurements were realized in the real house for the same air temperatures. It is also observable that the consumed electric power of the air heater is changed with the temperature of ambient air, and the graphs have the small fluctuations due to changing of the indoor air temperature that proves adequacy of the model; the modeled (the blue and green lines) and the measured

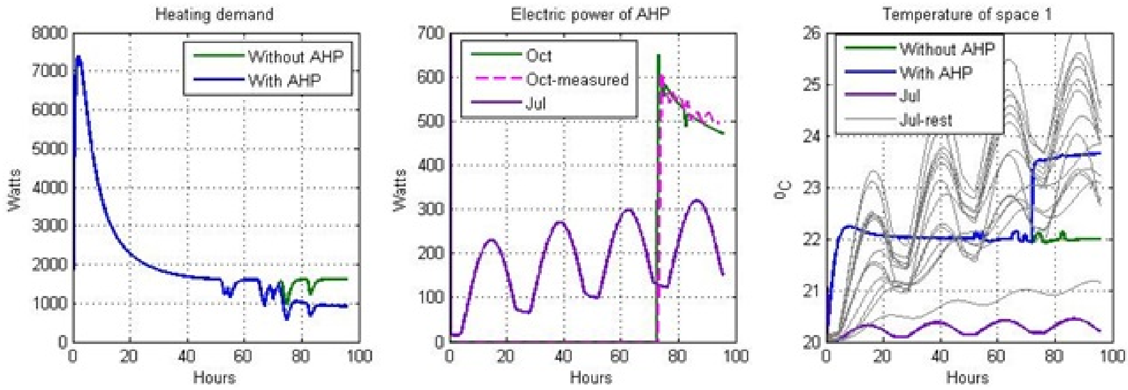

Figure 3.17 *The results of simulation test 2.*

(the magenta and red dashed lines) curves are close to each other that testifies to accuracy of the ventilation model. The consumed heating energy (delivered by the floor heating and ventilation systems) in a cold period is about 100 kWh/day (the average heating power consumption is 4.16 kW during a day as it reflects the first plot in Fig. 3.16) that is in general agreement with the values given in [23].

Simulation test 2. Performance of the AHP. This test illustrates comparison of the AHP works in heating mode (during October with the same settings as in simulation test 1) with the set temperature $+24^0$C and in cooling mode (with the set temperature $+20^0$C) in the summer with the ambient temperature $T_a = +25^0$C and the solar irradiance pattern for July (Fig. 3.15). The results are shown in the next Figure 3.17.

The first plot shows comparison of the heating demand curves for a cold period when the AHP works only during the last 24 hours of the simulation. As it can be seen, switching on of the AHP leads to decreasing of the heating power produced by the floor heating system. Furthermore, the modeled (the green line in the second plot) and the measured (the dashed magenta line in the same plot) values of the AHP power consumption (for October), given in the second plot, are in compliance. As it is possible to observe from the first plot, difference between the curves for the two cases (with and without the AHP) is not large; therefore, there is not point to use the AHP in heating mode together with the CHS. Though in practice, it can be switched on for a while to increase air temperature quickly (the blue graph in the third plot).

The third plot illustrates behavior of the temperature in space 1 when the AHP works in heating mode (compare the blue and green graphs). As the temperature reaches the set level, heating capacity of the AHP is decreased, and consequently the power consumption is falling (performed by the green line in the second plot). Moreover, according to the curves in Fig. 3.14, increasing of the heat carrier temperature in the AHP condenser (indoor air) causes slight decreasing of power consumption as well.

Another case is cooling mode in July. As it is possible to observe, the room temperatures constantly rise due to influence of solar irradiance (the third plot, the gray curves) and delivering hot air through the ventilation system. The room temperatures can be even higher than ambient $T_a = +25^0$C because solar energy is the input power P_{in} in (3.28), except for the temperature of space 1 (the third plot, the violet curve) because of cooling. The consumed power of the AHP for July is exposed in the second plot (the violet graph), and it has the periodic character due to changing of daily solar irradiance. It is slightly increased as well because of the rise of heating power delivered from the adjacent rooms (they are not cooled).

All before mentioned shows physical adequacy of the given AHP, the house and the ventilation models. It is the equipment associated with indoor air, and the next tests demonstrate work of the GHP and the WAC for producing hot water.

Simulation test 3. Performances of the GHP and WAC. This test illustrates behavior of the most interesting parameters of the water heating system. The simulation has been carried out for the settings given in simulation test 1, that is during January and October. The measurements were carried out for the same time periods and indoor conditions. They are used for estimation of the model accuracy and the DHW consumption profile. These profiles (for January and October) are produced for 2 days on the ground of the peaks of the GHP electric consumption (as it will be seen, there is direct connection between these two variables), that is time of them is fixed, and the values are chosen according to the usual water discharge for family given in [25]. Such approach has been used to achieve better coincidence of the simulated and measured characteristics, namely the consumed electric power by the GHP. For simplicity of performance of the results, which are presented in Figure 3.18, time scale of the simulations is not matched with real time of the day.

Fig. 3.18 shows comparison of the consumed electric powers by the GHP, and it is possible to observe that the modeled (the blue line in the upper plots) and the measured (the dashed red line) values are quite close to each other. Obviously that the modeled characteristics are idealized and do not take into account factors related to presence of humans, as it was explained earlier. Consequently, it leads to discrepancy of the modeled and measured curves. In order to achieve more precise coincidence, thisunpredictable human behavior should be included in the model

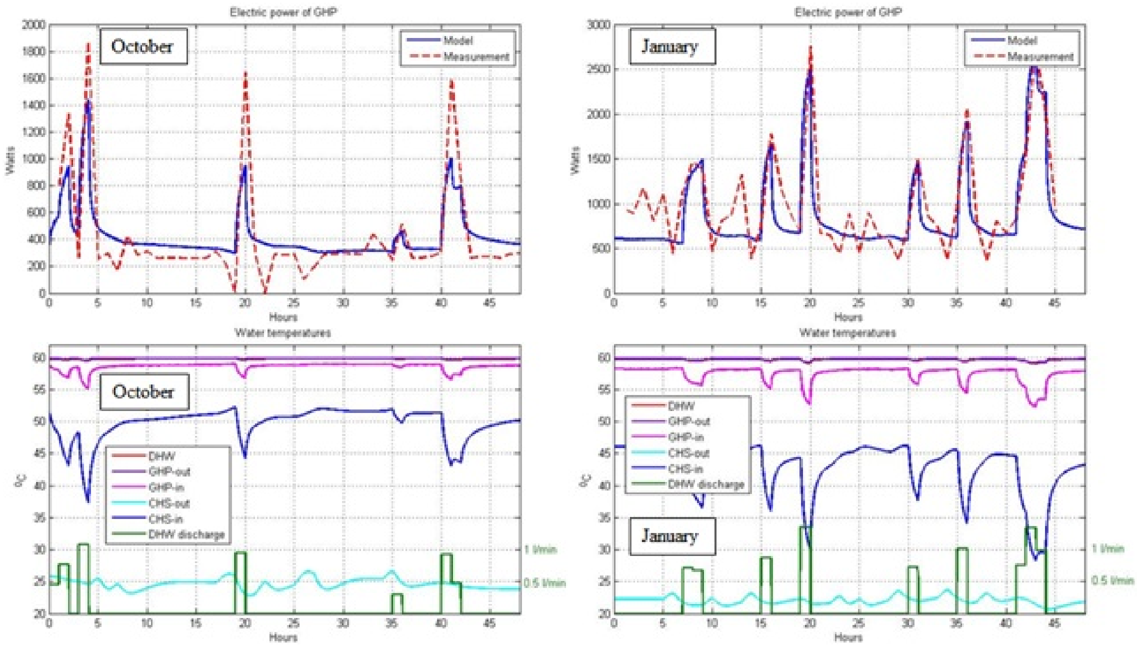

Figure 3.18 *The results of simulation test 3.*

what is hardly feasibly.

The large peaks of the power consumption are caused by usage of hot water for the domestic purposes; the corresponding scaled profiles are presented in the lower plots (the green curves). Thus, the bigger DHW consumption (the volume of water per time), the larger power is needed to heat it up. From the plots with the water temperature the following can be also deduced:

- The temperature of DHW (the red lines in the lower plots called "DHW") is at the desirable level - 60^0C;
- The temperature of the output water flow of the GHP (violet, "GHP-out") is close to this value in spite of the sagging of the return water flow temperature (magenta, "GHP-in"). These pits are covered by increasing of the electric power consumption;
- Falling of ambient temperature causes decreasing of the input water flow temperature in the CHS (blue, "CHS-in", the left and right lower plots can be compared) due to increasing of the heating demand (as it is observable from Fig. 3.16), and consequently the water flow in the CHS. As a matter of fact, the temperature "CHS-in" cannot be higher than 40^0C (the typical optimal value) in case of water floor heating, using the plastic pipes, which do not

withstand high temperatures. Therefore, by the mean of a mixing valve actual temperature after the WAC (from the plots it is $45^0 - 50^0$C) is reduced below 40^0C with respect to such rule: the colder outdoor air, the higher temperature "CHS-in". In order to exclude a bulky and complex model of this hydronic system with mixing equipment, the first simplification mentioned in the beginning of this section has been applied;

- The described event diminishes also the temperature of the GHP return water flow ("GHP-in"), therefore, the total electric power consumption is increased (compare the upper plots);
- The output power flow temperature from the CHS (cyan, "CHS-out") for big water flows in the system (as in January) is less comparing with medium water flows (as in October);
- When the DHW consumption is zero, the electric power of the GHP is minimum, and it is wasted on covering of heat losses of the tank and heating up of the water flow of the CHS.

Simulation test 4. The solar collector performance. In this test the power consumption of the GHP is compared for the two cases - the water tank uses the additional heat exchanger connected with the solar collector (the geometric characteristics can be found in Appendix C) and without this additional heater. Figure 3.19 illustrates it for the July solar pattern (Fig. 3.15), $T_a = +25^0$C and the DHW profile set according to [25].

As it can be seen from the plots above, presence of the additional heater inside the tank has positive effect - the power consumption is decreased (5.6 kWh versus 4.2 kWh for the two days time range). It is seen that the temperature of glycol after the solar collector (the blue line in the second plot called "SC-out") is higher than before (cyan, "SC-in", solar irradiance acts as the heat source) only for the day time (the maximum of solar energy). At the moments with opposite situation ("SC-out" is less than "SC-in") the WAC wastes some insignificant amount of energy for heating of the glycol flow which temperature is close to ambient due to absence of solar irradiance. In fact, at these times the collector can be disconnected from the WAC by shutting a valve.

The conclusion that can be drawn from these analyses of the air and water heating equipment as well as the thermodynamic model of the house is the model behaves quite realistic and reflects real physical processes with sufficiently high precision.

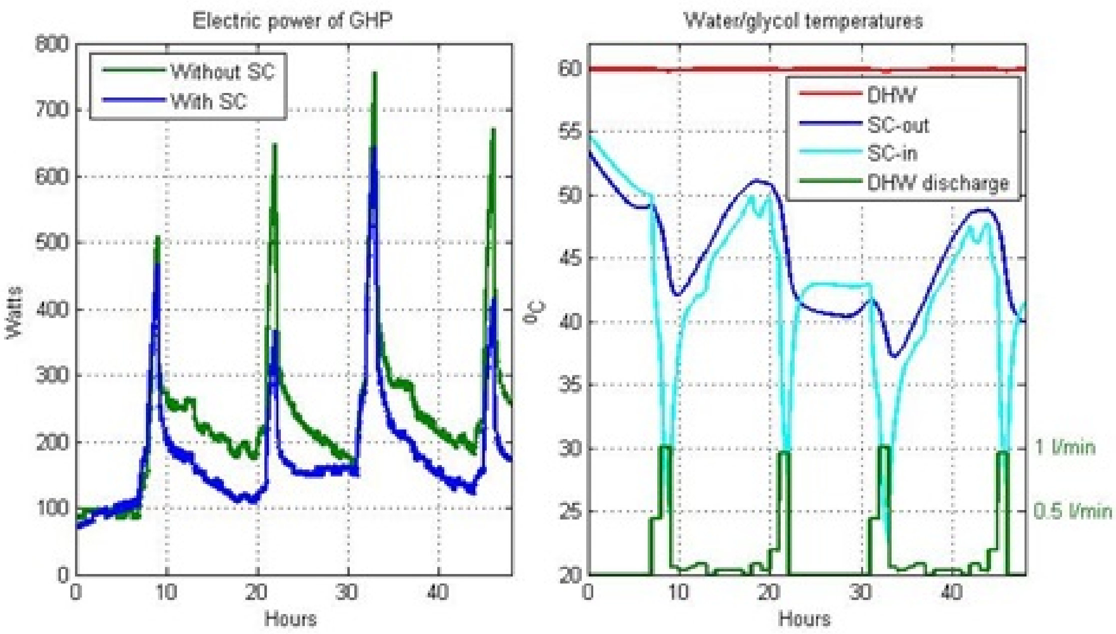

Figure 3.19 *The results of simulation test 4.*

Obviously that this math model is imperfect and built using the many simplifications, but nevertheless its accuracy is enough to be considered as a quite adequate and appropriate tool for further modeling of DR actions.

4. RESULTS AND ANALYSIS

In this chapter the results obtained with the help of the described model are presented. As it was discussed in chapter 3, the constructed model, described and verified in the previous chapter, will be subjected to various DR actions performed in a general way in chapter 2. First of all, the main initial conditions for the tests are presented:

1. In all tests effectiveness of a DR event is estimated as it presented in Fig. 2.1. Generally the term energy and power in this chapter denote only electrical values (they are not related to heat) associated with saved or consumed power/energy from a power network;
2. Duration of an each DR event is determined on the ground of the temperature limitations: for room air it is 22 ± 2^0C, and for DHW it is $+55... + 60^0$C according to [10]. As DHW is produced (heated up) and stored in the water tank, the same temperature limitation $+55... + 60^0$C is used for the WAC;
3. In a DR program only the equipment performed in the beginning of section 3.3 participates. The baseline (Fig. 2.1) for winter DR actions is calculated as the sum of consumed power of the GHP and the air heater (AH) in the ventilation system. During summer DR programs the GHP and the AHP are considered;
4. As power consumption of the GHP depends on a DHW profile, the standard curve is used according to [25] and presented in Figure 4.1;
5. According to Fig. 4.1, the power consumption profile of the GHP will have at least two peaks; therefore, it is necessary for some tests to obtain results for the two different times: peak and off - peak;
6. Customers in the residential sector can be ascribed to one group which is characterized by minimal electric consumption during the night time; therefore, DR actions during this time is not applied in the current thesis because probability of night power peaks which should be reduced is small.

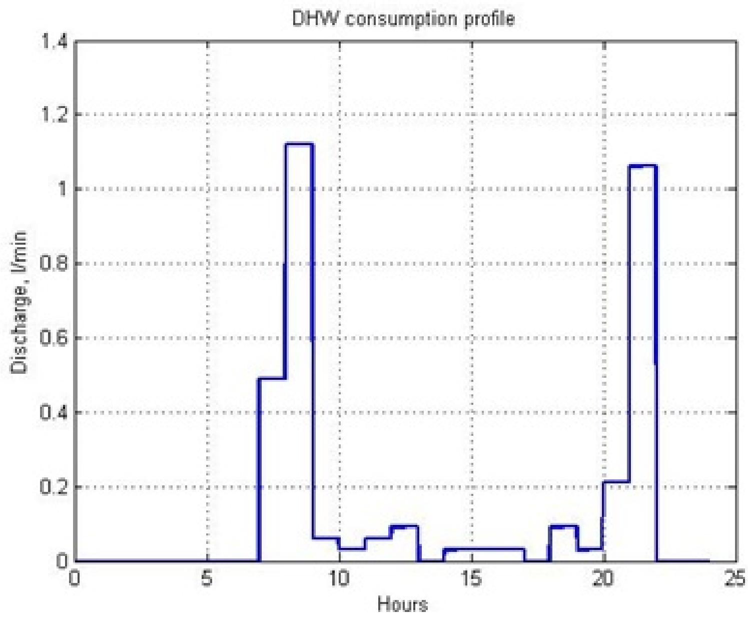

Figure 4.1 *The standard DHW profile.*

4.1 Changing of ambient conditions

First of all, it is of interest to estimate an amount of energy that can be saved due to natural dynamic of environmental conditions such as oscillations of ambient temperature and solar irradiance. Figure 4.2 illustrates the consumed electrical energy during a day in compliance with the different ambient temperatures from September to January (during this period solar irradiance is supposed to be zero) for the room temperature $T_r = 22^0$C. During this period the following electrical equipment works: the ground heat pump and the air heater in the ventilation system; the standard DHW profile is used (Fig. 4.1).

The obtained values of the consumed energy (the dots in the plot) are combined through the approximated curve (valid for $|T_2 - T_1| \leq 5^0$C, where T_1 and T_2 are the current and predicted for the next day in the day - ahead market temperatures correspondingly) which is described as:

$$E = -0.4778T_1 + 19.589, \text{ [kWh/day]} \tag{4.1}$$

More convenient to use difference of the consumed energies in compliance with the temperature difference $T_2 - T_1$ for various times:

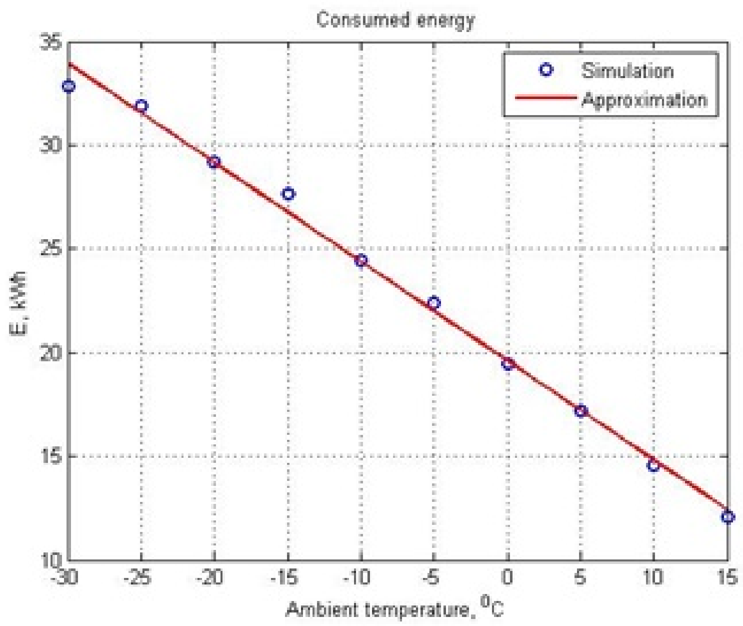

Figure 4.2 *The consumed energy during the cold period.*

$$\Delta E = -0.4778(T_2 - T_1), \text{ [kWh/day]} \tag{4.2}$$

This value depends only on the ambient conditions and does not require information about arbitrary variations of the interior environment (switching appliances, additional losses and heating etc.). Considering different conditions of ambient temperature changing, the consumption of energy can be increased ($\Delta E > 0$) or decreased ($\Delta E < 0$). Having actual energy consumption and its natural (because of ambient conditions) variation ΔE helps to predict future energy demand for a specific house and to improve a power profile, flattering it, namely:

- An unused ($\Delta E < 0$) amount of energy delivered to a customer can be stored or applied to cover peaks;
- Overconsumption ($\Delta E > 0$) will be expected in energy scheduling of a house that allows avoiding emergency situations by the mean of foreseeing planning (e.g. utilization of the previously stored energy).

Analogously, summer time is modeled when instead of the air heater in the ventilation the air heat pump is used (in cooling mode) with the setting $+20^0$C.

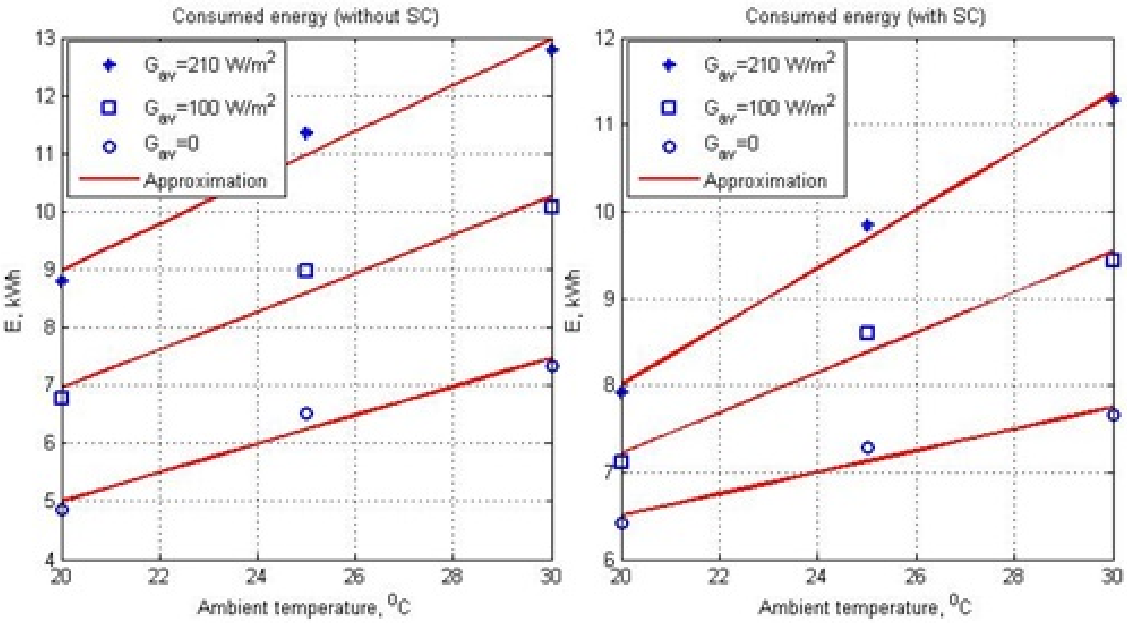

Figure 4.3 *The consumed energy during the warm period.*

Figure 4.3 shows the changing of the energy (required for the GHP and AHP) according to the ambient temperatures and the daily average solar radiation G_{av}.

The increasing of the energy (the blue points in the plots) is connected with the consumed power rise of the air heat pump because of the ambient temperature growth. These points for the case without the solar collector (SC) can be approximated by the following expressions (the red line is the approximation line):

$$
\begin{aligned}
E &= K_1 T_1 + K_2, \ \text{[kWh/day]} \\
K_1 &= -0.72 \cdot 10^{-3} G_{av} + 0.4, \ [\text{kWh/day/}^0\text{C}] \\
K_2 &= -4.53 \cdot 10^{-3} G_{av} + 0.95, \ \text{[kWh/day]}
\end{aligned} \tag{4.3}
$$

Thus, the difference in the consumed energies in compliance with changing of the ambient temperatures and average irradiance can be expressed from this equation (4.3) for predicting electricity demand for the next time.

Changing of solar radiation affects also required energy for water heating because, as it is described before, the solar collector contour takes place in the water tank. Comparing the plots in Fig. 4.3, it is possible to notice the falling of the required energy. The coefficients K_1 and K_2 of these plots are described as:

$$
\begin{aligned}
K_1 &= -10^{-3}G_{av} + 0.34,\ \ [\text{kWh/day}/^0\text{C}] \\
K_2 &= 12.94 \cdot 10^{-3}G_{av} + 1.28,\ \ [\text{kWh/day}]
\end{aligned} \tag{4.4}
$$

Thus, dynamic of environmental conditions, especially ambient air temperature during a cold period of the year, can be taken into account and considered as an additional opportunity for day - ahead DR actions. During summer time saved electrical energy is comparatively low, and an affecting factor here, besides ambient temperature, is solar irradiance; though, warm time is under consideration because a final amount of energy depends on a number of consumers with whom the system operator has an agreement about DR programs. It should be noticed that all expressions derived in this section are valid only for the chosen parameters (collected in Appendix C) describing the existing equipment.

4.2 Shut off actions

In this section shut off actions together with preheating and individual control strategies are considered. As it was performed earlier, shut off actions are one of the directions of DR programs. They imply switching off of electrical or another equipment, which can affect electricity utilization, in order to decrease power consumption at a certain time determined by the system operator. Specifically, in this work all possible heating equipment is considered including not only electrical, but water type such as the floor heating system and solar collector for summer time. Below the following tests for shut off actions are performed:

1. Test 1. Only the water type equipment that affects indoor air is considered. It is the water floor heating systems in the rooms regulated by the local thermostats individually for the each room. The room heatings are switched off in the different places and switched on back on the ground of the air temperature limitations 22 ± 2^0C;

2. Test 2. The same type of equipment is considered. The purpose of this test is to find ways of increasing of a DR event (from Test 1) duration which is limited by the room air temperature. Here other opportunities for DR strategies are performed such as: the preheating and individual control strategy for the floor heating equipment;

3. Test 3. This test includes the water type equipment (floor heating) together with the electrical appliances (the GHP and AH) as well as only the electrical

equipment and their combination. Here the time limitation of a DR event is caused by the room air (22 ± 2^0C) or the DHW temperatures ($+55...+60^0$C);

4. Test 4. Studying summer time DR actions with only the AHP. The limitations are the room air temperatures;

5. Test 5. Including in the summer DR events the electrical equipment, namely the GHP and AHP as well as studying of solar collector impact on DR event duration. As in Test 3, the limitations are the room air or the water temperatures.

4.2.1 Test 1

The test's setups are: the initial conditions described at the beginning of this chapter; the start time of the DR action is 7 a.m. that corresponds to the maximum of the DHW consumption (Fig. 4.1), and consequently the peak electricity consumption of the GHP (the basic equipment for water heating). The stop time is determined by the first room where the air temperature achieves $+20^0$C. The initial room temperature is $+22^0$C. The test is managed for the conditionally constant ambient temperature -24^0C (January) and zero solar irradiance (the level is comparatively low for this time of the year, Fig. 3.15).

The considered cases:

1. The thermostat only in one room switches off room heating;
2. The thermostats in the two rooms switches off room heating;
3. The heatings in all rooms in the first floor (Fig. 3.1) are shut off;
4. The heating of the whole house is switched off.

The simulated results of these cases are performed in Figure 4.4. In this figure plot 1 shows the power consumptions for all above listed cases in comparison with the baseline (no DR action). The power in this plot is the sum of the GHP consumed power and by the air heater in the ventilation system. Plots 2 - 5 illustrate behavior of the room temperature for the cases from 1 (corresponding plot 2) to 4 (corresponding plot 5). Plots 6 - 9 demonstrate the difference in the hourly consumed energy ΔE (between the baseline and the actual consumption for the each case, Fig. 2.1) for cases 1 - 4 correspondingly. Any another time span, which is less than the one hour,

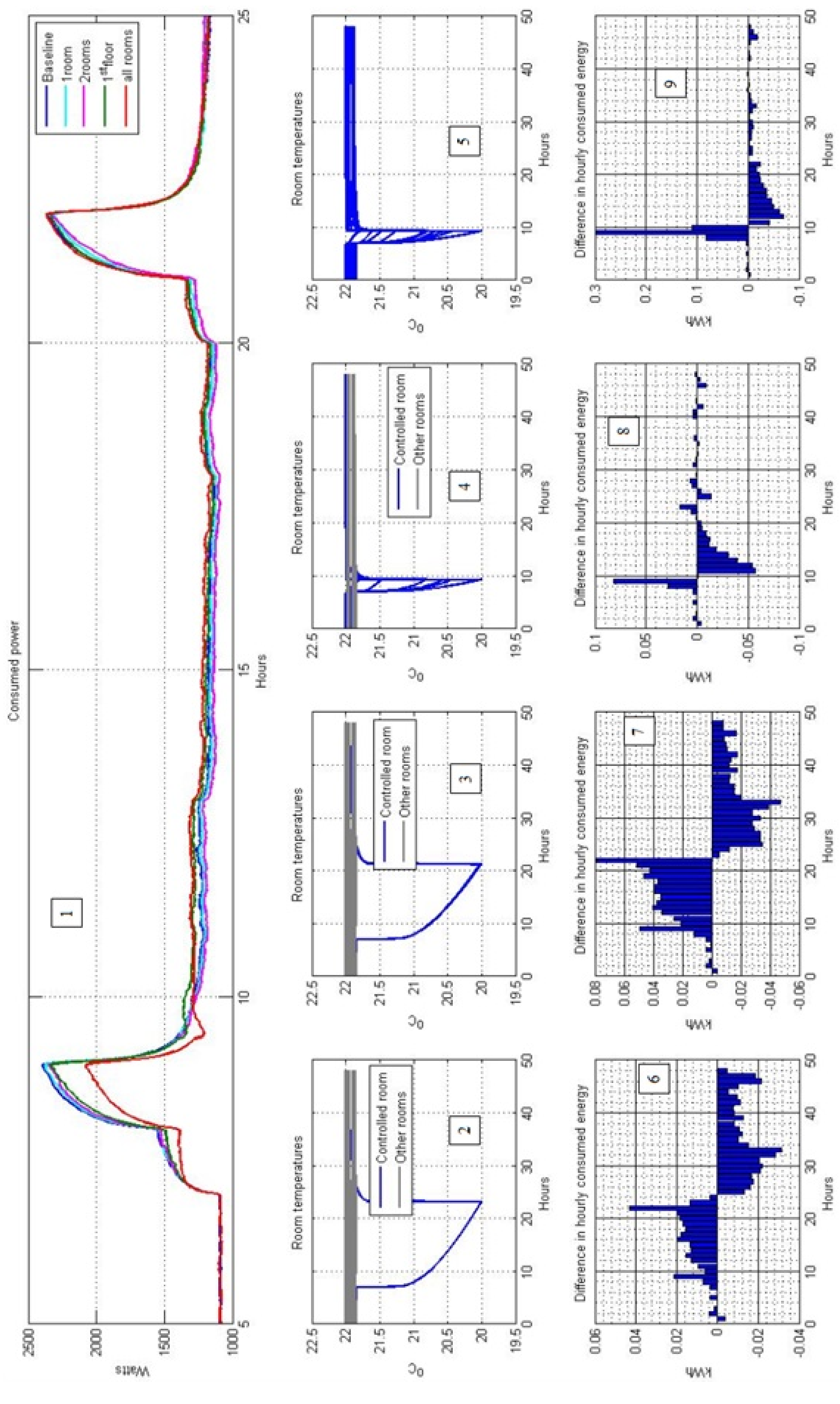

Figure 4.4 *The results of Test 1.*

gives a smaller amount of energy during this period, but more columns in plots and vice versa for bigger time spans.

Such representation is convenient because, firstly, the day - ahead electricity market uses the hourly prices of electrical energy and, secondly, energy consumption during one hour (unit is [kWh]) numerically equals to the average power for this hour (unit is [kW]). It allows also calculation of the average power for any duration of time (adding the energy of an each column and dividing this value by the number of the summed columns). Moreover, the moment of changing of sign of the energy (from positive to negative) reflects the stop time of a DR event because when the difference in the energy greater than zero ($\Delta E > 0$), it means saving of energy, and less ($\Delta E < 0$) means overconsumption (greater than the baseline) or pay - back energy. This pay - back energy is consumed in the recovery period (Fig. 2.1) in order to heat up a room again up to $+22^0$C.

In plots 6 - 9 any small deviation of the difference in the consumed energy before the DR event or long time after the stop time is caused by the numerical calculation errors during the data processing and by the simulations with the different time step sizes.

Analysis of Test 1

Analyzing these plots, it is possible to conclude that:

- As it is seen from plot 1, the bigger the number of the rooms, the more significant decreasing of the peak. Looking at the baseline curve, it is seen that the power demand before the DHW peak is about 1.1 kW (about 650 W of the GHP and 450 W of the AH) and during the peak - about 2.4 kW, that is power 1.3 kW ($2.4 - 1.1$) is wasted for the DHW and room heatings. Switching off of the heating, for instance in all rooms (the last case, the red line), leads to the peak reduction by 300 W. The rest 1 kW ($1.3 - 0.3$) is used for the DHW heating and losses compensation: external, that is through the heat insulation and internal - heating the lower cold layers inside the tank (the multilayer structure of the WAC model Fig. 3.10). Moreover, situation is worsened because of the moving cold water masses (the water consumption peak) inside the tank;
- Looking at plots 2 - 5, it is observable that the DR duration is larger for the small amount of the rooms (time during which the room air temperature(s) reach(es) $+20^0$C) due to less heat losses (the less area);

- The further calculations (according to plots 6 - 9) can reveal the numerical values for cases 1 - 4 which can be found in Table 4.1. This information can be useful for foregoing analyses;

Table 4.1 *The numerical values of Test 1.*

Case	**Saved energy[1], kWh**	**Saved power[2], kW**	**Maximum power[3], kW**	**Duration, h**
1	0.27	0.016	0.044	17
2	0.6	0.04	0.08	15
3	0.11	0.055	0.08	2
4	0.5	0.16	0.3	3

1. Hereinafter, it is determined as the sum of the hourly saved energies in Fig. 4.4 during the DR event. 2. Hereinafter, it is determined as the average value for the whole event. 3. The maximum available power during an hour.

- As only the GHP and AH are considered, the amount of the saved energy is not high - the largest hourly value for the last case (plot 9) is 0.3 kWh (0.3 kW is also the maximum available power for this DR action). However, the duration of the DR event is the shortest;

- The most appropriate case is the fourth for events when a large amount of power is requested during a short time. It gives also the comparatively low level of the pay - back energy;

- The other cases are suitable for long lasting DR actions, with the exception of the third case when heat losses are significant, and therefore the DR duration is short. It is also concerned cases where a number of the participating rooms is more than the half of all rooms in the house;

- For a number of the rooms (participating in a DR event) which is less than the half of all (the available rooms for controlling in the house), the following regularity is valid: power utilized from the N_2 rooms is higher than from the N_1 rooms, where $N_2 > N_1$. However, the pay - back period is quite large. For a number of the rooms greater than the half of all, a reduction of a DR event duration takes place.

Figure 4.5 contains also information about the total saved and the pay - back energies for the considered cases.

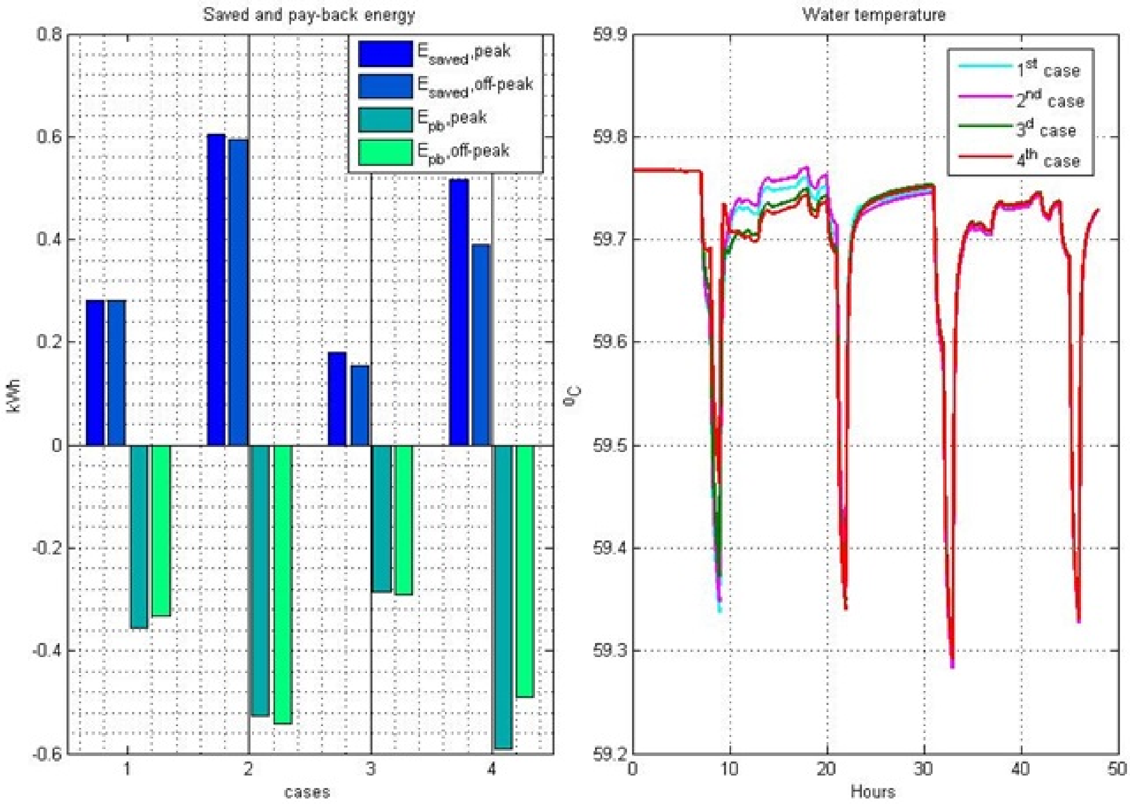

Figure 4.5 *Comparison of the results of Test 1.*

Off - peak DR actions

As in the DR events considered in Test 1 only the air heating equipment participates (the AH and the floor heating systems), that is the appliances which do not affect water temperature, then there is no point to carry out shut off actions for the moments after the peak of the DHW consumption (Fig. 4.1). The reason here is that the cases above do not affect the DHW temperature too much (it is in the range $+55...+60^0$C), but the saved energy for an off - peak time is less (or the same) than for the peak time. Fig. 4.5 clarifies this point. In this figure the pay - back energy is calculated as the sum of the hourly saved energies in Fig. 4.4 for the times after the DR event.

As it is seen from Fig. 4.5, the summarized energy for case 4 is even less than for case 2; though the saved power is notable larger (Table 4.1). The reason of that is the short DR duration (Fig. 4.4, plots 8 - 9) for the cases with the big number of the regulated rooms. In order to enlarge the saved energy, there are two ways: the preheating actions and the individual control approach. The first one, as it was explained earlier, implies increasing of the indoor temperatures within the tolerated range before a DR event, and the second is a separate tracking of an each room temperature (switching on of a heating back only in a specific room where an air temperature has already reached $+20^0$C, and the heatings in other rooms continue to be shut off). These approaches are probated in Test 2.

4.2.2 Test 2. Preheating and individual strategies.

The test's setups are: the same as in Test 1. Exception is the stop time of a DR event for some cases performed below.

The considered cases:

1. The indoor air temperatures in all rooms are increased up to $+24^0$C before the DR event starts (3 hours in advance);
2. The DR event stops (completely for the whole house) when the air temperature reaches $+20^0$C in the first three rooms;
3. Combination of the preheating and individual control strategies.

Figure 4.6 demonstrates these cases. In this figure plots 1 - 3 (the corresponding cases are from 1 to 3) show the room temperatures and 4 - 6 (the corresponding cases are from 1 to 3) the difference in the hourly consumed energy.

Analysis of Test 2

Looking at the plots in Fig. 4.6, it can be seen that:

- Case 1 demonstrates the increasing of the room temperatures (plot 1) before the DR event and, as a consequence, the consumed energy (plot 4). Furthermore, there is no pay - back energy due to the short time of the event during which not all temperatures have reached the level less than $+22^0$C, and these rooms do not require heating power (after the stop time of the DR action) which is used to compensate pay - back power for the other rooms;
- Case 2 (plots 2 and 4) can be directly compared with Test 1 (plots 5 and 9 in Fig. 4.4) - the DR event duration and the amount of the energy have notably been increased;

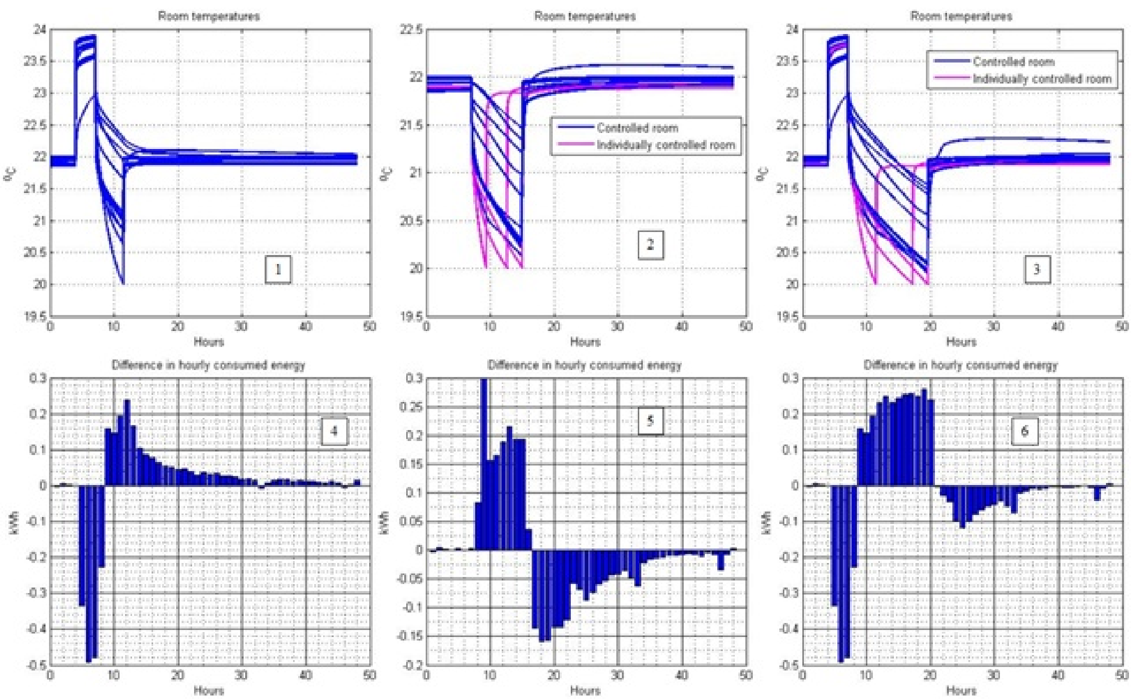

Figure 4.6 *The results of Test 2.*

- The last case 3 (plots 3, 6) combines advantages of the previous two, and as a result it is possible to get the high level of the saved and the low level of the pay - back powers. Furthermore, the first hour of the DR action according to plots 4 and 6 represents consumption of the energy instead of saving (the forth column in the preheating period is negative, whereas it must be the three negative columns that corresponds the three hours of preheating). The reason here is that the baseline does not have this additional power consumption for the preheating actions that gives such discrepancy;

Moreover, analyzing these plots and comparing them with Test 1, case 4 (Fig. 4.4, plot 9), that is shutting off of the thermostats of all rooms in the house, it is possible to indicate for case:

1. The preheating action allows to increase the total saved energy only slightly as much as 4.66% (0.5 kWh versus 0.52 kWh), and the maximum power is decreased up to 0.24 kW. The saved power due to the extension of the DR event duration is reduced to 0.1 kW (versus 0.16 kW in Table 4.1 case 4). In order to increase the indoor temperature of the house up to $+2^0$C, it is needed to over consume 1.3 kWh energy (during 3 hours). However, this case demonstrates saving of the energy even after the DR event (up to 1.15 kWh), and therefore it is very good strategy in pay - back point of view;

2. Having, for example, the three rooms with the individual control system can increase the saved energy as much as 211.5% more (0.5 kWh versus 1.53 kWh) with the same maximum power. Though the statement that the bigger a number of the rooms with the individual control, the larger energy can be saved, is valid only for the eight rooms (the half of all); after this number pay - back energy of the rooms escaped from the DR event will be more than energy saved by the other rooms where the air temperature has not reached yet $+20^0$C (still participating in the DR event). The maximum possible energy harvested using such approach is 2.11 kWh (330.3%);

3. The combination of the preheating actions and the individual control approach yields the total saved energy (for the three rooms with separate regulation) 2.5 kWh (the increase is 63% comparing to the previous case) and the short pay - back period. The saved power for case 2 is 0.17 kW, whereas for this case is 0.192 kW due to the DR duration rise. This case can be considered as the most valuable because of the minimal pay - back energy (among the other in this and the previous test) and the extended duration of the DR event (in spite of the small reduction of the maximum available power).

As we can see from Test 1 and Test 2, governing only the water type air heating equipment (the floor heatings regulated by the thermostats) allows achieving the maximum power levels less than 0.3 kW. In order to enlarge this number, the electrical equipment can participate in the DR events, namely the air heater (AH) in the ventilation system and the ground heat pump. The next Test 3 performs this approach.

4.2.3 Test 3

The test's setups are: the same as in Test 1. Additionally, the electrical equipment (the GHP and AH) is participating in the DR events. In this test the stop time is determined on the ground of achieving by a room temperature the level $+20^0$C or by the DHW temperature the level $+55^0$C.

The considered cases:

1. Switching off of the air heater (AH) in the ventilation system for the three hours;

2. Repetition of case 4 in Test 1 (all rooms are under the DR action), with the exception of adding of the AH as the equipment under the DR event;

3. Shutting off of the GHP, and it is assumed that the CHS does not work during this action;

4. The GHP and AH are curtailed together.

The results of Test 3 are presented in Figure 4.7. Where, as in Test 1, plot 1 shows the power consumption of the GHP and AH for all cases. In this plot the end time of the DR event (a duration is easily detected as a time during which the consumed power curve is less than the baseline) is followed by the peak of the power consumption caused by back switching of the electrical equipment. Plots 2 - 5 illustrate the room and DHW temperatures for the cases from 1 (corresponding plot 2) to 4 (corresponding plot 5). Plots 6 - 9 demonstrate the difference in the hourly consumed energy for cases 1 - 4 correspondingly.

Analysis of Test 3

Analyzing the plots in Fig. 4.7, the following can be concluded:

- Plots 2 and 6 (case 1) demonstrate switching off of the AH, and as it can be seen, this case does not have the pay - back period. However, the reason here is the short time of the shut off state (only the three hours) during which heat energy stored in the materials of the house is enough to support optimal conditions. Increasing the duration, it is possible to achieve a situation when the room temperatures start to fall (due to incoming cold air through the ventilation system) and power consumption of the GHP will rise (due to increasing of heating demand) causing the pay - back period;

- Plots 3 and 7 (case 2) can be directly compared with plots 5 and 9 in Fig. 4.4 (Test 1, case 4). The difference is shutting off of the AH that leads to shortening of the DR event (due to incoming cold air through the ventilation system that forces to decrease the room air temperature faster), but the saved power is increased. The corresponding numerical values can be found in Table 4.2 and compared with the values from Table 4.1;

- Plots 2 - 5 contain also information about the DHW temperature, and as it was stated earlier, the air heating equipment does not affect it (cases 1 and 2);

- Considering plots 4 (case 3) and 5 (case 4), it is seen that switching the GHP causes the DHW temperature falling (the admissible level is $+55^0$C), and it

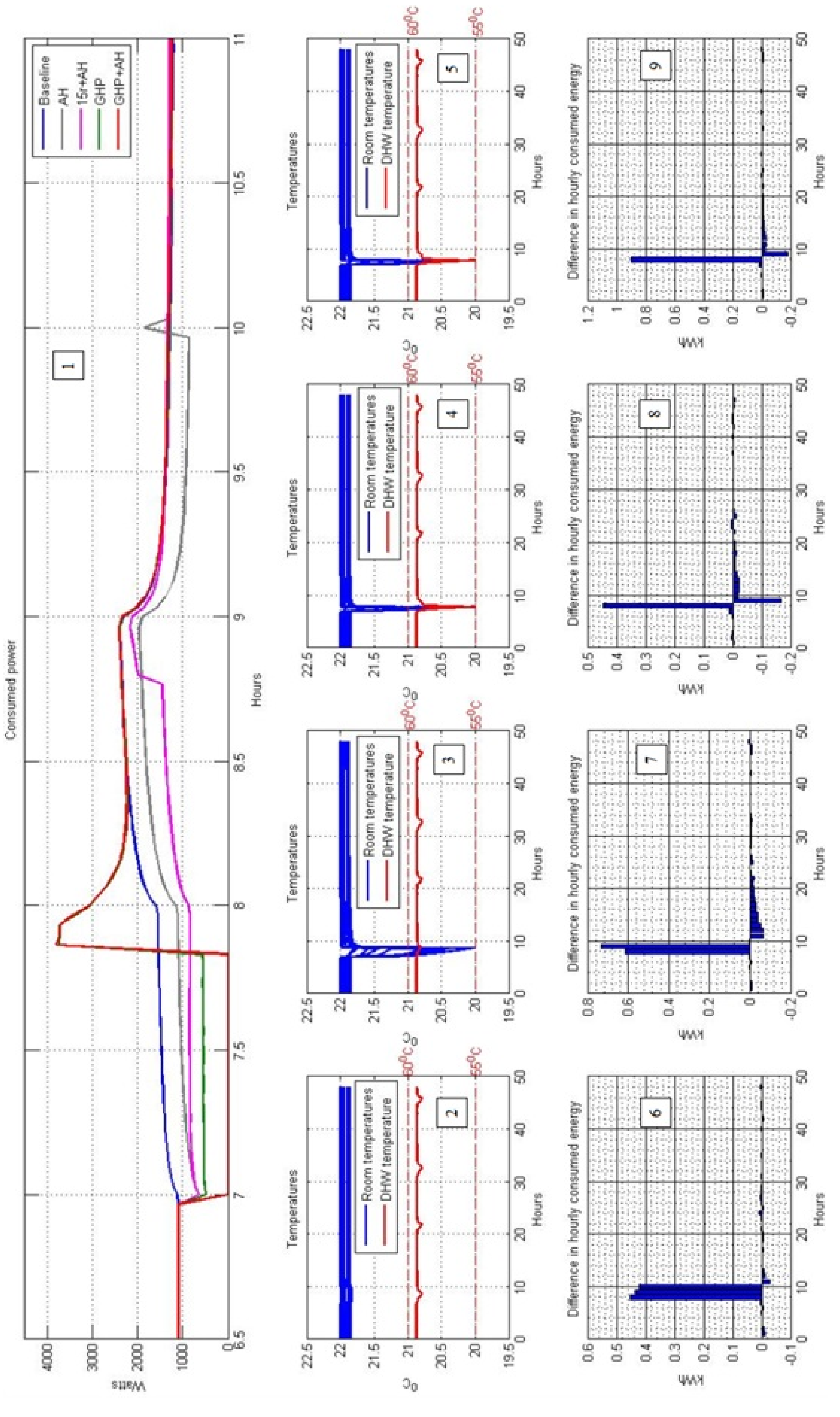

Figure 4.7 *The results of Test 3.*

determines the DR action duration. As it is followed from these plots, during this time the room temperatures do not reach +20^{0}C;

- Including the AH in the DR actions in case 4, in comparison with case 3, helps to achieve the bigger level of the saved power. The calculations for all cases are gathered into Table 4.2.

Table 4.2 *The numerical values of Test 3.*

Case	Saved energy, kWh	Saved power, kW	Maximum power, kW	Duration, h
1	1.31	0.44	0.43	3
2	1.35	0.45	0.75	3
3	0.45	0.45	0.42	1
4	0.9	0.9	0.9	1

The simulations have also revealed that moving the start time of the DR event to the minimum of the DHW consumption (for example, 9 a.m. according to Fig. 4.1), or even applying the zero level of discharge, leads to much slower DHW temperature decreasing as much as 7 - 9 hours from +60^{0}C to +55^{0}C. Therefore, the stop time of the DR action will be again determined by the room air temperatures (they fall faster) as in Test 1, case 4 (Fig. 4.4) because of the nonworking CHS during the GHP shutting off.

Lastly, there is no opportunity to preheat DHW more than +60^{0}C (for the given model because water tanks with electric heaters allow doing it) because the output flow temperature of the GHP is fixed by the producer.

Comparison of the tests

Figure 4.8 illustrates comparison of all considered tests and their cases for the ambient temperatures $T_a = -24^0$C and $T_a = -15^0$C. Results for other temperatures can be derived trough the linear interpolation because, as it seen from Fig. 4.2, the consumed energy by the house is in the proportional dependency on the outdoor air temperature.

Analysis of Fig. 4.8 has revealed for case (the place on the horizontal axis of the histogram) number:

1. Test 1, case 1. The saved power from the one room is about 0.016 kW and varies with the ambient temperature not significantly (0.013 kW). The energy

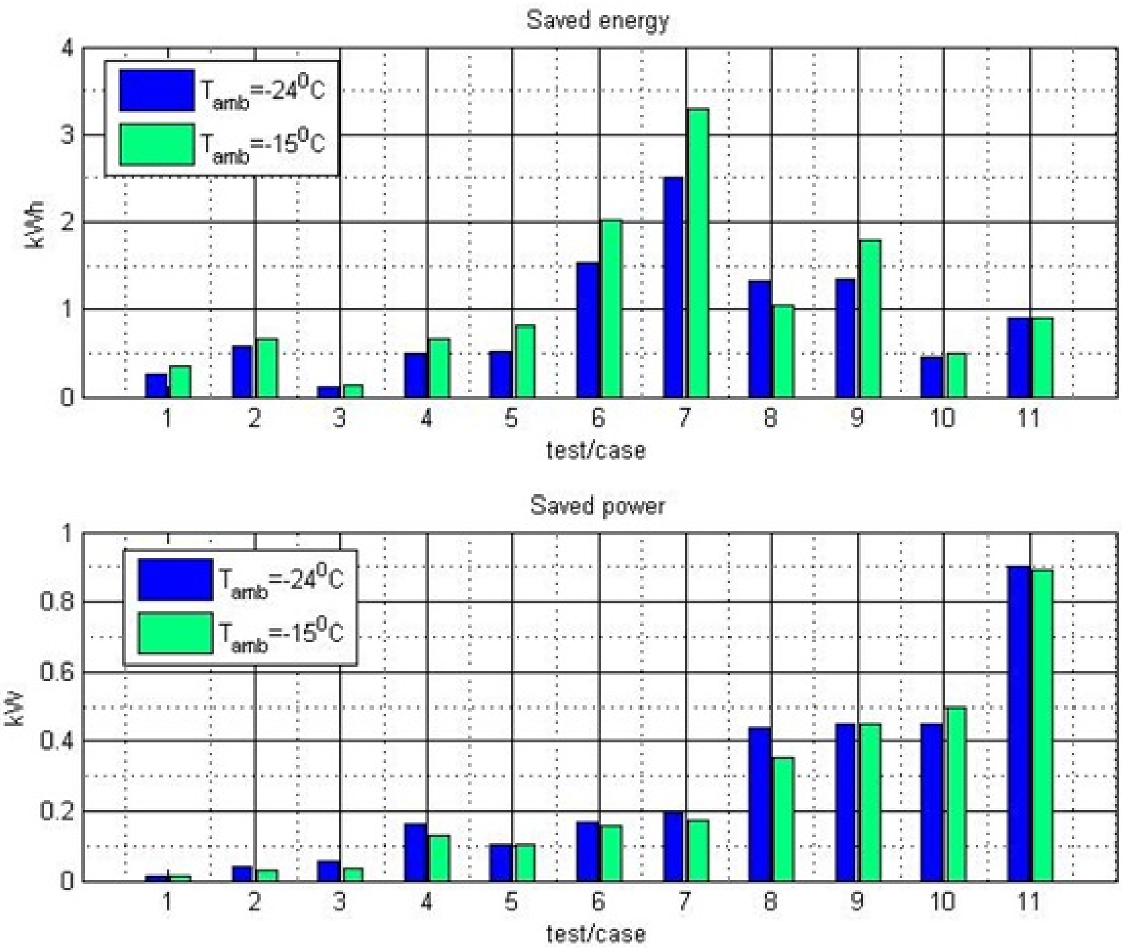

Figure 4.8 *The saved energy and power for the different tests.*

is slightly increased (from 0.27 kWh to 0.35 kWh for $T_a = -24^0$C and $T_a = -15^0$C correspondingly) with the rise of the outdoor air temperature (due to falling of heat losses);

2. Test 1, case 2. For the two rooms the saved power is larger, about 0.04 kW. The difference in it for the various ambient temperatures is more notable (0.027 kW). The reason here is decreasing of electrical energy consumption for the house heatings due to falling of losses and the DR event duration rise; therefore, the energy is increased (from 0.6 kWh to 0.67 kWh for the two ambient temperatures as in the previous case). This conclusion concerning the energy for the warmer temperature (influence of losses) is valid for the rest cases;

3. Test 1, case 3. The power harvested due to the regulation of the whole first floor (0.055 kW and 0.033 kW for the two temperatures) is higher than in the previous cases; however, the DR action duration is reduced due to rise of heat

losses, and the energy is 0.11 kWh and 0.13 kWh;

4. Test 1, case 4. The biggest amount of the power (comparing to the previous cases) is delivered regulating all rooms in the house (0.16 kW and 0.13 kW for $T_a = -24^0$C and $T_a = -15^0$C respectively). From cases 1 - 4 it is followed that the greater a number of the rooms, the larger power can be curtailed. The energy is about 0.5 kWh and 0.66 kWh (hereinafter, the two numbers are related to $T_a = -24^0$C and $T_a = -15^0$C respectively);

5. Test 2, case 1. The preheating action yields the small increasing of the energy (0.51 kWh and 0.82 kWh) and the decreasing of the average power comparing with case 4 (0.1 kW and 0.1 kW). However, it has an inarguable advantage - the minimal level of the pay - back energy;

6. Test 2, case 2. The individual control approach for the three different rooms leads to the slight increasing of the saved power (compare with 4 and 5 that have the same initial settings) 0.17 kW and 0.155 kW. Though, the energy raises somewhat - 1.53 kWh and 2.02 kWh;

7. Test 2, case 3. As it was performed earlier, the combination of cases 5 and 6 has emerged the biggest level of the saved power available through the controlling only the water type heating equipment (the floor heating systems with the thermostat control) - 0.19 kW and 0.17 kW; as well as the energy among all cases - 2.5 kWh and 3.3 kWh;

8. Test 3, case 1. This case is valuable only during short times (less than the three hours) in order to ensure the zero pay - back energy. As it will be shown, this case can be used for minimization of the pay - back period and power. Nevertheless, it helps to curtail the power 0.44 kW and 0.35 kW as well as the energy 1.31 kWh and 1.06 kWh;

9. Test 3, case 2. This case includes the electrical equipment in the DR event with the water type equipment, namely the air heater. Usage of it decreases the DR action duration, but because of the considerable amount of the saved power - 0.45 kW and 0.45 kW, the saved energy has also the big values (comparing with case 4) - 1.35 kWh and 1.8 kWh.

10. Test 3, case 3. The shut off action of the GHP yields the quite large amount of the saved power - 0.45 kW and 0.5 kW. In spite of this, a time limitation factor is the temperature of DHW; therefore, the amount of the energy is low - 0.45 kWh and 0.5 kWh. The difference in the energies for $T_a = -24^0$C and $T_a = -15^0$C cannot be high (but it exists due to ground temperature variations,

and consequently the glycol temperature and the GHP performance) because the end time of the DR event is determined by the water temperature and for various months it is almost the same;

11. Test 3, case 4. This case performs the combination of cases 8 and 9; therefore, the amount of the energy and power is increased: 0.9 kWh and 0.89 kWh; 0.9 kW and 0.89 kW.

From Fig. 4.8 it is seen that from one case to another the saved power is increased. Basing on the amount of the saved power, the most significant case is the combined curtailing of all electrical equipment (it means the GHP and AH), that is case 11; however, it is limited by the DR event duration. Though, in energy point of view, the most desirable is case 7 - the combination of the preheating and individual control approaches which, apart from that, has the minimal pay - back amount of the energy (comparing with cases 1 - 6).

General thoughts about what kind of a strategy should be chosen are performed in last chapter 6 of the given work. The common recap which can be drawn from here is that a requested by the system operator amount of power must be less than a possible available value from the house, and it has to correlate with a corresponding rate of energy (associated with a DR action duration).

4.2.4 Test 4

Equally, as in the previous sections, summer DR actions can be implemented. The possible equipment is: the air heat pump in space 1 for cooling air and the ground heat pump for DHW heating. Apart from that, influence of solar collector presence can be studied, as it is done in section 4.2.5.

The test's setups are: the initial conditions described at the beginning of this chapter; for this test the start time of the DR action is the middle of the day (12 p.m.) because it corresponds to the maximum of the solar irradiance pattern (Fig. 3.15), and therefore the peak of the AHP power consumption; the end time is determined by the air temperature in space 1 (Fig. 3.1) when it reaches $+22^0$C; the temperature setting of the AHP is $+20^0$C, the other rooms are not cooled and the temperatures are not observed; ambient conditions are varied as the different ambient air temperatures $T_a = +25^0$C and $+30^0$C, as well as the solar irradiance set for July (Fig. 3.15) is changed from 100% to 90%.

The considered cases:

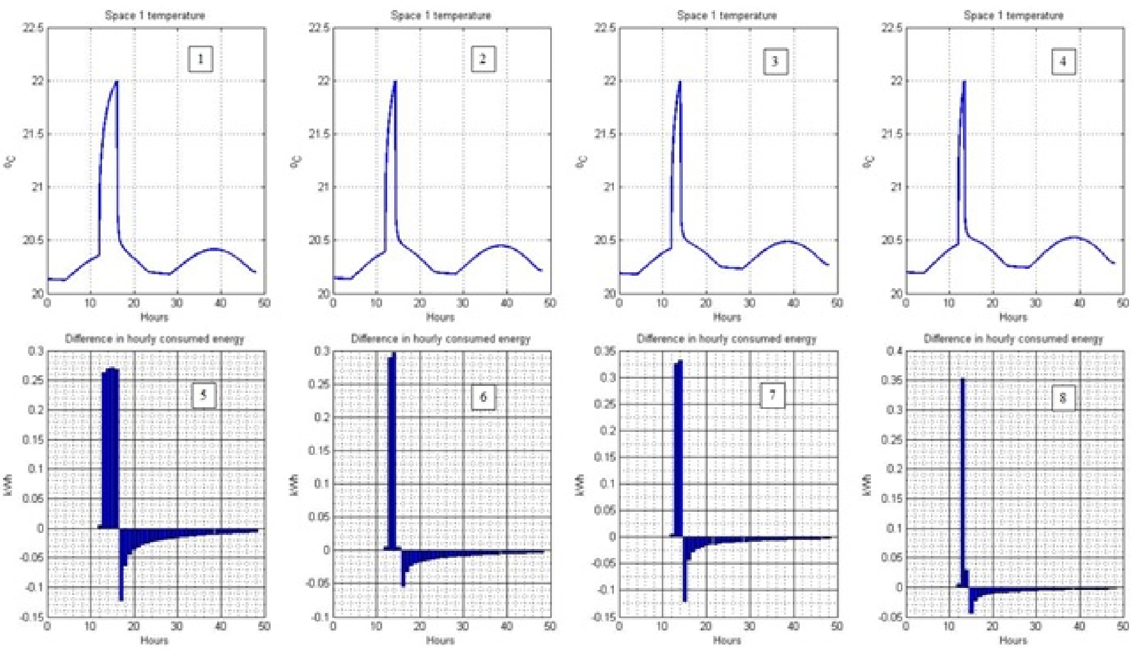

Figure 4.9 *The results of Test 4.*

1. $T_a = +25^0$C, the average daily irradiance is 90% from $G_{av} = 210$ W/m^2 (the value for July), that is $G_{av} = 190$ W/m^2;
2. $T_a = +25^0$C, $G_{av} = 210$ W/m^2;
3. $T_a = +30^0$C, $G_{av} = 190$ W/m^2;
4. $T_a = +30^0$C, $G_{av} = 210$ W/m^2.

The results of Test 4 are presented in Figure 4.9. Where plots 1 - 4 present the variances of the air temperature that denotes also the DR event duration. Plots 5 - 8 illustrate the difference in the consumed energy due to the DR action which is only calculated for the two appliances (the heat and cooling producers) that work during the summer - the GHP and AHP. Plots 1 and 5 are related to case 1, plots 2 and 6 to case 2 and so on.

Analysis of Test 4

Analysis of the plots in Fig. 4.9 leads to the common conclusions:

- For the concrete ambient temperature the solar irradiance increasing leads to the DR event duration and the saved energy shortage: 1.07 kWh for case 1, 0.6 kWh for case 2;

- The ambient temperature rise causes the increasing of the required power for the AHP and, as it is seen from plots 3 and 7, the saved power is getting larger comparing with cases 1 and 2. However, due to the increasing of the temperature difference between the ambient and room temperatures, achieving of the level $+22^0$C becomes faster that decreases the DR event duration. Thus, the energies are: 0.66 kWh for case 3 and 0.38 kWh for case 4. As it is seen, the decreasing of the energy with the irradiance growth is also valid;
- It is seen from the plots that the amount of the saved power for the considered cases is in the range from 0.25 kW to 0.35 kW (the other numerical values can be found in Table 4.3), and it rises constantly from one case to another in compliance with the ambient conditions. It means that for this strategy the amount of the saved power depends totally on the environmental conditions;
- On the ground of the linear dependency performed in Fig. 4.3, other cases with dissimilar temperature and irradiance can be extrapolated using the linear law.

The saved power level can be extended in the same way as it was performed in the previous tests, namely including in the DR event additionally the GHP as it is presented in the test below.

4.2.5 Test 5

The test's setups are: the same as in Test 4, with exception of the GHP presence undergoing the DR action. Moreover, the cases are implemented in comparison with each other at presence and absence of the solar collector connected to the water tank.

The considered cases: the ambient conditions are the same as in Test 4. The each case from Test 4 is repeated for the connected and disconnected water solar collector. The results are performed in Figure 4.10 where all plots reflect the difference in the hourly consumed energy (calculated for the AHP and GHP) for the two cases (with and without the SC).

Analysis of Test 5

Looking and comparing the plots in Fig. 4.10, it is possible to conclude that:

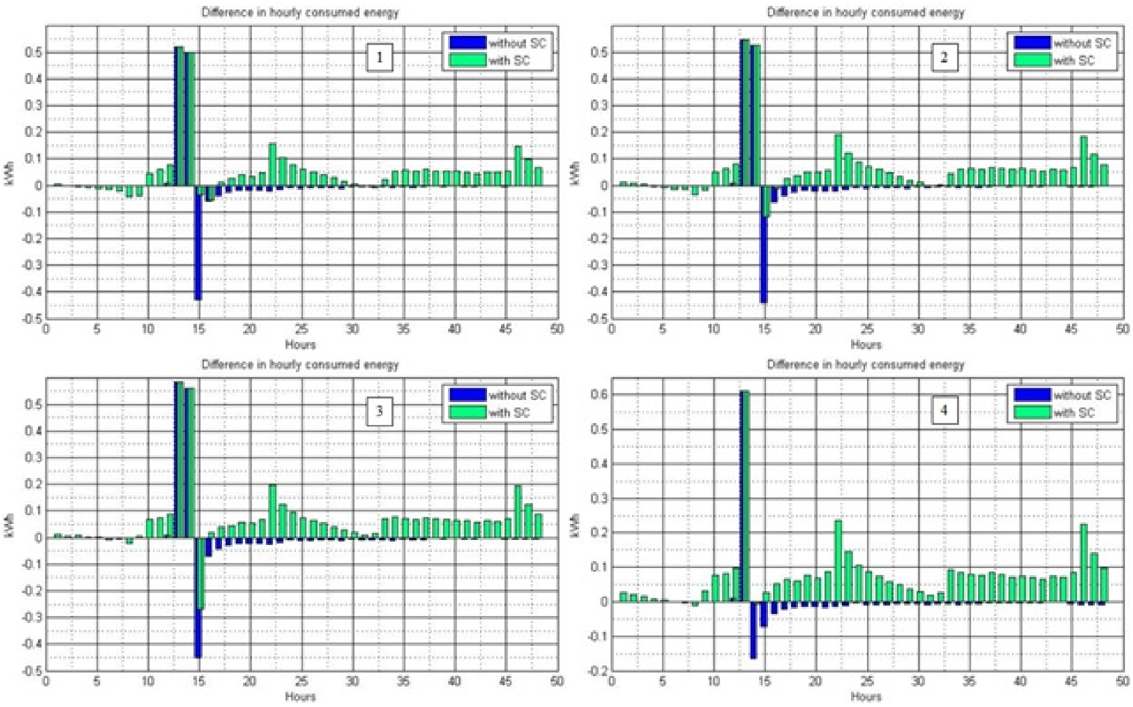

Figure 4.10 *The results of Test 5.*

- Using of the GHP for the DR purposes extends the amount of the saved power, that is from 0.5 kW to 0.6 kW (versus 0.25 kW to 0.35 kW). The DR action durations are no more than the two hours;

- In order to compare the numerical values for Tests 4 and 5 (without the SC), all results are collected in Table 4.3.

Table 4.3 *The numerical values of Tests 4 and 5 (without the SC).*

Case	Saved energy, kWh	Saved power, kW	Maximum power, kW
1	1.02(1.07)[1]	0.51(0.27)	0.52(0.27)
2	1.07(0.6)	0.535(0.2)	0.55(0.3)
3	1.14(0.66)	0.57(0.33)	0.58(0.33)
4	0.61(0.38)	0.305(0.19)	0.61(0.35)

1. The numbers in the brackets are for Test 4.

As it is possible to observe from the table above, the saved energy under the same environmental conditions in Test 5 is much higher than in Test 4 due to participation of the GHP. The rise from one case to another is stipulated by the irradiance growth and the temperature increasing;

- For case 4 it is notable the significant falling of the DR duration in consequence of the temperature and irradiance rise;

- Considering of the solar collector which is connected with the water tank is performed as well in Fig. 4.10 (the green color columns) for comparison. It is seen that during the DR action using of the SC does not affect the saved energy (because the DR event stop time is determined by the room air temperature); however, it helps to save the electrical energy during the whole day (the irradiance is sufficient). Table 4.4 contains the corresponding values of the daily saved energy;

  As it is followed from this table, the higher the ambient temperature and irradiance (consequently the heat that increases the glycol temperature inside the SC), the larger the amount of the energy that can be saved due to connection of the SC with the water tank (heat contribution of the SC to the water tank rises).

Summer DR during the maximum of DHW consumption

Test 4 and 5 are performed for the middle of the day, it is time of the minimal DHW consumption according to Fig. 4.1. Applying the DR start time at 7 a.m. (the maximum of the DHW discharge), the following results will be achieved:

- Due to changing of the start time, the saved energies for the first three cases are decreased (comparing with the values in Table 4.3 presenting the start time at 12 p.m.). Now the DR event duration is determined by the DHW temperature, whereas in the morning, when the AHP is switched off, the room air temperature rises slowly. For the last fourth case the energy is higher because of the ambient conditions. The corresponding values are in Table 4.4;

Table 4.4 *The numerical values of Test 5 for the different start times.*

Case	Saved energy, kWh	Daily saved energy[1], kWh
1	0.7[2](0.35)[3]	1.16
2	0.73(0.47)	1.4
3	0.8(0.7)	1.58
4	0.84(0.85)	1.86

1. The daily saved energy due to usage of the SC (comparing with the cases without the SC) for the last 24 hours of the simulation. 2. The start time of the DR event is at 7 a.m., and the SC is disconnected 3. The numbers in the brackets are for the start time at 7 a.m., and the SC is connected.

- Connection of the solar collector leads to the saved energy decreasing during the DR event for the low ambient temperature (+25^{0}C) as it is seen from Table 4.4. The reason of the energy falling is the low irradiance at 7 a.m. Therefore, presence of the SC has negative influence on the DR event - a part of the stored heat energy in the water tank is wasted for the glycol heating (which is normally heated by the sun) as it is demonstrated in Fig. 3.19. Eventually, increasing of ambient temperature compensates this effect. In fact, the WAC is protected by the control system against such situation;
- Obviously that the daily saved energy for the both cases (the start time is either at 7 a.m. or 12 p.m.) is the same.

Though the SC decreases the saved energy due to the DR event at the specific time (in the model it is the earlier morning; however, in reality it is not true), for the rest day it works in the same way as it was described above - it decreases the electrical energy for the water heating needs. Considering alone the GHP participating in the DR action is out of interest because this case will not be significantly differ from the results obtained in Test 3, because the DR event duration is determined only by the DHW temperature.

4.3 Diversification of temperature settings

One of the possible ways to curtail energy consumption is diversification of the temperature settings of the different equipment such as: the room thermostats, the water and air heating equipment. In the scope of this work the most appropriate choice is changing of the thermostat settings because the model of the water tank with the GHP is not feasible for these purposes (as it was stated in chapter 2). Although for other models of the water tanks with additional electric heaters it is achievable. Moreover, changing of temperature settings is the simplest way that does not require additional special equipment. The AH can be also considered as the suitable equipment for these actions, but as it is followed from Test 3 case 1 (Fig. 4.7, plot 6), it can be totally curtailed for several hours without serious consequences; therefore, there is no point in changing of its settings.

Obviously, that for the energy saving aims it is needed to decrease the temperature set points. The main difference from shut off actions is control of DR event duration because the new set points do not exceed the tolerance levels. Some results of this control strategy are performed in the table below.

Table 4.5 The results of the energy saving strategy.

Facility	Saved energy, kWh	
	$T_a = -24^0$C	$T_a = -15^0$C
1 room	0.0657	0.0528
2 rooms	0.1371	0.1263
1^{st} floor	0.2327	0.1749

In Table 4.5 the following results are gathered: the values of the saved energies are represented for the different amount of the rooms participating in the event (one, two rooms and all rooms of the first floor), where the temperature setting is changed from $+22^0$C to $+21^0$C (the one degree difference is convenient because can be used for recalculation for other temperatures; obviously that for delivering a larger amount of energy this difference should be higher) during the night time - from 0 a.m. till 6 a.m., and namely for this time span the energy is calculated; at 6 a.m. the initial room set point is returned; it is assumed that only these rooms can be regulated because they are not used by inhabitants during the indicated time; these values are also collected for the different ambient temperatures, and other can be interpolated; the initial settings are the same as in Test 1 (section 4.2.1).

As it is possible to observe, the rise of the saved energy can be obtained by involving in the event as much rooms as possible (that is in agreement with the results received earlier for the shut off actions 4.2.1); though, this rule is limited by customer habits. Furthermore, after the end of the saving action some amount of the energy is over consumed (comparing with a case without this action), that is the pay - back energy consumption takes place. Figure 4.11 illustrates the consumed power (the GHP and AH) as the baseline (no DR action) and the two more curves demonstrating the changing of the temperature settings in the first floor of the house (considered above). The initial settings are as in Test 1 (section 4.2.1), the applying time of the action is from 0 a.m. till 6 a.m., the temperature setting is changed from $+22^0$C to $+21^0$C (as in Table 4.5).

The green line in the both plots in Fig. 4.11 is associated with the simple control strategy performed in the right plot, and it shows the changing of the set point of the room temperature from $T_{set} = +22^0$C to the tolerated level $T_{tol} = +21^0$C at the time $t_{DR-start} = 0$ a.m., and returning to the set point at $t_{DR-end} = 6$ a.m. (as it was proposed before). Analyzing the left plot in this figure (the consumed power), it is observable that: due to the changing of the temperature settings, the power consumed from 0 a.m. till 6 a.m. is less, that is the red and green lines are under the blue one (saving of the energy); after 6 a.m. the pay - back period starts: the

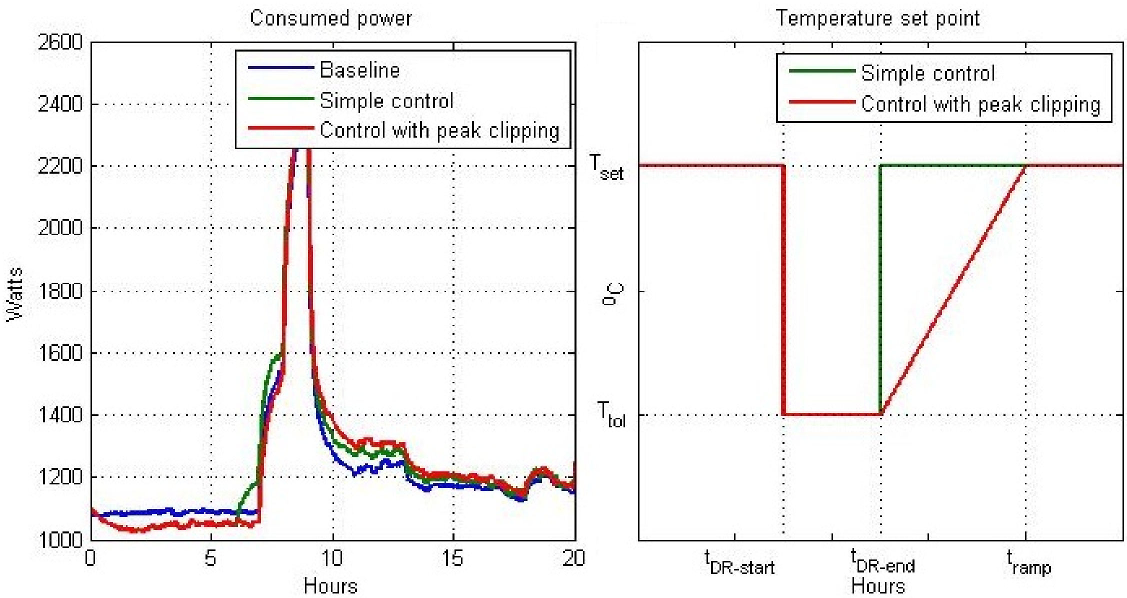

Figure 4.11 *The consumed power and the control strategies.*

green line (the simple control strategy) is above the blue one (overconsumption).

Here, the peak clipping strategy implies the gradual changing of the temperature settings (the second plot in Fig. 4.11, the red line) of the room thermostat from $T_{tol} = +21^0$C to $T_{set} = +22^0$C during the specific time determined as $t_{ramp} - t_{DR-end}$ in order to avoid peaks of hot water consumption in the CHS. It can also shift the start time of the pay - back period and reduce peaks of the electric consumption at a specific time. Thus, by the mean of this approach and $t_{ramp} - t_{DR-end} = 3$ h, the reduction of the power after the DR event has been achieved: the red line (the first plot in the figure above) after 6 a.m. is still under the blue line and, even after that, is under the green one; however, the pay - back period is shifted because DR is not an energy saving strategy. On the other hand, this shifting has the positive effect enabling avoiding the following situation: if a peak of pay - back energy occurs at the same time when the overall electric peak for the whole house happens (calculated for all electrical appliances inside the house, not only for the GHP and AH), then their summarizing can lead to sudden excess of required electrical energy. Such event is not desirable (a flat power profile is more preferable) in power network point of view because it can cause excessive currents in lines.

4.4 Minimization of pay-back energy

A couple of pay - back minimization strategies have been considered in the previous sections of this thesis. It is, firstly, the preheating action (Fig. 4.6, the results

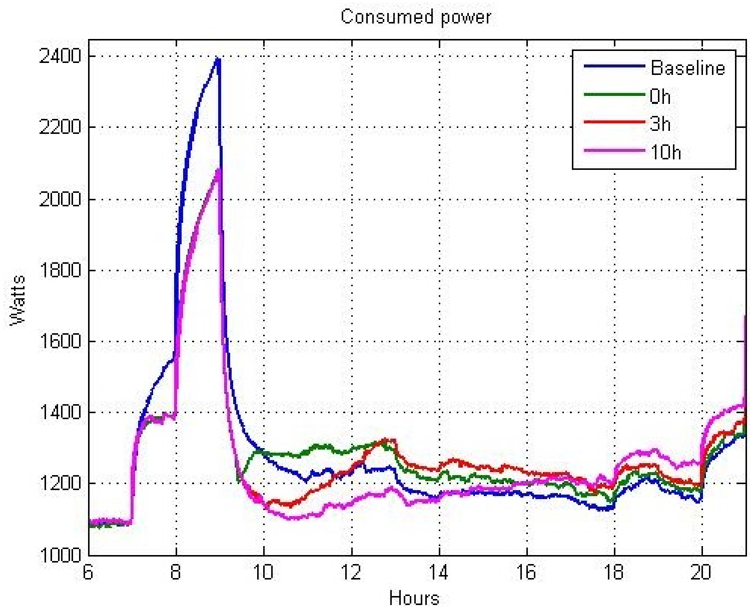

Figure 4.12 *The consumed power for the different times* t_{ramp}.

of Test 2) which decreases significantly over consumed power after an DR event; secondly, it is the special set point control approach for the temperature settings illustrated in Fig. 4.11 (the right plot) that contains a ramp between the tolerance temperature T_{tol} (for the shut off actions it is considered as $+20^0$C) and the desired level of a room air temperature; a steepness is determined by the time difference $t_{ramp} - t_{DR-end}$. For this approach decreasing of pay - back power (keep in mind the curves of the consumed powers presented in Figure 4.12) for equipment under a DR action can be achieved at a specific time: consumed power after a DR event is decreased and shifted to another time in order to flatter an overall domestic power profile. Furthermore, it worth noting that additional energy after a DR action will be consumed due to cooling down not only the interior air, but also the construction materials (the walls) that decreases heat content of the house.

For any DR action the time t_{DR-end} is detected by a DR controller, after then it starts to work as a temperature regulator till the time t_{ramp} (as in Fig. 4.11 the right plot demonstrates), and this time should be chosen carefully. The reason of that is illustrated in Figure 4.12. In this figure the case for the fifteen rooms regulation is demonstrated (with the same settings as in Test 1, Fig. 4.4), with the exception of adding of the peak clipping control approach for the two cases: $t_{ramp} - t_{DR-end}$ equals to the three hours and ten hours. As it is possible to see, the increasing of t_{ramp} leads to the pay - back power falling (the red and magenta lines are under the green) and moving its start time further from the basic value (the green line performs the simple control approach illustrated in Fig. 4.11, the right plot). It helps to extend an useful amount of energy; the set of experiments reveals that the optimal time $t_{ramp} - t_{DR-end}$ should do not exceed a DR event duration in order to support a balance between a saved (during a DR action) and over consumed (after a DR event) amount of energy.

There is another approach of the pay - back energy minimization strategy which is connected with a DR event including combination of the different electrical appliances as in Test 3 (Fig. 4.7), that is not only the thermostat controlling equipment (the water floor heating systems) is considered. The most appropriate equipment for this strategy is:

1. The room thermostats and the air heater. The point is do not switch on back the air heater when the room temperatures have reached $+20^0$C in order to cover a part of pay - back energy by power that is not consumed by the air heater.

2. The GHP, the AH and the room thermostats. The point here is do not switch on back the air heater and the room thermostats because a stop time of a DR event is determined by the water temperature (that reaches $+55^0$C). It is seen from Figure 4.7 (plots 4 and 5), Test 3: the room temperatures do not reach $+20^0$C during the DR event.

3. The GHP and the AHP for summer DR actions. The logic is the same as above.

Obviously, that combination of 1 and 2 is also possible. Hence, Figure 4.13 demonstrates approaches 1 - 3 described above. In this figure: the first plot is for the first approach (the list of the most appropriate equipment is above) the initial settings of which repeat case 2 in Test 3 (section 4.2.3, Fig. 4.7), plots 3 and 7); the second plot is for the second approach the initial settings of which are the same as for case 4 in Test 3; the third plot is for the third approach the initial settings of which are the same as for case 1 in Test 5 (section 4.2.5, Fig. 4.10), plot 1 without the SC).

Analysis of the plots in Fig. 4.13 reveals:

- The power peaks during the pay - back period can be changed (actually decreased) only at a specific time. After that time the smaller peaks are possible;

- Plot 1 shows the pay - back energy decreasing by holding the AH in the nonworking state during the three hours after the back switching on of the

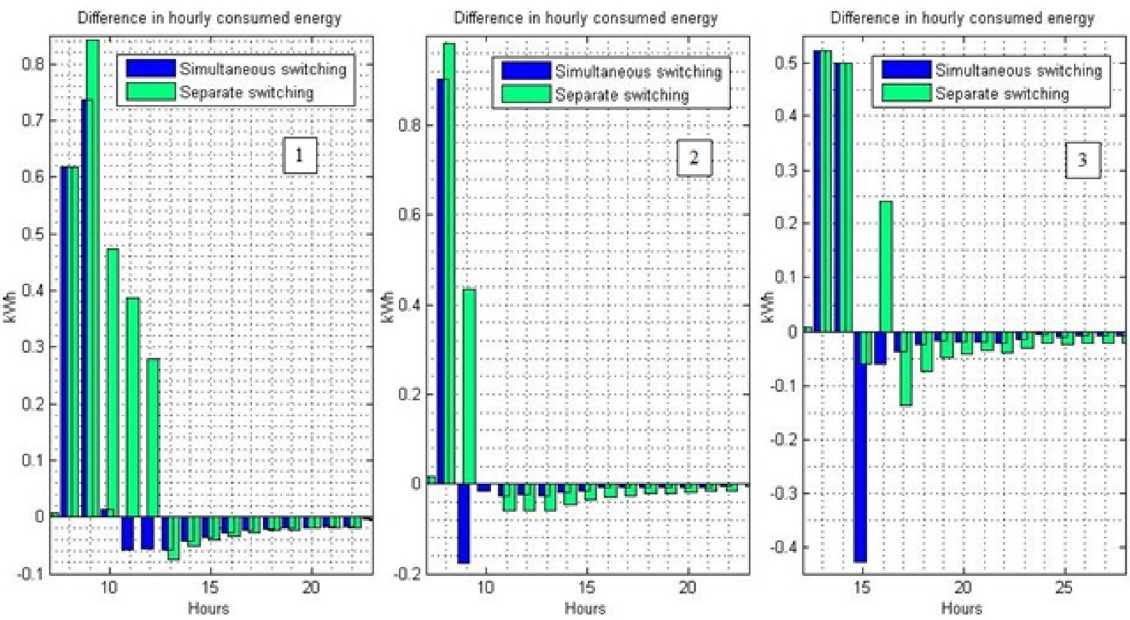

Figure 4.13 *The results of the separate back switching strategy.*

heatings in all rooms (the green columns). It helps to change the amount of the pay - back energy (calculated after the stop time for the simultaneous switching, that is the negative blue columns) from −0.43 kWh to +0.287 kWh;

- Analogously, the second plot demonstrates the nonworking period extension for the room heatings together with the AH after excluding of the GHP from the DR event (the DHW temperature has reached $+55^0$C). The full stop of the DR event occurs when only the room air temperature reaches $+20^0$C. It causes changing of the pay - back energy from −0.34 kWh to −0.0054 kWh;
- Eventually, the case for the summer DR is considered shown in the plot 3. Here the AHP does not work after the moment when the GHP starts to work again (the reason is the same as in the previous case). The AHP is switched on back when the room air temperature reaches $+22^0$C (the summer condition). It leads to the pay - back energy decreasing from −0.78 kWh to −0.58 kWh.

4.5 Chapter summary

In the current chapter the following has been achieved:

- The variation in the consumed electrical energy due to changing of the environmental conditions has been considered. The calculation laws have been derived for the two seasons - the winter and the summer;

- The largest possible DR strategy has been studied, namely the shut off actions for the different types of the equipment and the ambient conditions. Analyses of the tests have been revealed the necessary numbers describing the effectiveness of the each DR action. All actions have been compared with each other to illustrate their difference and to allow choosing the most appropriate for a specific event;

- The ways to extend a DR event duration have been found - the preheating and individual control strategies that lead to increasing of saved energy; Here it is worth noting that the thermodynamic model of the house is quite idealized because the proper heat insulation supports the appropriate temperature field inside the house without participation of the heat sources. The real situation is differed from the modeled due to the open doors, windows, presence of furniture (its heat capacity contributes also in heating processes), people and air infiltrations; consequently, a shut off duration will be differed from a modeled; though, anyway, it is several hours;

- It is shown the connection between the combined control of the electrical and the water type equipment. The DR actions for them are basically limited by the water rather than the air temperature;

- The positive influence of the SC on the summer DR actions has been studied. Although the SC does not exist in the real house, it has been chosen as the object for modeling;

- Additionally, the strategies associated with changing of the temperature settings of the equipment have been performed;

- On the ground of the temperature settings diversification actions the useful approach of the pay - back energy minimization strategy has been revealed. Apart from that, it was declared that such actions as the preheating and separate back switching can serve for the same purposes.

5. APPLICATION OF THE HOUSE DETAILED MODEL IN ENERGY MANAGEMENT

In this chapter possible utilization for the energy management purposes of the considered model and the obtained results are considered. Energy management is a quite broad term which encompasses many different aspects in power networks. In the scope of this work we will consider only management related to the residential sector, namely the home regulations. Basically this approach implies the process of monitoring, controlling and conserving of electrical energy at the domestic level. Therefore, first of all, the most studied and promising way to implement this process which is referred to as home energy management will be performed.

5.1 Home energy management

Home energy management plays a vital role in any smart energy grid system enabling benefits and for a distribution system operator (improved supply and efficient utilization) and for a customer (cost effective energy offerings). Moreover, home energy management system (HEMS) is considered as a part of the electricity market and network management. HEMS can be achieved by informing energy service providers of the requirements of consumers and the characteristics of their domestic environment. Such kind of data is preserved in a domestic information system which is referred to as a home area network (HAN). The HAN collects information about a certain consumer and has two - way communication by the mean of smart meters with a superior information system called a neighborhood area network (NAN). The NAN encompasses other consumers and transmits information to a wide area network (WAN) which is connected with an energy suppliers [1]. The NAN has also connection with a HEMS controller which is basically a smart device enabling the following functions: two - way connection with the HAN, gathering and processing information about measured quantities describing the domestic physical and electrical environment, controlling of domestic electrical appliances, delivering information to a customer through an interface.

In order to ensure these functionalities, a HEMS controller affects a domestic equip-

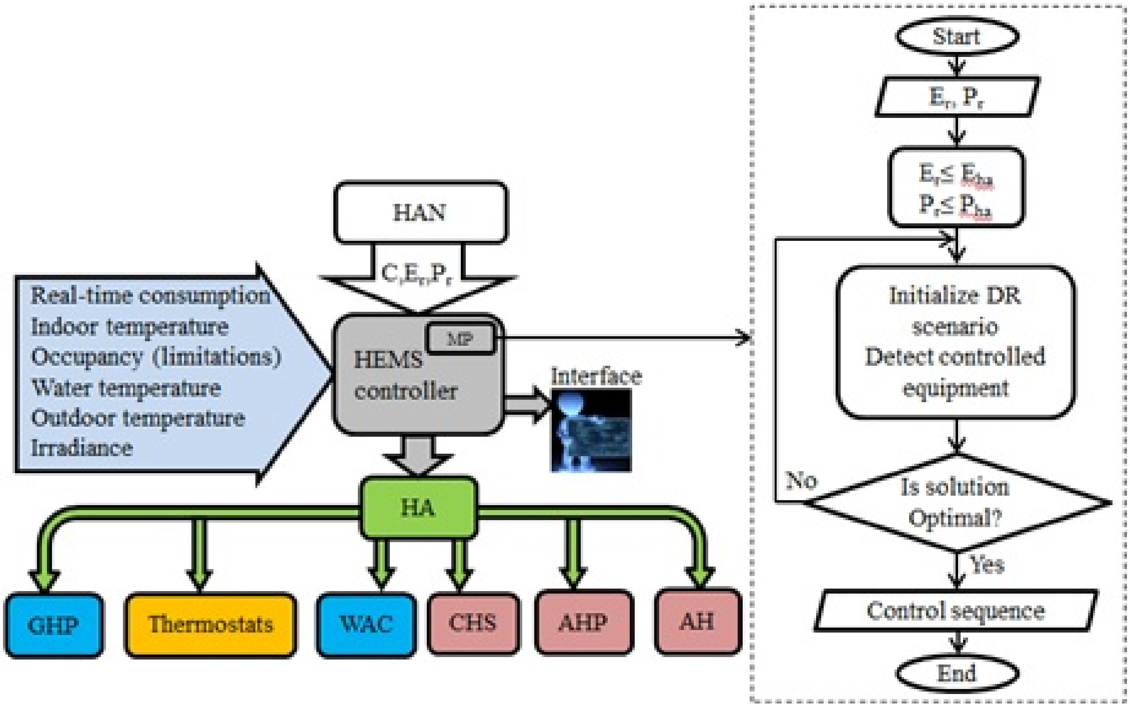

Figure 5.1 *The HEMS hierarchy and algorithm.*

ment by the mean of a home automation (HA), such as relays, thermostats, switchers and other devices. Moreover, it should receive information from an equipment through a feedback signal from different types of sensors, such as temperature and occupancy sensors, smart meters and another equipment. Gathered information is most often data about the interior environment (room and water temperatures, presence of inhabitants), exterior (weather conditions), time of a day, the spot prices of electricity and real - time energy consumption. Figure 5.1 shows the structure of HEMS with a controller in conformity with the modeled house. One of the main functions of the HEMS controller is energy scheduling of the electrical equipment that means switching on/off at specific times during the day time on the ground of the electricity prices applying the different optimization techniques. It is done in order to manage energy consumption profiles, that is to reduce peaks of electric demand, to find the best way to save energy as well as to keep the reasonable energy prices; hence, HEMS in smart grids enables DR programs.

Another possible application of the controller is load control according to queries from distribution network. This task implies determination of the HEMS controller algorithm of actions after receiving information from the power grid about the necessary amount of power or energy that can be curtailed from a specific house. The term algorithm here stands for what an equipment should be controlled and how in order to ensure the requested energy. The simplified version of such algorithm is demonstrated in Fig. 5.1.

In the presented HEMS structure the MP is the microprocessor of the controller. With reference to the stated problem, its task is handling of the received information from the power grid about the required energy and power (E_r, P_r) and determination of a control sequence of the most appropriate domestic appliances. It occurs through detection of a suitable DR scenario and an equipment which can be used on the ground of the available energy and power inside the house (E_{ha}, P_{ha}).

5.2 Utilization of the house model in energy management

As it was stated earlier, the obtained detailed and accurate model of the house is used for diagnosis and control strategy analysis. Such model allows carrying out experiments in a fast way without using real objects that can help to develop new devices, tools and programs. There are, at least, two ways of the house model application:

- In HEMS for the domestic purposes and energy scheduling;
- As a basis (an off - line tool) for creation simplified sub - models for further real - time usages (on - line) in energy management.

5.2.1 HEMS application

At the customer level in a power network energy management is implemented by a HEMS controller which can use the house model in the two cases performed below.

Comfort condition tracking

There are many studies dedicated to home energy scheduling the main of which is the money saving strategy. However, little attention has been paid to the problem of preserving of comfort conditions for inhabitants during regulation of the domestic appliances.

Typically, a scheduler (a HEMS controller) sets a necessary time of switching on/off for an electrical equipment inside a house according to the following possible scenarios that are, in fact, the optimization tools [26]:

- Optimization based on residential energy management which governs energy consumption by scheduling home appliances in suitable time slots;

- In - home energy management which uses the time - of - use pricing scheme [1] in order to shift a load from peak to off - peak times;
- Coordination of domestic energy resources (a space heater, a photovoltaic panel, an electric vehicle) on the ground of the co - evolutionary particle swarm optimization;
- Combination of an electricity price predictor and energy scheduling algorithms;
- Optimization the main aim of which is monetary cost minimization applying the different pricing schemes: time - of - use, real time, day ahead and critical peak pricing [1].

In the each task above the house model can play an essential role in maintaining of comfort condition inside a house. When a HEMS controller deals with equipment affecting thermodynamic parameters of a house (or it can be other appliances that concern implicitly these parameters), embedded in a calculating algorithm, the model brings the necessary limitations for this equipment regulation. Thus, combination of the optimization tools and the thermodynamic model can lead with a reasonable chance to a customer life in money and energy saving, comfortable and environmentally friendly conditions.

Request handling

Another possible application of the house model is assistance in processing of the energy requests from the system operator. As it was considered in section 5.1, for implementation of a DR program in a power network (mainly a peak reduction or valley filling) the system operator considers all possible energy resources included in the network, that is the residential houses as well. In such event the WAN can send a signal about curtailing of some amount of energy or power at a specific time to the HEMS controller (performed as E_r, P_r in Fig. 5.1).

Hence, the house model in the controller algorithm helps to rebuild an energy schedule determining the available power and energy harvesting from a curtain appliance on the ground of preserving of living comfort conditions. Having information about the saved energy and power, as in in the section with results 4, it is possible to detect the needed equipment. For example, the appropriate case for the winter DR action can be obtained by drawing the horizontal lines in Fig. 4.8 that perform the required power and energy for the house, and every case which column in the both plots (that is E_{ha} and P_{ha}) is higher than the level limited by these lines (that is $E_r \leq E_{ha}$, $P_r \leq P_{ha}$) is the suitable solution for the control strategies.

Such requests can also occur as a result of the optimal network control strategy which considers:

- Load management which includes local distributed generation: solar, wind power installations and other resources;
- Decreasing of the electricity cost and greenhouse gases during productions.

On the other hand even in home management, optimization is required because the level of E_{ha} and P_{ha} can be obtained by the means of several ways. This optimal solution can be performed, for instance, by limitation of the number of the rooms and equipment that participate in a DR event (the smaller number, the better), pay - back power can also restricts choices. In order to achieve the optimum, a customer should provide necessary information about what kind of equipment and rooms can be involved and at what time (occupancy, limitations). Other information is gathered automatically and, together with information about the electricity cost ("C" in Fig. 5.1), is used for implementation of market based DR in the residential sector.

5.2.2 WAN application

Usually the WAN encompasses a large number of customers, and it is vital to have information about their energy consumption. Obviously, that a power profile of a single residential consumer depends on many factors, especially such as weather conditions, lifestyle, household equipment and so on. Therefore, the detailed house model can be applied for forecasting of energy consumption for the specific group of similar consumers because it gives direct relation between user behavior together with the environmental conditions and the power demand. Such example is given in section 4.1, where the laws reflecting changing of the power consumption with respect to the variation of the outdoor conditions are derived.

Another example is using of the models by the system operator in order to analyze foregoing DR actions studying possibilities in the residential sector. In such situation there is often a trade - off between accuracy and computational time which is necessary for real - time calculation (for example, determination of DR opportunities for the next hour of operation). One of approaches here is to make some assumptions and to simplify the model in order to speed up the execution of a simulation deteriorating a confidence interval of the computed results. Another method is to create small sub - models with a reduced number of input variables on the ground of the existing large detailed model.

Such mean requires a number of preliminary simulations for the house model to establish the following connection:

$$\begin{pmatrix} y_1 \\ y_2 \\ ... \\ y_n \end{pmatrix} = \mathbb{K} \begin{pmatrix} w_1 \\ w_1^2 \\ ... \\ w_1^{n_1} \\ w_2 \\ w_2^2 \\ ... \\ w_2^{n_2} \\ ... \\ w_n^{n_n} \end{pmatrix}, \tag{5.1}$$

where:

$\mathbb{W} = (w_1\ w_1^2\ ...\ w_1^{n_1}\ ...w_n^{n_n})^T$ is the input variables vector, that is changing parameters such as: ambient temperature, solar irradiance, time of a day/season, a specific place inside a house or an equipment, human presence/absence and so on. This vector contains only necessary parameters (the less number, the faster calculation) for a given time, and their the first and/or the higher order terms (where n_1, n_2, ..., n_n are the highest orders of the corresponding input variables);

$\mathbb{Y} = (y_1\ ...\ y_n)^T$ is the output information such as: available summarized energy and power which can be utilized from the domestic sector, DR program durations and so on;

$\mathbb{K}$ is the connection coefficients matrix which is derived by the means of simulations of the total house model (the off - line tool) and processing the gathered data.

To sum up, having the different ways of application in energy management (and not only in home), need for the thermodynamic model of a house is getting more and more evident. The main reason here is enabling to conduct DR programs in the most efficient way without disturbing customers and predicting possible emergency situations.

6. CONCLUSION AND FUTURE WORKS

In this research work the developed thermodynamic model of the house with the electrical appliances is subjected to the various actions in order to study the DR potentials for this house on the whole. The obtained research findings and their meaning are performed below.

1. The detailed thermodynamic model of the house has been developed.

   This model is supplemented by the various electrical loads models that perform the heating/cooling solutions of the given house. The applied simplifications do not affect final accuracy too much that is proved through the verification process. Therefore, in future models the same assumptions can be done and the analogous approaches can be used to achieve better performance in mathematical description of real objects and to save calculation times.

   The revealed during the simulations discrepancies with real physical behavior or the measured values helped to conclude that the constructed model requires including disturbances caused by inhabitants. Real human behavior can be modeled, for instance, as it is proposed in [8]. Though the proposed model is imperfect, its precision is enough to accomplish tasks related to study of home DR events.

2. The correlation between the energy consumption changing and the natural ambient condition variations has been revealed.

   The obtained dependencies in section 4.1 can be useful for future predictions of the house energy consumption changing due to the environmental reasons. Expressions (4.2) and (4.3) include such variable input parameters as the ambient temperature and solar irradiation. Furthermore, for the summer time possible presence of the water solar heater is taken into account.

3. The most widely applicable winter DR strategy, namely the shut off actions, applied in the given house has been studied.

   This finding can be divided into the several research achievements:

(a) Regulation of only the room heatings through switching off of the local thermostats showed that for extracting the largest power, all rooms should be exposed to the DR event. This case is also attractive because of the small pay - back period in energy point of view.

In order to achieve the maximum available DR event duration, the small number of rooms should be involved. However, it has been noted that the saved energy is roughly equal to the pay - back. Moreover, the utilized power from one room is about 10 % from the whole potential of the house.

(b) It is found that such approaches as the preheating and individual control strategies (considered in section 4.2.2) implemented by the room thermostats during the DR event bring the positive effects: in the both study cases the extension of the DR event duration is observed; furthermore, in spite of the over consumed energy before the DR start time, the preheating actions might cause drastic decreasing of the pay - back period and even save some amount of energy.

The individual control strategy is easily feasible and can also to decrease pay - back energy, especially in combination with the preheating action.

(c) Combination of the thermostatically controlled heating equipment with the different electrical appliances has been probated. Such consolidation allows enlarging of the curtailed energy and power from the appropriate DR events. Moreover, it has lead to the reduction of the pay - back energy comparing with the cases in 3a. Thus, the most powerful resulting strategy is controlling of all electrical heating equipment; however, it leads to the reduced DR action duration. The most promising case in energy point of view is combination of the preheating and separate control actions for the room thermostats.

4. The summer DR programs have been considered.

   The results demonstrate the energy potential for the air cooling and water heating equipment under the variation of the two outdoor parameters: the air temperature and solar irradiance because it has significant influence. The best control strategy is combination of these electrical appliances; moreover, presence of the water solar heater might affect the water heaters performance saving electrical energy, and it can even extend the DR event duration if the indoor air temperature will be neglected.

5. The changing of the room air temperatures in the unoccupied places inside the house has been examined.

This study case is basically considered as the energy saving mean. Though it can be also applied for the DR action because the main difference from the shut off actions is controlling of the stop time of the DR event, but the smaller amount of the utilized energy, about 50 % from the possible achieved through the analogous shut off program, has been extracted.

6. The several pay - back minimization strategies have been reviewed.

   Apart from the considered preheating actions, the following approaches have been probed: acting the HEMS controller as the temperature regulator and the consecutive back switching of the equipment participated in the DR event. The first one gives the reduction of the pay - back energy at the specific times shifting it to another time slot which can be regulated. The second one causes the reduction of the peaks during this period.

In future works the algorithm performed in Fig. 5.1 could be developed. The necessary results for its implementation can be gathered from section 4 and extrapolated for other cases. Furthermore, as these results have been derived for the specific building (with the concrete equipment), one of the directions of scientific works can become finding of the ways of the given results extrapolation for other types of houses with different geometry and equipment. Another possibility is developing of sub - models for on - line simulations gathering necessary study cases and deriving for them expressions similar to (5.1).

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A. APPENDIX A. GEOMETRIC PARAMETERS OF THE HOUSE

Below used geometric parameters of the modeled house are performed as variables in Matlab script:

```
%space1
H1=2.7; %Height of the first floor,[m]
Fs1w=25.3457*H1; %area of outer walls,[m2]
Fs1f=69.9019; %floor area,[m2]
Fs1af=5.3541; %area of attic floor,[m2]
%below area of inner walls between:
FiwS1S2=2.2667*H1;%space1 and space2,[m2]
FiwS1S3=2.0044*H1; %space1 and space3,[m2]
FiwS1S7=0.9366*H1;%space1 and space7,[m2]
FiwS1S5=5.0766*H1;%space1 and space5,[m2]
FiwS1S6=5.0579*H1;%space1 and space6,[m2]
%below area of ceiling between:
FcS1R1=14.9529;%space1 and room1,[m2]
FcS1R2=11.6205;%space1 and room2,[m2]
FcS1R6=3.0166;%space1 and room6,[m2]
FcS1R7=1.6988;%space1 and room7,[m2]
FcS1R8=13.4990;%space1 and room8,[m2]
Fch=16.3935;Fcs=4.2816;%stairs area,[m2]
%windows
lbw=0.57;hbw=1.36; %base dimensions of a window-width and height,[m];
%below areas of windows,[m2]
Fs1w1=2*lbw*(hbw+0.2);Fs1w2=Fs1w1;Fs1w3=Fs1w1;
Fs1w4=lbw*hbw;Fs1w5=Fs1w4;Fs1w6=Fs1w4;
Fs1w7=2*lbw*(hbw+0.2);
%doors
lbd=0.86;hbw=2.16; %base dimensions of a door- width and height,[m]
Fd=lbd*hbw; %area,[m2]

%space2
Fs2w=6.2756*H1; %area of outer walls,[m2]
Fs2f=9.0911; %floor area,[m2]
%below area of inner walls between
```

```
FiwS2S3=1.5361*H1;%space2 and space3,[m2]
FiwS2S4=2.2292*H1; %space2 and space4,[m2]
%below area of ceiling between
FcS2R3=Fs2f;%space2 and room3,[m2]
%windows area,[m2]
Fs2w1=lbw*(hbw);

%space3
Fs3f=4.4564; %floor area,[m2]
%below area of inner walls between
FiwS3S4=1.9857*H1;%space3 and space4,[m2]
FiwS3S7=4.0463*H1; %space3 and space7,[m2]
%below area of ceiling between
FcS3R3=2.5396;%space2 and room3,[m2]
FcS3R5=1.6016;%space2 and room5,[m2]

%space4
Fs4w=1.9857*H1; %area of outer walls,[m2]
Fs4f=3.0373; %floor area,[m2]
%below area of inner walls between
FiwS4S7=1.5361*H1;%space4 and space7,[m2]
%below area of ceiling between
FcS4R4=Fs4f;%space4 and room4,[m2]
%windows area,[m2]
Fs4w1=lbw*lbw;

%space7
Fs7w=5.9196*H1; %area of outer walls,[m2]
Fs7f=10.2797; %floor area,[m2]
%below area of inner walls between
FiwS7S5=2.8099*H1;%space7 and space5,[m2]
%below area of ceiling between
FcS7R5=Fs7f;%space7 and room5,[m2]
%windows area,[m2]
Fs7w1=lbw*hbw;Fs7w2=2*lbw*(hbw+0.2);

%space5
Fs5w=8.8420*H1; %area of outer walls,[m2]
Fs5f=10.9619; %floor area,[m2]
Fs5af=6.8280; %area of attic floor,[m2]
%below area of inner walls between
FiwS5S6=1.3862*H1;%space5 and space6,[m2]
%below area of ceiling between
FcS5R5=1.9610;%space5 and room5,[m2]
FcS5R6=1.6339;%space5 and room6,[m2]
%windows area,[m2]
Fs5w1=lbw*(hbw);Fs5w2=Fs5w1;
```

```
%space6
Fs6f=2.5403; %floor area,[m2]
%below area of ceiling between,[m2]
FcS6R7=Fs6f;%space6 and room7,[m2]

%room1
H2=2.6; %Hight of the second floor; ,[m2]
Fr1w=7.7555*H2; %area of outer walls,[m2]
Fr1af=14.9529; %area of attic floor,[m2]
%below area of inner walls between
FiwR1R2=1.5174*H2;%room1 and room2,[m2]
FiwR1R8=3.9901*H2;%room1 and room8,[m2]
FiwR1h=2.0419*H2;%room1 and hall,[m2]
%windows area,[m2]
Fr1w1=2*lbw*hbw;Fr1w2=Fr1w1;

%room2
Fr2w=6.6877*H2; %area of outer walls,[m2]
Fr2af=11.6205; %area of attic floor,[m2]
%below area of inner walls between
FiwR2R3=1.4986*H2;%room2 and room3,[m2]
FiwR2h=4.1400*H2;%room1 and hall,[m2]
%windows area,[m2]
Fr2w1=lbw*hbw;Fr2w2=Fr2w1;

%room3
Fr3w=6.5565*H2; %area of outer walls,[m2]
Fr3af=12.8477; %area of attic floor,[m2]
%below area of inner walls between
FiwR3R4=2.9598*H2;%room3 and room4,[m2]
FiwR3R5=2.2667*H2;%room3 and room5,[m2]
FiwR3h=2.0419*H2;%room1 and hall,[m2]
%windows area,[m2]
Fr3w1=Fr1w1;Fr3w2=Fr1w1;

%room4
Fr4w=2.0794*H2; %area of outer walls,[m2]
Fr4af=3.4219; %area of attic floor,[m2]
%below area of inner walls between
FiwR4R5=2.9598*H2;%room4 and room5,[m2]

%room5
Fr5w=6.9312*H2; %area of outer walls,[m2]
Fr5af=14.0851; %area of attic floor,[m2]
%below area of inner walls between
FiwR5R6=1.9108*H2;%room5 and room6,[m2]
```

```
FiwR5h=1.8358*H2;%room5 and hall,[m2]
%windows area,[m2]
Fr5w1=Fr1w1;Fr5w2=Fr1w1;

%room6
Fr6w=2.5664*H2; %area of outer walls,[m2]
Fr6af=4.8652; %area of attic floor,[m2]
%below area of inner walls between
FiwR6R7=1.9295*H2;%room6 and room7,[m2]
FiwR6h=2.5664*H2;%room6 and hall,[m2]
%windows area,[m2]
Fr6w1=lbw*hbw;Fr6w2=(lbw+0.4)*hbw;

%room7
Fr7w=2.4728*H2; %area of outer walls,[m2]
Fr7af=4.7414; %area of attic floor,[m2]
%below area of inner walls between
FiwR7R8=3.1284*H2;%room7 and room8,[m2]
FiwR7h=1.4050*H2;%room7 and hall,[m2]
%windows area,[m2]
Fr7w1=lbw*hbw;

%room8
Fr8w=6.8750*H2; %area of outer walls,[m2]
Fr8af=13.4990; %area of attic floor,[m2]
%below area of inner walls between
FiwR8h=1.8546*H2;%room8 and hall,[m2]
%windows area,[m2]
Fr8w1=Fr1w1;Fr8w2=Fr1w1;
```

B. APPENDIX B. GEOMETRIC AND PHYSICAL PARAMETERS OF THE CONSTRUCTION MATERIALS

Below used geometric and physical parameters of the construction materials are performed as variables in Matlab script::

```
% outer wall
Rsi=0.13; %Internal surface resistance, [m2*K/W]
Rse=0.04; %External surface resistance, [m2*K/W]
Rg=0.18; %Thermal resistance of cavity air, [m2*K/W]
lambda=[0.2 0.1 1.6 0.04]; %Thermal conductivity of
%gypsum-fibre-concrete-wool, [W/m*K]
ro=[800 1.25 800 2300 60]; %Density of
%gypsum-air-fibre-concrete-wool, [kg/m3]
C=[890 1000 1400 850 850]; %Heat capacity of
%gypsum-air-fibre-concrete-wool, [J/kg*K]
x=[25 22 25 150 150 50 50 22]*1e-3; %thickness of layers, [m]

%Thermal resistances of wall layers, [m2*K/W]
Rw=[x(1)/lambda(1) Rg x(3)/lambda(2) x(4)/lambda(3) x(5)/lambda(4)...
    x(6)/lambda(3) x(7)/lambda(4) x(8)/lambda(4)];
%Capacity of wall layers, [J/m2*K]
Cw=0.5*[C(1)*ro(1)*x(1) C(2)*ro(2)*x(2) C(3)*ro(3)*x(3) C(4)*ro(4)*x(4)...
    C(5)*ro(5)*x(5) C(4)*ro(4)*x(6) C(5)*ro(5)*x(7) C(1)*ro(1)*x(8)];

% ground floor (without heating)
Rsif=0.17; %Internal surface resistance, [m2*K/W]
Rgf=0.21; %Thermal resistance of cavity air, [m2*K/W]
Rground=1.2; %Thermal resistance of ground, [m2*K/W]
lambda=[0.1 1.6 0.033 2.42]; %Thermal conductivity of timber-concrete-
%-polystyrene-ground, [W/m*K]
ro=[450 2300 45 1.25 2800]; %Density of timber-concrete-
%-polystyrene-air-ground, [kg/m3]
C=[1200 850 1130 1000 840]; %Heat capacity of timber-concrete-
%-polystyrene-air-ground, [J/kg*K]
x=[20 100 150 50 250]*1e-3; %thickness of layers, [m]
```

```
%Thermal resistances of floor,[m2*K/W]
Rf=[x(1)/lambda(1) x(2)/lambda(2) x(3)/lambda(3) Rgf Rground];
%Capacity of floor, [J/m2*K]
Cf=0.5*[C(1)*ro(1)*x(1) C(2)*ro(2)*x(2) C(3)*ro(3)*x(3) C(4)*ro(4)*x(4)...
    C(5)*ro(5)*x(5)];

% attic floor
Rsiaf=0.1; %Internal surface resistance, [m2*K/W]
Rseaf=0.04; %External surface resistance, [m2*K/W]
Rgaf=0.16; %Thermal resistance of cavity air, [m2*K/W]
lambda=[1.6 0.04]; %Thermal conductivity of concrete-wool, [W/m*K]
ro=[2300 1.25 60]; %Density of concrete-air-wool, [kg/m3]
C=[850 1000 850]; %Heat capacity of concrete-air-wool, [J/kg*K]
x=[150 50 500]*1e-3; %thickness of layers, [m]

%Thermal resistances of attic floor,[m2*K/W]
Raf=[x(1)/lambda(1) Rgaf x(3)/lambda(2)];
%Capacity of attic floor, [J/m2*K]
Caf=0.5*[C(1)*ro(1)*x(1) C(2)*ro(2)*x(2) C(3)*ro(3)*x(3)];

% ceiling (without heating)
Rsic=0.17; %Surface resistance, [m2*K/W]
Rgc=0.21; %Thermal resistance of cavity air, [m2*K/W]
lambda=[0.1 1.6]; %Thermal conductivity of timber-concrete, [W/m*K
ro=[450 1.25 2300]; %Density of timber-air-concrete, [kg/m3]
C=[1200 1000 850]; %Heat capacity of timber-air-concrete, [J/kg*K]
x=[20 50 150]*1e-3; %thickness of layers, [m]

%Thermal resistances of ceiling,[m2*K/W]
Rc=[x(1)/lambda(1) Rgc x(3)/lambda(2)];
%Capacity of ceiling, [J/m2*K]
Cc=0.5*[C(1)*ro(1)*x(1) C(2)*ro(2)*x(2) C(3)*ro(3)*x(3)];

% Solid inner wall
Rsisiw=0.13; %Surface resistance, [m2*K/W]
lambda=[0.7 1.6]; %Thermal conductivity of plaster-concrete, [W/m*K]
ro=[2000 2300]; %Density of plaster-concrete, [kg/m3]
C=[850 850]; %Heat capacity of plaster-concrete, [J/kg*K]
x=[13 100 13]*1e-3; %thickness of layers, [m]

%Thermal resistances of solid inner wall layers, [m2*K/W]
Rsiw=[x(1)/lambda(1) x(2)/lambda(2) x(1)/lambda(1)];
%Capacity of solid inner wall layers, [J/m2*K]
Csiw=0.5*[C(1)*ro(1)*x(1) C(2)*ro(2)*x(2) C(1)*ro(1)*x(1)];

% inner wall
```

```
Rsiiw=0.13; %Surface resistance, [m2*K/W]
Rgiw=0.18; %Thermal resistance of cavity air, [m2*K/W]
lambda=[0.21]; %Thermal conductivity of cement chipboard, [W/m*K]
ro=[1100 1.25]; %Density of cement chipboard-air, [kg/m3]
C=[1200 1000]; %Heat capacity of cement chipboard-air, [J/kg*K]
x=[13 75 13]*1e-3; %thickness of layers, [m]

%Thermal resistances of inner wall layers, [m2*K/W]
Riw=[x(1)/lambda(1) Rgiw x(1)/lambda(1)];
%Capacity of inner wall layers, [J/m2*K]
Ciw=0.5*[C(1)*ro(1)*x(1) C(2)*ro(2)*x(2) C(1)*ro(1)*x(1)];

roair=1.25; %density of air, [kg/m3]
cair=1000; %heat capacity of air, [J/kg*K]

Kul=1.1; %coefficient of uncounted losses
```

C. APPENDIX C. GEOMETRIC AND PHYSICAL PARAMETERS OF THE EQUIPMENT

Below used geometric and physical parameters of the equipment are performed as variables in Matlab script:

```
%===================================================================
%Boiler
%===================================================================

Ef_b=0.90; %efficiency of boiler
q_b=10e-3/60; %water flow in boiler, [m3/s]
P_b=11000; %Consumption of boiler, [W]
V_b=10e-3; %Volume of boiler, [m3]

%===================================================================
%Water accumulator tank
%===================================================================

%water constants
c_wtr=4200; %density of water, [kg/m3]
ro_wtr=1000; %heat capacity of water, [J/kg*K]

V_tank=300*1e-3; %volume of the tank, [m3]
D_tank=0.5; %diametr of the tank, [m]
h_tank=4*V_tank/(pi*D_tank^2); %height of the tank, [m]
x_thi=0.1; %thickness of heat insulation, [m]

N_tank=15; %number of layers inside the tank

%overall heat resistance for side heat insulation of the tank, [m2*K/W]
R1_thi=(h_tank/N_tank)*log((D_tank+2*x_thi)/(D_tank))/(2*0.04)+1/15;
A1_tank=(h_tank/N_tank)*pi*(D_tank+2*x_thi); %side area of 1 layer, [m2]
%overall heat resistance for bottom and closure of the tank, [m2*K/W]
R2_thi=x_thi/0.04+1/15;
A2_tank=(pi*D_tank^2)/4;%bottom and closure area of the tank, [m2]
```

```
R_wtr=1/500; %heat resistance between layers in water, [m2*K/W]

%coil heat exchangers (CHEX) inside the tank
R_chex=1/5000; %overall heat resistance for pipe, [m2*K/W]
D_chex=20e-3; %outer diametr of the coil pipe, [m]
A_chex_in=pi*(0.8*D_chex)^2/4; %inner area of the pipe, [m2]
A_chex_out=pi*(D_chex)^2/4; %outer area of the pipe, [m2]
C_chex=pi*D_chex; %length of the circle of the pipe, [m]

L_chex_r=0.9*pi*D_tank; %length of one turn of the radiator pipe CHEX, [m]
N_turn_r=3; %number of turns per layer
loc_r=[6:10]; %location inside the tank according to layers (down to up)

L_chex_sc=0.5*pi*D_tank; %solar collector CHEX, [m]
N_turn_sc=2;
loc_sc=[1:5];

L_chex_ghp=0.9*pi*D_tank; %ground heat pump CHEX, [m]
N_turn_ghp=3;
loc_ghp=[11:15];

%======================================================================
%Ventilation with heat recovery
%======================================================================

AFR=0.5; %standard air flow rate, [1/h]
Vroom=[Fs1f*H1+Fch*H2 [Fs2f Fs3f Fs4f Fs5f Fs6f Fs7f]*H1 [Fr1af Fr2af...
    Fr3af Fr4af Fr5af Fr6af Fr7af Fr8af]*H2]; %Volumes of the rooms, [m3]
q_rair=Vroom*AFR/3600; %Air flow in rooms, [m3/s]
q_fan=sum(q_rair); % Air flow in fan, [m3/s]
V_recup=100e-3; %volume of recuperator, [m3]
K_recup=100; %heat transfer coefficient inside recuperator, [W/m2*K]
A_recup=1e1*V_recup; %Useful area of recuperator, [m2]
eff_recup=0.85; % efficiency of recuperator
Pair_h=1000; %power of air heater, [W]

%======================================================================
%Floor heating
%======================================================================

D_pipe=20e-3; %Outer diametr of the floor pipe, [m]
% Floor area, [m2]
F=[Fs1f+Fch Fs2f Fs3f Fs4f Fs5f Fs6f Fs7f Fr1af Fr2af Fr3af Fr4af Fr5af...
 Fr6af Fr7af Fr8af];
% Length of the parts of pipe, [m]
L_pipe=(1.3*0.9/0.15)*F;
```

```
V_pipe=((pi*(0.75*D_pipe)^2)/4)* L_pipe; %Volume of the pipe, [m3]
% Coefficient connecting heat demand with discharge as q=P_q*P, [m3*W/s]
P_q=[5.42   23.08   501.25  108.26  16.73   961.05  20.54   14.77   17.3
15.93   117.61  15.41   29.28   52.01   15.59]*1e-10;

%=======================================================================
%Solar collector for DHW
%=======================================================================

c_g=3850; %heat capacity of glycol, [J/kg*K]
ro_g=1110; %dencity of glycol, [kg/m3]
q_sc=0.0214/ro_g; %glycol flow in the solar collector, [m3/s]

%Parameters of glazed solar collector
Frta=0.68; %Coefficients of heat losses, absorption and transmission of
%solar energy
FrU=4.9; %U factor for collector, [W/m2*K]
Ac=2.97; %Area of collector, [m2]
Vc=75*Ac*1e-3; %Volume of storage water, [m3]

%=======================================================================
%Heat pumps
%=======================================================================

%ground heat pump
q_cond=11e-3/60; %water flow in condenser, [m3/s]
%calculation of glycol temperature, [0C]
Tgly=4.25*sin(u*2*pi/12+1.1*pi)+0.75, where u=month

%monthly mean temperatures of air, [0C]
T_air=[-4.9 -1.8 -5.2 3.1 12.6 17.5 18.1 17.2 12.6 7.5 4.7 2.3];
T_airm=sum(T_air)/12; %average temperature of air, [0C]
T_aira=max(T_air)-T_airm; %amplitude of temperature variation, [0C]
a_soil=3600*25e-8; %thermal diffusivity of soil, [m2/h]
[T_airmin k_airmin]=min(T_air); %month of minimum temperature
%calculation of ground temperature, [0C]
%Tg=T_airm-T_aira*(exp(-u*((pi*a_soil/365)^0.5))*...
%cos((2*pi/365)*(month*30-k_airmin*30-(u/2)*((365*a_soil/pi)^0.5)))), ...
%where u=depth, [m]

%Air/air heat pump
PHcond_aa=3150; %heating capacity, [W]
PHcond_aaMax=3500;% maximum, [W]
PHcond_aaMin=900;% minimum, [W]
Pcomp_aa=500; %power consumption of compressor, [W]
Pfan_aa=230; %power consumption of fan, [W]
```

```
PCcond_aa=2500; %cooling capacity, [W]
PCcond_aaMax=3000;% maximum, [W]
PCcond_aaMin=1300;% minimum, [W]
loc_aahp=[1 0 0 0 0 0 0 0 0 0 0 0 0 0 0]; %location of AAHP

%======================================================================
%Solar radiation
%======================================================================

absorb_w=0.6; %absorptivity of outer wall
absorb_wd=0.94; %absorptivity of window
trans_wd=0.86; %transmittance of window
```