BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF CIVIL ENGINEERING
INSTITUTE OF BUILDING SERVICES

FAKULTA STAVEBNÍ
ÚSTAV TECHNICKÝCH ZAŘÍZENÍ BUDOV

NEARLY ZERO-ENERGY BUILDING RETROFITTING: CASE STUDY OF A CONVENTIONAL SINGLE-FAMILY HOUSE IN DENMARK

BUDOVA S TÉMĚŘ NULOVOU SPOTŘEBOU ENERGIE: PŘÍPADOVÁ STUDIE REKONSTRUKCE KONVENČNÍHO RODINNÉHO DOMU V DÁNSKU

SHORT VERSION OF DISSERTATION
TEZE DISERTAČNÍ PRÁCE

AUTHOR AUTOR PRÁCE	ING. ROBERT WAWERKA
SUPERVISOR VEDOUCÍ PRÁCE	DOC. ING. JIŘÍ HIRŠ, CSc.

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1 Introduction

The topic of doctoral thesis is related to energy retrofitting method of a conventional building into a nearly zero-energy building. The topic was chosen due to the actual topic relevance, wide international topic attention together with comprehensive discussion and real necessity of solving and improving energy efficiency in buildings all over the world. Many national and international, governmental and non-governmental tools, regulations and legislations are attempting and describing ways and methods how to improve energy performance of buildings [1], [2], [3], [4], [5] and [6].

In 2010 the European Commission introduced the Europe 2020 – A European strategy for smart, sustainable and inclusive growth. One of the EU 2020 targets is related to climate and energy and aims "*to reduce greenhouse gas emissions by at least 20% compared to 1990 levels or by 30 % if the conditions are right, increase the share of renewable energy in our final energy consumption to 20 %, and achieve a 20 % increase in energy efficiency*" [7].

If we focus and analyse in detail the European residential and non-residential construction industry we see enormous effort at the European Union and the Member states level to decrease energy use, improve building energy efficiency and increase the use of renewable energy in the building sector. In Europe, the buildings are responsible for 40 % of total energy use [8].

The European Commission's proposal announced in November 2008 for an update of the 2002 Energy Performance of Building Directive (EPBD) was implemented in Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. "*By 31 December 2020, all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings*" [9].

There are some efforts under way to improve primary energy efficiency in new buildings. According to the European Union market detail research, most of the residential buildings are single-family houses (60 %) and the apartments (40 %). However, 38 % of these buildings were built before 1960 and 45 % were completed in the period from 1961 to 1990 [11]. From the facts mentioned above there should be an assumption of considerable need of massive building energy retrofitting and significant potential of energy efficiency improvements in the existing residential building sector.

After extensive research, future expectation and energy efficiency requirements from the residential market, a reference residential building fulfilling all necessary criteria and boundary conditions for proposed research will be found. All research goals, including energy modelling, monitoring, building optimisation, verification, conclusions and recommendations how to refurbished building to nearly zero-energy building via different passive and active design methods together with renewable energy systems implementation will be carried out in this doctoral thesis.

2 Literature review

2.1 History of zero and nearly zero-energy buildings

The term "nearly zero-energy building" has been in use only for a few years, the term "zero energy building" for past decades, but the vision and idea of designing buildings with nearly or zero energy consumption has been known for thousands of years. Since that time people have known general design parameters influencing energy efficiency and indoor air quality of the building which include for example building orientation, openings location or shading element placement known nowadays as a passive architecture design features.

Nowadays buildings are categorised by their energy consumption to nearly zero-energy buildings, zero energy buildings or energy-plus buildings, etc. Nearly zero-energy building is defined in the Directive 2010/31/EU: "*nearly zero-energy building means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*" [9].

For building with zero energy consumption are at the moment many designations, for example zero energy building (ZEB), zero net energy (ZNE), net zero energy building (NZEB), or net zero building (NZB) [12], [13], [14], [15]. Similar difficulty is with the terms associated to zero energy building definition. Extensive discussion has been kept in the zero energy building definition or calculation methodology implementation. In our study we identify with the general definition written by Jens Laustsen in 2008 for ZEB: "*Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid.*" [16].

2.2 Nearly zero-energy buildings analysis

Some nearly zero-energy and zero energy building case studies have been already developed or built and it is proven that these building energy targets are achievable [17], [18] and [19]. In 2012 the Kapsalaki, Leal and Santamouris have discussed the optimal building design parameters for NZEB: *However, it has not been proven that the design choices are, besides technically effective, also efficient from the point of view of the use of economic resources. For instance, it is important to develop methodologies that allow building designers to identify the combinations of design variables (from potentially millions of possible combinations), while ensuring the achievement of the energy and environmental targets established, also have near-optimal lowest LCC, or lowest IC, or a good compromise between IC and LCC* [20].

The retrofitting methodology for nearly zero-energy building is a comprehensive analytical process that starts from the early design stage. Through building design, construction and commissioning a lot of aspects, boundary conditions and tools have to be taken into consideration. This can be for example current building orientation, facade and type of the existing construction system. All aspects of building design are interlinked and it is important to implement an overall integrated design process and to have in mind that no single factor should be considered without taking into account its relation to all the others – a holistic approach is essential [10]. To decide which adequate nearly zero-energy design solutions have to be selected, firstly energy use demands of the existing building have to be determined. Each major energy use factor can be influenced by a number of building design variables that are further extended and described by a wide range of input parameters (Fig. 1). Every combination of building design variables leads to a specific total annual energy consumption based on a typical building use conditions. Therefore each combination of building design variables have to be identified from many points of view, for example: initial cost (IC), life cycle cost (LCC), technical or architectural criteria to apply and decide on the final design strategy.

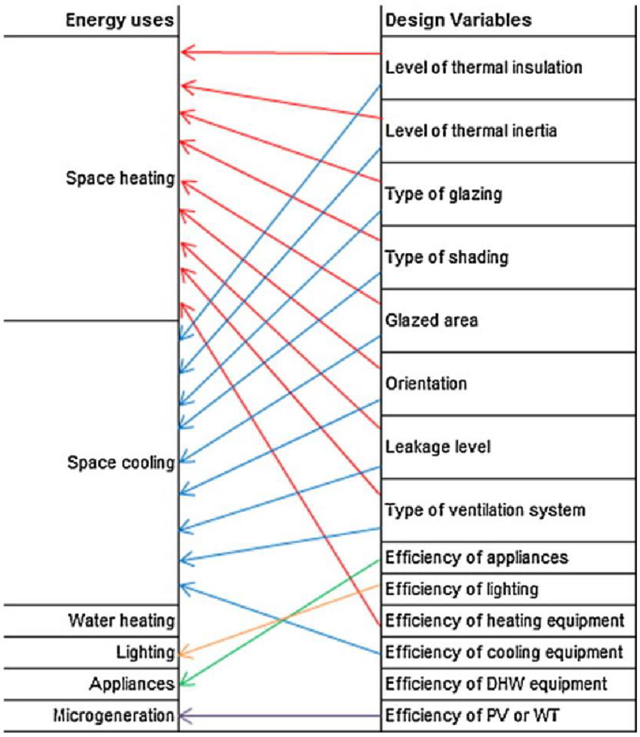

Fig. 1 Energy use versus design variables [20]

After reviewing and summarising all design variables and their impact on the overall building efficiency and energy consumption, the list of the most important building design elements includes: building envelope optimisation, HVAC system design and operation optimisation, decrease energy use of appliances and lighting, renewable energy application.

2.3 Building envelope optimisation

Building envelope is the most crucial part of the building in terms of energy distribution. In 2011 Mwasha et al (2011) indicated that the building envelope contributes over 50 % of the embodied energy distribution in major residential building elements and around 50–60 % of the total building heat gains or losses [21]. Typically, nearly zero-energy buildings are very well insulated with minimised thermal bridges and optimised solar gains. Retrofitting strategies include areas such as roof, walls, windows, doors and the foundation floor slab. For each area there is a number of alternative building envelope retrofit strategies that are feasible as a part of an overall near net zero retrofit, provided that appropriate control of air, water and vapour are addressed [22]. Fig. 2 shows basic features of retrofitting the building envelope.

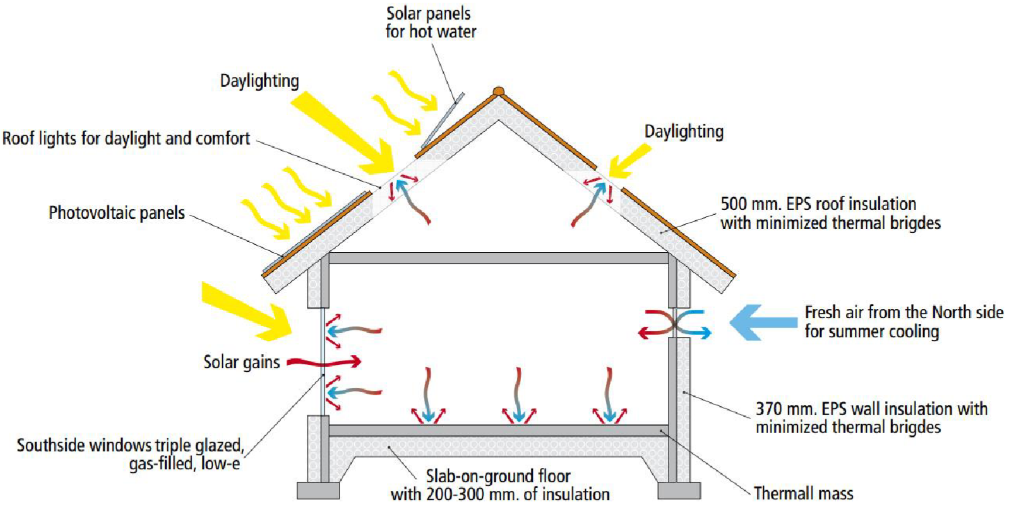

Fig. 2 Building envelope design principles for a nearly zero-energy building [10]

Nowadays a new trend in building envelope retrofit strategies is developed and implemented – prefabrication. Some prefabricated solutions have been developed lately to facilitate the buildings retrofit and also to provide more attractive solutions with simpler and quicker application methods [19]. Other advantages of prefabricated solutions are weather independency, quality control and cost savings in comparison to site-built construction.

2.4 Building service systems

Building service systems as heating, ventilation, air condition (HVAC) and domestic hot water (DHW) typically represent one of the highest energy consumption contributions within the building sector. In detail, HVAC systems are the most consuming representing approximately 50 % of the total building consumption, equivalent to 10–20 % of the final energy consumption [23]. Therefore the main focus on building service systems efficiency is appropriate. HVAC system design principles including many variables such as occupancy, user requirements, indoor air quality, weather conditions and others have to be carefully analysed. The overall HVAC system has to be comprehensive from the accurate boundary conditions specification, efficient equipment selection, operation, maintenance to life cycle cost analyses. There are many building service systems technologies that can be used in single-family houses fulfilling nearly zero-energy building requirements, for example radiant floor heating or mechanical ventilation with heat recovery.

2.5 Renewable energy sources

Renewable energy is a form of energy that can be constantly regenerated in a short time period. Renewable energy is represented by many forms of energy sources, such as solar, wind, biomass, hydro and geothermal energy. Life cycle cost of most renewable energy technologies is still lower than conventional energy systems, mainly because of an initial investment and maintenance cost and their operational intermittency. Renewable energy sources (RES) have some significant advantages as well, mainly ensuring fossil fuel resources independency and helping with carbon emission reduction [24]. Nearly zero-energy building design has some limitations and requirements. For the nearly zero-energy building retrofitting only selected renewable energy systems are considered, such as solar thermal system, PV panels, heat pumps and small scale wind turbines.

2.6 Energy generation

Type of energy generation plays an important role in the overall building energy consumption. Energy can be generated by non-renewable or finite resources and renewable energy. In most countries the total energy consumption in buildings consists of a mix of different types of energy. In order to estimate and evaluate building energy performance in the same units the site energy is transferred to primary energy. Primary energy is the energy coming from the nature which is not converted or transformed by any process and is described by Primary Energy Factor.

Energy generation supply options terminology is still widely discussed internationally. Basically energy generation can be categorised by its location boundaries and perimeters to the building on-site, nearby or distant production [26]. On-site generation defines energy production on building footprints or on an adjacent parcel of land; nearby energy generation is an energy produced only at local or district level and distant energy specifies all the other energy sources.

2.7 Weather data

It is necessary to know the exact location and weather condition before the building design, simulation or optimisation starts. For energy simulation in a certain location it is important to select the weather data within 30–50 km and within several dozens of meters of elevation [27]. The weather data file for simulation has to represent typical long-term weather patterns, using of a single year weather data have to be avoided. The long-term weather patterns are methods producing an artificial one-year weather period data set that represents the collection of hourly values of selected meteorological elements (temperature, humidity, solar radiation, wind, etc.) in a certain location in a period longer than a year. The artificial one-year weather data ensure more accurate results prediction in building energy consumption, production, energy costs and thermal comfort.

2.8 Building energy simulation software

Building energy simulation software and platforms facilitate the building sustainable design, optimisation and operation. Building energy simulation helps to estimate the future building energy consumption or production, carbon footprint, daylighting, artificial lighting and comfort performance. Buildings and their environmental control systems are complex (i.e. transient, multi-dimensional and highly interactive), making this optimisation task difficult and time consuming. In order to deal with this complexity, building energy simulation tools should be used [28]. Building energy simulation software requires a great knowledge to building energy science and expertise. Each computing model based on the selected calculation method is very sensitive to physical and geometrical input data. Improper choice or undesired commutation of input can cause irrelevant output information and errors. For each building energy simulation programs validation methodology has to be done to prevent the source of inaccuracy which can be divided into external and internal errors.

3 Objectives

The doctoral thesis objectives are comprehensive studies and analysis of a single-family house energy retrofitting into a nearly zero-energy building. Innovative way of building energy retrofitting will be introduced and new methods will be provided to architects and planners. The right understanding of comprehensive building energy retrofitting process to nearly zero-energy building, consideration and application of all necessary input factors and boundary conditions will ensure to reach a cost effective, energy efficient and indoor environment friendly building.

3.1 Objectives specification

- Suitable building selection and detail analysis.
- Study of suitable dynamic energy simulation software.
- Definition of boundary condition for simulation and model description.
- Building energy simulation and optimisation.
- Monitoring system installation and software study.
- Intensive long term energy and indoor climate monitoring.
- Evaluation and validation of measured data.

4 Methodology

Nearly zero-energy building energy retrofitting process is a very complex topic with many variables, input and output information and boundary conditions. Therefore the theoretical and experimental methods have to be necessarily used.

4.1 Theoretical/Numerical methods

Theoretical methods are applied to analyse and validate building operation, thermal comfort and energy uses that are modelled in a computer simulation software. Dynamic energy simulation software will be used to provide accurate and convenient estimation for nearly zero-energy building energy retrofitting method and its validation.

4.2 Experimental methods

Experimental methods are used to measure and validate real building operation, energy consumption, thermal comfort and weather data for selected object.

5 Analysis and results

5.1 Building selection and detail analysis

Detail residential single-family houses market research was carried out. The main research ideas and targets were to find a typical representative of standardised single-family house which represents repetitive construction trends in a specific period. The single-family house had to be located in Denmark due to the Danish project developer and leader and future involvement of the Danish companies in this project. From various potential and suitable cases in several locations one suitable semi-detached house was found and chosen for the future studies. Object is located in Albertslund area close to Copenhagen, Denmark (Fig. 3).

Fig. 3 City district of Albertslund [Google Earth]

The house was built in 1970s as a two storey semi-detached single-family house with concrete panel superstructure. The dwelling is currently occupied by one person with a total gross floor area of 67.1 m^2. The initial and current design of the house can be described by many various parameters which are presented in chapters below.

5.1.1 Initial building condition (Before energy retrofitting)

The facade was originally made from insulated concrete panel blocks with estimated U-value of 0.43 W/m^{2}K. Wooden windows were double glazed with U-value of 2.90 W/m^{2}K. The pitched roof had a tilt of 6° from horizontal axis and U-value of 0.41 W/m^{2}K. DHW and space heating were connected to district heating network. Heating system in the house was provided by double-pipe hot water radiators from 1970s.

5.1.2 Current building condition (After energy retrofitting)

Initial building design was subjected to very intensive studies to achieve at least nearly zero-energy building standards (current design). All major and minor building elements and tenant′s requirements were considered in the proposal and afterwards in the design phase, for example, building envelope, efficient lights and appliances, building service systems, renewable energy sources. After that the whole building and systems were altogether optimised. The building was designed as a nearly zero-energy building but the project target was to achieve a better performance; an energy self-sufficient (zero energy) building where the required energy is covered by renewable sources. Simple sketch of the energy retrofitting process is shown in the Fig. 4.

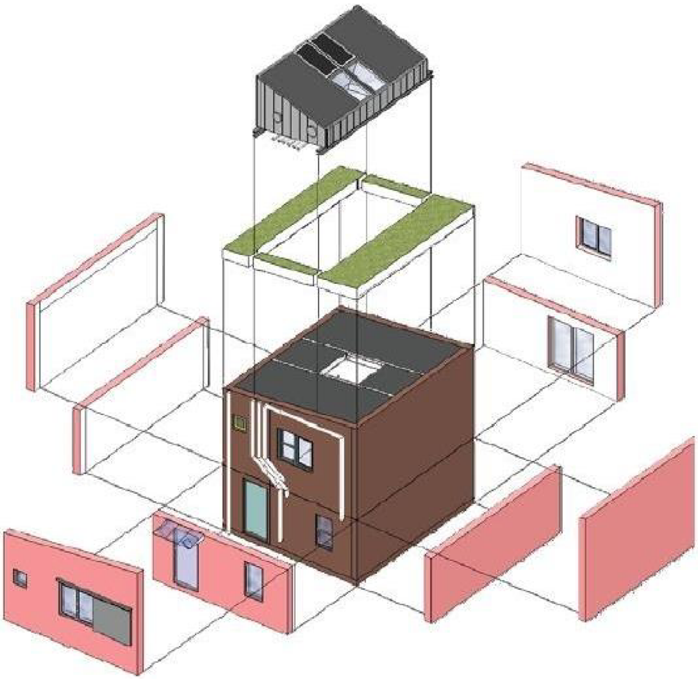

Fig. 4 Scheme of house energy retrofitting [30]

5.1.2.1 Unique prefabricated rooftop element

A very unique part of this building energy retrofitting is a special wedge prefabricated element (Fig. 5) that is placed on the initial roof structure. The rooftop element enables implementation of renewable energy systems and all technical installations needed for building operation into one compact unit. This rooftop element has a significant influence on the building energy efficiency, performance, indoor climate and installation process. The introduced element shape was accurately designed and tested and afterwards implemented onto the selected reference building.

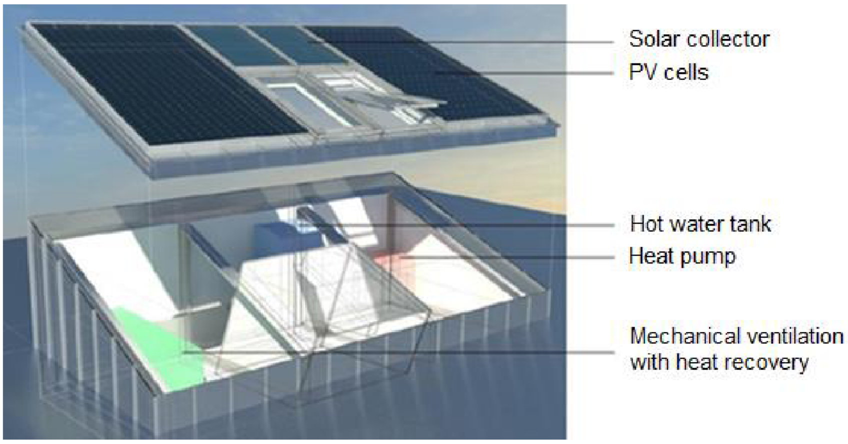

Fig. 5 Detail of the unique prefabricated element [30]

The external surface of the rooftop element is covered with 2.4 m^2 of solar thermal collector and 10.5 m^2 of photovoltaic panels. Two additional skylights help to improve the indoor environment by achieving better daylight penetration into the second floor (bedroom area) and help to reduce the energy need for artificial lighting in the building. All building technologies and systems that are completely built-in inside the prefabricated element are: mechanical ventilation with heat recovery, heat pump and hot water tank. Flexible ventilation ducts are fixed under the new prefabricated facade elements.

5.1.2.2 Building envelope

Building envelope has to be very well insulated and airtight. Thermal bridges should be reduced to minimum. This target is achieved by mounting special large scale prefabricated mineral wool panels on the current facade and pitched roof with tilt of 6 °. This prefabricated solution enables to improve even more thermal properties and thermal bridges of the building by minimising amount of joint connections in the final building envelope structure and the target U-value for external walls of 0.07 W/m^{2}K and for roof 0.06 W/m^{2}K were achieved. All openings such as windows and doors are part of the insulated façade panels as well. Windows were replaced with triple glazed one with the U-value of 1.10 W/m^{2}K and 1.20 W/m^{2}K for doors. Skylights have the U-value of 1.80 W/m^{2}K. Building envelope air tightness test was performed. The performance of refurbished building envelope components depending on thermal properties was improved in range of 45 % to 85 %.

5.1.2.3 Renewable energy sources

Renewable energy application is necessary to target nearly zero-energy building standard. Detail weather condition, geothermal and other studies were carried out in Albertslund area. The final result of using combination of three main renewable energy sources (geothermal, solar and wind energy) was decided. The highest energy contribution is ensured by horizontal ground source heat pump with the ground heat exchanger placed in frost-free depth. Part of the heat exchanger is mounted in the septic tank. Energy source for domestic hot water (DHW) is partially covered by the solar water heating system consisting of a 2.4 m^2 flat plate solar collectors mounted on the prefabricated element. Electric power is delivered by 10.5 m^2 of a photovoltaic grid connected monocrystalline cells. The last renewable energy source installed in the building is a small scale vertical axis wind turbine (VAWT) with the power input of 0.5 kW. Later the VAWT was replaced by additional 8 m^2 of photovoltaic cells.

5.1.2.4 Building services

Mechanical ventilation with heat recovery (MVHR) delivers minimum amount of outdoor fresh air into the house during the whole year to meet indoor air quality requirements. During the heating season the air is treated (preheated and heated) in a central air-handling unit and distributed by flexible ducts into rooms – living room with kitchen and bedroom. Heat recovery efficiency is about 90 %. One flat water tower rail radiator is mounted in the bathroom. A stratified storage water heater is custom made for this project with two heat exchangers and additional electric heating rods as a backup. The storage tank volume is 160 litters and is placed inside the prefabricated element. The method of building service systems for the single-family house energy retrofitting was designed carefully to meet at least the target of nearly zero-energy building.

5.2 Dynamic energy simulation software

At the market there are several dynamic energy simulation software such as ESP-r, DesignBuilder as an EnergyPlus graphical user interface, IES –VS, OpenStudio, TRNSYS, etc. Each simulation tool has a certain characteristic, different level of complexity and variables response. Some software is focused more on building envelope modelling; other more on building service systems, etc. Therefore it is really necessary to select the proper software which meets most of user's requirements and needs. In order to select the suitable building simulation software, detail studies and tests were done with the focus on selected criteria: building model and geometry, templates and libraries, building services and renewable sources, simulation complexity, other features, software application and licenses. After the building energy simulation software evaluation was done it was decided to perform energy calculation in DesignBuilder as an EnergyPlus graphical user interface. This software had the best performance in selected criteria with worldwide application in private and research sector.

5.3 Definition of boundary conditions

5.3.1 Weather data

Weather data analysis is usually the first step in any energy efficient design for nearly zero-energy building. The important information for the design can provide outside temperature, relative humidity, diffuse and direct solar radiation, wind speed and direction, etc. Other aspects and limitations from the analysis of weather data profile are providing key information for the future selection and implementation of building service systems and renewable energy sources. For further studies and simulations a typical meteorological year hourly weather data from International Weather for Energy Calculation (IWEC) in epw format are used. The nearest location with the IWEC weather data information is Copenhagen Airport in Denmark, which is around 20 km far from our location in Alberstlund, Denmark.

5.3.2 Model description and layout

The selected area of the Albertslund city district where the selected single-family house is located was modelled (Fig. 6). The city district model helps to simulate influences of outdoor boundary conditions on studied building, such as building shading, solar radiation or wind effect.

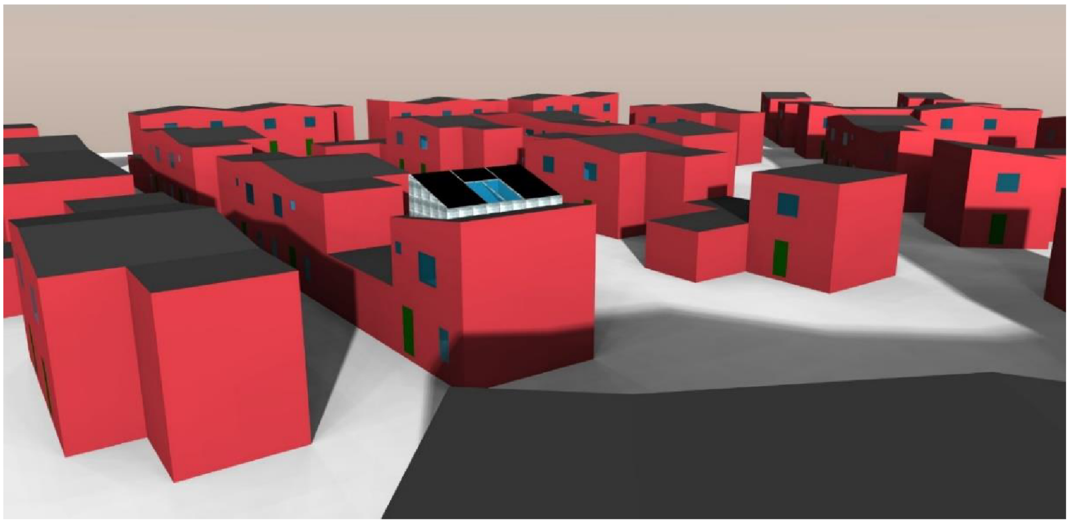

Fig. 6 Albertslund city district model [author]

The detail building model geometry for thermal, energy and indoor climate studies of the initial and current design is built in DesignBuilder and it is shown in Fig. 7. Superstructure and internal disposition have not been changed and the floor area of the dwelling is the same as before energy retrofitting. The gross floor area is 67.1 m^2. The building orientation is almost following the north-south axis, exactly 8 ° according to the azimuth angle.

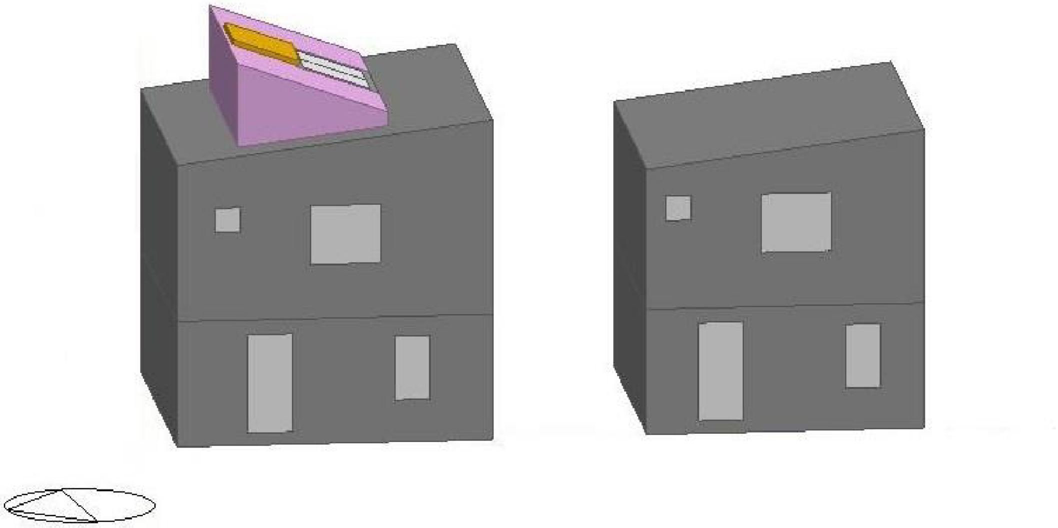

Fig. 7 Geometric model of current (left) and initial (right) house in DesignBuilder

The DesignBuilder model is created by building blocks which are formed by building elements such as external walls, slabs and roof. Internal partitions divide object into 6 thermal zones on two floors. Ground floor includes entry, corridor with staircase to the first floor and living room with kitchen. Corridor, bathroom and bedroom with home office are situated on the first floor. The floor plans and zone location are shown in the Fig. 8.

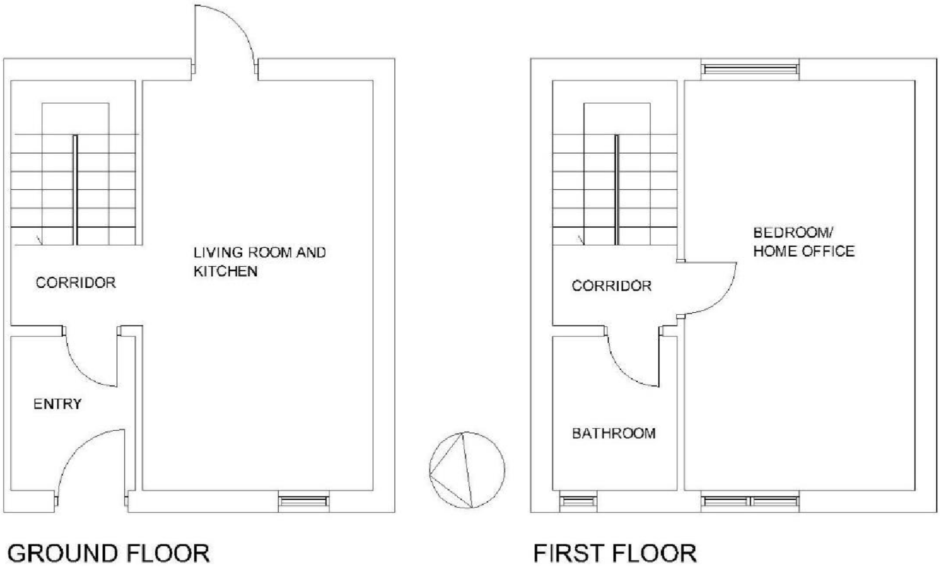

Fig. 8 Ground floor and first floor plan

5.3.3 Occupancy and internal gains

The building operational variables such as occupancy, metabolic rate, clothing factor, tenant′s activity, internal gains, indoor air temperature etc. are very difficult to predict due to the inconsistent tenant´s behaviour and building operation in time. Therefore the tenant´s behaviour studies were performed. The studies were based on one person living in the dwelling and a typical operation schedules (working person), both for the studied building before and after energy retrofitting.

5.3.4 Building services

The building services include all major energy systems needed for building operation (HVAC and DHW). For the simulation the whole building energy system was simplified and divided into four main core functional parts – mechanical ventilation with heat recovery (MVHR), ground source heat pump (GSHP) and heating system, solar assisted domestic hot water (DHW) system and photovoltaic (PV). Fig. 9 shows the detail building service systems scheme design modelled in DesignBuilder software without photovoltaic system.

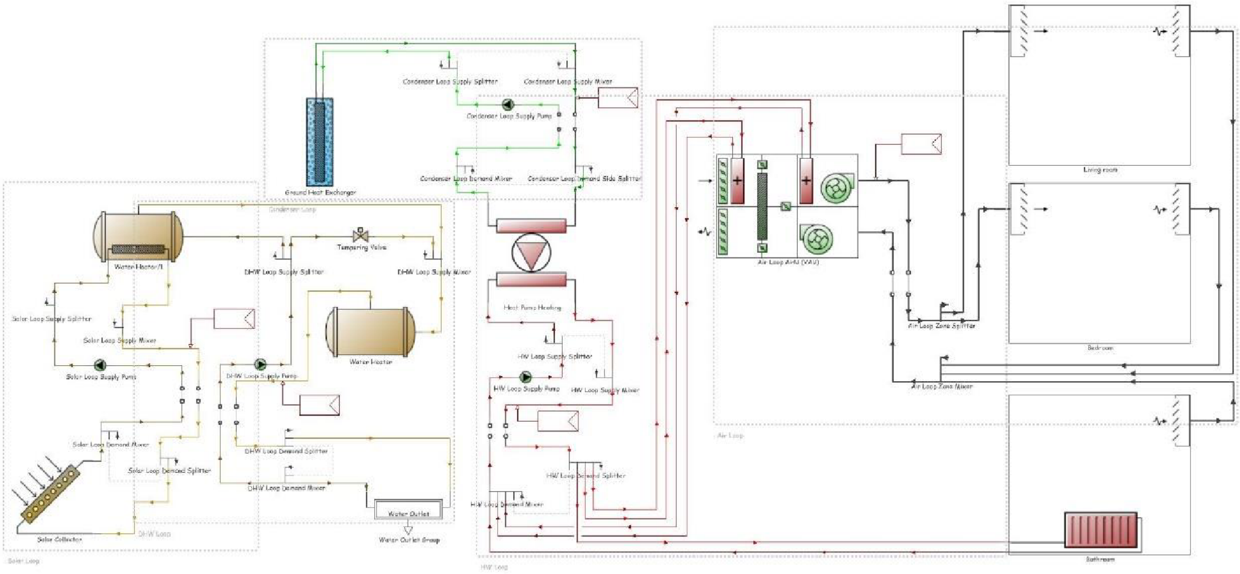

Fig. 9 Building service systems scheme in DesignBuilder software

5.3.4.1 Mechanical ventilation with heat recovery

Mechanical ventilation with heat recovery system is created in detail HVAC DesignBuilder template and subjected to energy simulation. The mechanical ventilation (MV) air loop in the model is made up of two sides – air loop supply side and air loop demand side. Air loop supply side is an air handling unit (AHU) with water pre-heating coil, water heating coil, two radial EC fans and counter flow type heat exchanger with very high efficiency. The air loop demand side includes building zones (living room with kitchen, bedroom and bathroom) where AHU supplies or extracts the required amount of air.

5.3.4.2 Ground source heat pump

Ground source heat pump model with horizontal loop is simplified for the energy simulation. Heat pump produces heat energy only for space heating (preheating and heating coils in AHU and radiator). In reality the GSHP system is connected through heat exchanger to water storage tank and supports heating of DHW as well. In the model the heat pump system consists of condenser loop (supply side) and hot water loop (demand side). Condenser loop is furthermore split into supply side which represents horizontal ground heat exchanger and demand side where heat pump, more precisely evaporator is located. The hot water loop is located inside the building and delivers the medium into AHU heating coils and into the flat water tower rail radiator. The hot water loop is divided into supply side (heat pump condenser) and demand side (heating coils and radiator).

5.3.4.3 Solar assisted domestic hot water system

Solar assisted domestic hot water system in the simulation is an independent system which treats only DHW for all hot water outlets (taps, shower heads, etc.). As it is solar assisted DHW system, the system comprises of two main loops; solar loop and DHW loop. Solar loop is split into demand and supply side. Demand side contains two flat plate solar collectors of a total gross area of 2.40 m^2 connected through heat exchanger to the stratified hot water tank. Solar collector orientation is 98 ° from the north axis with the tilt of 19.5° from horizontal axis. DHW loop consists of a stratified hot water tank with the volume of 160 m^3 and a circulation pump on the supply side and hot water outlets on demand side.

5.3.4.4 Photovoltaic system

The photovoltaic system is mounted on the prefabricated element and covers almost 10.5 m^2 of its tilted roof area. An extra 8 m^2 of monocrystalline cells is mounted on nearby roof to cover energy production of removed vertical axis wind turbine. The system is grid connected.

5.3.5 Results and discussion

The boundary conditions have to be specified accurately and precisely to get the functional overview on the building energy model. If any boundary condition is not available the user can use the data sets from component or template libraries or use his own theoretical and practical simulation experience. As well it is not so necessary to go deeply into every building geometry or building services detail. This can only cause significant extension of the simulation time or incorrect assignment of boundary conditions, etc. If the energy model accuracy is set optimally, the differences between simulation results of the very detail and optimally designed model are negligible.

5.4 Building Simulation

Building simulations are divided into five main categories. The first category focuses on the building envelope with its thermal characteristic, the second category describes thermal comfort, the third category on internal gains and tenant′s behaviour, the fourth on daylighting and the last category are building service systems with heat and energy flows, such as heating, ventilation, domestic hot water system and renewable energy sources. For building simulation a typical simulation periods were selected and used: annual simulation (from 1st January to 31st December), winter design week (from 10th February to 16th February), and summer design week (from 3rd August to 9th August). The calculation option is set to 30 time steps per hour to improve calculation accuracy. Output data interval is set to an hourly frequency.

5.4.1 Heating design calculation

The building heat loss calculations were performed for the building before and after energy retrofitting (Fig. 10) under the same indoor and outdoor boundary conditions; the average indoor air temperature was 19.6 °C and an average outside dry-bulb temperature was -9.9 °C. In average, the overall heat loss from the building was reduced from 3.05 kW to 1.03 kW, which is approximately 66 % reduction.

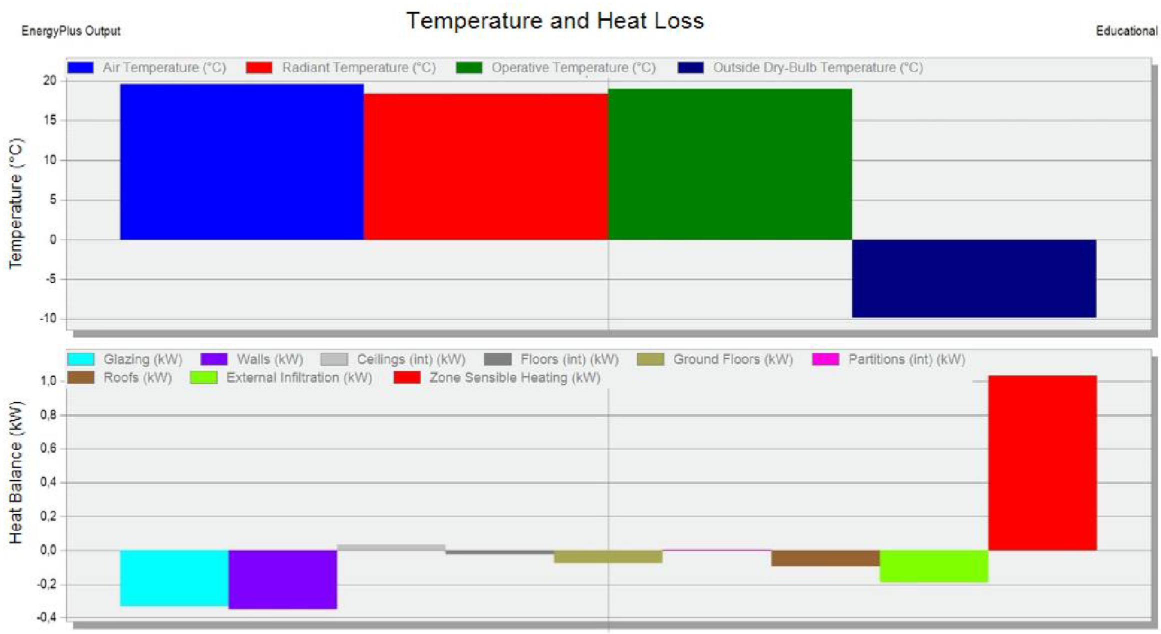

Fig. 10 Heat losses and temperature of the house after energy retrofitting

5.4.2 Internal heat and solar gains calculation

The highest gains were from solar radiation through exterior windows. For the winter design week the solar heat gain through exterior window varied between 0.3 kW and 1.5 kW (Fig. 11) and for the summer design week was the variation between 0.6 kW and 2.3 kW. The rest of the internal gains, such as lighting, domestic appliances or occupancy had negligible impact on the overall heat gains (below 0.2 kW) in the studied single-family house. Solar gains have significant impact on overall building energy method. Based on these findings it is necessary to consider solar gains impact on the building during the design and operation stage.

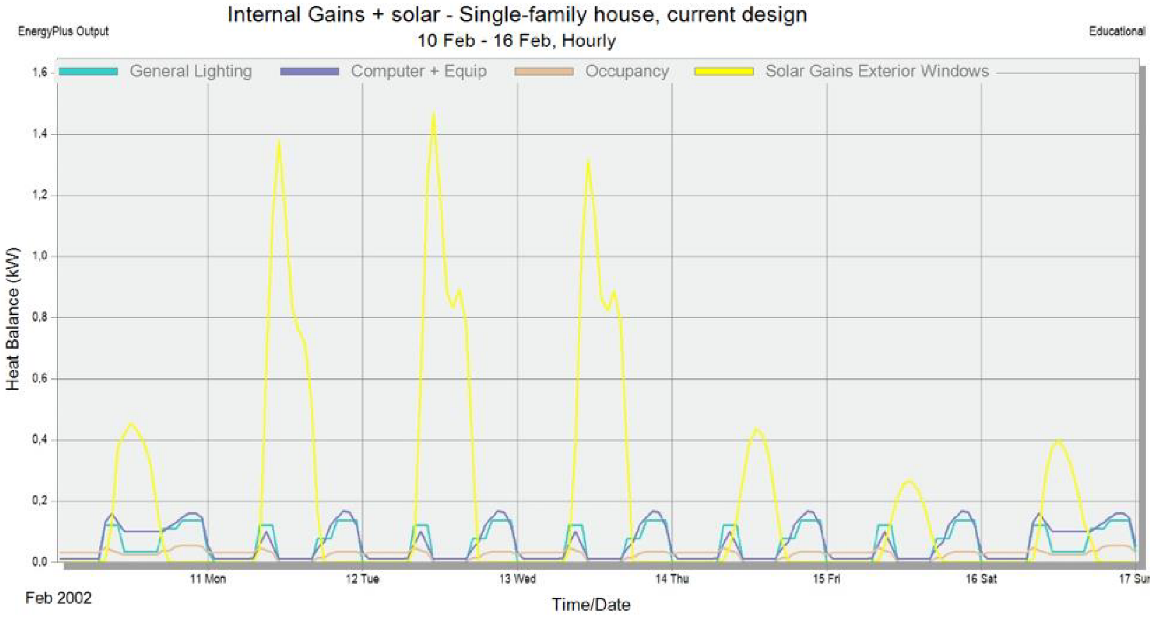

Fig. 11 Internal and solar heat gains for winter design week

5.4.3 Thermal comfort calculation

Thermal comfort calculations were performed for the living room the kitchen and the bedroom. During the heating occupied period the heating set point temperature was set to 22 °C with heating set back to 18 °C. For summer period the maximum allowed temperature was set to 26 °C if the space is occupied (Fig. 12). If the indoor air temperature of 26 °C is met and the outdoor air temperature was lower than the indoor air temperature the natural ventilation through openable windows was activated to cool the space.

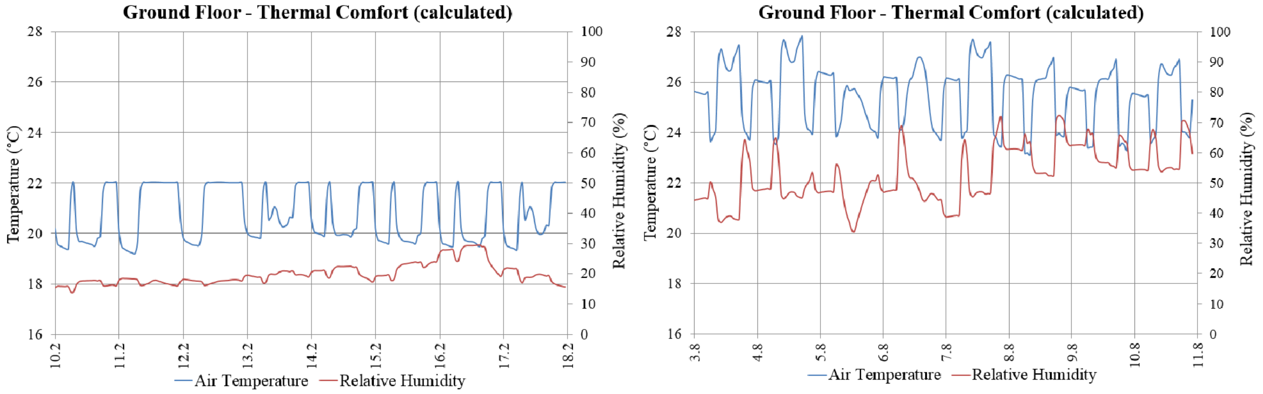

Fig. 12 Indoor air temperature and relative humidity (winter and summer design week)

5.4.4 Daylight analysis

The daylight analysis results demonstrated benefits of the extra skylights implementation and its significant impact on the daylight penetration into the studied bedroom area. Floor area above required daylight factor (DF) of 2.0 under overcast sky conditions (10 000 lux) increased from 32.6 % to 88.1 %. The daylight penetration increment has positive influence on the occupant comfort, health and emotional well-being as well as on the energy savings in the building.

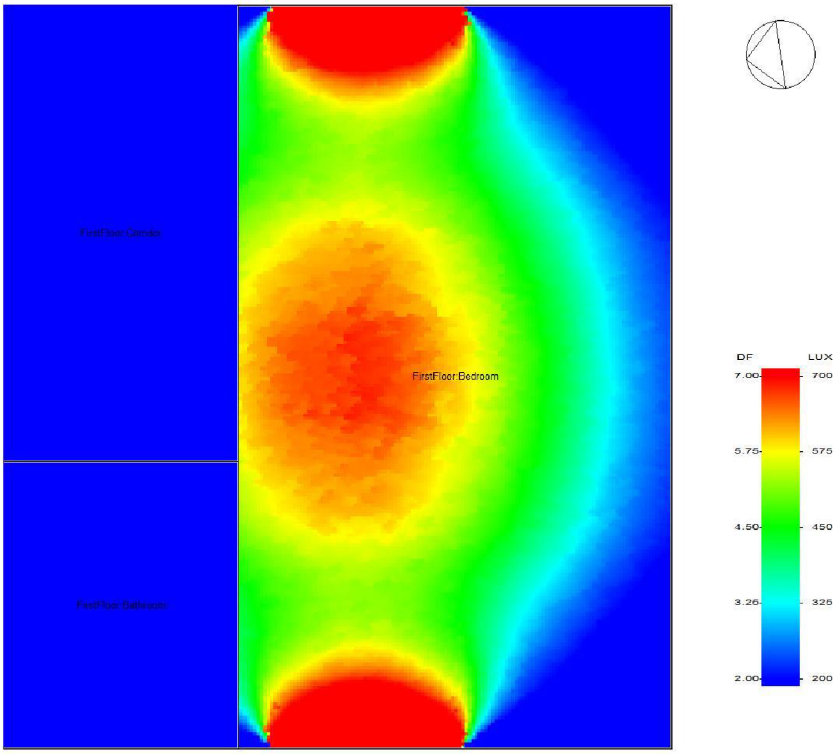

Fig. 13 First floor daylight illuminance map of current design

5.4.5 End-use energy calculation

The overall heat energy consumption of the building was 2830 kWh/year and heat energy production was 2467 kWh/year. The highest amount of the heat energy went for domestic heating, about 1755 kWh/year, where 63 % of the heat energy was produced by GSHP and the rest of 27 % was ensured by heat recovery in AHU. The total energy needed for DHW heating was 1075 kWh/year and 712 kWh/year was generated by solar collectors and the rest was secured by auxiliary electric water heater.

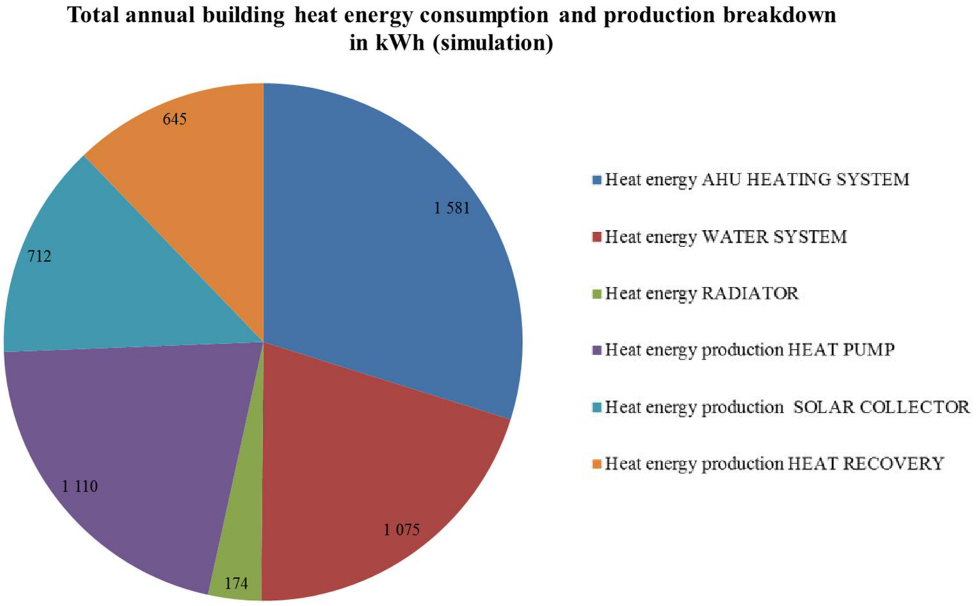

Fig. 14 Annual heat energy production and consumption breakdown

The overall electric energy consumption for the building was 1670 kWh/year and electric energy production was 2095 kWh/year. The highest amount of electrical energy was consumed by household (535 kWh/year) followed by ground source heat pump (426 kWh/year) and auxiliary electric water heater (363 kWh/year). The sufficient amount of electric energy was secured by photovoltaic which produced 2095 kWh/year.

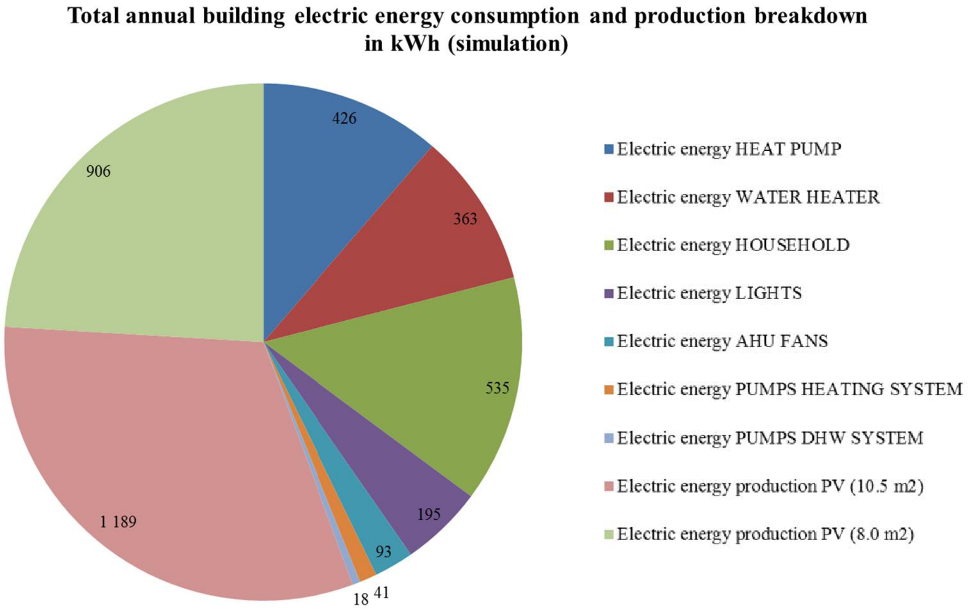

Fig. 15 Annual electric energy production and consumption breakdown

5.4.6 Results and discussion

Building energy simulation showed that the overall building energy production and consumption are in balance with very little power surplus of 61 kWh/year. It can be assumed that the building belongs to the zero energy building type. Building simulation experience showed the importance of capturing and precisely specifying boundary conditions to get the most accurate simulation results. Most of the results were optimised and validated by long term onsite monitoring, described in the chapters below.

5.5 Installation of monitoring system and software study

Two independent online monitoring systems were mounted into the building. One system is monitoring building services energy flows from main loops such as ventilation with heat recovery, heat pump, solar collector loop, DHW and heating loop. The monitoring time step was set to 4 minutes. The second installed system was monitoring thermal comfort in the main rooms; indoor air temperature, and relative humidity in living room with kitchen and bedroom.

The study has proven that it is necessary to install sensor properly in selected location and set the suitable monitoring time steps and units of measurements to get a sufficient amount of the data. Monitoring system has to be checked permanently and unexpected operation errors have to be immediately alerted to avoid improper building operation. Any building operation problems have major influence on the overall building energy performance.

5.6 Intensive long term energy, thermal comfort and weather data monitoring

Intensive long term energy, thermal comfort and weather data monitoring was carried out for almost two years (from middle of the year 2010 till middle of the year 2012) in order to verify the research main target: nearly zero-energy building energy retrofitting. To achieve this goal it was necessary to monitor, verify and eventually optimize building service systems operation. Only selected monitoring data are presented, such as outside dry bulb temperature, relative humidity, solar global radiation and wind speed. From thermal comfort indoor air temperature and relative humidity was monitored. Building energy consumption and production monitoring is represented by mechanical ventilation with heat recovery, ground source heat pump, solar assisted DHW, photovoltaic system and household.

The long term energy, thermal comfort and weather data monitoring showed in the most cases standardised line and column charts trend over the time period. Only few unusual findings had appeared during the long term energy monitoring. The indoor air temperature in the living room (Fig. 16) was during the winter period in the range of 21.0 °C to 25.0 °C. From the experience this room was overheated and it had interesting potential for further building energy savings.

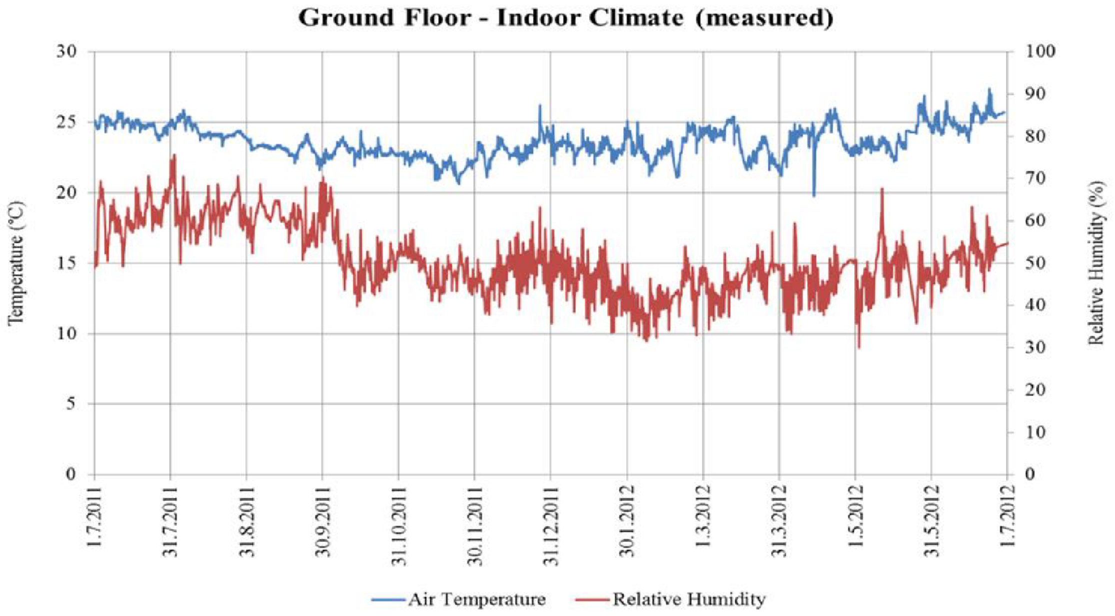

Fig. 16 Ground floor air temperature and relative humidity

Furthermore one small problem occurred with GSHP energy monitoring when the monitoring system did not work properly and the operation data were not available for two months period (Fig. 17). The last finding was related to very low AHU fans energy consumption during the first three months period (summer period). It is assumed that the tenant preferred natural ventilation instead of mechanical ventilation which was most of the time switched of.

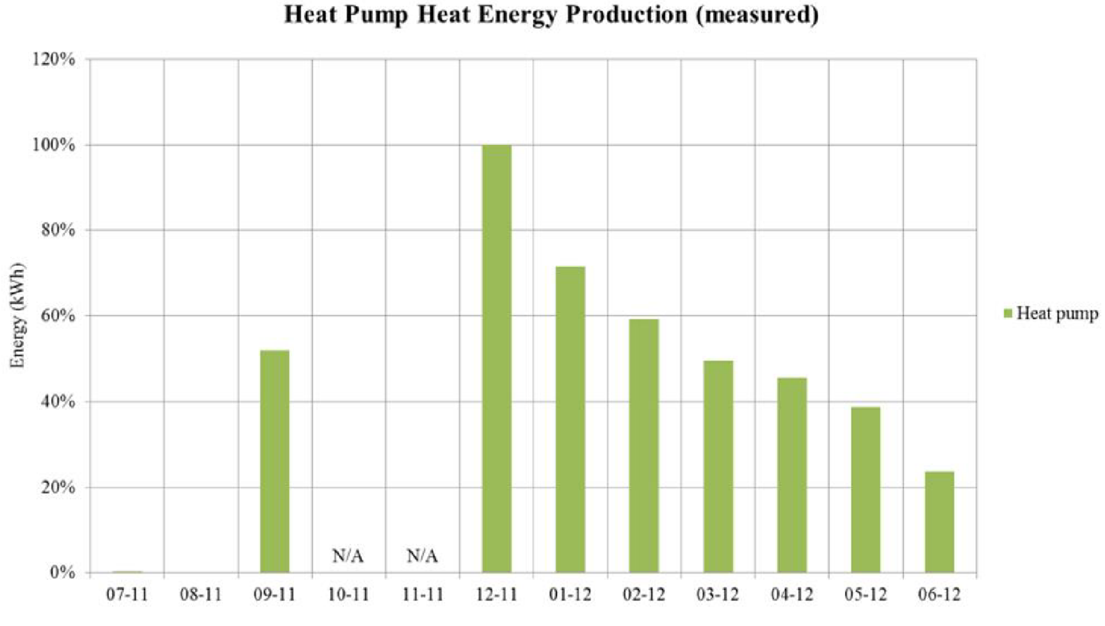

Fig. 17 Heat pump heat energy generation

In our research case, almost the first half year of monitoring required building services system optimisation and evaluation together with tenant's education in proper building and its system operation. Therefore monitoring system and data collection have to be frequently checked to avoid the possibility of building services system or data collection failures. The tenant's behaviour feedback is essential as well.

5.7 Building energy, thermal comfort and weather data verification

In this chapter data from energy simulations are verified by in-situ monitoring data. The verification is based on the data from chapters 5.4 Building simulation and 5.6 Intensive long term energy, thermal comfort and weather data monitoring which were present as annual simulated and monitored operational and thermal comfort data. The verification method was carried out on the selected time period (minimum of eleven consecutive days) and only daily simulated and monitored values were applied to get accurate and meaningful results.

5.7.1 Weather data

The comparison and verification of annual weather data are described in this chapter. Outside dry-bulb temperature from simulation software in IWEC format and monitored outside dry-bulb temperature and relative humidity from 1st July 2011 until 30th June 2012 are shown in Fig. 18. It is apparent that monitored daily weather data do not copy entirely the temperature curve represented by the typical meteorological year pattern used in simulation. Weather data deviations have a certain impact on further building energy results verification. The average annual outside dry-bulb temperature and relative humidity for typical meteorological year was 8.3 °C and 77 % compared to 9.1 °C and 83 % from the in-situ monitoring.

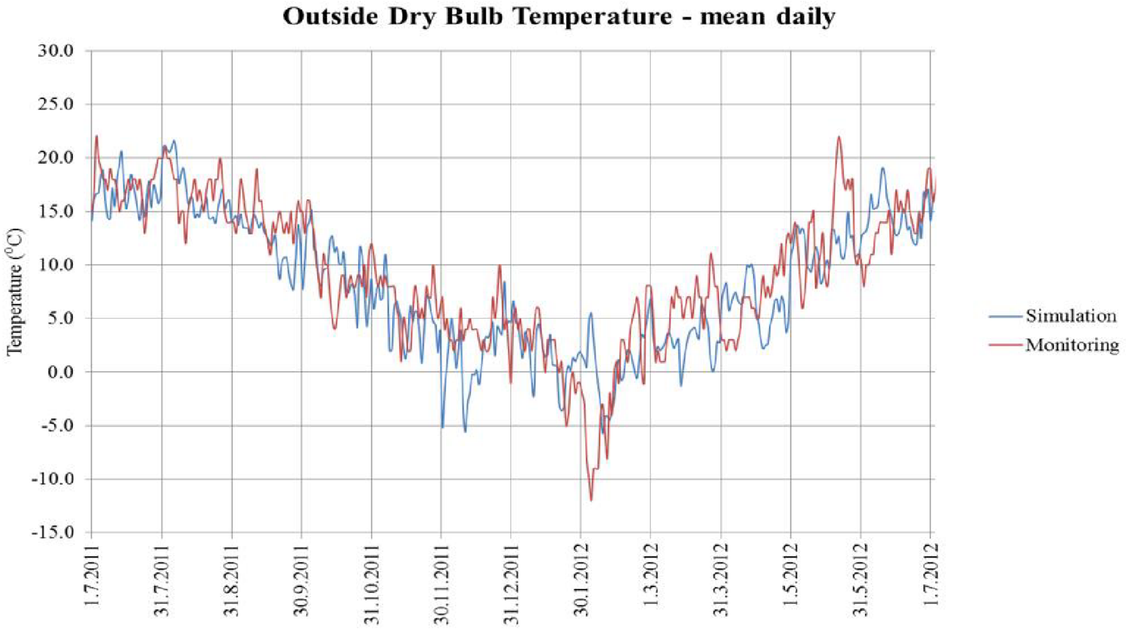

Fig. 18 Simulated and monitored outside dry-bulb temperature

Global solar radiation on horizontal surface (Fig. 19) shows no significant deviation between typical meteorological year and measured data. The month May 2012 was probably extremely sunny with high solar global radiation gain of 328 W/m^2 on horizontal surface. For example May 2011 in the same location had solar global radiation of 289 W/m^2.

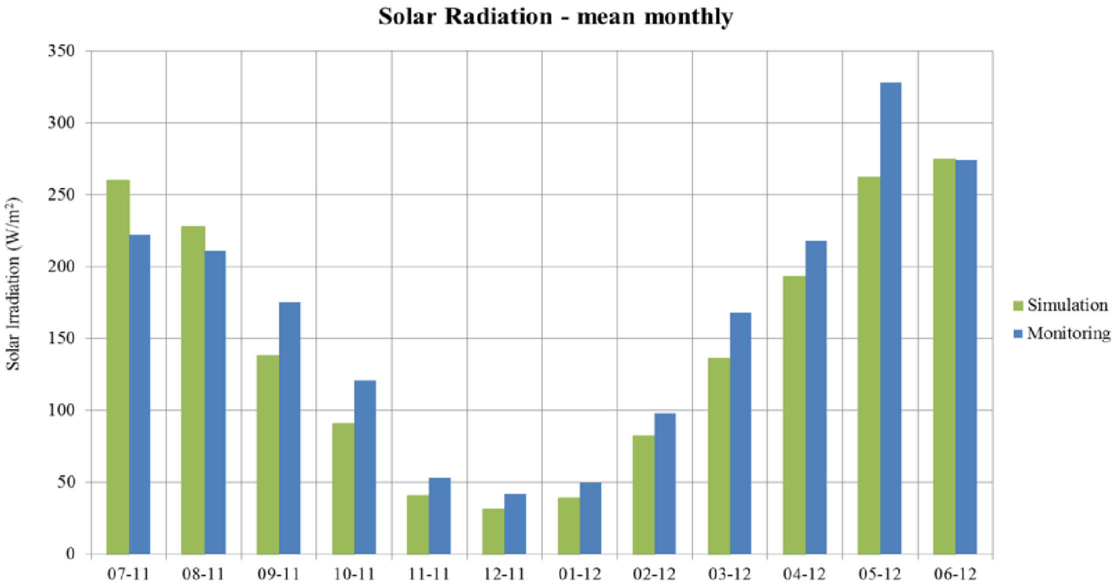

Fig. 19 Simulated and monitored mean monthly solar global radiation in W/m^2

5.7.2 Thermal comfort

The indoor air temperature (Fig. 20) in the period of 1st October 2011 to 31st March 2012 was in the living room with kitchen 21.8 °C (simulation) and 23.0 °C (monitoring) which means relative deviation about 5.5 %. Similar values were in the bedroom on the first floor (22.7 °C from simulation compared to 22.0 °C from monitoring). Air relative humidity for the same space is about 34 % in comparison to 51 % from the monitoring.

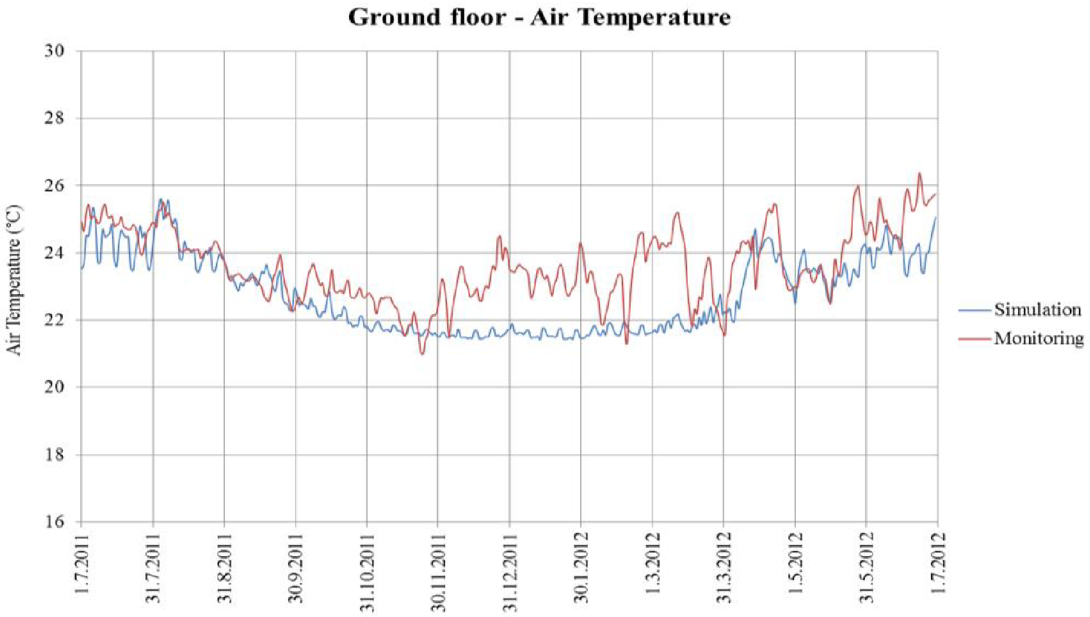

Fig. 20 Simulated and monitored indoor air temperature on ground floor

5.7.3 Mechanical ventilation with heat recovery

Mechanical ventilation with heat recovery energy consumption during the winter period is shown in Fig. 21. The average monitored daily heat energy consumption and outside dry bulb temperature for selected period (20th December 2011 to 30th December 2011) is 8.1 kWh/day and 4.9 °C compare to 7.2 kWh/day and 4.2 °C coming from energy simulation software.

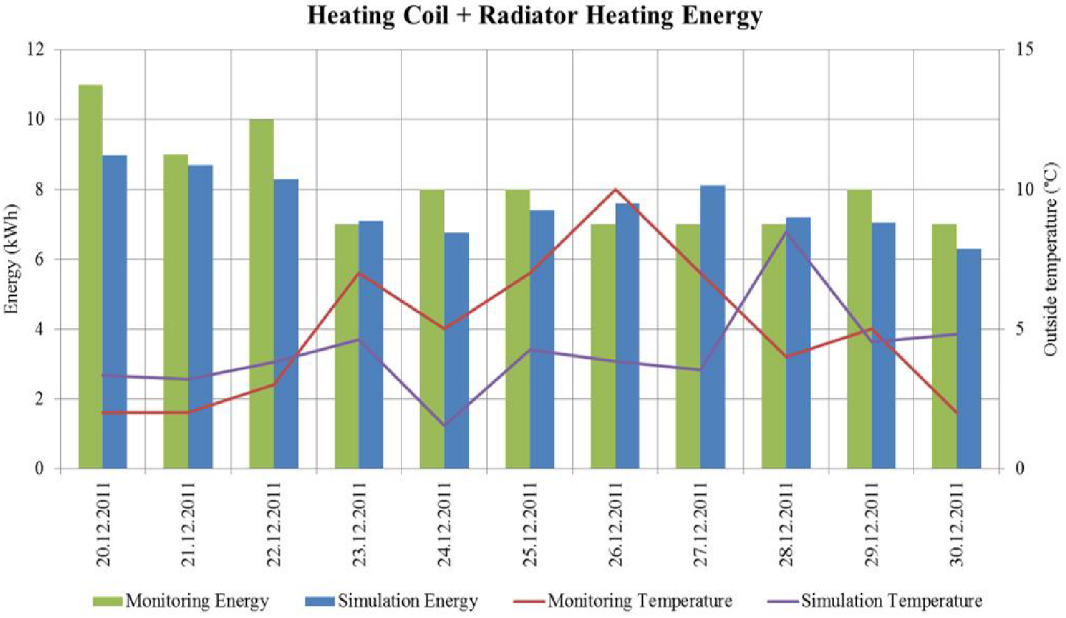

Fig. 21 Simulated and monitored heating coil and radiator energy consumption

5.7.4 Ground source heat pump

Ground source heat pump heat energy production for selected period (from 15th January 2012 to 26th January 2012) is presented in Fig. 22. The chart shows similarity in energy production and outside air temperature curves. The average daily energy production by ground source heat pump in relation to outside air temperature for selected period is 6.1 kWh/day at 0.2 °C for the real operation, and 6.1 kWh/day at -0.1 °C from the dynamic energy simulation.

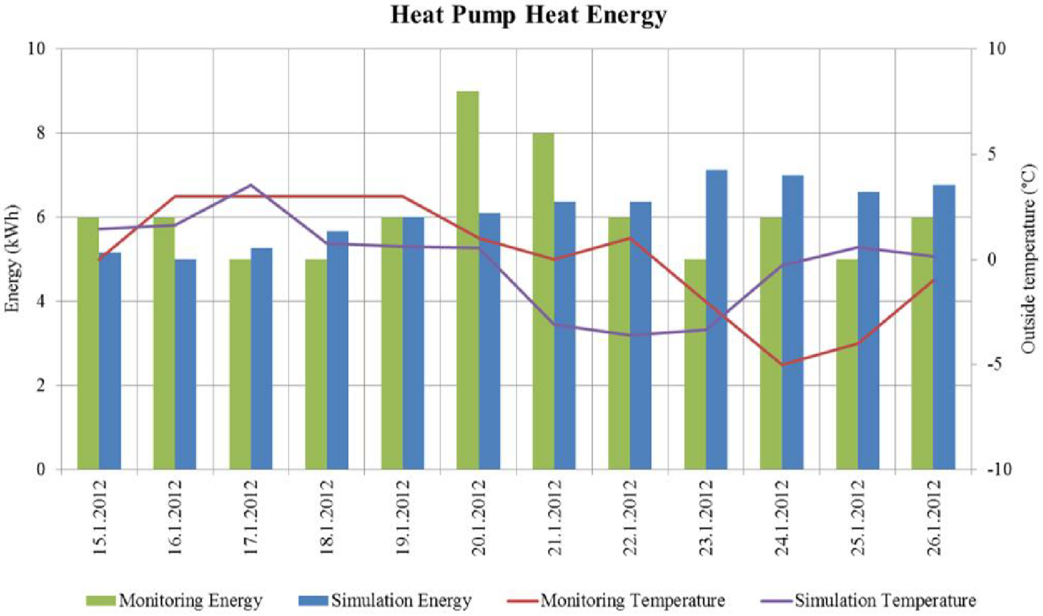

Fig. 22 Simulated and monitored ground source heat pump energy generation

5.7.5 Solar assisted domestic hot water system

The verification of a solar collector heat energy production provides reliable information in longer time period due to the daily weather data deviation (rain, sunny, overcast sky, etc.). Fig. 23 shows a daily solar collector heat energy production for twenty days in June 2011. Differences in the global solar radiation energy production for each day are noticeable from the chart. The daily average measured solar radiation and heat energy production is 284 W/m^2 and 82.0 kWh in comparison to 264 W/m^2 and 83.1 kWh from simulation. In this case the relative deviation between simulated and measured heat energy production and solar radiation is almost insignificant.

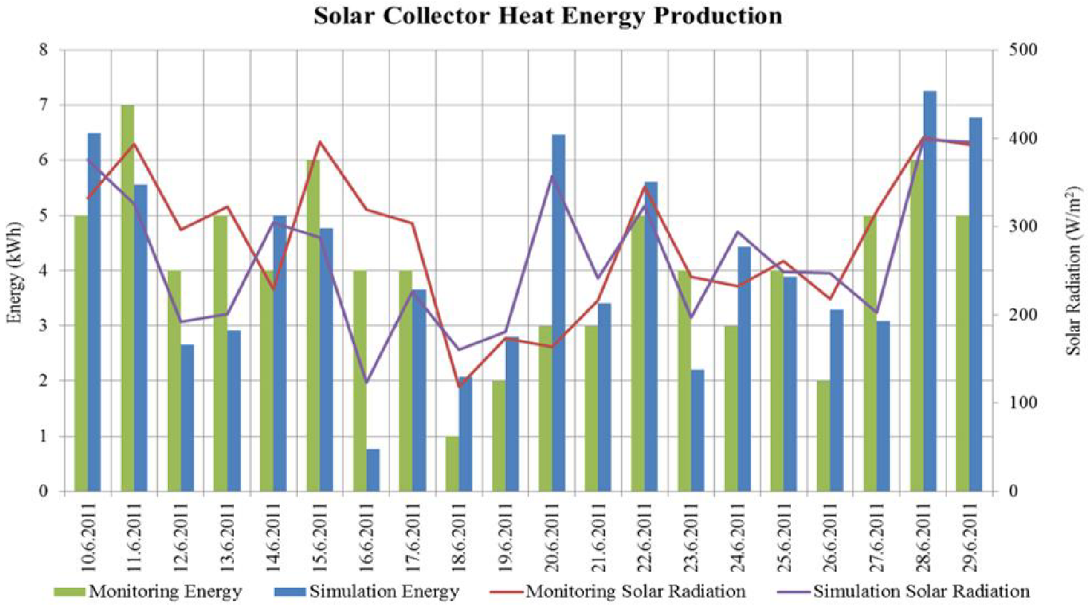

Fig. 23 Solar collector heat energy production and global solar radiation

5.7.6 Photovoltaic system

Photovoltaic system production verification during short term period has not predicative information. Fig. 24 shows an almost four weeks studied period (from 21st April 2011 to 15th May 2011) with high fluctuation due to different weather conditions. On average the total mean daily measured energy production and global solar radiation for selected period is 4.6 kWh and 339 W/m^2 in comparison to the simulation results of 4.5 kWh and 202 W/m^2. The differences in global solar radiation and produced energy might arise from lower PV cell and system efficiency or it can be significantly affected by various outside boundary conditions (weather data, shading, etc.).

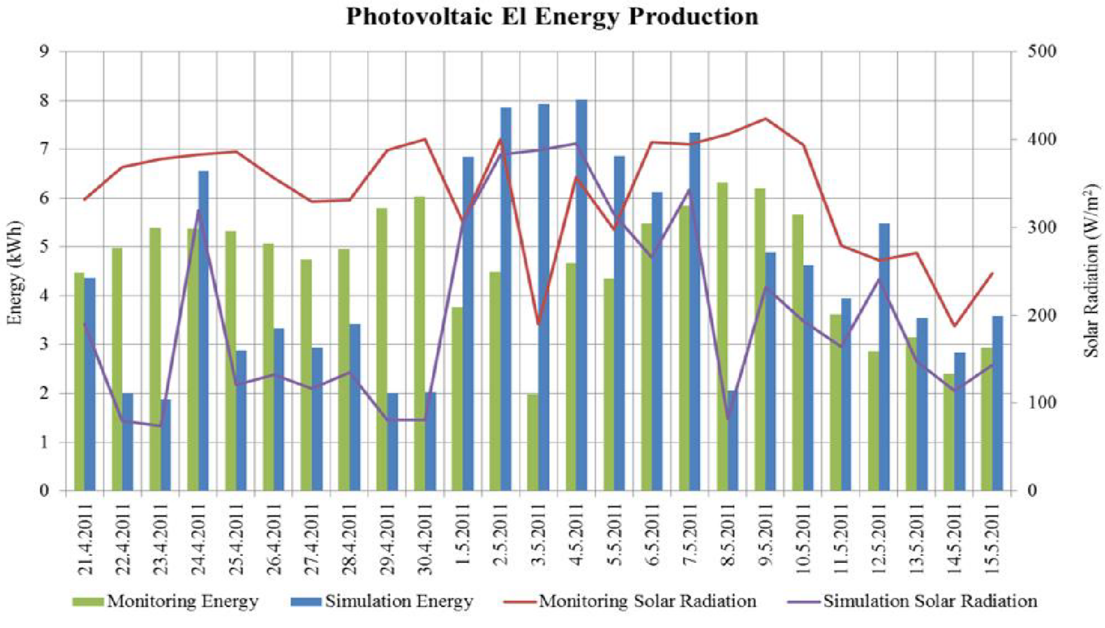

Fig. 24 Photovoltaic EL energy generation and global solar radiation

5.7.7 Results and discussion

The verification process confirmed the assumptions of properly chosen research objectives, methodology and goals. The research target of nearly zero-energy building energy retrofitting was simulated and afterwards verified by real in-situ measurements on the single-family house. The research target of nearly zero-energy building energy retrofitting method for single-family houses was achieved and the building is even reaching parameters of zero energy building.

6 Conclusions and recommendations

The research demonstrated and processed close link between European Union directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings [9] and the theoretical and practical application methods of building energy retrofitting process into the nearly zero-energy building.

The pilot project of the single-family house energy retrofitting according to nearly zero-energy building standard represents innovative, energy efficient and environmental friendly way of building energy retrofitting through implementation of unique prefabricated rooftop element together with progressive technologies. The doctoral thesis objectives, goals and targets are concluded and described in chapter 3 Objectives.

In the chapter 5.1 was described the selection process of the suitable building for the research located in Denmark. Subsequently the single-family house analysis of the initial design was described and the nearly zero-energy building energy retrofitting method was introduced. The unique prefabricated rooftop element as the pivotal part of the energy retrofitting was developed. The building was designed as a nearly zero-energy building but the project target was to achieve a better performance; an energy self-sufficient (zero energy) building where the required energy is covered by renewable sources. The performance of refurbished building envelope components depending on thermal properties was improved in range of 45 % to 85 %.

The study and suitable dynamic energy simulation software selection is described in chapter 2.8 and 5.2. The result showed that each simulation tool has a certain characteristic, different level of complexity and variables response. Therefore it is really necessary to select the proper software which meets most of user′s requirements and needs. The software DesignBuilder as an EnergyPlus graphical user interface had the best overall performance and was used for building energy design and verification.

The definition of boundary conditions for energy simulation is described in chapter 5.3. From the simulation experience it is recommended to specify boundary conditions accurately and precisely to get functional building energy model. It was confirmed that it is not necessary to go deeply into each building geometry or building services detail. This can only cause significant extension of the simulation time or incorrect assignment of boundary conditions. If the energy model accuracy is set optimally, the differences between simulation results of a very detail and optimally designed model are negligible.

The design of the nearly zero-energy building energy retrofitting was verified in energy simulation software and is described in detail in chapter 5.4. The overall heat energy consumption is 2830 kWh/year and production 2467 kWh/year. The building electricity consumption is 1670 kWh/year compared to 2095 kWh of annual electricity production. The energy model confirmed the assumption that the building energy retrofitting method was set correctly and the building has even better performance than nearly zero-energy building. It can be assumed that the building with an insignificant power surplus of 61 kWh/year belongs to the zero energy building type.

Monitoring system installation and intensive long term energy and thermal comfort monitoring was carried out for almost two years and is described in chapter 5.5 and 5.6. Two independent online monitoring systems were mounted into the single-family house. The long term monitoring confirmed the necessity of proper sensors placement in selected areas together with the appropriate monitoring time steps and units settings to get a sufficient amount of the data. In our research case almost the first half year of monitoring required building service systems optimisation and evaluation together with tenant′s education in proper building and its system operation. Therefore monitoring system and data collection have to be frequently checked and unexpected operation errors have to be immediately alerted to avoid improper building operation. The frequent tenant′s behaviour feedback is essential as well. Any building operation problems have major influence on the overall building energy performance.

The simulated and measured building energy, thermal comfort and weather data verification are described in chapter 5.7. The building energy model was generally validated by several variable magnitudes (weather data, indoor temperature or building operation variables). It was necessary to verified simulated data in longer period, at least eleven consecutive days with a daily time step. This time period provides sufficiently accurate data for results validation. The annual weather data verification described in subchapter 5.7.1 shows acceptable mean relative difference between typical meteorological year and measured weather data; outside dry bulb temperature and relative humidity was below 10 %. The mean relative difference between simulated and measured air temperature values during the winter period was below 6 %. Most of the building service systems had energy consumption values within the acceptable relative difference limits in verified time period. The mean relative difference of MVHR energy consumption (subchapter 0) between simulated and measured data during the verified eleven days period in December 2011 did not exceed 13 %. The mean relative difference between simulated and measured GSHP energy production (subchapter 5.7.4) in 12 days period in January 2011 was 0 %. Solar energy generation systems verification such as solar thermal (subchapter 5.7.5) and photovoltaic (subchapter 5.7.6) was rather difficult in a short term period. The weather data variation (particularly global solar radiation) in a selected daily period was significant due to the different typical meteorological year and actual measured weather data. The solar assisted DHW system and photovoltaic energy production mean relative difference was below 3 % in verified period of several weeks.

The theoretical and experimental methods used and applied in the research validated the close interconnection in most of the building design and building operation stages. The building design stage represented by building mathematical model was verified by in-situ monitoring of the single-family house operation. Assumptions of properly chosen research objectives, methodology and goals were hereby confirmed. The research target of nearly zero-energy building energy retrofitting method for single-family houses was achieved and the building is even reaching parameters of zero energy building.

6.1 Contribution to practice

Nowadays the topic of nearly zero-energy building is a very important in building industry due to the European Union targets and regulation on energy savings, carbon dioxide reductions and are enshrined in EU legislation, for example the directive 31/2010/EU. The thesis demonstrates one of the EU targets, improving energy efficiency in buildings by implementing nearly zero-energy buildings.

The significant thesis finding for practice is the introduction of the pilot single-family house energy retrofitting method fulfilling nearly zero-energy building requirements. The pilot project confirmed the necessity of the long term building operational monitoring together with the tenant′s behaviour education. The thesis and pilot project itself brought important and original solutions of building energy retrofitting method into nearly zero-energy building in practice. The simplicity of the energy retrofitting method solution can be used worldwide without any major modifications for large numbers and types of the refurbished buildings.

6.2 Contribution to science

In the end the thesis will provide an essential contribution to the knowledge of energy efficiency retrofitting. The research has shown the importance of using energy simulation modelling and mathematical models in building design process and building operation. The dynamic energy simulation modelling can predict, optimize and verify the future building design, thermal comfort and building operational costs. The energy simulation engines and software can be further optimized, developed and extended with new simulation and functional features. Especially the link between the building and building service systems offer a great potential for the future development.

6.3 Recommendations for future research

Recommendations for future research resulted from author′s long term nearly zero-energy buildings investigation and research are listed in this chapter. During the research the author came across important nearly zero-energy findings. The most substantial findings requiring furthermore development and research are listed below:

- Research and development on building service systems components and libraries for nearly zero-energy buildings.
- Research, development and verification on RES prefabrication components suitable for nearly zero-energy buildings.
- Implementing, verification of rainwater recycling system in the building and its effect on domestic water reduction.
- Research on daylighting, daylight sensors, glazing and shading elements synergy with the focus on building energy efficiency and indoor air quality improvement.
- Research on tenant′s behaviour effect on building energy efficiency.
- Research on system application in the Czech Republic weather conditions.

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Curriculum Vitae

Name	Robert Wawerka
E-mail	wawerka.r@fce.vutbr.cz

Professional Experiences

05/2013 - present	PhD student at AdMaS Centre, Brno University of Technology, Faculty of Civil Engineering, Czech Republic
01/2011 - 02/2013	Energy & Sustainability Consultant at Neapoli Sdn Bhd, Malaysia
11/2009 - 10/2010	Energy Efficiency Engineer at Cenergia Energy Consultants, Denmark

Education

2008 - present	Brno University of Technology, Faculty of Civil Engineering, Building Constructions specialization, Doctoral Degree
2002 - 2008	Brno University of Technology, Faculty of Civil Engineering, Building Constructions specialization, Master′ s Degree
1996 - 2002	Grammar School Třinec

Courses

2005 - 2008	Brno University of Technology, Faculty of Civil Engineering, Theoretical and practical training for construction companies organized by Skanska CZ
2006 - 2007	University College Vitus Bering Denmark, Faculty of Building Technology and Construction Management, student exchange programme

Professional Memberships

01/2011 - 12/2012	Member of the Environment, Energy and Green Technology Committee, EU-Malaysia Chamber of Commerce and Industry

Languages

English	Advanced
German	Beginner
Polish	Intermediate

Skills

PC skills	MS Office, MS Project, AutoCad, Ecotect, Google SketchUp, DesignBuilder, EnergyPlus, Radiance

Abstract

This doctoral thesis proposes a new method of energy retrofitting of existing residential buildings towards nearly zero-energy status. The topic of energy retrofitting of existing buildings is widely discussed and lamented within the European Union and the Member states and is enshrined in the Directive 2010/31/EU. This research is in line with the European Union strategy Europe 2020 which sets targets for climate change and energy sustainability.

The thesis describes the study of building energy performance of a pilot energy retrofitted residential building towards nearly zero-energy where progressive design technologies, such as energy modelling, monitoring, building optimisation and verification were used. This case study helped to formulate the recommendations on the effectiveness of various passive and active design methods together with renewable energy systems and after the extensive research it contributes to model and verify the future expectation and energy efficiency requirements of the residential market.