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

DOCTORAL THESIS
DISERTAČNÍ PRÁCE

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

BRNO 2015

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 [1], [2], [3], [4], [5], [6] and is enshrined in the Directive 2010/31/EU [9]. This research is in line with the European Union strategy Europe 2020 [7] 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.

Keywords

Nearly zero-energy buildings, energy retrofitting, prefabrication, renewable energy sources, simulation, monitoring

Abstrakt

Disertační práce se zabývá navržením nové metody rekonstrukce stávajících budov s cílem dosažení budovy s téměř nulovou spotřebou energie. Téma energetických rekonstrukcí stávajících budov je v rámci Evropské unie a jejich členských států [1], [2], [3], [4], [5], [6] detailně probíráno, včetně zakotvení této problematiky ve směrnici 2010/31/EU [9]. Výzkum je taktéž v souladu se strategii Evropské unie Evropa 2020 [7], která stanovuje cíle pro změnu klimatu a energetiku.

Dizertační práce se zabývá studiem energetické náročnosti konvenčního rodinného domu, který pomocí aplikace progresivních návrhových technologií, jako např. energetického modelování, monitorování, optimalizace a verifikace bude po rekonstrukci splňovat parametry budovy s téměř nulovou spotřebou energie. Tato případová studie rekonstrukce rodinného domu pomáhá formulovat doporučení jak efektivně využívat různé pasivní a aktivní prvky při návrhu budovy spolu s aplikací systémů obnovitelných zdrojů energií. Výzkum se dále zabývá možnosti řešení budoucích požadavků energetické náročnosti budov v rámci residenčního trhu.

Klíčová slova

Budovy s téměř nulovou spotřebou energie, rekonstrukce, prefabrikace, obnovitelné zdroje energií, simulace, monitorování

Bibliographic citation VŠKP

WAWERKA, Robert. *Nearly Zero-Energy Building Retrofitting: Case Study of a Conventional Single-Family House in Denmark.* Brno 2015, 112 pages. Doctoral thesis. Brno University of Technology, Faculty of Civil Engineering, Institute of Building Services. Doctoral thesis supervisor was doc. Ing. Jiří Hirš, CSc.

Declaration

I hereby declare that this thesis was entirely my own work and that any additional sources of information have been duly cited.

Brno, 14th November 2015

…………………………………………

Signature

Acknowledgement

At first I would like to express my appreciation to associate professor Jiří Hirš for his guidance during the term of my candidature. Without his valuable assistance, this work would not have been completed.

My deep sense of gratitude to Peder Vejsig Pedersen to give me the opportunity to undertake an internship in the Cenergia Energy Consultats; to get me involved in such an interesting project implemented in Denmark and also for his support and guidance. Thanks and appreciation to the helpful people of Cenergia Energy Consultants, for their support.

My deep sense of gratitude to Dr. Stellios Plainitotis for guiding and supporting during my two years stay in Neapoli Sdn Bhd. His valuable knowledge and experiences have opened me the door into green building industry in South East Asia and helped me open up a new perspective on the topic of my doctoral thesis. Thanks and appreciation for the help and support provided by the Neapoli staff.

Finally my deepest sense of gratitude to my family for their endless support during my long PhD study, either morally, financially or physically.

Table of contents

List of figures

List of tables

List of abbreviations

AHU	Air handling unit
AMY	Actual Meteorological Year
ASHP	Air source heat pump
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BREEAM	Building Research Establishment Environmental Assessment Methodology
COP	Coefficient of Performance
CSWD	Chinese Standard Weather Data
DF	Daylight factor
DHW	Domestic Hot Water
DOE	Department of Energy
EPBD	Energy Performance of Building Directive
EPW	EnergyPlus Weather
EU	European Union
EWT	Entering water temperature
GSHP	Ground source heat pump
GUI	Graphical user interface
HAWT	Horizontal axis wind turbine
HP	Heat pump
HVAC	Heating, ventilation, air conditioning
IC	Initial cost
IES-VE	Integrated Environmental Solutions Virtual Environment
IWEC	International Weather for Energy Calculations
LCC	Life cycle cost
MVHR	Mechanical ventilation with heat recovery
NCDC	National Climatic Data Centre
NREL	National Renewable Energy Laboratory
NZB	Net Zero Building

NZEB	Net Zero Energy Building
PHI	Passive House Institute
PV	Photovoltaic
RES	Renewable energy sources
SGHC	Solar Heat Gain Coefficient
SWEC	Spanish Weather for Energy Calculations
TMY	Typical Meteorological Year
TRY	Test Reference Year
VAWT	Vertical axis wind turbine
VLT	Visible Light Transmittance
WSHP	Water source heat pump
WYEC	Weather Year for Energy Calculations
ZEB	Zero Energy Building
ZNE	Zero Net Energy

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]. Fig. 1 shows the approach of the building energy reduction to target nearly zero-energy building by reducing the primary energy use by 80 % and increase renewable energy supplies by 20 % by the year 2020.

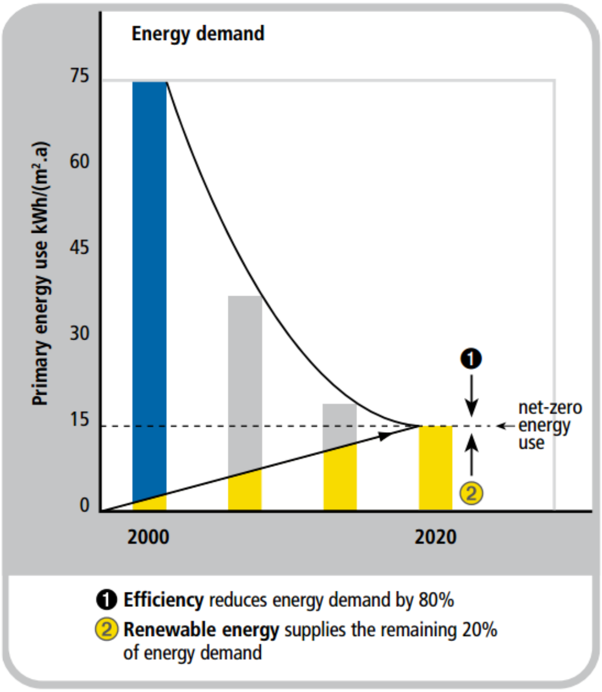

Fig. 1 Approach for achieving nearly zero-energy building [10]

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 for only for a few years, the term “zero energy building” for past decades, but the vision and idea of designing buildings with 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].

In Germany the research demonstration projects focused on energy efficiency improvements in buildings during last 30 years were performed [17]. Fig. 2 shows the primary energy demand curve for heating in several steps based on the building demonstration projects; for example in 1977 the primary energy demand for heating in solar houses was almost 180 kWh/m^2/annum while in 1997 the heating demand was reduced to 0 kWh/m^2/annum by introducing zero-heating energy buildings. In 2010 the demonstration project shows a plus-energy houses.

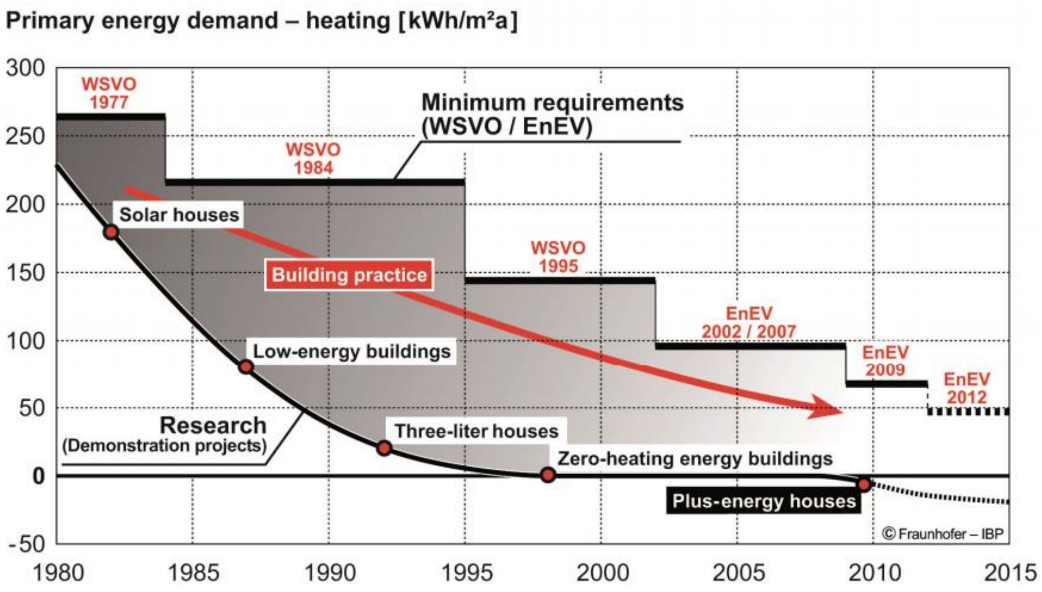

Fig. 2 Development of the building energy performance in Germany [17]

2.2 Nearly zero-energy buildings analysis

Already some nearly zero-energy and zero energy buildings case studies have been developed or built and it is proven that the zero energy building target is achievable [18], [19] and [20]. 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) that, 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* [21].

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.

Nearly zero-energy building energy retrofitting is a complex process due to many limitations and factors which do not need to have to be taken into consideration in new construction. 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. Implementing changes in one area can negatively affect other areas of the building. It is important 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]. Most important design criteria, such as the link between wall to window ration and energy consumption are shown in Fig. 3.

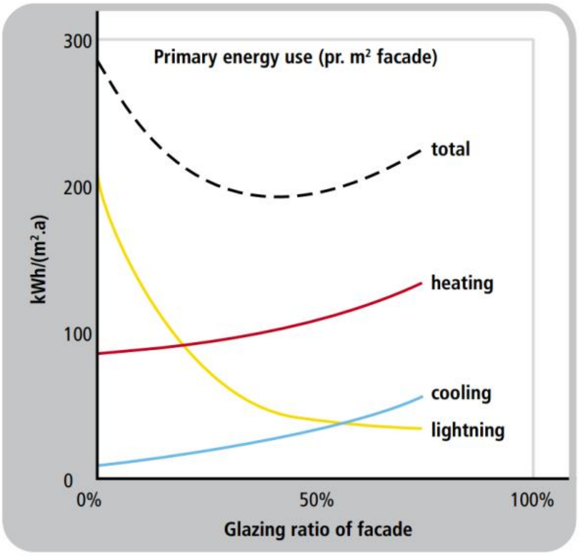

Fig. 3 Approach for achieving nearly zero-energy building [10]

To decide which adequate nearly zero-energy design solutions have to be selected, firstly the end use energy demands of the existing building have to be determined. According to statistical survey, the end-use energy in the residential sector is consumed for: space heating and cooling, domestic hot water, lighting, cooking, refrigeration and other appliances (multimedia devices and computers) [21]. The pie chart (Fig. 4) shows the residential energy use breakdown in EU countries in 2007.

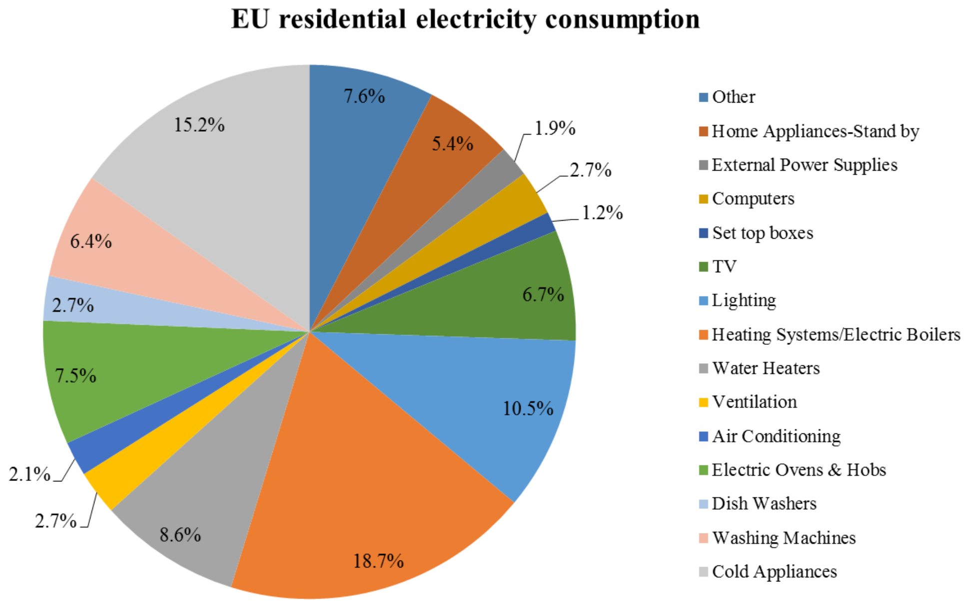

Fig. 4 Breakdown of EU-27 residential electricity consumption, year 2007 [21]

If the overall energy use of the building is known, the retrofitting design strategy can be determined. Each major end-use energy 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. 5 shows the coherence between major energy use and design variables.

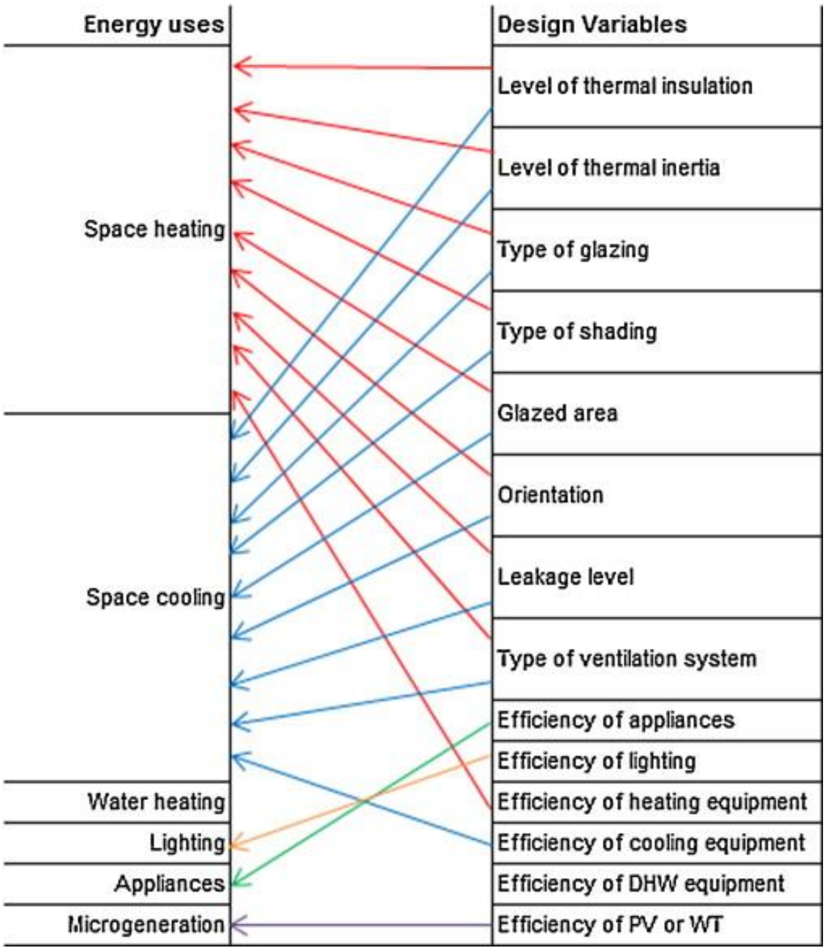

Fig. 5 Energy use versus design variables [21]

Every combination of building design variables leads to a specific total annual energy consumption based on a typical building use conditions. To balance the total annual energy consumption requirements based on nearly zero-energy standard, a certain amount of building integrated renewables have to be included. 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.

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 [22]. Fig. 6 shows an example of uninsulated building envelope with reference thermal losses through the different elements.

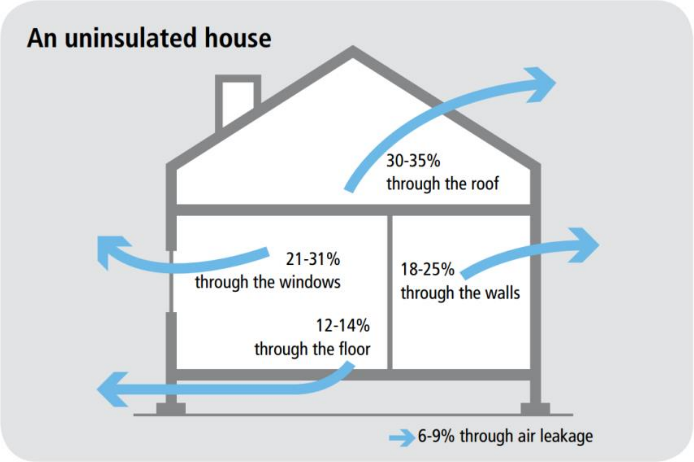

Fig. 6 Thermal losses in an average uninsulated house [10]

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 and 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 nearly zero-energy retrofit, provided that appropriate control of air, water and vapour are addressed [23]. Fig. 7 shows basic features of retrofitting the building envelope with focus on the main construction elements.

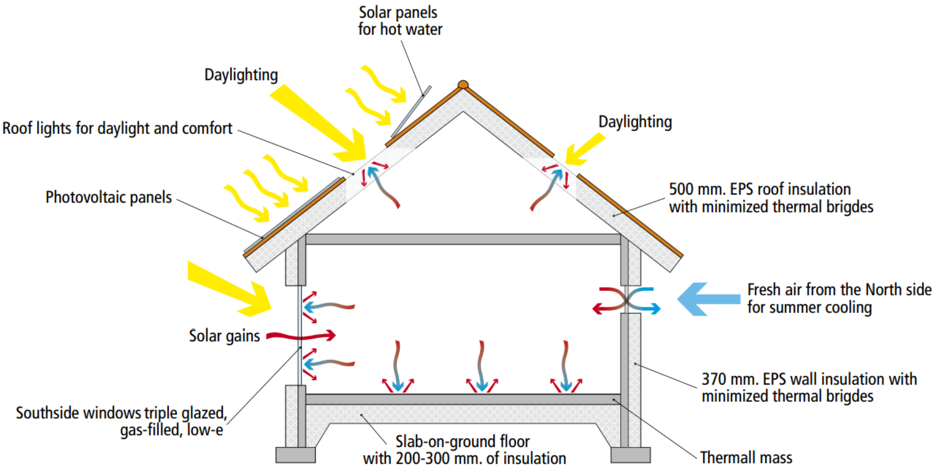

Fig. 7 Building envelope design principles for a nearly zero-energy building [10]

The building envelope insulation thickness varies according to the climate conditions. Recommended insulation thicknesses and U-values for building envelope for temperate continental climate can be applied from the German Passive House method developed by The Passive House Institute (PHI).

For all building envelope opaque components the heat transfer coefficient (U-value) should not exceed the value of 0.15 W/m^2K. The windows should have a U-value lower than 0.80 W/m^2K and a total solar transmittance (g-value) should be around 50 %. Airtightness of the building (uncontrolled leakage though gaps) must be below 0.6 of the total house volume per hour during a pressure test of 50 Pascal under the pressurised and depressurised conditions [24].

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 [20]. 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 [25]. 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. Fig. 8 shows a basic HVAC system structure from equipment side through subsystems to global HVAC system.

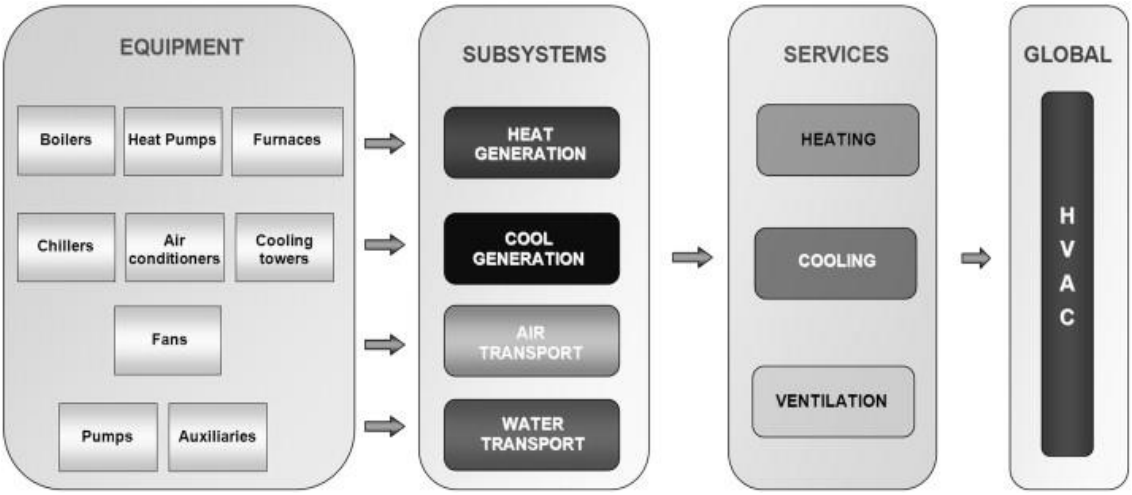

Fig. 8 Basic HVAC system structure description [25]

There are many building service systems technologies that can be used in single-family houses fulfilling nearly zero-energy building requirements. The selections of the most common systems without RES application are described below.

2.4.1 Radiant Floor Heating

Radiant floor heating is a very efficient way how to achieve optimal thermal comfort in buildings with a low energy demand. Radiant floor heating uses either underfloor resistant cables (electric systems) or a heated fluid running through loops of underfloor tubing (hydronic systems) that can be cast in a concrete floor slab, placed under the floor covering or attached to the underside of the subfloor. A parametric study on radiant floor heating performance is described in [26].

BS EN 1264-1:2011 specifies maximum floor surface temperatures and design room temperatures for radiant floor heating [27]. The required maximum temperature values are shown in the Table 1.

Table 1 Maximum floor surface and design room temperatures for floor heating

Area	Maximum floor surface temperature (°C)	Design room temperature (°C)
Occupied area	29	20
Peripheral area	35	20
Bathroom or similar	33	24

2.4.2 Mechanical ventilation with heat recovery

Mechanical ventilation with heat recovery (MVHR), known as heat recovery ventilation (HRV) is based on the principle of transferring heat from exhaust air through heat exchanger and to warm up the supply fresh air. The growing shares of mechanical ventilation applications in single-family houses increase the demand for ventilation heating load. Therefore the use of heat recovery in conjunction with the mechanical ventilation systems represents one of the best solutions to reduce the heat losses and simultaneously to generate energy savings [28].

Mechanical ventilation with heat recovery has been described in many literatures and scientific research [28], [29] and [30]. For instance, installing MVHR in passive houses has been shown to reduce energy for space heating and ventilation by 55 % in comparison to conventional buildings without MVHR [30]. Therefore installing energy-efficient mechanical ventilation with heat recovery to nearly zero-energy buildings is highly recommended. Table 2 presents different types of heat recovery technologies for air distribution systems.

Table 2 Types of heat recovery systems [29]

Types of heat recovery	Typical efficiency	Advantages
Fixed-plate	50–80 %	Compact, highly efficient due to high heat transfer coefficient, no cross contamination, can be coupled with counter-current flow which enabling to produce close end-temperature differences.
Heat pipe	45–55 %	No moving parts, no external power requirements, high reliability, no cross contamination, compact, suitable for naturally ventilated building, fully reversible, easy cleaning.
Rotary wheel	Above 80 %	High efficiency, capability of recovering sensible and latent heat.
Run-around	45–65 %	Does not require the supply and exhaust air ducts to be located side by side, supply and exhaust duct can be physically separated, no cross contamination.

2.4.3 Domestic hot water

In the European Union, the domestic hot water (DHW) has a significant share in the total housing energy consumption. For example in Greek residences, the heating of domestic hot water is the second largest energy consumer after space heating [31]. Typically domestic hot water systems consist of an electric or fuel burn heater and hot water tank.

Based on the research made in United Kingdom the mean domestic hot water consumption in dwellings is around 122 litres/day with the mean energy consumption of 16,8 MJ/day [32]. Fig. 9 shows hourly DHW consumption profile.

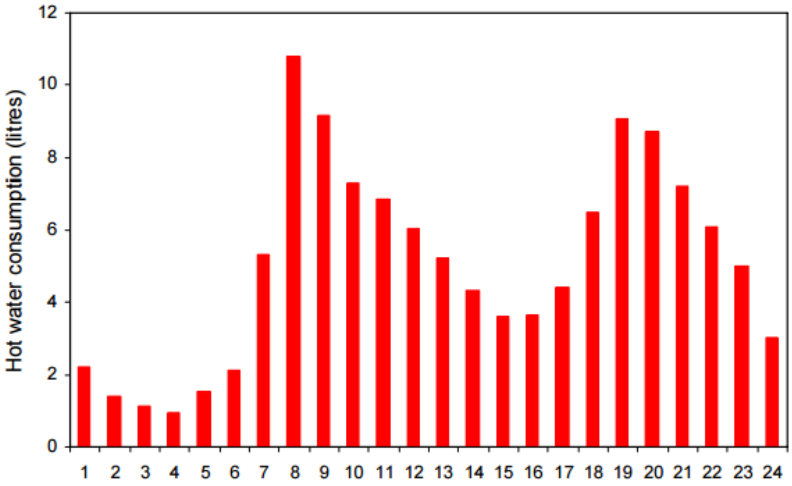

Fig. 9 Hourly DHW consumption profile [32]

There are several case studies available comparing conventional to solar DHW systems [33]. The results show that high energy reduction can be achieved in a single-family house by implementing solar DHW system instead of the conventional. In fact, the solar DHW system allows final energy savings in the Southern European single-family houses of around 95 % and around 75 % for the Central and Northern European areas compared with the conventional DHW systems, which represents the similar high of CO_2 emissions reduction [34].

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 [35].

Nearly zero-energy building design has some limitations and requirements. For example, it is recommended that only low or middle temperature energy sources are used (temperature range between 20–50 °C) for heating. This is a very attractive for RES application, especially geothermal energy [36].

For the nearly zero-energy building retrofitting only selected renewable energy systems are considered and presented, such as solar thermal system, PV panels, heat pumps and small scale wind turbines.

2.5.1 Solar thermal systems

The solar thermal technologies for DHW for heating or partially space heating have been well known for decades. During that time the massive industrial development has converged solar thermal systems into a few types of utilisation today. The most widespread solar thermal system for domestic hot water applications include:

- thermosyphonic systems,
- integrated collector storage systems,
- direct circulation systems,
- indirect water heating systems,
- air system.

Solar thermal systems' efficiency depends on the type of solar thermal collector and the storage tank size. The most common collector types are evacuated tube and flat plate collectors. Each collector has a different performance which varies according to physical and weather conditions. The solar collector efficiency curves of different solar collectors based on an irradiance of 800 W/m^2 are shown in Fig. 10.

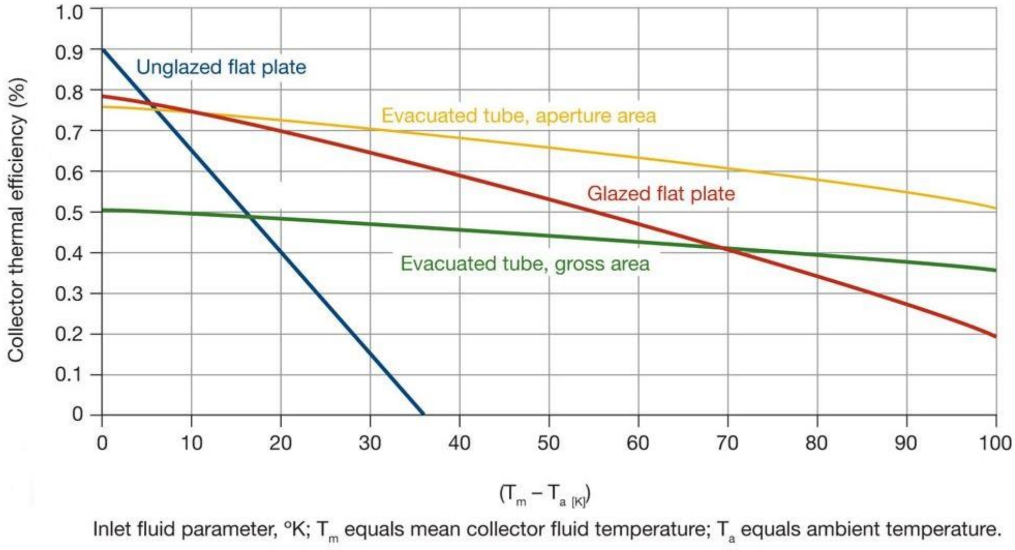

Fig. 10 Efficiency of different types of solar thermal collector [37]

The technical and economic aspects of solar thermal systems have to be considered, in order to define the optimal design solution for the building. These design features have to be considered [38]:

- power of the system,
- solar panel inclination,
- power of the system,
- direct or indirect solar system,
- natural or forced circulation system.

2.5.2 Photovoltaic systems

Photovoltaic (PV) system can be reliable and independent generator of electricity for the building with relatively easy installation and able to provide zero greenhouse gas emission energy. In recent years, PV systems have improved their Life Cycle Costing and environmental performance.

As of October 2015 there are many PV technologies on the market or in the development. Every PV cell technology has different manufacturing process and the efficiency of each type of cell can vary in tens of percent. The most commercialised technologies at the market are crystalline silicon and thin film.

2.5.2.1 Crystalline silicon

There are generally two types of crystalline silicon cells – monocrystalline and polycrystalline. Monocrystalline solar cells are made from a single large crystal of silicon. This type of panel is the most efficient but the most expensive to produce. The performance is better in lower light conditions compared to other types. The average efficiency of monocrystalline panel on the market at the time of writing is between 17–21 % [39].

Polycrystalline solar panels are the most common on the market in 2015. The panel cell is made from smaller amount of silicon crystals. This technological process and production is simpler and more cost effective then monocrystalline. Polycrystalline panels are slightly less efficient then monocrystalline, about 14–16 % [39].

2.5.2.2 Thin film

Thin film PV cells consist of a thin film semiconductor layer placed onto different types of surfaces. This allows wide range of surface uses and flexibility. The most common thin film materials are amorphous silicon (α-Si), cadmium telluride (CdTe). The manufactured technology is simpler and cost price is lower than other PV solutions. The disadvantage of thin film cells is very low efficiency, about 6–9 % for α-Si and 9–12 % for CdTe [39].

2.5.2.3 Hybrid

Hybrid solar cells are made from a nanostructures mixture of organic and inorganic materials. The manufactured process of hybrid cells uses solid state dye-sensitised solar cells or the bulk heterojunction method with different nanoparticles such as TiO_x, ZnO, CdSe, PbS, Ti and others. The hybrid cells based on TiO_2 technology have efficiency about 6 % [40].

2.5.3 Heat pump

Heat pumps (HP) offer one of the most efficient way in providing energy for heating and cooling. Heat pumps use renewable heat sources from the surroundings (air, ground or water) that are continuously replenished by the sun. In the Directive 2009/28/EC is heat pump defined: *„Heat pumps enabling the use of aerothermal, geothermal or hydrothermal heat at a useful temperature level need electricity or other auxiliary energy to function. The energy used to drive heat pumps should therefore be deducted from the total usable heat. Only heat pumps with an output that significantly exceeds the primary energy needed to drive it should be taken into account"* [41].

Even the temperatures of heat sources are not considered to be high; they are sufficient and very suitable for heat pump technology application and operation. Heat pumps can save around 30–40 % of the electricity energy used for heating in a real operation [42]. In buildings different heat pump technologies are applied varying in type of heat source – air, water and ground.

2.5.3.1 Air source heat pump

Air source heat pump (ASHP) uses the outside air as a heat source. Nowadays there are two main technologies of air source heat pump with the difference in heat transfer, air-to-air HP or air-to-water HP. ASHP performance always depends on actual weather conditions, in particular on air temperature and humidity fluctuation during the whole year. Air source heat pumps are less efficient than other types of heat pumps.

The most common type of air source heat pump mounted in dwellings is air-to-water heat pump [43]. Heat pump coefficients of performance (COP) factor case studies for air-to-air heat pump were done by Swedish Energy Agency and the results are shown in Fig. 11; and for air-to-water heat pumps are presented in Fig. 12.

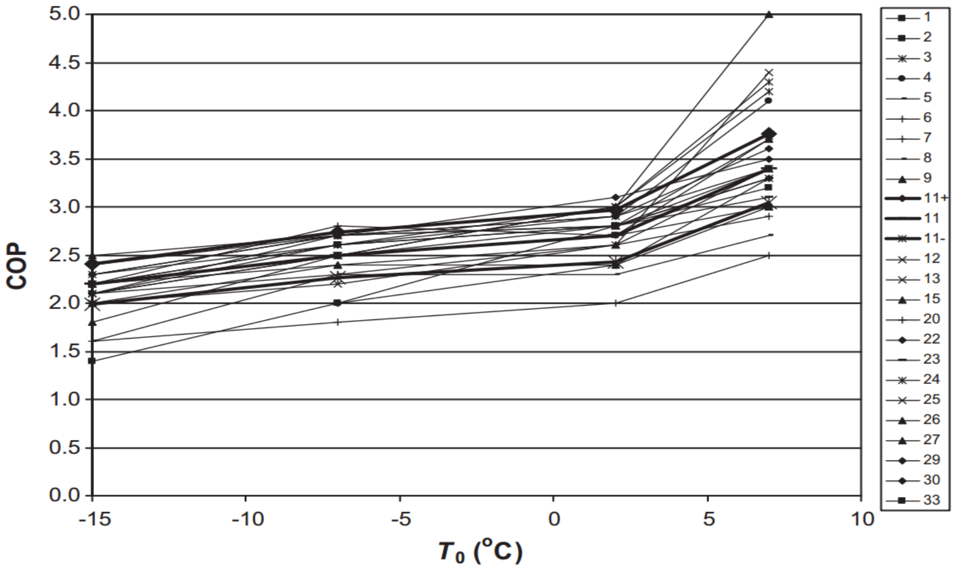

Fig. 11 Test of COP factors for air-to-air heat pump [44]

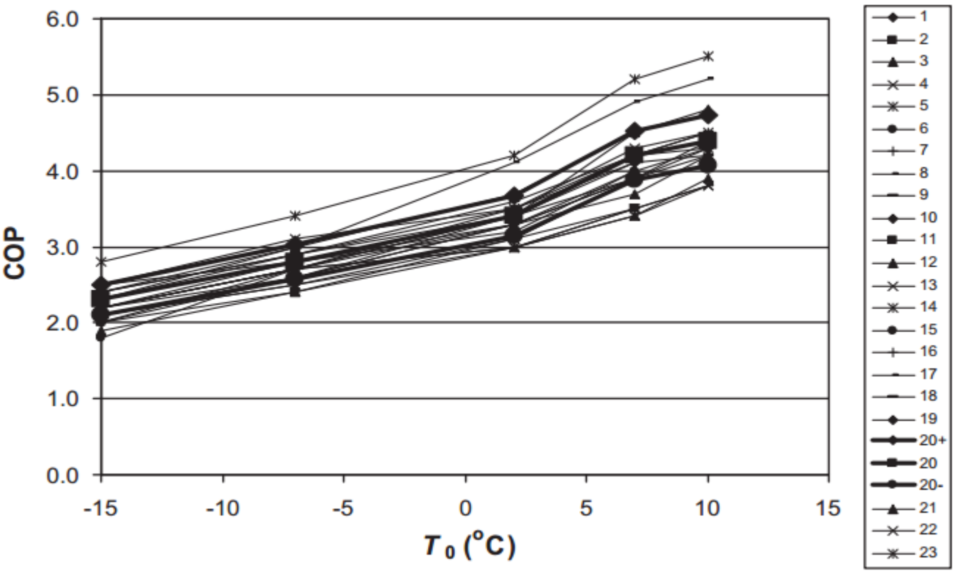

Fig. 12 Test of COP factors for air-to-water heat pump [44]

2.5.3.2 Ground source heat pump

Ground source heat pump (GSHP) uses the heat energy from the soil as a heat source. The soil temperature at the depth of 5 meters and below is almost constant during the year with small fluctuations. The heat capacity of the soil varies on the geological condition in the area. GSHPs are characterised by a ground loop configuration that can be vertical, horizontal or slinky (Fig. 13).

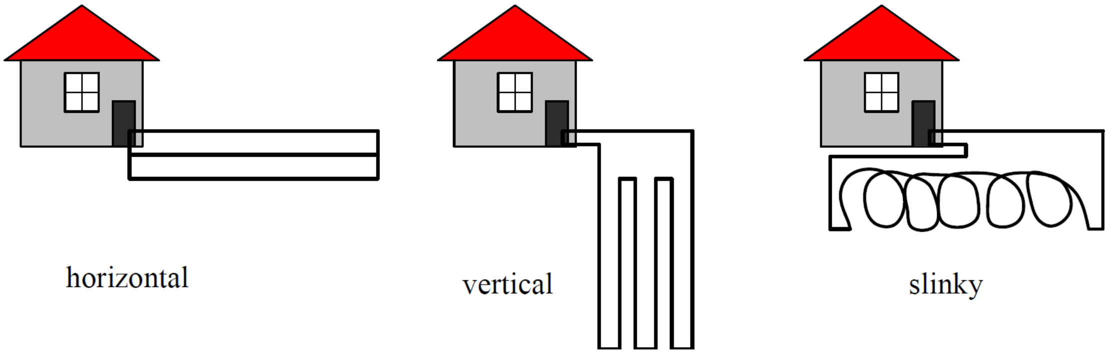

Fig. 13 Ground loop configuration [author]

Horizontal loop consists of plastic pipes placed horizontally in trenches. The depth of pipes laid in series will vary according the initial design, location and soil parameters, but the general recommendation is 1–2 m deep. Horizontal loop application is cheaper than the vertical one, but it requires much more surface area.

Vertical loop is a drilled borehole with a U-shaped plastic pipe inside. The depth and number of boreholes depends on building heating capacity. In average the borehole can be spaced at around 5 meters grid with the depth up to 150 m in standard application. The drilling process requires using special equipment, process and filling material as bentonite grout. The advantages of vertical boreholes application is the space requirement and better system efficiency during the year than for horizontal loop.

Slinky coils are a variation of a horizontal ground loop containing flattened coils of overlapped pipes which can be laid in the ground horizontally or vertically. Slinky coils are more space efficient (about one third to two thirds shorter) than a horizontal ground loop.

The medium used in the closed-loop circuit for ground source heat pumps is usually a mixture of anti-freeze and water. Generally, a GSHP will produce from three to four times more thermal energy (heat energy) than is used in electrical energy for heat pump operation, meaning COP factor ranging from 3 to 4 [42].

2.5.3.3 Water source heat pump (WSHP)

Water source heat pump (WSHP) uses the heat energy from the water as a heat source. Ground water is great source for heat pumps, similar to the ground source type of heat pump. The water temperature is almost constant during the year with minor fluctuations. The water heat pumps can be divided based on the water loop to open and closed loop.

Open loop system pumps water directly to the heat pump where the heat is removed and discharged medium is send back to other water source. For open loop system the quality of water (corrosiveness, hardness, etc.) has to be considered to prevent future operation and technical problems of the heat pump.

Closed loop system for heat pump works on the principle of a series of pipes laid in the water source, as a river, lake, pound or stream. The heat is transferred between the medium in closed pipe (mixture of anti-freeze and water) and the heat source surface water. Closed loop system needs less maintenance then the open loop system.

2.5.4 Wind Energy

Other renewable energy source under consideration is a wind energy. Renewable energy sources application is very limited when compared to others, but in some cases should be considered as an alternative possibility such as small scale wind turbines. Wind turbines can be generally divided into two categories by rotor shaft rotation, on horizontal axis wind turbine and vertical axis wind turbine.

2.5.4.1 Horizontal axis wind turbines

Horizontal axis wind turbines (HAWT) have a massive tower structure with main rotor shaft and electric generator placed on the top of the tower. Blades have to be always pointed to the wind direction, for small scale wind turbine by simple wind vane and by servo motor with wind sensors for big scale one. The high speed two bladed HAWT can obtain efficiency of up to 47 % of the power available from the wind [45]. The best application for HAWT is off-site location.

2.5.4.2 Vertical axis wind turbines

Vertical axis wind turbine (VAWT) is good solution for urban areas with great possibility of building integration design. The wind turbine does not have to be orientated into the wind direction; it can work in areas with variable and lower speed wind conditions. Vertical axis wind turbines are not tower mounted, and the generator together with other components are located on the ground. VAWT can have efficiency as high as 37 % power extraction from the wind [45].

2.5.4.3 Comparison of HAWT and VAWT

Several studies and research have been done on a small scale HAWT and VAWT [46], [47], [48], [49], [50] and [51]. The Fig. 14 shows comparison of horizontal and vertical axis wind turbines in rural area. The best small scale wind turbine application for housing sector is the turbines with the range of power from 0.5 kW to 6.0 kW.

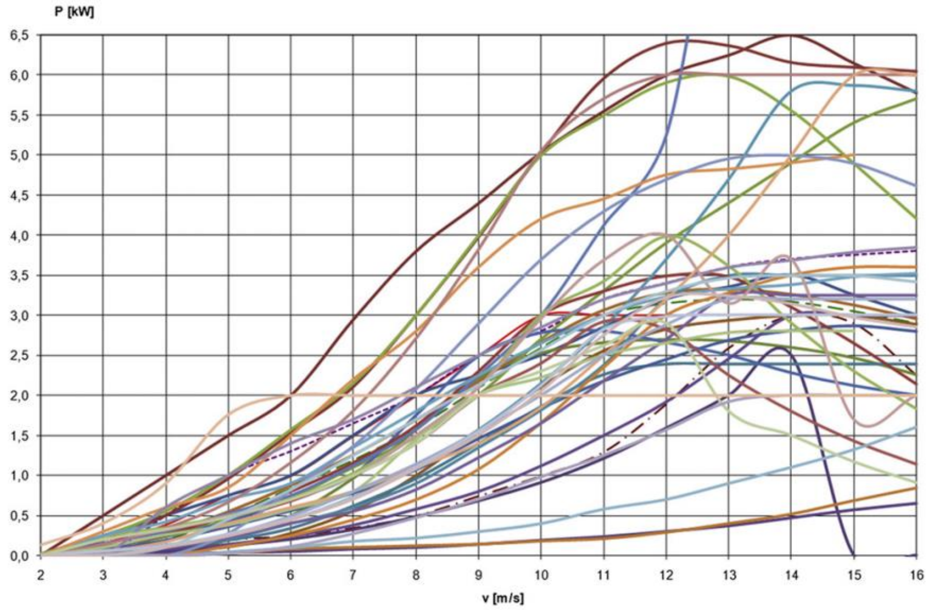

Fig. 14 Power curves for small scale wind turbines [51]

2.6 Energy generation

Type of energy generation plays an important role in the overall building energy consumption. Energy generation is affected by several factors; in our case the focus will be on the primary energy factor and energy generation supply option parameters.

2.6.1 Primary energy factor

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 (final) energy is transferred to primary (source) energy. Primary energy is the energy coming from the nature which is not converted or transformed by any process. Primary energy describes Primary Energy Factor (PEF) that converse site to primary energy. Table 3 shows an example of PEF used in different countries [52], [53] and [54].

Table 3 Example of primary energy factors in different countries

Energy type	Primary Energy Factor (PEF)			
	USA	Canada	Czech republic	Poland
Electricity (grid purchase)	3.14	2.05	3.00	3.00
Photovoltaic (grid connected)	1.00	1.00	0.20	0.70
Natural gas	1.05	1.02	1.10	1.10
Coal	1.00	1.00	1.10	1.10

2.6.2 Energy generation supply options

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 [55]. 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. Fig. 15 shows another more detail distribution option of energy generation supply.

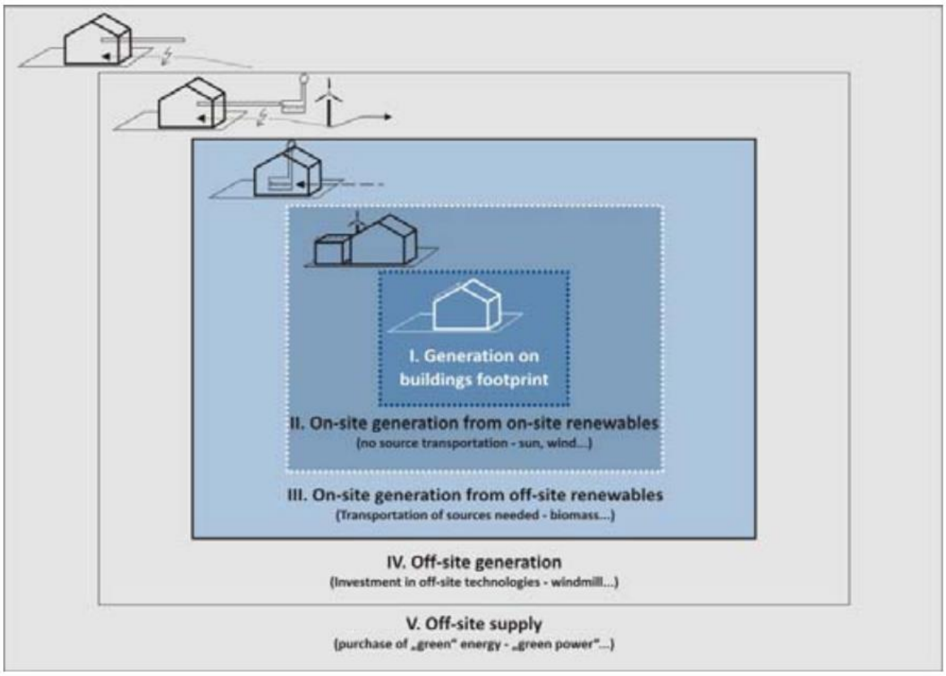

Fig. 15 Energy generation supply option [56]

2.7 Weather data

It is necessary to know the exact location and weather condition before the building design, simulation or optimisation starts. Incorrect location or building orientation can cause significant problems during design stage which afterwards would negatively affect the overall building operation costs or inadequate thermal comfort.

For energy simulation in a certain location it is necessary to select the weather data within 30–50 km and within several dozens of meters of elevation [57]. 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. The typical synthetic one year weather data formats are for example Typical Meteorological Year 3 (TMY3), Weather Year for Energy Calculations 2 (WYEC2), International Weather for Energy Calculations (IWEC), Spanish Weather for Energy Calculations (SWEC) and Chinese Standard Weather Data (CSWD) [57]. More information about weather data consideration and selection for energy simulation is described in the papers [58], [59] and [60].

2.7.1 Weather data sources

The weather data for energy simulations are available from different sources. The weather data for energy simulation can be purchased or provided free of charge depending on the location and the quality and quantity of provided data.

Energy simulation software works with hourly intervals data and most software have own weather file format. The weather data in different formats are converted into required format by available weather data converters. Some of the weather data suppliers for energy simulation are briefly described below:

- Weather Analytics – weather data based on latest 30 year of hourly data on more than 600 000 grid tile (35 x 35 km) across the world, available in TMY or AMY format.
- Weather Bank – hourly and daily historical data from National Weather Service stations across USA and other location around the world, data available since 1994.
- National Climatic Data Centre – the largest weather data archive in the world, operates the World Data Centre for Meteorology.

- Meteonorm – extrapolates hourly data from a statistical data for selected location, if the data are not available than interpolates from the nearest location.
- Weather Source – provides real-time and historical weather data from more than 10 000 locations around the world.

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 [61].

The input and boundary conditions for the building simulation are interdependent and altogether give comprehensive information of future building behaviour. The building behaviour depends on many aspects and boundary conditions, such as weather condition, building orientation, tenant’s behaviour and needs, HVAC system selection and optimisation, etc. All these variables are incorporated into simplified detailed building model. These combinations provide nearly unlimited variation for the building design or building optimisation.

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 program validation methodology has to be done to prevent the source of inaccuracy which can be divided into external and internal errors. The internal errors are related to the process of developing a simulation program, while the external errors are related to the process of using these simulation tools. Validation methodologies are divided into three categories: analytical verification, inter-model comparison and empirical validation [61]. Another publication describing methodology for validating building energy analyses was published by National Renewable Energy Laboratory [62].

The whole process from identifying the right input parameters to optimising and validating the model is extremely demanding. That is the reason of using simulation only in unusual and atypical cases of buildings where empirical and other typical calculation methods are inadequate.

2.8.1 EnergyPlus

EnergyPlus is a dynamic energy simulation engine developed by U.S. Department of Energy (DOE) in 1995 which combines capabilities and features from DOE-2 and BLAST along with new capabilities. DOE-2 and BLAST have many user interfaces developed by independent third-party developers. Fig. 16 shows an overall EnergyPlus structure.

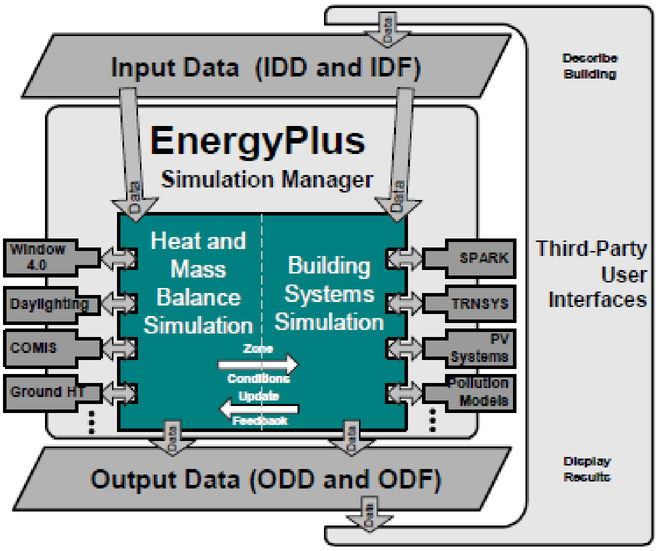

Fig. 16 Overall EnergyPlus simulation engine structure [63]

The structure of EnergyPlus simulation manager is shown in Fig. 17. EnergyPlus simulation manager integrates three major groups – surface and heat balance, air heat balance and building system simulation. Each group comprises of different type of modules, for example sky model, shading, daylighting, zone equipment, plant loop, PV.

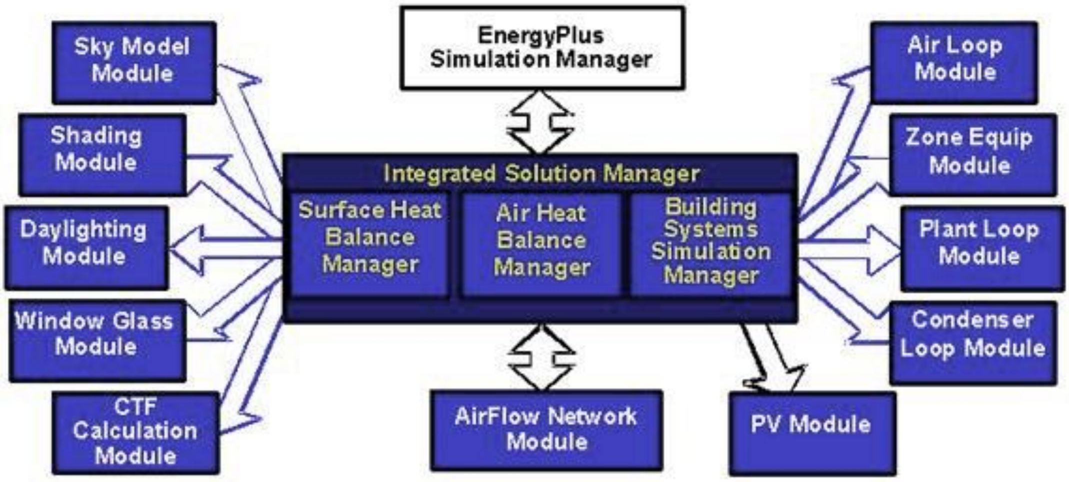

Fig. 17 EnergyPlus simulation manager structure with input modules [57]

All input, output or weather data files associated with EnergyPlus have simple and usual formats. These formats can be easily used and processed by other programs as databases or spreadsheets.

A lot of studies, software testing and evaluation methods have been done and research papers and articles have been published on EnergyPlus simulation engine [64], [65], [66], [67], [68]. The EnergyPlus software is fully validated and approved in many global and regional standards and methodologies – ASHRAE Standard 140-2011, International Energy Agency Solar Heating and Cooling Programme, EnergyPlus Global Energy Balance Tests, EnergyPlus HVAC Component Comparative tests, etc.

2.8.2 IES-VE

Integrated Environmental Solutions (IES) was established in 1994 in Glasgow. In the late 1990s the IES introduced the first commercial version 3.0 of Virtual Environment (VE) software. IES-VE is a dynamic building energy simulation software consist of a suite of integrated analysis tools and modules (Fig. 18).

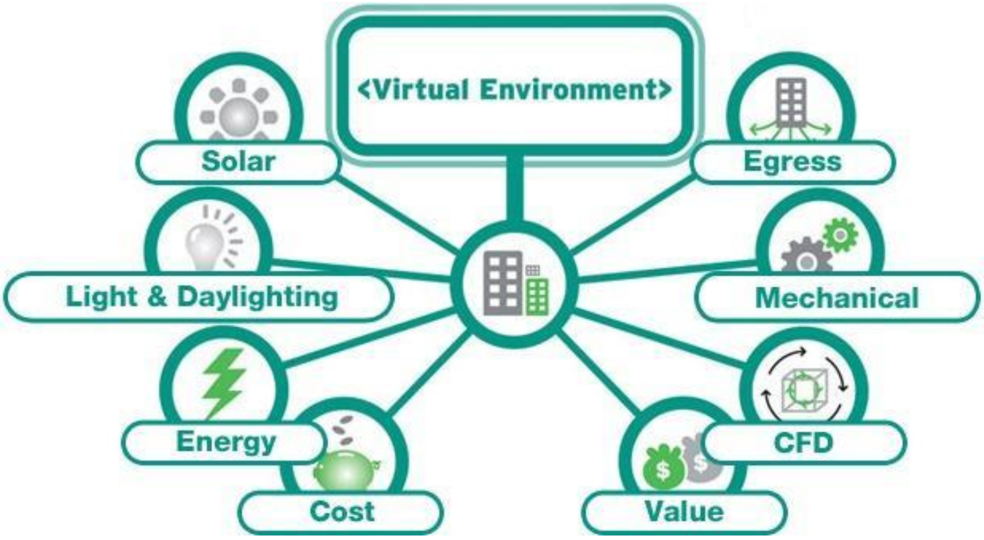

Fig. 18 IES-VE analysis tools and modules [69]

For example in the module “ModelIT” building geometry can be constructed, the module “Radiance” is suitable for daylighting analysis and the “Apache” is a thermal analysis module providing dynamic analysis of building energy consumption or indoor climate conditions.

The IES-VE software is fully validated and approved in many global and regional standards, for example ASHRAE 140:2007, CIBSE TM33, European Union EN13791:July 2000 and methodologies, for example UK National Calculation methodology (NCM), ASHRAE 55 calculation procedure or ISO 7730 calculation procedure. Many scientific papers using IES-VE software have been published [70], [71] and [72].

2.8.3 DesignBuilder

DesignBuilder is one of the most advanced graphical user interface (GUI) for EnergyPlus and provides comprehensive software tools for simulating building energy, comfort performance, lighting and carbon footprint.

DesignBuilder workflow chart starts with location and weather data specification and building geometry creation. Afterwards other building and operational definable input parameters are described in five main templates (activities, construction types, openings, lighting and HVAC systems), as shown in Fig. 19. Comprehensive libraries (building components, templates, weather data, HVAC systems, etc.) are available in the software. The library data can be easily modified by users.

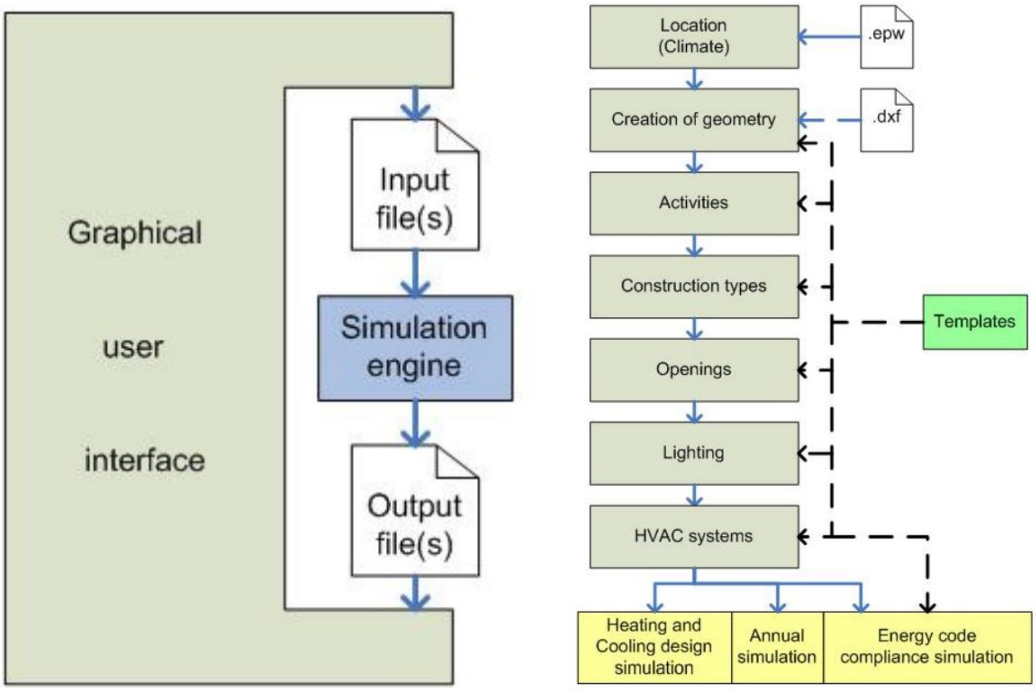

Fig. 19 DesignBuilder GUI architecture and workflow chart [73]

DesignBuilder provides building evaluation and analysis in several areas, as daylight or solar shading analysis, façade optimisation, thermal simulation, natural ventilation optimisation or HVAC equipment and systems sizing. Many scientific research topics are performed with DesignBuilder software [74], [75], [76].

2.8.4 OpenStudio

OpenStudio is a free open platform software product developed by a National Renewable Energy Laboratory (NREL) and U.S. Department of Energy (DOE). OpenStudio is an open source platform of different software tools for a complex building energy modelling using simulation engine EnergyPlus and software Radiance for daylight analyses. OpenStudio consists of two distinct components: application suite which works as a graphical interface, and software development platform known as Software Development Kit (SDK).

The graphical application suite includes following applications: ResultsViewer, RunManager and Trimbe SketchUp Plug-in (Fig. 20). The Trimble SketchUp Plug-in allows users to create geometry in SketchUp software and transfer geometry information into EnergyPlus. RunManager provides necessary support for simulation process and access to the output files; and ResultsViewer enables final operation and work with output data.

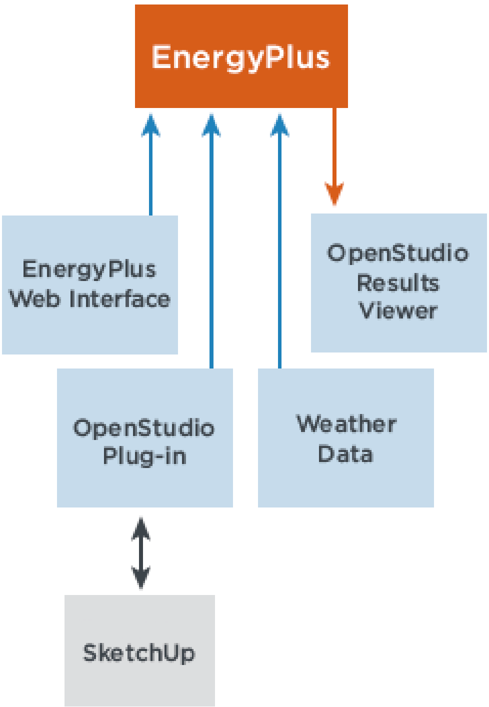

Fig. 20 OpenStudio graphical application suite scheme [57]

The OpenStudio development platform allows software developers and researcher developing and optimising the software through multiple programming languages, including C#, C++, or Ruby.

OpenStudio software together with EnergyPlus simulation engine applications are described in many scientific papers [77], [78] and [79].

2.8.5 Radiance

Radiance is a simulation software tool that enables validation of lighting and daylighting. In the complex environmental simulation platforms (EnergyPlus, IES-VE, etc.), is Radiance software always included as a module for daylight simulation. The development started in 1984 at the Lawrence Berkeley Laboratory and the first software release was in 1989.

Radiance uses a geometrical (Cartesian coordinate system) description of the scene based on the boundaries of objects. Fig. 21 shows general structure of the software with sequence of tasks involved in calculation.

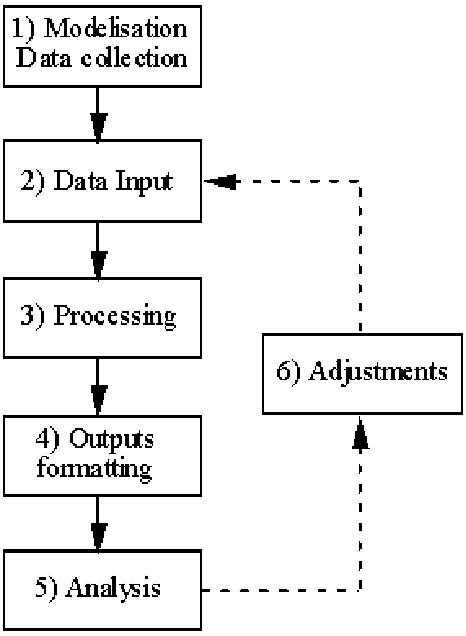

Fig. 21 Sequence of tasks involved in calculation [80]

Radiance is a very popular tool in research and design community and many academic papers and articles have been published [80], [81], [82] and [83].

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. 22).

Fig. 22 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. The details of building thermal properties can be found in Table 4. 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 to meet at least the target of building with nearly zero-energy consumption. Simple sketch of the energy retrofitting process is shown in the Fig. 23.

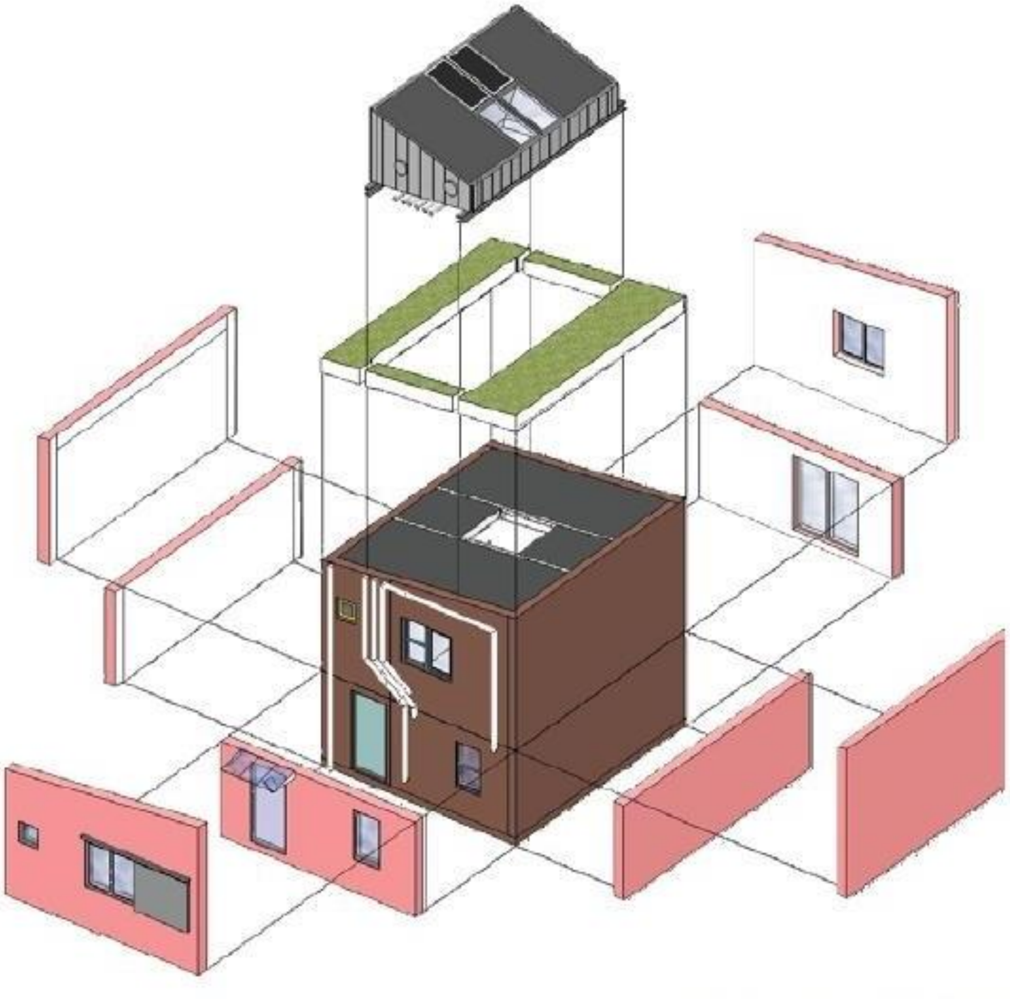

Fig. 23 Scheme of house energy retrofitting [84]

5.1.2.1 Unique prefabricated rooftop element

A very unique part of this building energy retrofitting is a special wedge prefabricated element 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. The detail of the prefabricated rooftop element with the description is shown in Fig. 24.

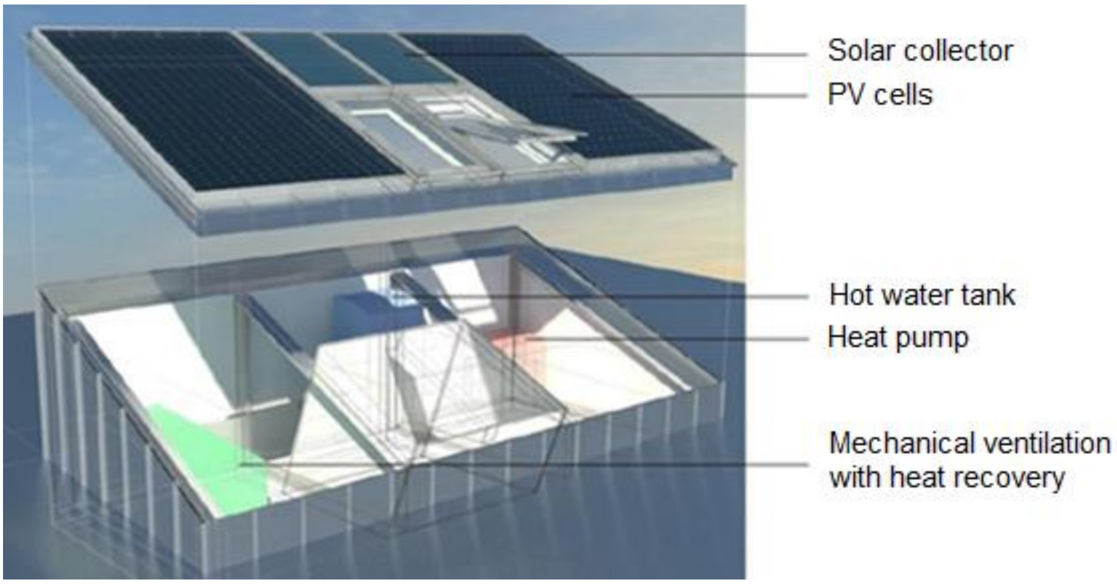

Fig. 24 Detail of the unique prefabricated element [84]

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. 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. Building envelope air tightness target is 1.5 l/s per m^2 at DP = 50 Pa regarding the Danish Building Regulations (BR08), compare to estimated one of 5 l/s per m^2 at 50 Pa [85].

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. The traditional roof structure was replaced by green roof. The building envelope and internal partitions estimated thermal properties before and after energy retrofitting are described in the Table 4.

Table 4 Thermal properties of building elements

Input data	Initial design	Current design
	W/m^2K	W/m^2K
External walls	0.43 *	0.07 *
Roof	0.41 *	0.06 *
Slab-on-grade floor	0.42 *	0.42 *
Windows	2.90 *	1.10 *
Skylight	-	1.80 *
Doors	2.25 *	1.20 *
Internal partitions	2.24 *	2.24 *
Internal floors	1.22 *	1.22 *

*estimated thermal properties values used for calculations

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 (Fig. 25).

Fig. 25 Additional 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 comparison of building service systems before and after energy retrofitting is described in the Table 5.

Table 5 Building services in the house before and after retrofitting

Input data	Initial design	Current design
Mechanical ventilation	No	Yes
Domestic heating	District heating	MVHR + water coil
DHW	District heating	Storage water heater
Heat pump	No	Yes
Solar thermal collector	No	Yes
PV panels	No	Yes
Wind turbine (VAWT)	No	Yes

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. Detail building services system operation scheme after energy retrofitting is shown in Fig. 26.

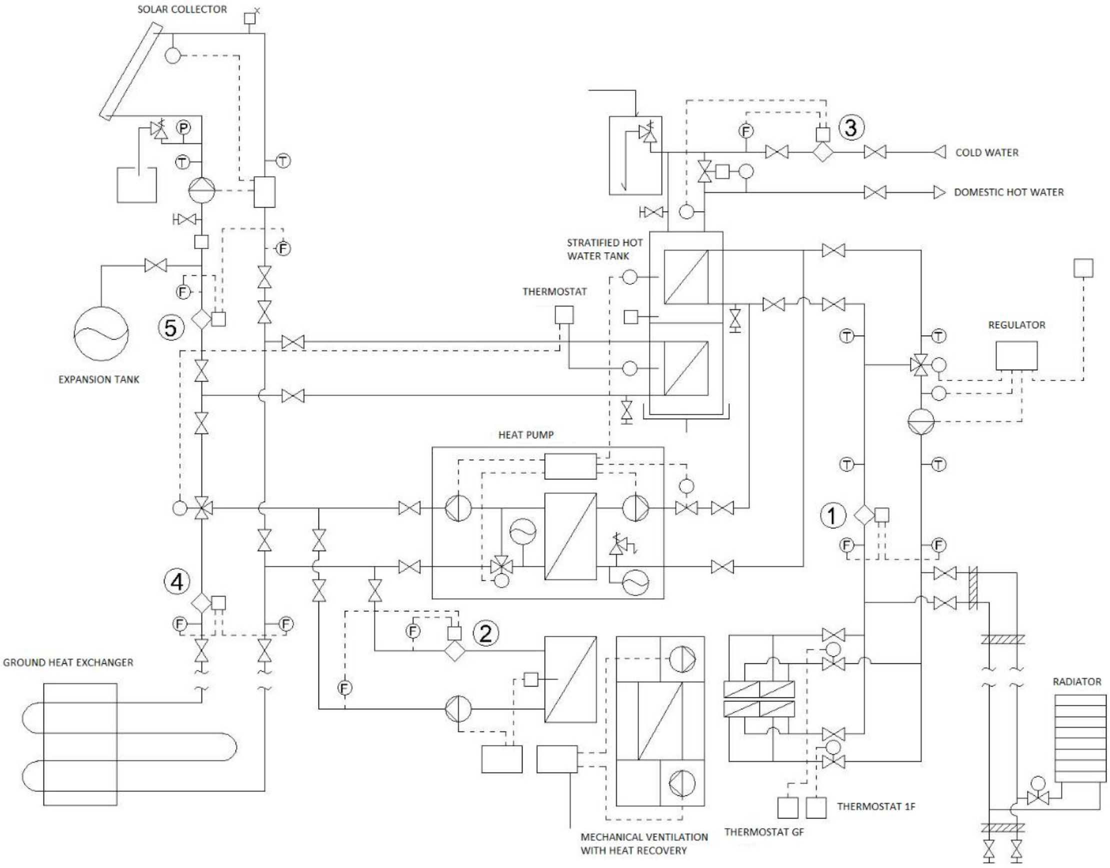

Fig. 26 Building services principle diagram in the retrofitted house [86]

5.1.3 Results and discussion

The suitable building for the research, prefabricated single-family house from 1970s was found in Denmark, close to Copenhagen. The building is located in a small residential area with dozens of identical houses. Building was assessed into initial and current design. The unique prefabricated rooftop element as the pivotal part of the energy retrofitting was developed for the refurbished single-family house. Detail analyses of the building and its components before and after energy retrofitting were performed and described with focus on prefabricated rooftop element, building envelope, renewable energy sources or building services.

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 %.

5.2 Dynamic energy simulation software

Dynamic energy simulation software is used to simulate, evaluate and validate the building performance. As of 2015, a dynamic simulation is the most advanced computer modelling tool to simulate building energy use, indoor air quality and thermal comfort in buildings utilising the local weather data. Dynamic simulation provides a more sophisticated analysis of a building than it is possible with standard compliance 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. Selected software is described in detail in chapter 2.8. 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.

The Table 6 shows basic evaluation of selected building energy simulation software. The evaluation is 1-to-3 rating scale where 1 = excellent, 2 = good and 3 = poor. The evaluation is based on author’s subjective impressions and experiences.

Table 6 Building energy simulation software features (1 – best, 3 – worse)

Parameters	DesignBuilder	IES-VS	OpenStudio
Building model and geometry	1	2	2
Templates and libraries	1	1	2
Building services and renewable sources	1	1	2
Simulation complexity	1	1	2
Other features	1	2	3
Software application and licences	2	3	1
Resume	1	2	3

After the building energy simulation software evaluation described in Table 6 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. Detail description of the simulation software tool can be found in chapter 2.8.3.

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. The Fig. 27 shows a daily weather site data profile for Copenhagen (Denmark) in the DesignBuilder software.

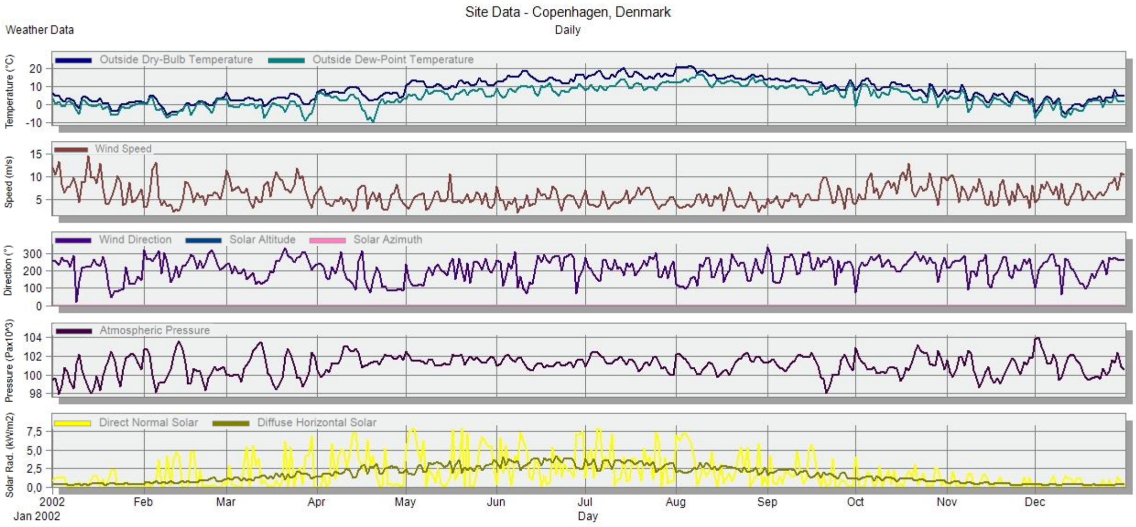

Fig. 27 Daily site weather data profile used for simulation – Copenhagen, Denmark

For the purpose of systems sizing the research identified a winter design week, the coldest week of the year. Winter design week starts from 10th February to 16th February with the minimum outside dry-bulb temperature of -9.9 °C, relative humidity of 17.0 % and wind speed of 14.4 m/s. The confidence of the design data is 99.6 %, which means that there is 0.4 % chance of more extreme winter weather occurring. For comparison in a typical winter week an average outside dry-bulb temperature is 1.20 °C. Fig. 28 shows the winter design week profile for Copenhagen.

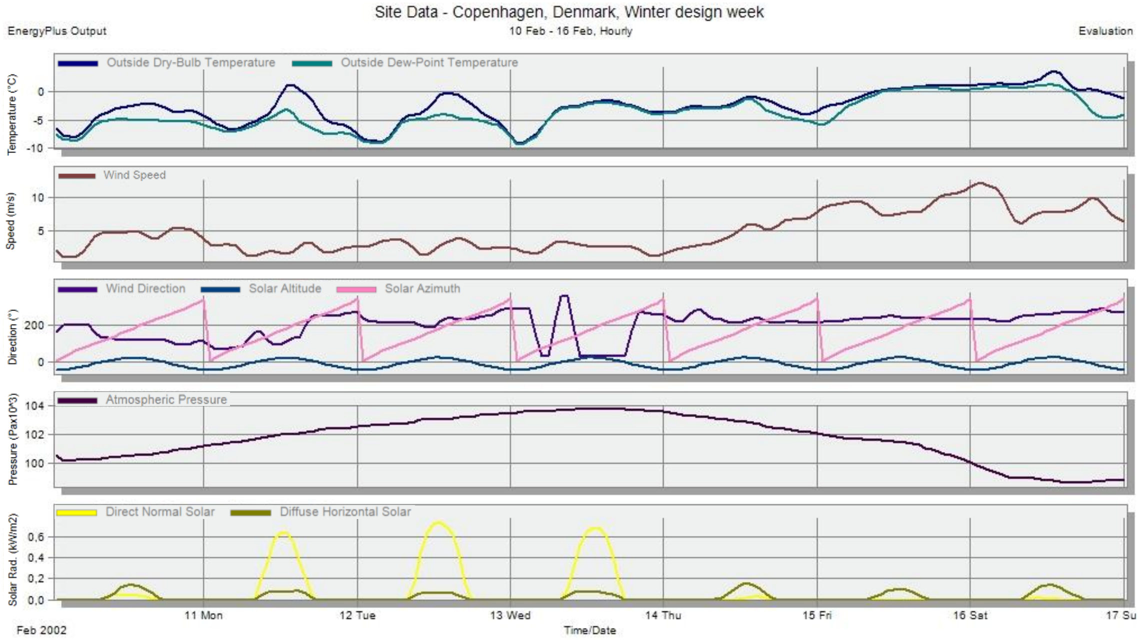

Fig. 28 Winter design week data profile for Copenhagen, Denmark

Similarly, in order to size the cooling system a summer design week was selected from 3rd August to 9th August with the maximum outside dry-bulb temperature of 25.3 °C and relative humidity of 39.3 % compare to the average temperature of 16.3 °C in typical summer week. Fig. 29 shows the summer design week for Copenhagen.

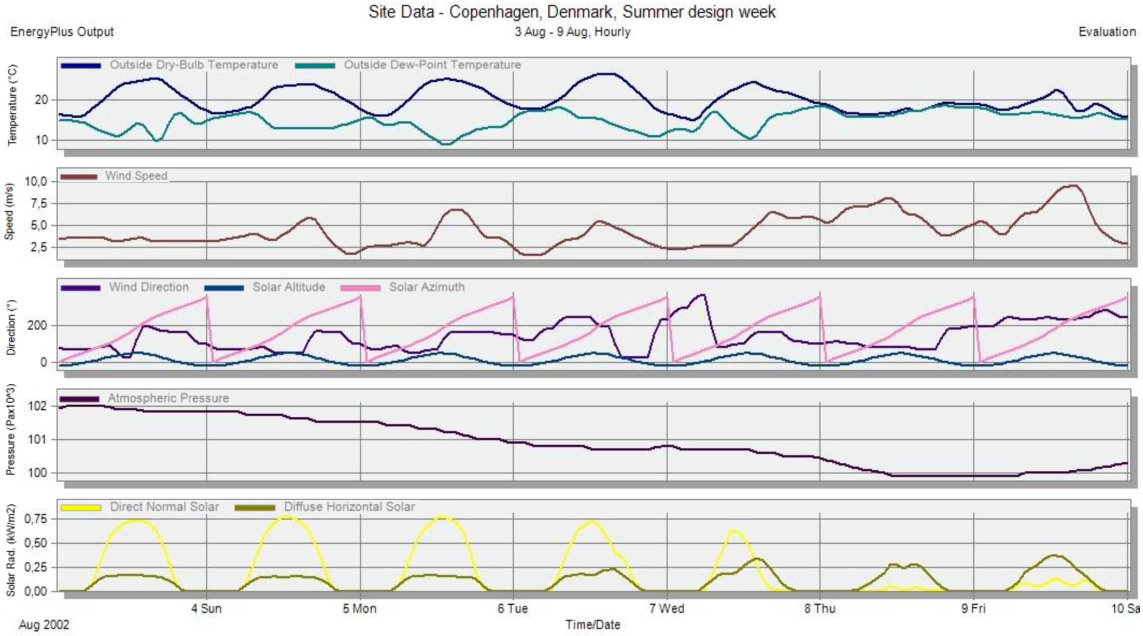

Fig. 29 Summer design week data profile for Copenhagen, Denmark

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. 30). The city district model helps to simulate influences of outdoor boundary conditions on studied building, such as building shading, solar radiation or wind effect.

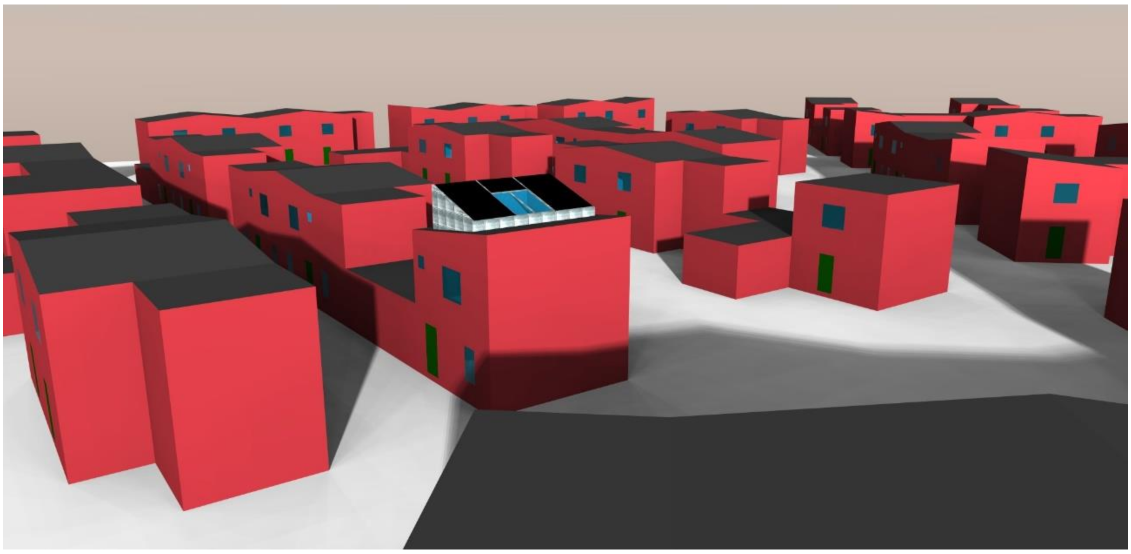

Fig. 30 Albertslund city district model [author]

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. 31. 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.

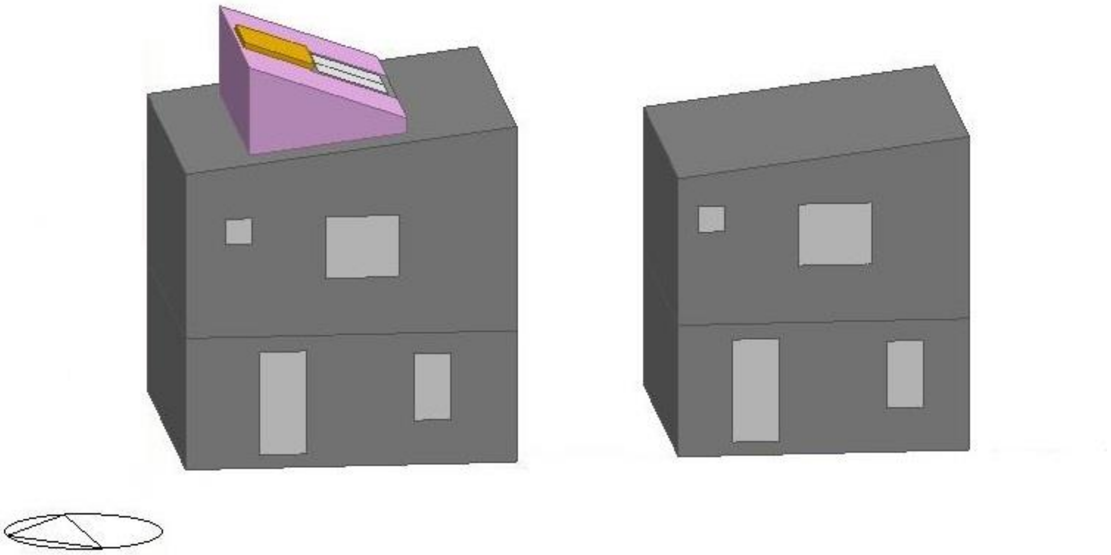

Fig. 31 Geometric model of current (left) and initial (right) house in DesignBuilder

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. 32.

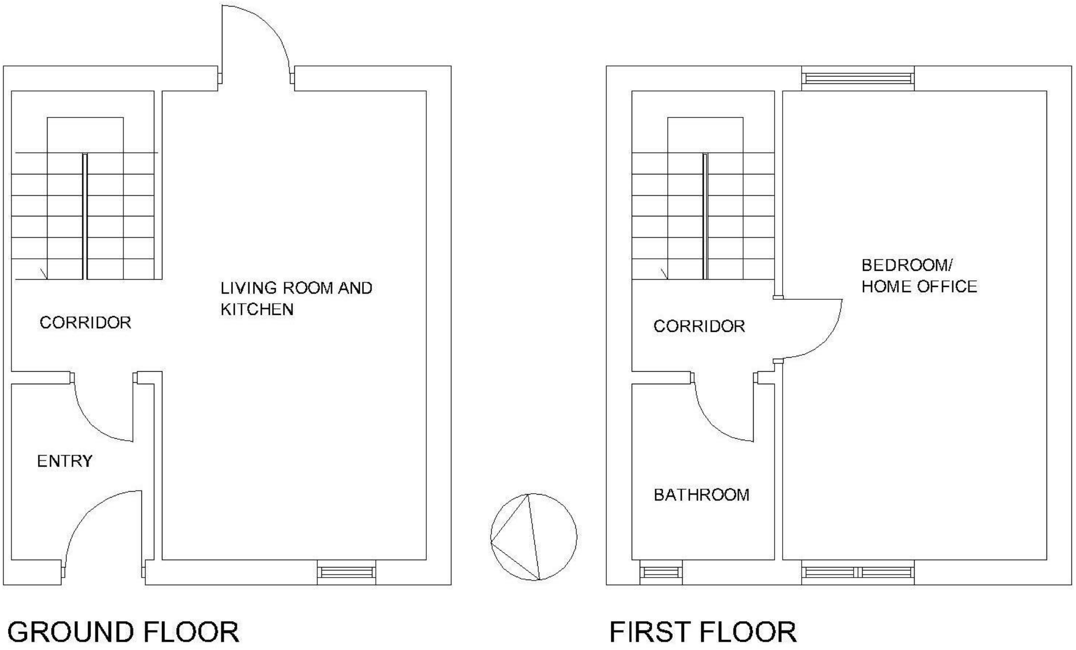

Fig. 32 Ground floor and first floor plan

The zone summary includes description of particular zones geometry, such as floor area, volume, etc. and is presented in Table 7. The floor height is 2.3 m for ground floor and about 2.8 m on average for the first floor. Each zone is described by templates such an activity, construction, openings, lighting or HVAC.

Table 7 Building geometric summary for each zone

Zone	Floor area (m^2)	Volume (m^3)	Gross wall area (m^2)	Windows glass area (m^2)
Entry	3.78	8.69	9.97	0.00
Corridor GF	6.02	13.85	13.23	0.00
Living room and kitchen	18.09	41.60	30.75	3.21
Corridor 1F	6.02	14.42	13.70	0.00
Bedroom	18.09	52.28	44.48	3.89
Bathroom	3.78	9.05	10.36	0.18

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.

The internal gains are furthermore divided into two categories - electrical equipment (domestic appliances, such as cooker, fridge with freezer, dishwasher, microwave own, etc.) and artificial lighting. Each activity is described by a detail schedule and defined for a typical working day and weekend. The house is divided into four activity zones - living room, bedroom, bathroom and corridor. Table 8 shows estimated operation variables for each zone together with the relevant operation schedules.

Table 8 Estimated tenant behaviour and internal gains used in simulations

Input data	Units	Bedroom		Bathroom		Corridor		Living room	
		Initial	Current	Initial	Current	Initial	Current	Initial	Current
Density	people/m^2	0.0553		0.2646		0.0632		0.0553	
Heating air temperature	°C	22		22		18		22	
Metabolic rate	W/person	90		180		180		110	
Occupancy schedule	-	Bed_Occ		Bath_Occ		Corr_Occ		Living_Occ	
Equipment load	W/m^2	3.58		1.67		1.57		3.9	
Equipment schedule	-	Bed_Equip		Bath_Equip		Corr_Equip		Living_Equip	
Lighting energy	W/m^2/100 lux	2.1	8.8	2.1	8.8	2.1	8.8	2.1	8.8
Illuminance	lux	200		150		100		200	
Lighting schedule	-	Bed_Light		Bath_Light		Corr_Light		Living_Light	

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. 33 shows the detail building service systems scheme design modelled in DesignBuilder software without photovoltaic system.

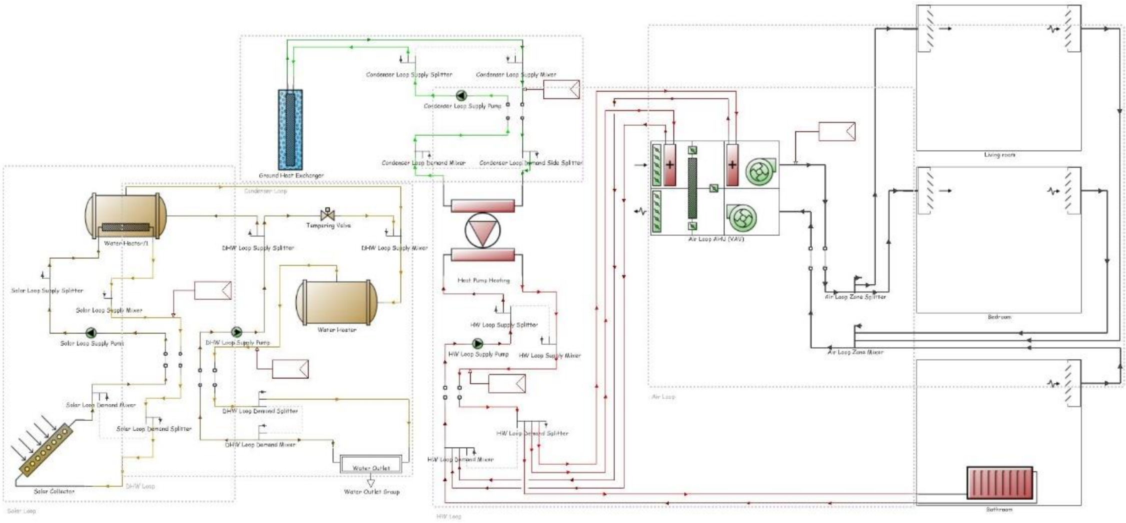

Fig. 33 Building service systems scheme in DesignBuilder software

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 as shown in Fig. 34. Air loop supply side is an air handling unit (AHU) with water pre-heating coil, water heating coil, two radial EC fans with B-wheel 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 minimum amount of outdoor fresh air based on the Danish Building Regulations [85].

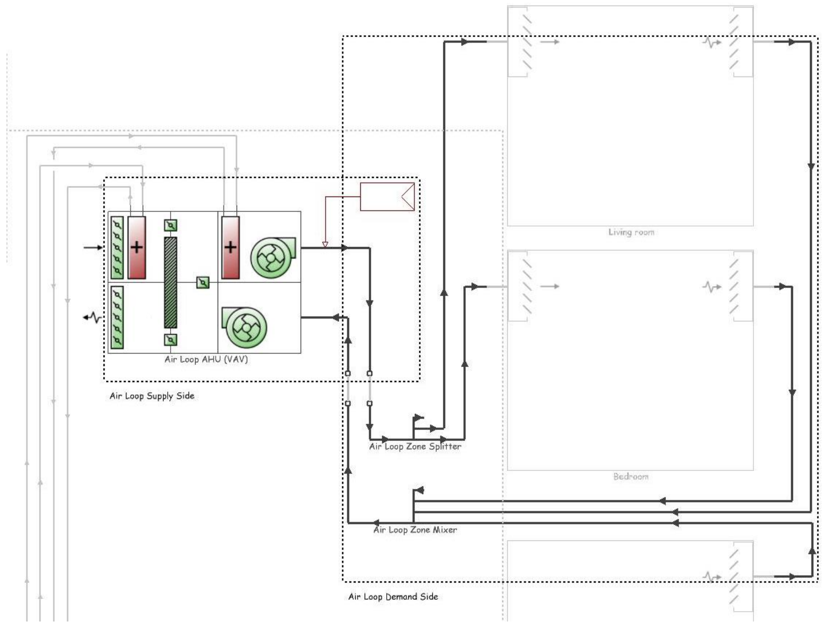

Fig. 34 Air loop in the simulation software with supply and demand side

Selected AHU technical input data and boundary conditions subjected to the energy calculations are shown in Table 9.

Table 9 Selected AHU technical data

Input data	Units
AHU fans	230 V, 50 Hz, max. 2 x 71 W
AHU speed control fans	20–100 %
Maximum AHU air flow at 100 Pa	400 m^3/h
AHU heat recovery	92 % at 200 m^3/h
Maximum ambient temperature	60 °C

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 (Fig. 35).

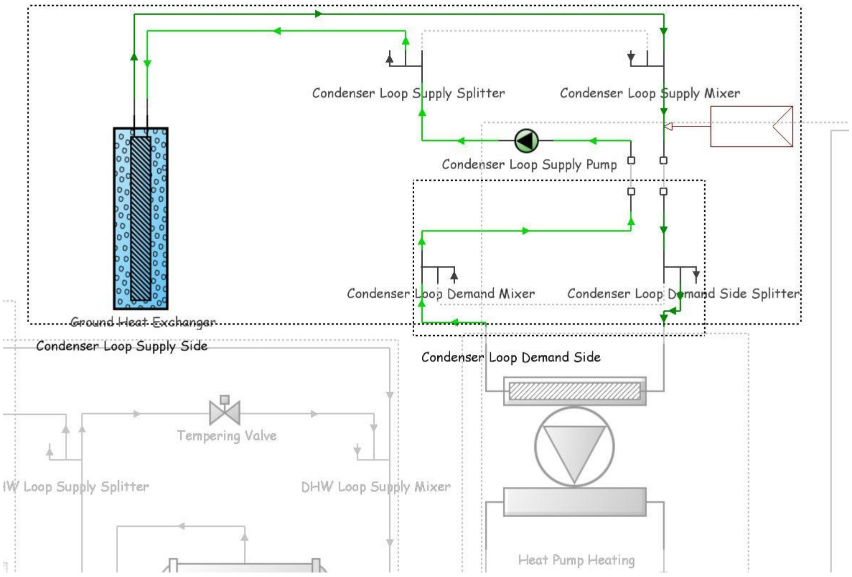

Fig. 35 Ground source heat pump – condenser loop in DesignBuilder

The hot water loop is located inside the building. The hot water loop delivers the medium into AHU heating coils and into the flat water tower rail radiator mounted in the bathroom. The hot water loop is divided into supply and demand side as it is shown in Fig. 36. If the heat pump is in heating mode, the heat pump condenser represents the hot water loop supply side. Water loop demand side is the hot water piping distribution system in the house; from the heat pump condenser to water pre-heating and water heating coil in AHU unit and radiator in the bathroom.

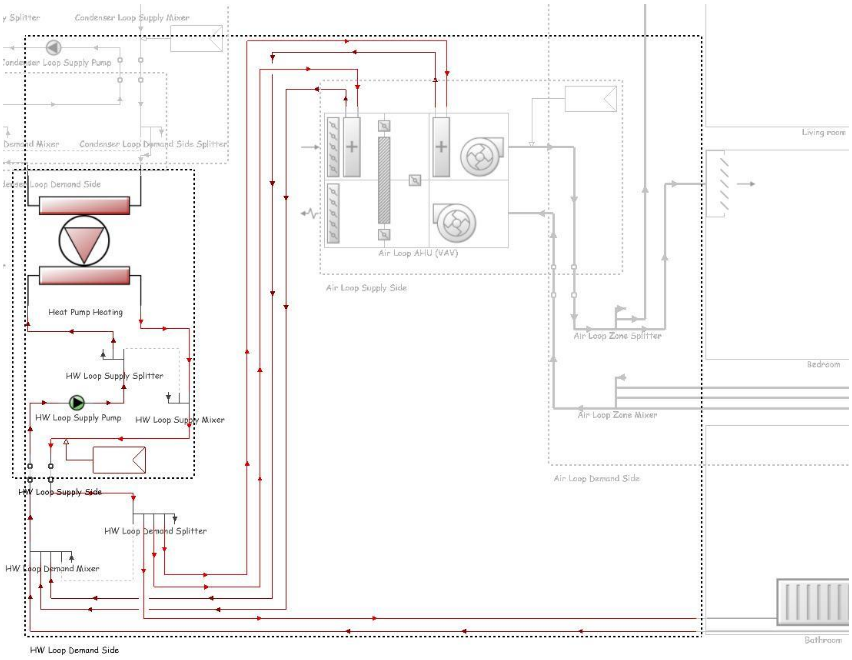

Fig. 36 Ground source heat pump – hot water loop in DesignBuilder

The technical data for ground source heat pump are presented in Table 10. The design of GSHP is made for source entering water temperature (EWT) of 5 °C and EWT on load side of 50 °C. The compressor power input of 1.9 kW and heating capacity of 6.0 kW corresponds to above mentioned entering water temperatures. The coefficient of heat performance (COP) of the heat pump for selected parameters is COP = 3.16.

Table 10 Ground source heat pump technical data

Input data	Units
Main supply	400 V 3-N-50Hz
Maximum power input, compressor	2.2 kW
Min/max temperature in heating circuit	20/55 °C
Refrigerant type	R407C
Sound power level	40 dB(A)
Source EWT	5 °C
Load EWT	50 °C
Heating capacity	6.0 kW
Power input	1.9 kW
COP factor	3.16

5.3.4.3 Solar assisted domestic hot water system

Solar assisted domestic hot water (DHW) 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 (Fig. 37). 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.

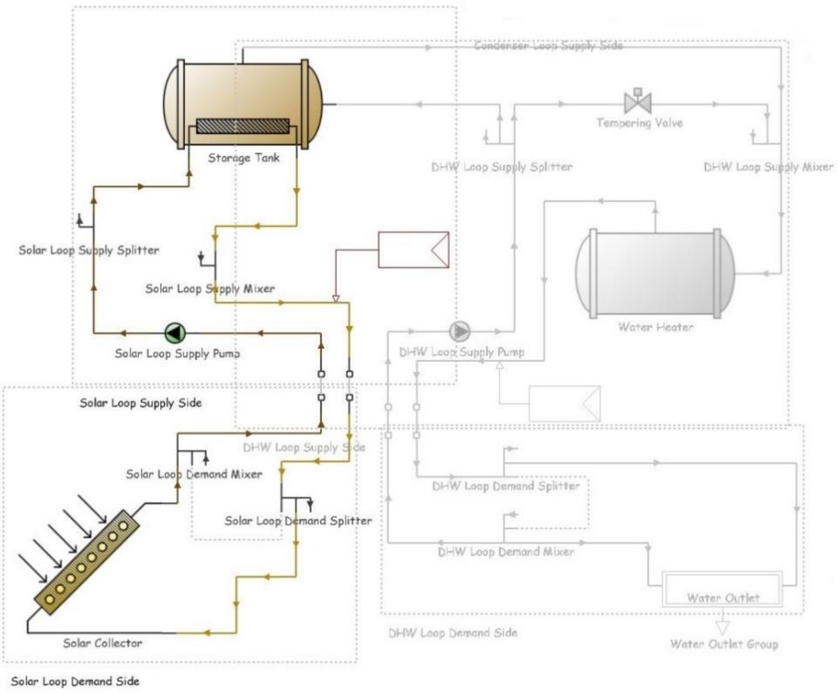

Fig. 37 Solar loop scheme in DesignBuilder

Solar collector technical data used in the calculation can be found below in Table 11.

Table 11 Solar collector technical data

Input data for one solar collector	Units
Collector gross area	1.20 m^2
Collector aperture area	0.90 m^2
Collector absorber area	0.90 m^2
Fluid volume	0.90 litres
Efficiency eta_0 (start efficiency)	0.7970
Efficiency a_1	4.1770 $W/(m^2K)$
Efficiency a_2	0.0039 $W/(m^2K^2)$

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. The best solution how to simulate a hot water tank is to use a two-tank system. The two-tank system includes a storage tank, auxiliary water heater and tempering valve (Fig. 38). The storage tank stores produced heat directly from solar collectors. The auxiliary water heater is placed downstream of the storage tank and provides additional heat energy to reach the targeted hot water leaving temperature together with a tempering valve.

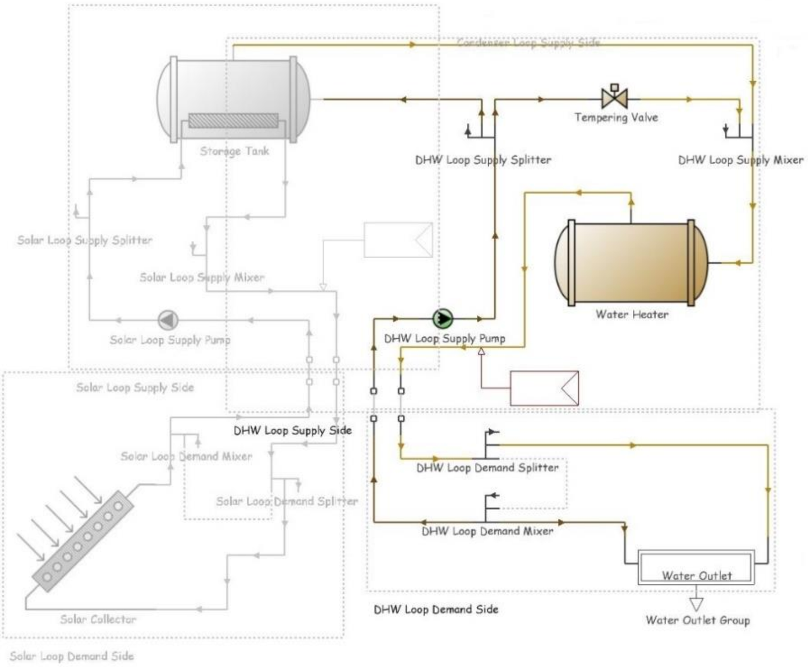

Fig. 38 DHW loop in DesignBuilder

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. The characteristics of a PV modules used for calculation are shown in Table 12.

Table 12 Photovoltaic cell performance data

Input data	Values
PV cell technology	Si-mono
Total gross area	10.5 m^2 + 8 m^2
PV cell efficiency	0.12
Surface area with active solar cells	0.90
Heat transfer integration mode	Decoupled
Inverter efficiency (DC to AC)	0.95

5.3.5 Results and discussion

Definition of boundary conditions and model description for dynamic energy simulation was described. The boundary conditions were defined for the building before and after energy retrofitting with the main focus on weather data, building envelope characteristic, indoor climate specification for different areas together with activity, and building services with operation schedules. All goals mentioned above meet the specified objectives together with theoretical research methodology mentioned in chapter 4.1 Theoretical/Numerical methods.

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 indoor air quality, 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

Heating design calculation was carried out in DesignBuilder using EnergyPlus dynamic thermal simulation engine to determine the steady-state heat losses for the building. The worst case simulation scenario with the winter design week data such as minimum outside dry-bulb temperature (winter design external temperature), wind speed and direction are used. Solar and internal gains (lighting, occupancy, equipment, etc.) are not included in the heating design calculation. Every zone is heated constantly to achieve the set point heating temperature by using a simple convective heating system.

The overall building heat losses, indoor and outdoor temperatures from heating design calculation are shown in Fig. 39 for the house before energy retrofitting and Fig. 40 shows values for current design. The temperature for heating design calculation is the same for both simulation cases (house before and after energy retrofitting); average indoor air temperature is 19.6 °C and an average outside dry-bulb temperature is -9.9 °C. If we compare heat losses (heat balance) for different building elements (Fig. 39 and Fig. 40), it can be seen the major heat reduction for wall structure (from 1.67 kW to

0.35 kW) and roof (0.51 kW to 0.10 kW). In total, the overall building heat losses are reduced from 3.05 kW to 1.03 kW, which is approximately 66 % reduction.

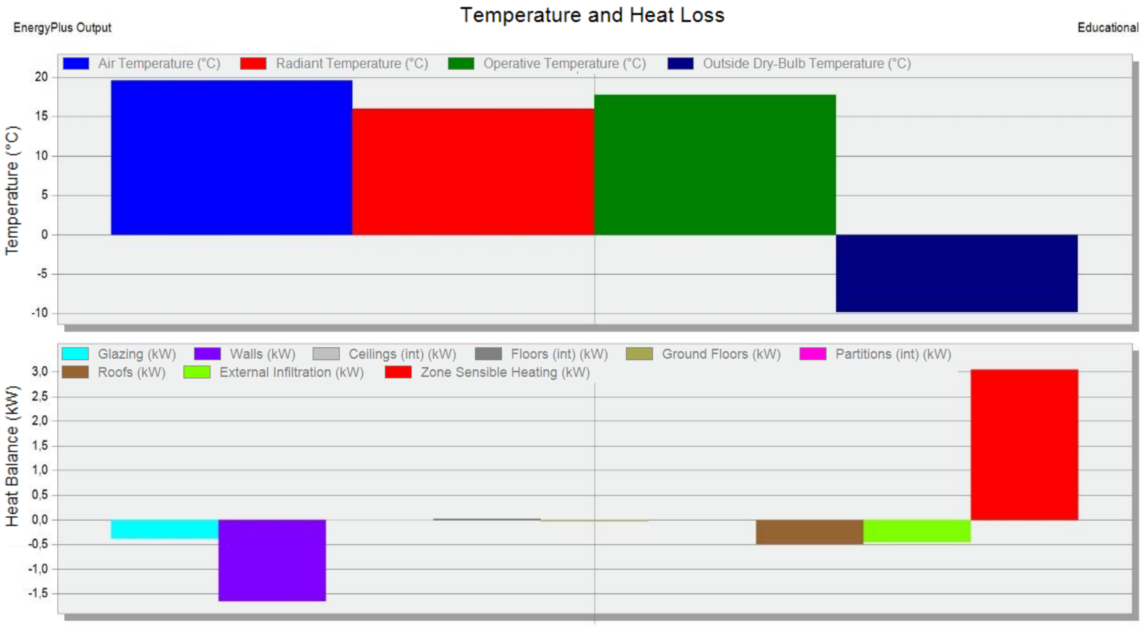

Fig. 39 Heat losses and temperature of the house before energy retrofitting

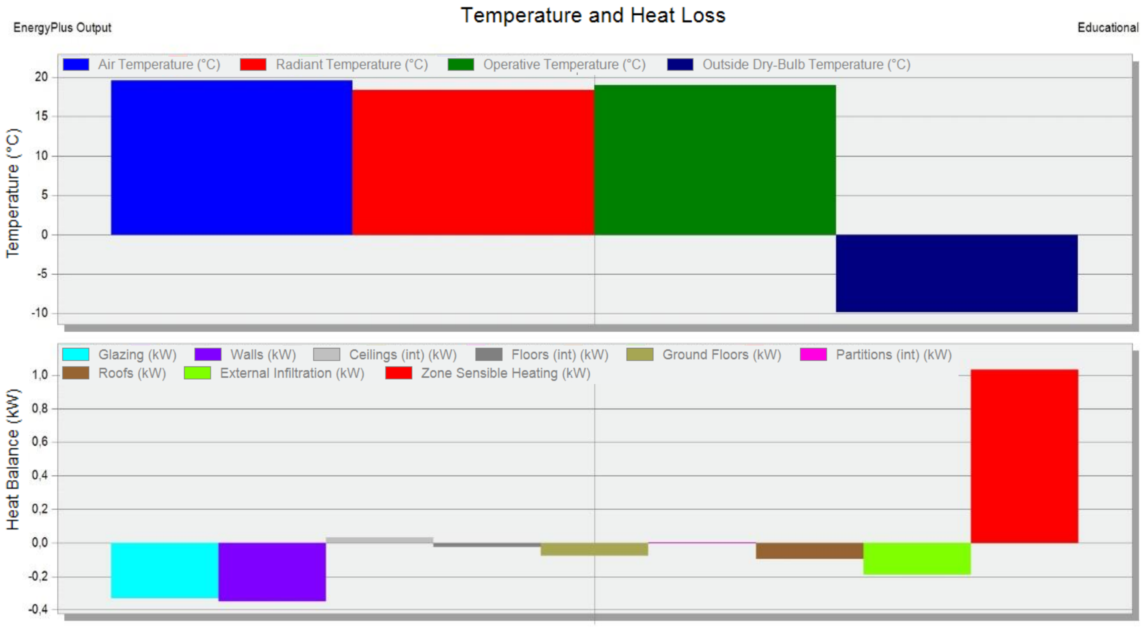

Fig. 40 Heat losses and temperature of the house after energy retrofitting

5.4.2 Internal heat and solar gains calculation

Internal heat and solar gains calculation for the refurbished building was carried out for summer and winter design week. Summer design week starts from 3rd August to 9th August and winter from 10th February to 16th February. The internal heat gains such as occupancy, household appliances (computer and other equipment), general lighting and solar gains are shown in Fig. 41 for winter and in Fig. 42 for summer period. Artificial fluorescent suspended lights are selected. The fraction of heat from lights consist of radiant fraction with the value of 0.42 (heat from lights that goes into the zone as long-wave, resp. thermal radiation), visible fraction with the value of 0.18 (heat goes as a visible, short-wave radiation) and convected fraction with the value of 0.40 (heat from lights convected to the zone air).

The major heat gain contribution during the summer and winter design week is coming from solar radiation through exterior windows. For the winter design week the solar heat gain through exterior window varies between 0.3 kW and 1.5 kW (Fig. 41) and for the summer design week is the variation between 0.6 kW and 2.3 kW (Fig. 42). The rest of the internal gains, such as lighting, domestic appliances or occupancy have negligible impact on the overall heat gain (are always below 0.2 kW) in the studied single-family house.

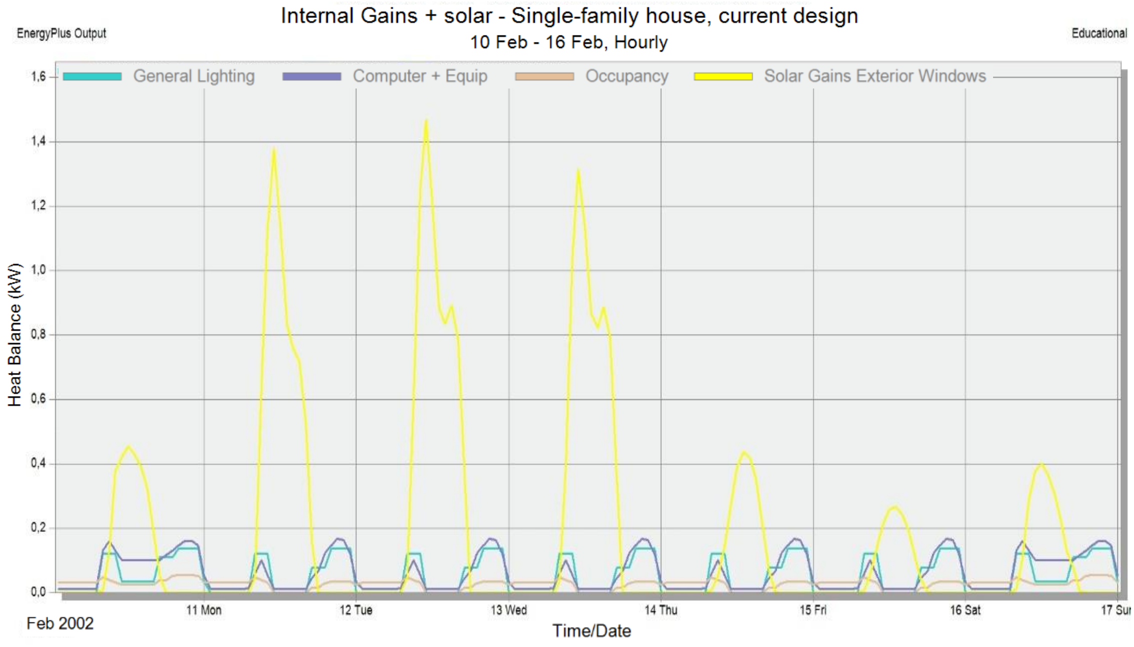

Fig. 41 Internal and solar heat gains for winter design week

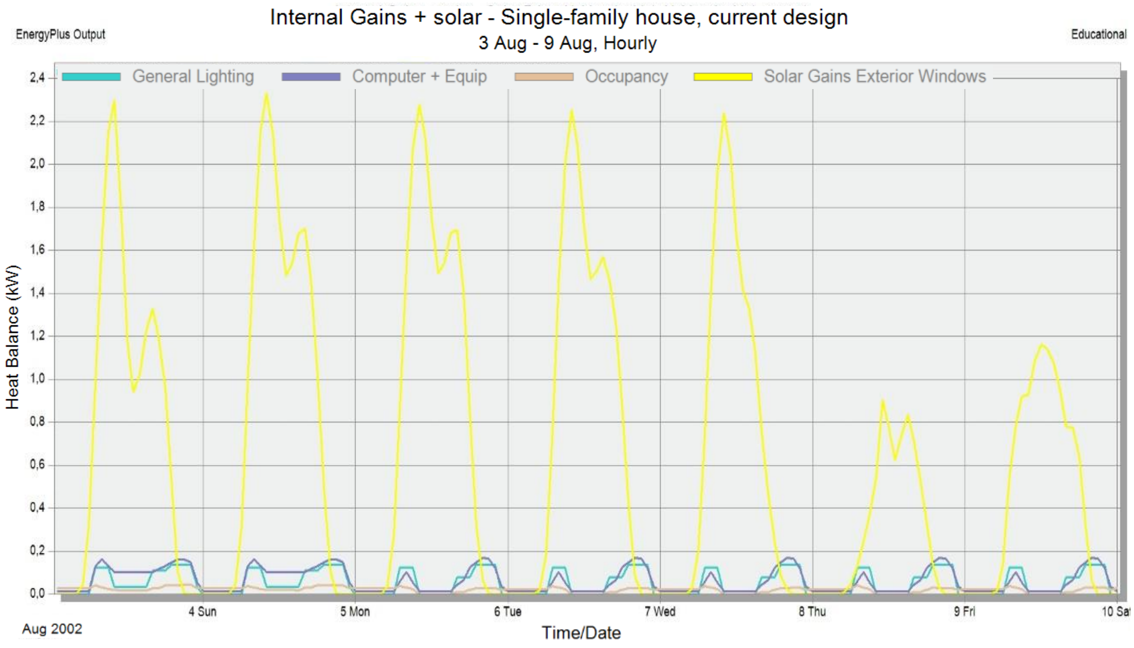

Fig. 42 Internal heat gains for summer design week

Fig. 43 shows annual solar heat gains through exterior windows for different areas. Solar heat gains in upper floor, bedroom are almost double compared to the living room with kitchen on the ground floor. The highest heat gains are during the summer period (May – July), almost constant with the value of 300 kWh for bedroom and 150 kWh for living room with kitchen.

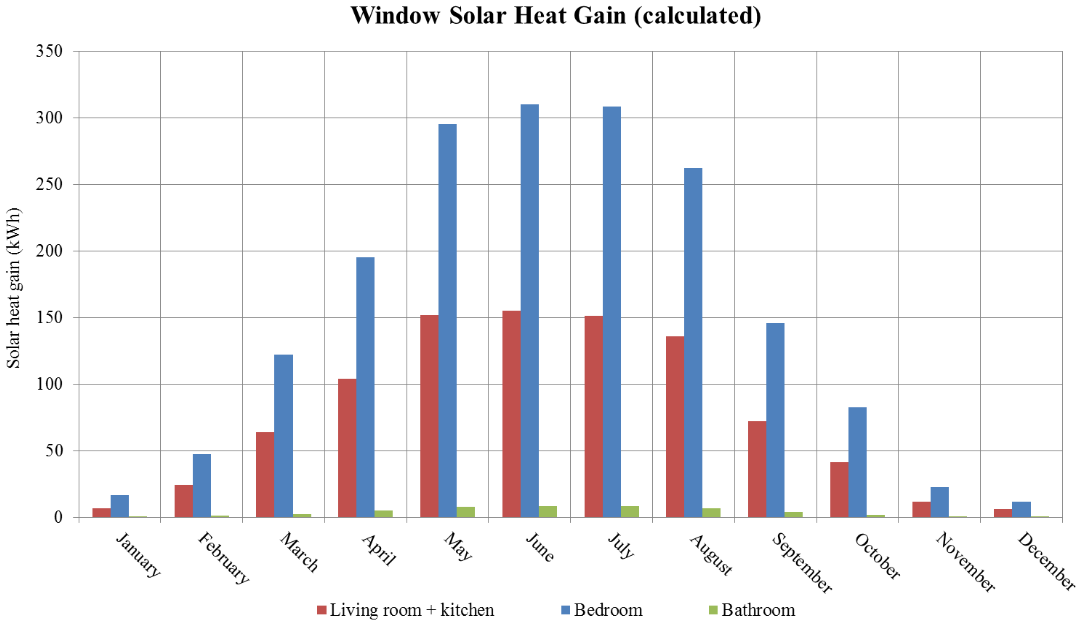

Fig. 43 Windows solar heat gains by building zones

5.4.3 Thermal comfort calculation

Thermal comfort calculations for the refurbished building were performed. Annual indoor air temperatures and relative humidity were calculated as an average for the whole house and the main zones (living room with kitchen and bedroom) with hourly time step.

Fig. 44 shows an annual indoor air temperature and relative humidity calculation with hourly time step for the living room and kitchen. If the space is occupied the minimum indoor air temperature is set to 22 °C. Heating setback temperature is 18 °C and is applied if the dwelling has no occupancy or during the night mode.

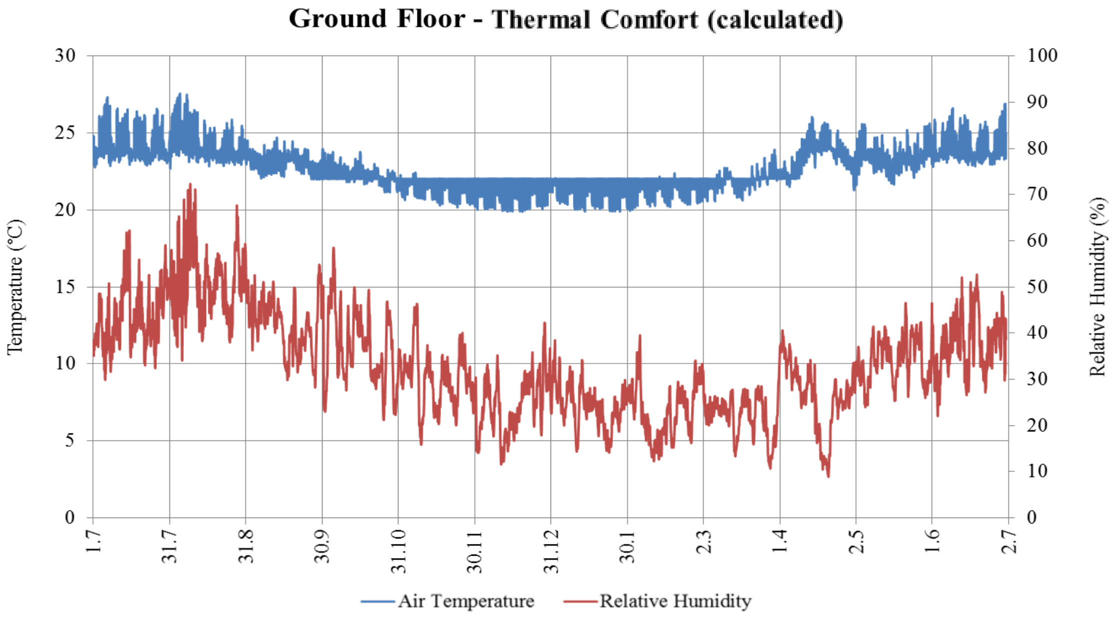

Fig. 44 Calculated indoor air temperature and relative humidity in the living room and kitchen located in ground floor

Detail hourly air temperature and relative humidity curve in the living room and kitchen during the winter and summer design week is shown in Fig. 45. It is apparent that during the heating (occupied) period the heating set point temperature is set to 22 °C. For summer design week the maximum temperature is set to 26 °C if the space is occupied. If the indoor air temperature of 26 °C is met and the outdoor air temperature is lower than the indoor air temperature the natural ventilation through openable windows is activated to cool the space as it is shown in Fig. 45.

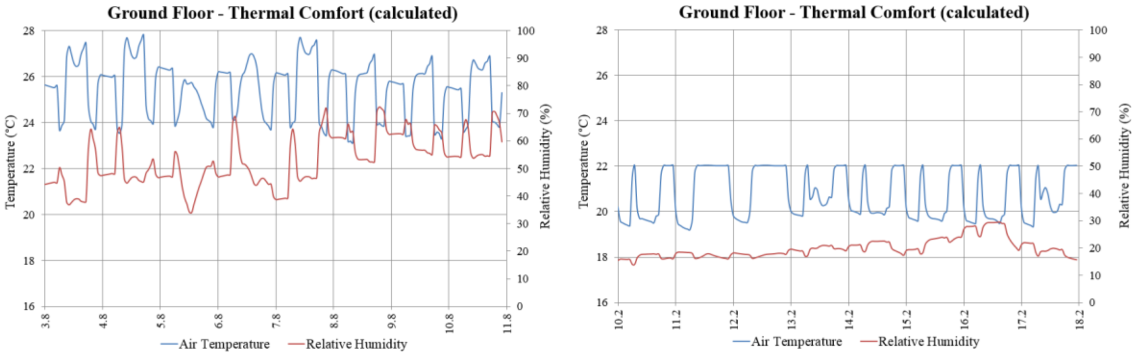

Fig. 45 Indoor air temperature and relative humidity for winter and summer design week in the living room and kitchen

For the first floor (bedroom area) the same boundary conditions are applied as for the ground floor. The indoor air temperature in the simulation increases up to 30 °C due to the skylights without shading elements (Fig. 46). Such a high temperature is only in the period when the dwelling is unoccupied and not ventilated. If the dwelling is occupied, shading skylights elements are active and natural ventilation through openable windows is applied to cool the living space up to 26 °C.

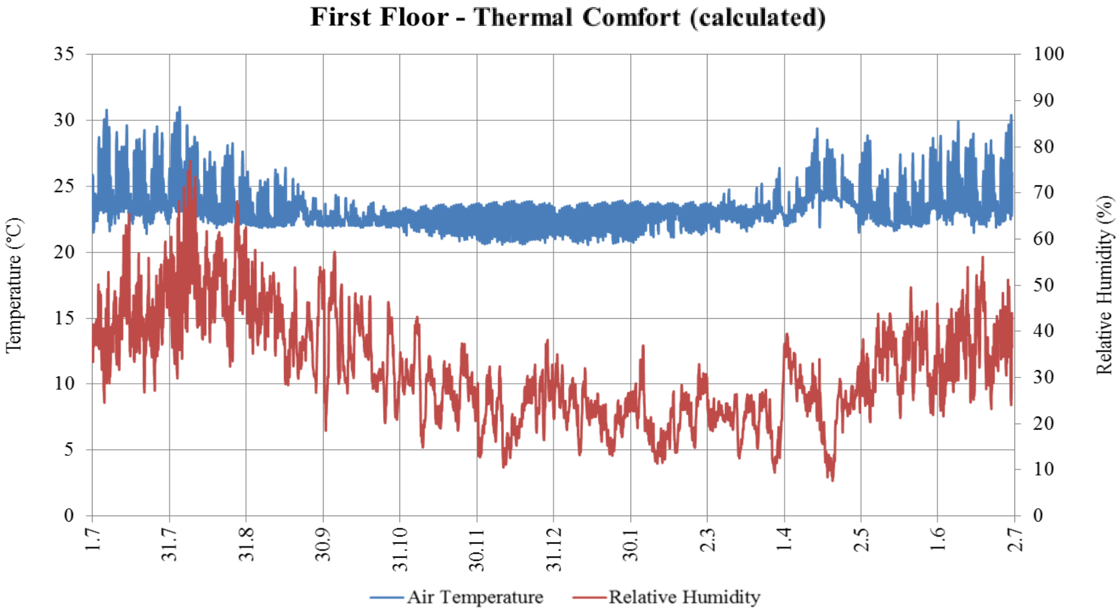

Fig. 46 Simulated indoor air temperature and relative humidity in bedroom, first floor

5.4.4 Daylight analysis

To verify the implementation and benefits of the extra skylights added into the prefabricated rooftop element, the daylight simulation study was performed in DesignBuilder with Radiance simulation engine. To evaluate natural internal lighting level in the building, daylight factor (DF) is established. DF is a ratio of internal light level to external light level on the selected working plane in our case 0.85 m above the floor level. For our study the required daylight factor of 2.0 (200 lux) is set to fulfil good visual performance for the residential building, such as kitchens, living rooms, dining rooms, studies, etc., based on BREEAM (Building Research Establishment Environmental Assessment Methodology) certification tool, credit Health and Wellbeing - Hea 01 Visual comfort for multi-unit residential buildings [87].

For the simulation overcast sky (10 000 lux) was set up together with other parameters and boundary conditions, such as Solar Heat Gain Coefficient (SHGC), Visible Light Transmittance (VLT) of the glazing and reflectance of all internal surfaces. Table 13 shows the input parameters used in the calculations.

Table 13 Input parameters for daylight simulation

Input data	Old design	Current design
External glazing gross area	3.36 m^2	3.36 m^2
External glazing SHGC	0.70	0.70
External glazing VLT	0.75	0.75
Skylight gross area	-	2.18 m^2
Roof glazing SHGC	-	0.69
Roof glazing VLT	-	0.75
Visible reflectance		
- Internal wall	0.60	0.60
- Ceiling	0.80	0.80
- Floor	0.22	0.22

The simulation shows an improvement by implementing two extra skylights of 2.18 m^2 into the prefabricated rooftop element. The total floor area of the bedroom is 18.09 m^2 and gross area of transparent surfaces in the bedroom increase from 3.36 m^2 to 5.54 m^2.

The floor area above daylight factor was greater than 2.0 increases from 32.58% for the house before the energy retrofitting to 88.11% after the energy retrofitting. Other daylight result values for studied area are shown in Table 14.

Table 14 Daylight study results in the house before and after energy retrofitting

Parameters	Initial design	Current design
Floor area bedroom (m^2)	18.09	18.09
Floor area above DF 2.0 (%)	32.58	88.11
Minimum DF (%)	0.34	0.85
Minimum illuminance (lux)	33.76	84.83
Average DF (%)	2.69	4.65

The comparison of the daylight illuminance map for selected zone (first floor – bedroom) before and after energy retrofitting is shown in Fig. 47 and Fig. 48.

The daylight study results evidently demonstrate the advantages of the extra skylights implementation and its significant influence on daylight penetration into the studied area (floor area above required DF of 2.0 increases from 32.6 % to 88.1 %). This measure has also a positive influence on the tenants feeling and the energy savings from the artificial lighting in the house.

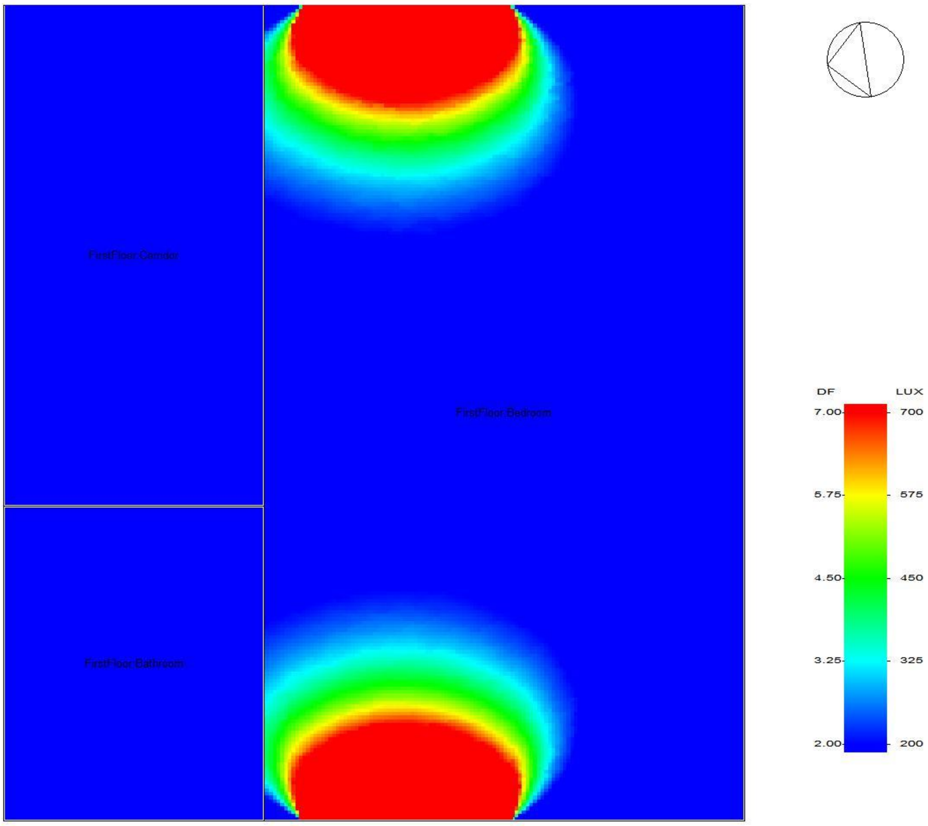

Fig. 47 First floor daylight illuminance map of initial design

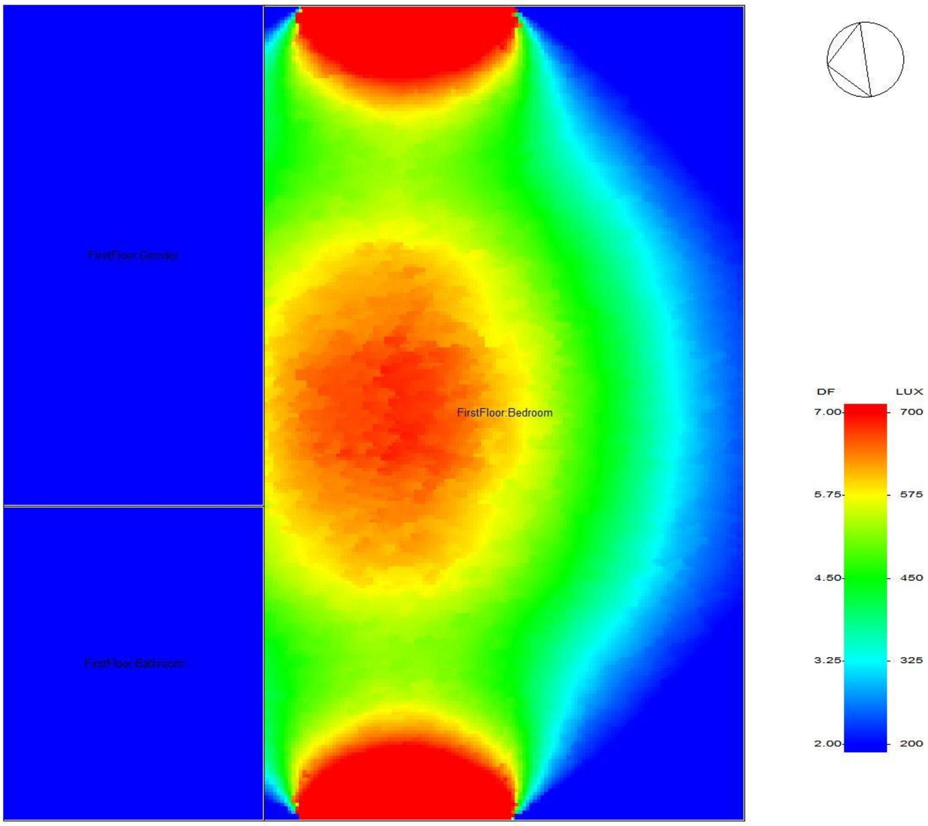

Fig. 48 First floor daylight illuminance map of current design

5.4.5 End-use energy calculation (consumption and production)

This chapter deals with the energy system flows in the dwelling. In particular, it focuses mainly on energy consumption and production of the building service systems described in chapter 5.3.4 Building services. All simulations are performed with the typical meteorological year data period with an hourly time step.

5.4.5.1 Mechanical ventilation with heat recovery

Mechanical ventilation with heat recovery calculation shows a heat energy consumption and production during the year. The heating season starts on 1st October and finishes 31st March. The thermal heat energy is treated by AHU and is divided into three elements: pre-heating coil, heating coil and heat recovery. Detail information of monthly heat energy production and consumption of the system is shown in Fig. 49. The heat energy peak is in December with the total heat energy demand of 373 kWh. If we compare the heat energy contribution for December, the pre-heating coil delivers around 10 % of heating energy, heating coil up to 56 % and heat recovery contributes approximately by 34 % of total heat energy.

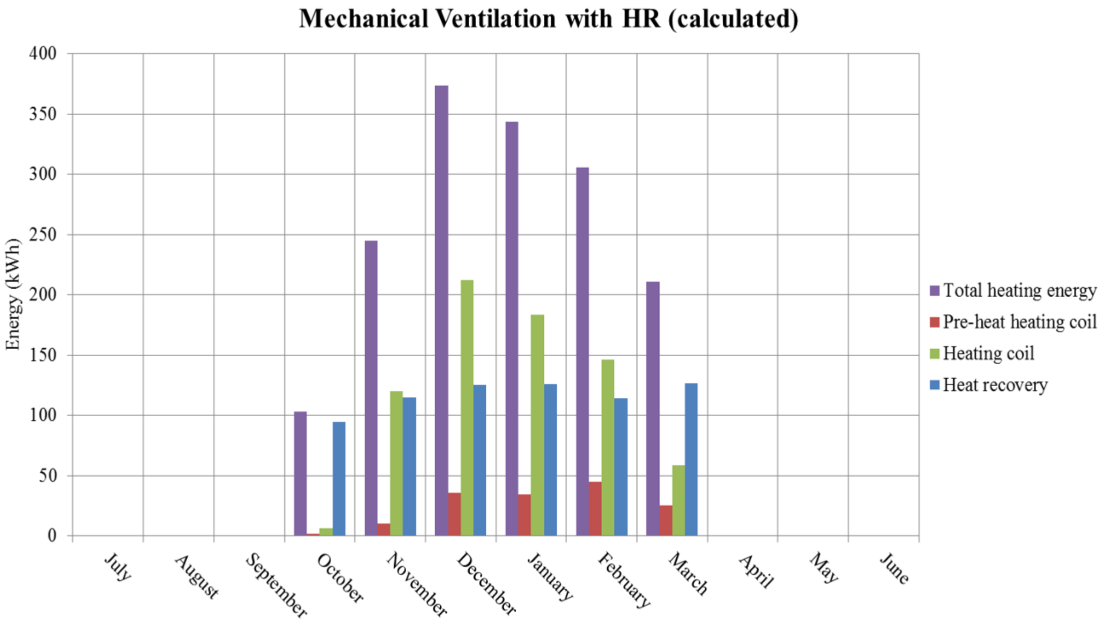

Fig. 49 MVHR heat energy flows

The electrical energy needed for AHU supply and extract fans operation during the year is presented in Fig. 50. The AHU variable volume fans operate constantly during the year and serve a minimum amount of outdoor fresh air requirements based on occupancy schedule in the house.

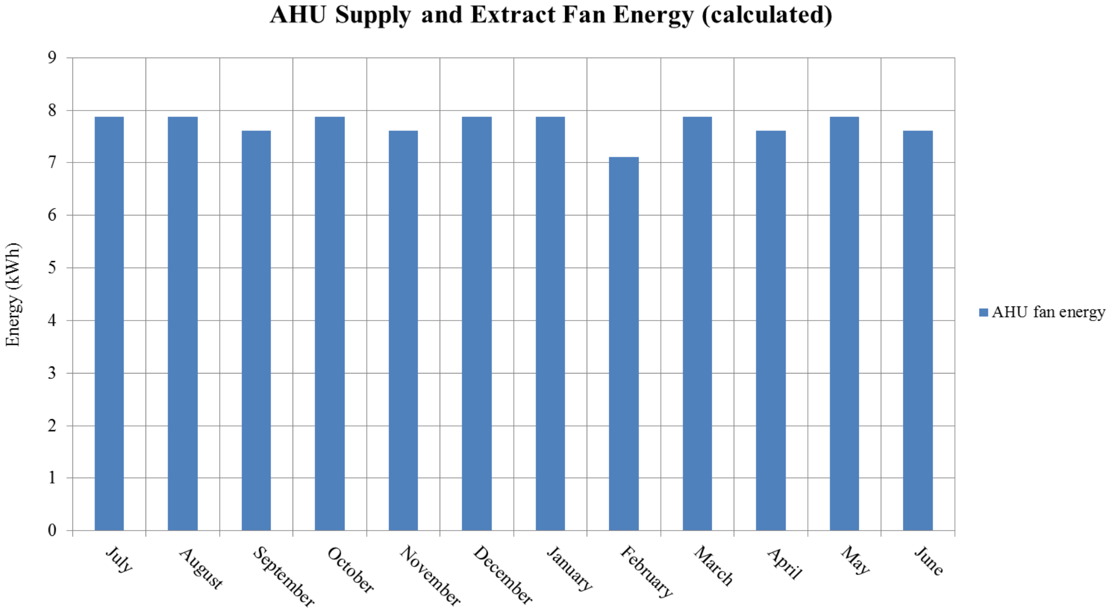

Fig. 50 AHU supply and extract fan electricity consumption during the year

5.4.5.2 Ground source heat pump energy balance

Ground source heat pump calculation is performed only for heating season (1^{st} October - 31^{st} March). GSHP delivers energy only for space heating due to the simulation model restriction. The energy production peak is during December, with the heat energy production of 298 kWh and 115 kWh of delivered electricity energy for heat pump operation (Fig. 51). The average calculated heat pump Coefficient of Performance (COP) is 2.60.

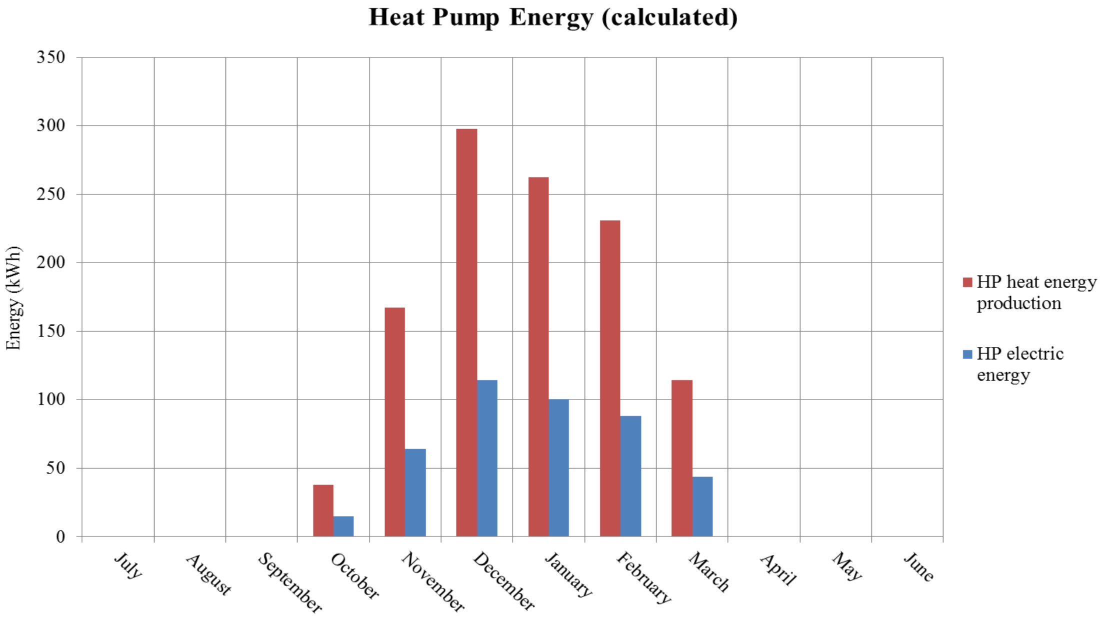

Fig. 51 Ground source heat pump energy flows

5.4.5.3 Solar assisted domestic hot water system

The solar assisted domestic hot water system delivers water to all hot water outlets. The flat plate solar collectors system cover almost 66 % of the total DHW heat energy and the remaining 34 % is secured by the auxiliary water heater. Detail heat energy contribution from solar collector and water heater during the year is presented in Fig. 52.

During the period from April to August, the DHW production is fully covered by flat plate solar collectors system. The rest of the year (from September to March) the DHW system requests energy from auxiliary water heater which covers from 10 % (in September) up to 87 % (in January) of the total heat energy consumption. In the real operation, the auxiliary water heater operation is minimised by GSHP which delivers requested heat energy into the stratified hot water tank.

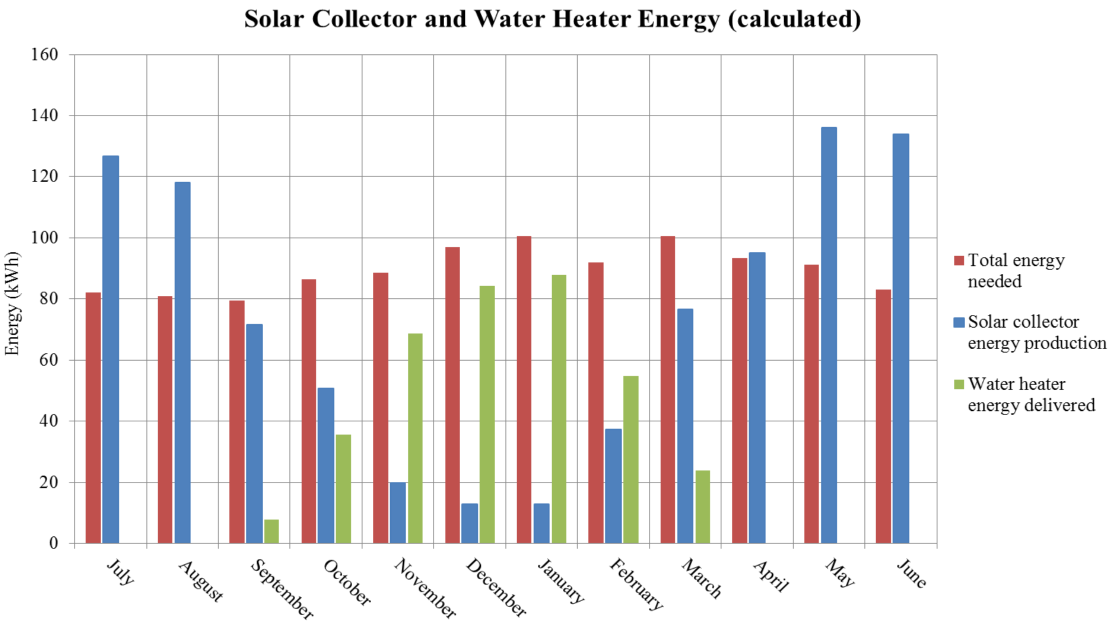

Fig. 52 DHW system energy production and consumption

5.4.5.4 Photovoltaic system energy generation

Photovoltaic cells are placed on the prefabricated element and additional PV cells are placed on the nearby building. Fig. 53 shows the electricity production by 10.5 m^2 of PV cells mounted on the prefabricated element and mean monthly solar radiation on the surface. The annual PV production is almost 1189 kWh with the peak production of 188 kWh in June. The electricity generation drop is during the winter period with nearly 20 kWh production in the month of December. The additional 8.0 m^2 of PVs produce roughly around 906 kWh of electrical energy.

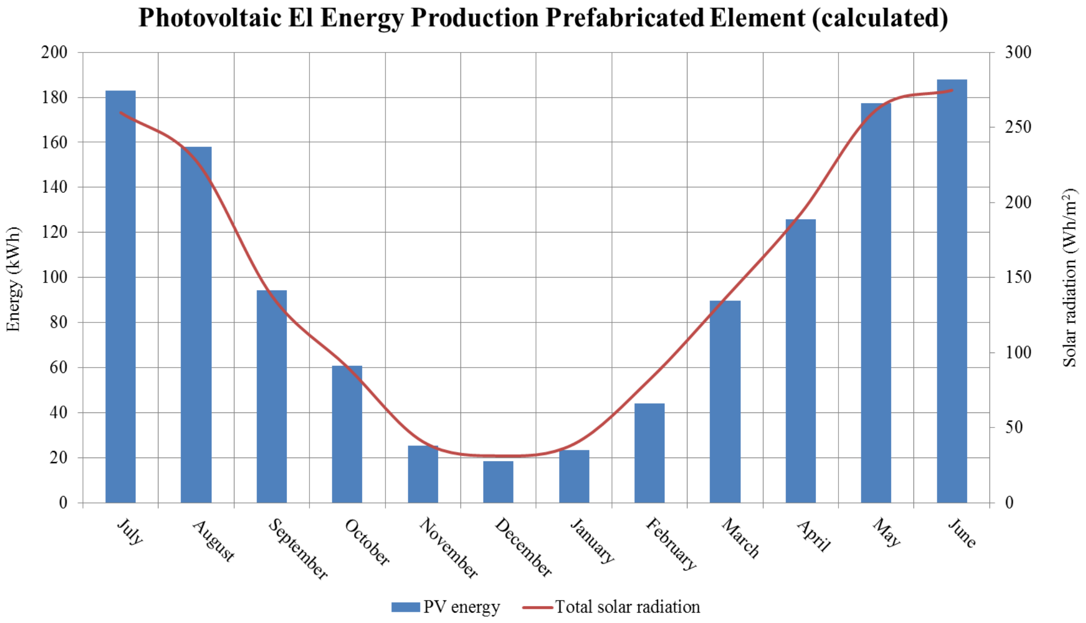

Fig. 53 Photovoltaics electricity generation

5.4.5.5 Household and artificial lighting energy consumption

Energy needed to run all household appliances such as freezer, washing machine, cooker, TV sets, electric kettle, etc. are shown in Fig. 54. The average monthly appliances energy consumption is assumed to be 45 kWh.

Artificial lighting energy consumption is shown in Fig. 54 with the average estimated monthly electricity consumption reaching 16 kWh. The lighting energy consumption varies during the period due to the large seasonal variations in daylight.

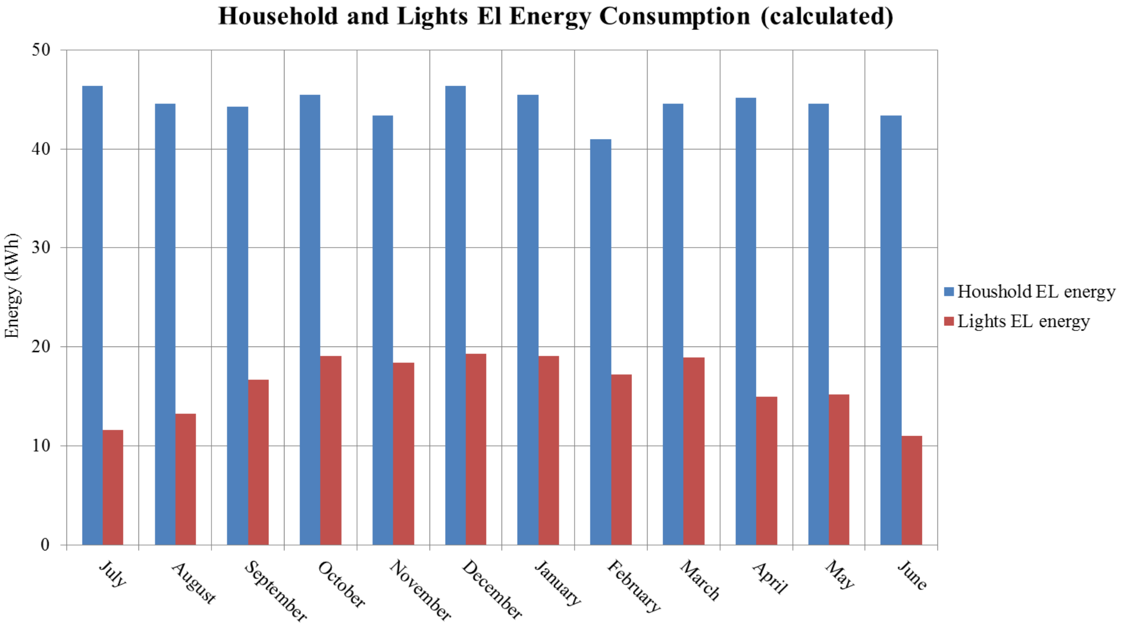

Fig. 54 Household and artificial lights electricity consumption

5.4.5.6 Total building energy end-use breakdown

The total building end-use energy consumption and production breakdown is summarised in this chapter. The simulated annual heat energy consumption and production breakdown is described in Fig. 55. The heat energy consumption for the building is 2830 kWh/year and heat energy production is 2467 kWh/year. The biggest amount of the heat energy goes for domestic heating, about 1755 kWh/year, where 63 % of the heat energy is produced by ground source heat pump and the rest of 27 % is ensured by heat recovery mounted in AHU. The total energy needed to heat DHW is 1075 kWh/year, where 712 kWh/year is generated by solar collectors and the rest is secured by auxiliary electric water heater.

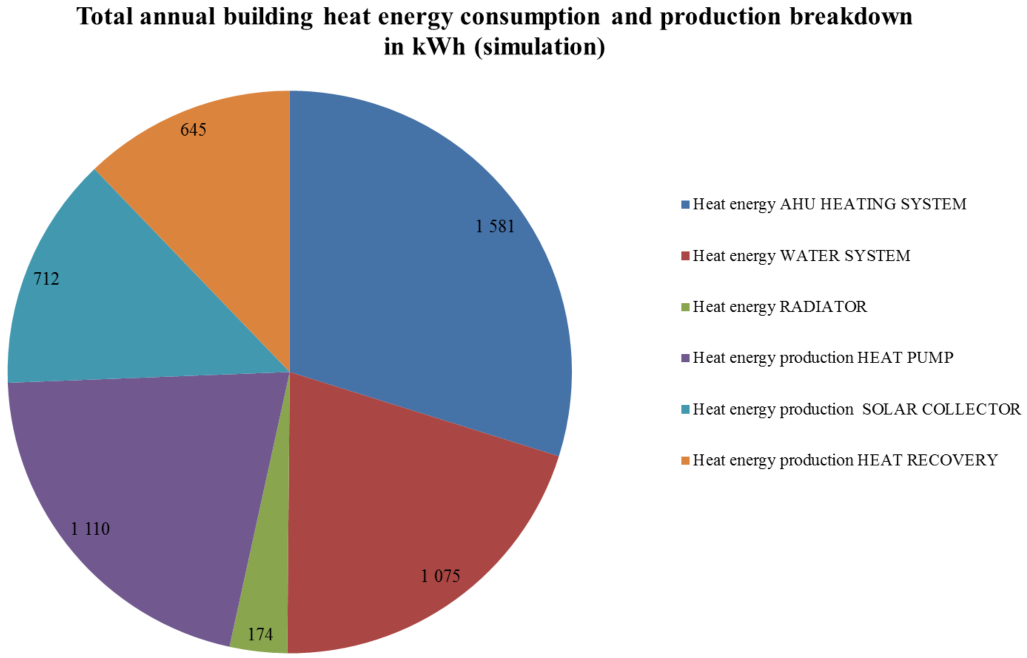

Fig. 55 Annual heat energy production and consumption breakdown

The simulated annual electric energy consumption and production breakdown is described in Fig. 56. The electric energy consumption for the building is 1670 kWh/year and electric energy production is 2095 kWh/year. The highest amount of electrical energy consumption is coming to 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 is secured by PV cells which are producing 2095 kWh/year.

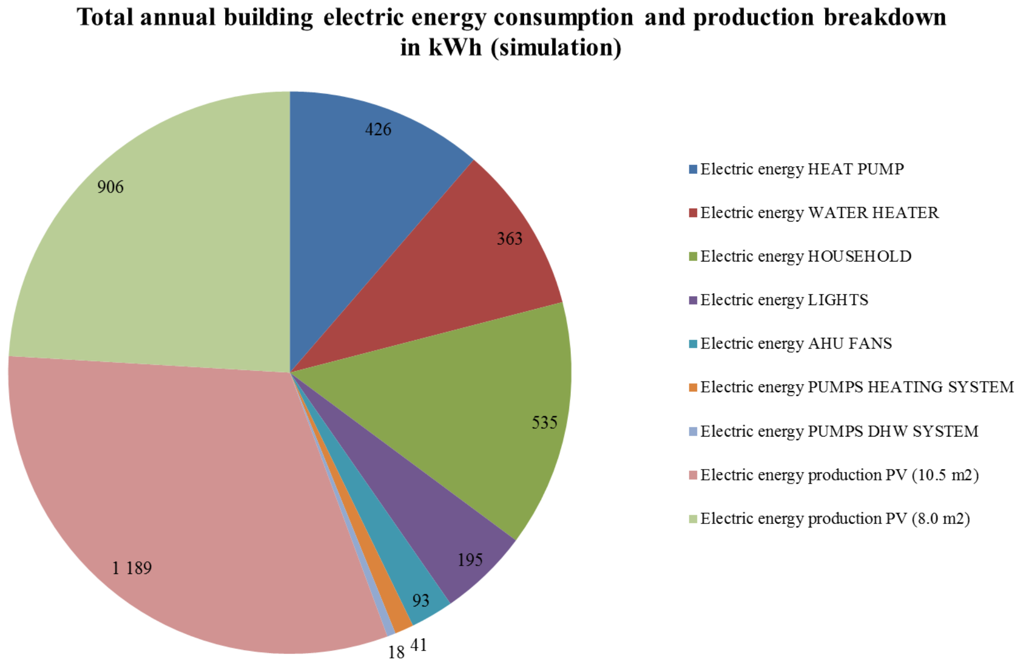

Fig. 56 Annual electric energy production and consumption breakdown

5.4.6 Results and discussion

The building energy simulation was performed in the software DesignBuilder based on boundary conditions described in chapter 5.3 Definition of boundary conditions. Building simulations were split into five categories – heating design, internal gains, thermal comfort, daylighting and end-use energy calculation. Daylight analysis was performed due to the considerable impact on the overall building energy consumption.

The building heat loss calculations were performed for the building before and after energy retrofitting 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.

Internal heat and solar gains calculations were performed. 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 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 (were always 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.

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. 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. In the bedroom area the indoor air temperature increased up to 30 °C due to the skylights without shading elements and only in the period when the dwelling was unoccupied and not ventilated.

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 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.

The overall heat energy consumption of the building is 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.

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 is producing 2095 kWh/year.

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

Detail study of a suitable monitoring system fulfilling all required monitoring criteria was carried out. Two types of online monitoring systems were chosen and installed to monitor energy flows and thermal comfort. Online monitoring systems were selected due to the need of active building performance monitoring and evaluation needs. The second reason was to capture and solve on time any future operational problems.

The energy meters Kamstrup Multical 601 are installed in the main building services circuits, such as ventilation with heat recovery, heat pump, solar collector loop, DHW and air preheating. In each circuit various parameters can be monitored, for example volume, flow, and energy consumption or production, supply and return medium temperature. Electricity consumption and production is measured for PV panels, pumps and fans. The pulse signals are synchronised every 4 minutes. Table 15 shows the detail information of measured parameters and one pulse output with relevant units.

Table 15 Energy meter monitoring information

Measured parameter	Units	One pulse value
Flow	l/h	1
Volume	Litter	1
Energy	Wh	1000
Flow temperature	°C	0.01
Return temperature	°C	0,01
Delta T	K	0,01
Running hours	Hours	1
Electricity energy	Wh	0.5

Extra Kamstrup 382 meters are mounted to measure electricity consumption of household appliances and artificial lighting, heat pump and electric heating rods in the water tank. The meters provide information of power, energy and running hours. The pulse signals are synchronised every 4 minutes and 1 pulse value for electricity energy represents 1000 Wh.

The second monitoring system from Brunata provides detail information about the thermal comfort in the two main areas in the house, living room with kitchen in the ground floor and bedroom in the first floor. The indoor air temperature, relative humidity and dew point are measured with the accuracy of 0.1 °C and 0.1 %. The data resolution can vary from 5 minutes to 24 hours.

5.5.1 Results and discussion

Two independent online monitoring systems were mounted into the dwelling. 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 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 performed for the single-family house together with weather data collection. The building was in a testing mode during the monitoring period with main focus on commissioning, system operation and data collection and evaluation. After the detailed data analyses the whole building has been optimized. The building during the testing mode caused sometimes some operational and data collection problems.

The weather data and indoor air temperature monitoring are presented with daily time step. Building service systems monitoring was set to 4 minutes time step as described in chapter 5.5 Installation of monitoring system and software study. For research purposes and data presentation the time step of building service systems was set to monthly period. More information about the monitoring results are described in the subsections below.

5.6.1 Weather data monitoring

Weather data was collected from two nearest weather stations – one is located in Herlev and the second one in Skovlunde which is approximately 10 km as the crow flies from the studied area in Albertslund. Annual daily outside dry-bulb air temperature and relative humidity is presented in Fig. 57. The minimum average daily outside dry bulb temperature was -12.0 °C with the relative humidity of 75.0 % in 4th February 2012. The maximum outdoor dry bulb temperature was reached in the 3rd July 2011 with the value of 22.0 °C and relative humidity of 84.0 %.

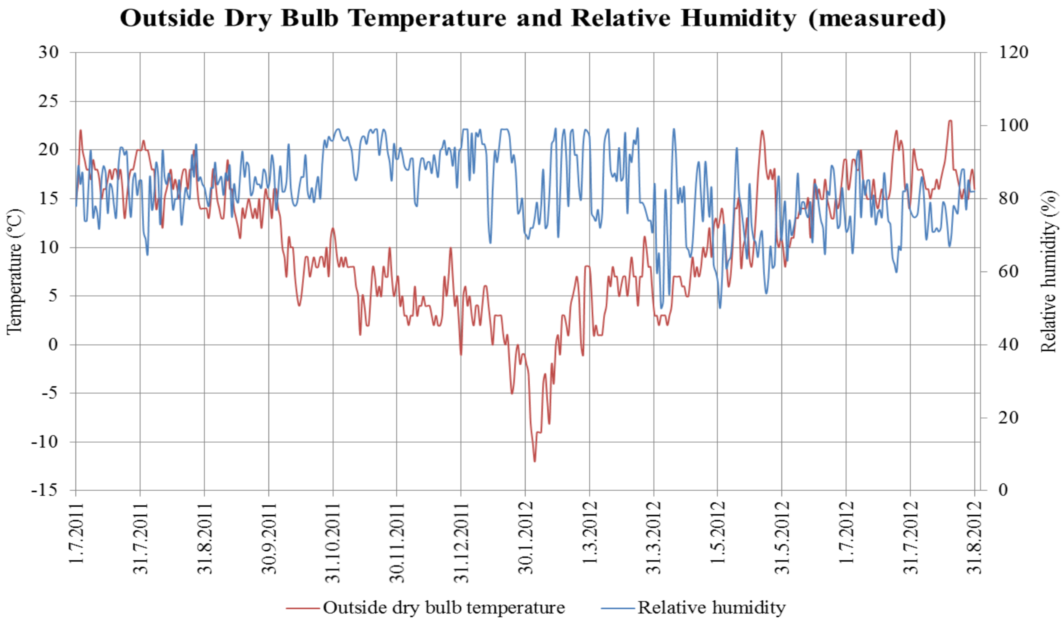

Fig. 57 Outside dry-bulb temperature and relative humidity

Annual solar global radiation together with the wind speed is shown in Fig. 58. The maximum average daily solar global radiation was 21st June 2012 with the value of 8380 Wh/m^2. The wind speed reached up to 11.1 m/s in November 2011.

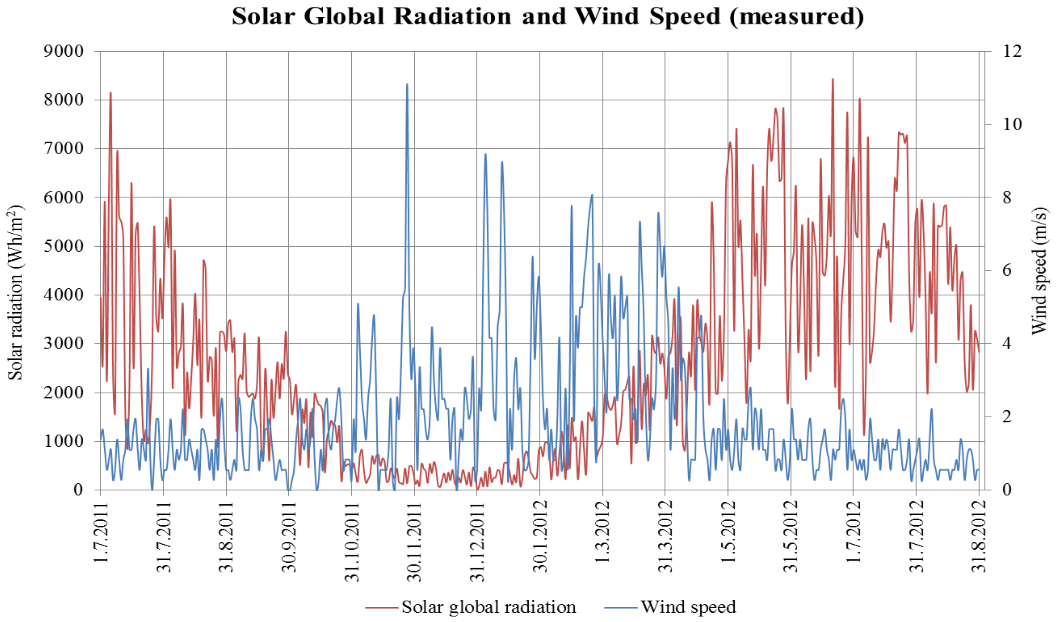

Fig. 58 Solar global radiation and wind speed in studied location

5.6.2 Thermal comfort monitoring

Thermal comfort was measured in two main areas in the house. Fig. 59 shows indoor air temperature and relative humidity curves on the ground floor – living room and kitchen. The air temperature varies between 20.0 °C and 27.1 °C with relative humidity ranging from 29.9 % to 75.2 %.

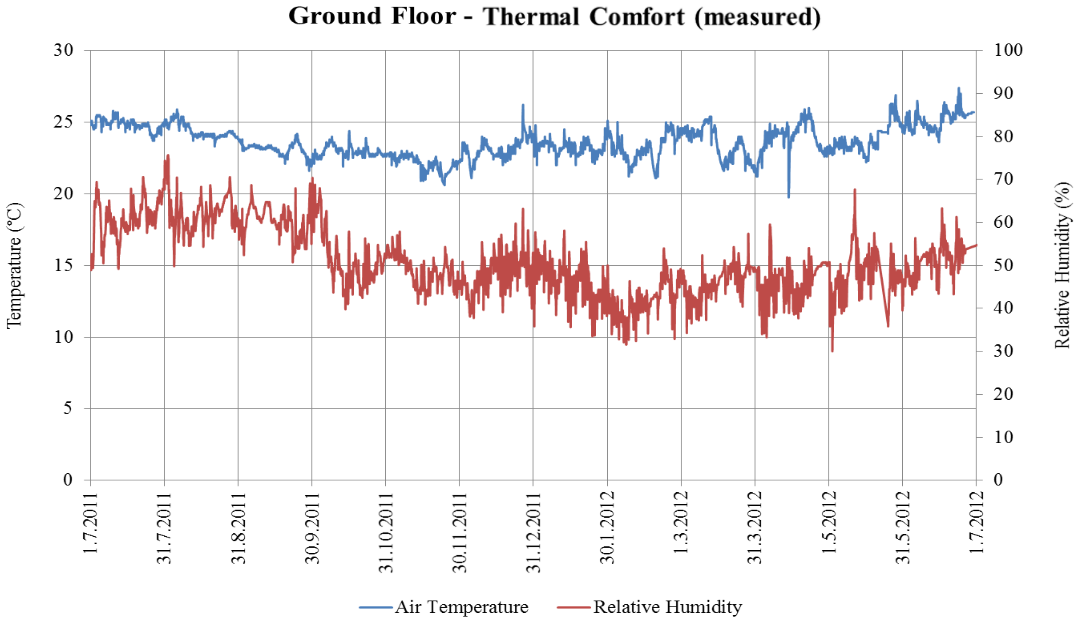

Fig. 59 Ground floor air temperature and relative humidity

The thermal comfort in the first floor - bedroom is shown in Fig. 60. The air temperature is in range of 15.0 °C to 27.2 °C. The temperature drop below 18.0 °C was the most probably caused by natural ventilation through opened windows. The air relative humidity reaches values from 32.8 % to 70.2 %.

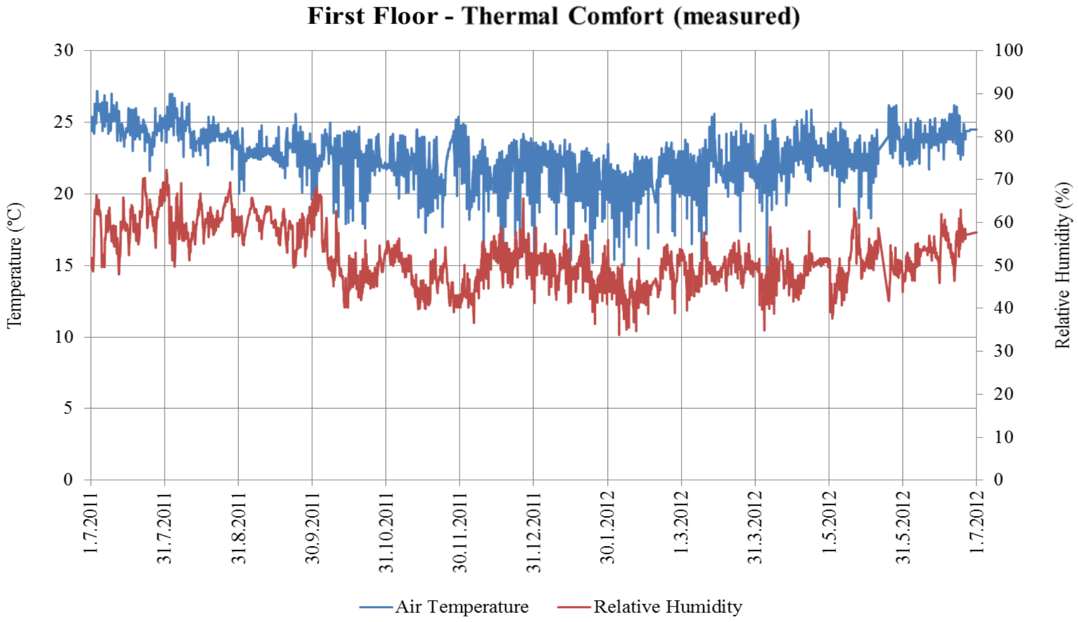

Fig. 60 First floor air temperature and relative humidity

5.6.3 Mechanical ventilation with heat recovery

For mechanical ventilation with heat recovery the energy consumption of heating coil and radiator together with an average monthly outside dry bulb temperature are shown in Fig. 61. The relative values are presented with the peak energy consumption for heating coil and radiator in December which represents 100 %. The energy consumption pattern shows correct annual energy consumption curve based on the estimated building energy demand.

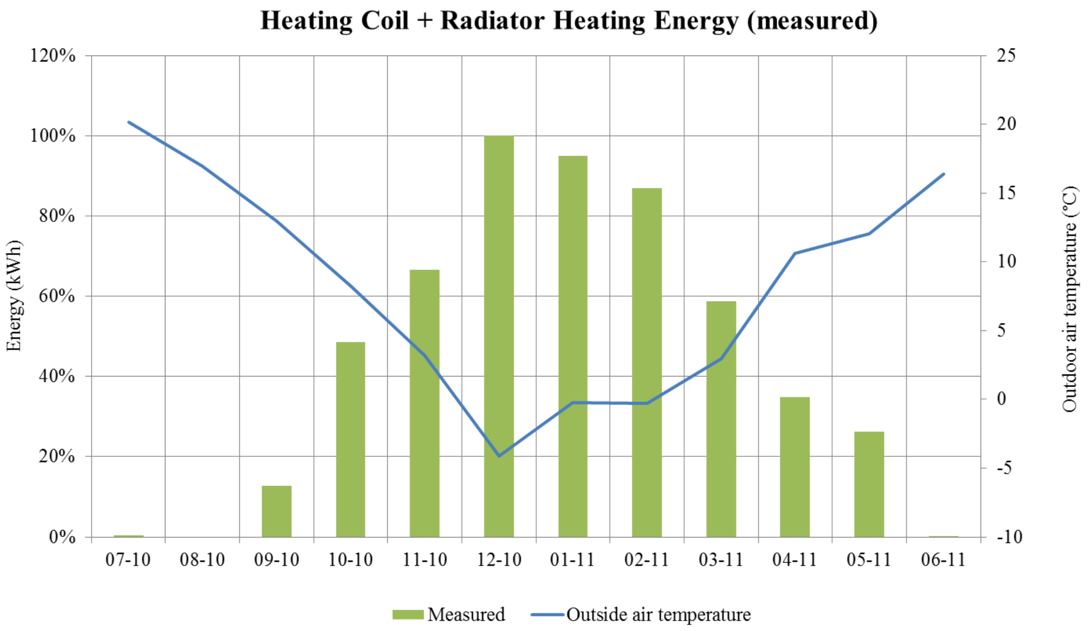

Fig. 61 Energy consumption for heating coil and radiator

Annual energy consumption of both radial AHU fans is shown below in Fig. 62. There was unusual fans operation for the first free months. It is assumed that it might be caused by a tenant's natural ventilation preferences instead of the mechanical one in that period. Fans energy consumption besides the mentioned period does not show any significant operation problems.

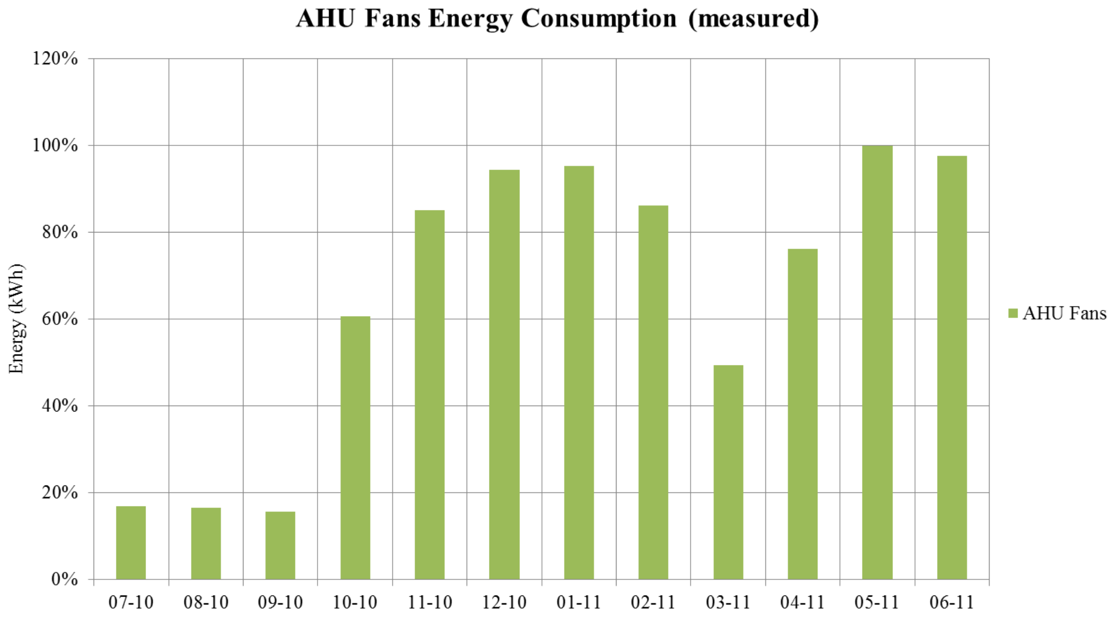

Fig. 62 AHU fans electrical energy consumption

5.6.4 Ground source heat pump

The monthly energy generation from the GSHP is presented in Fig. 63. In this real operation mode the GSHP is generating heat energy for domestic heating and DHW as well. For the months of October and November 2011 the measured data are not available due to the technical problem. The energy peak generation occurs in December 2011 with the gradual decrease in the following months.

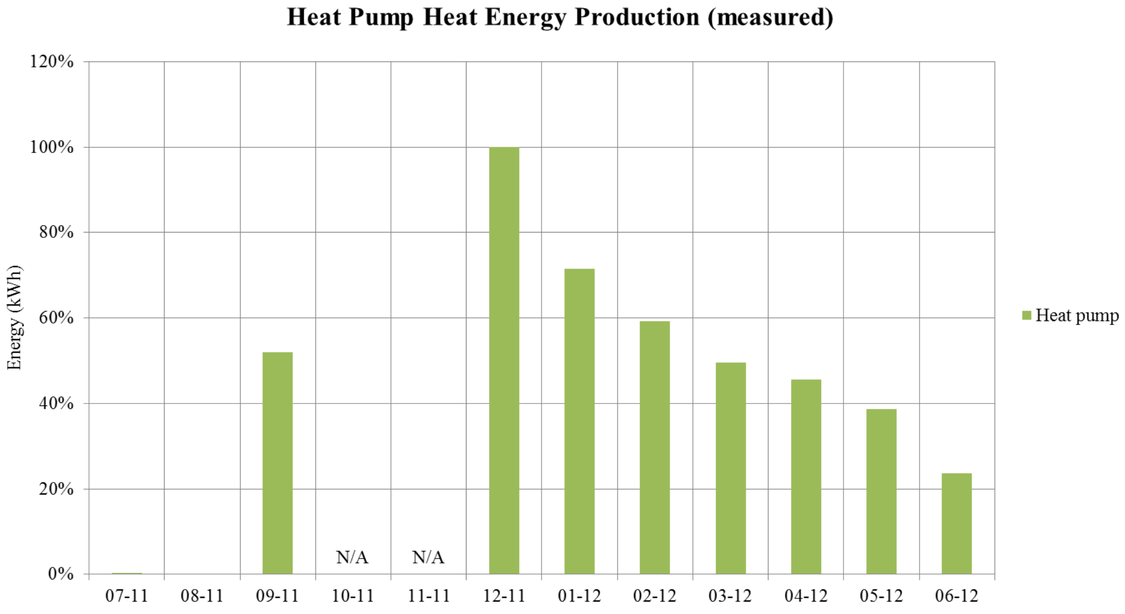

Fig. 63 Heat pump heat energy generation

Total monthly delivered electrical energy for the heat pump and other pumps in GSHP system are shown in Fig. 64. The electricity energy delivery peaks are in the winter period with the energy drops during the summer months when the GSHP is used only exceptionally for a DHW heating.

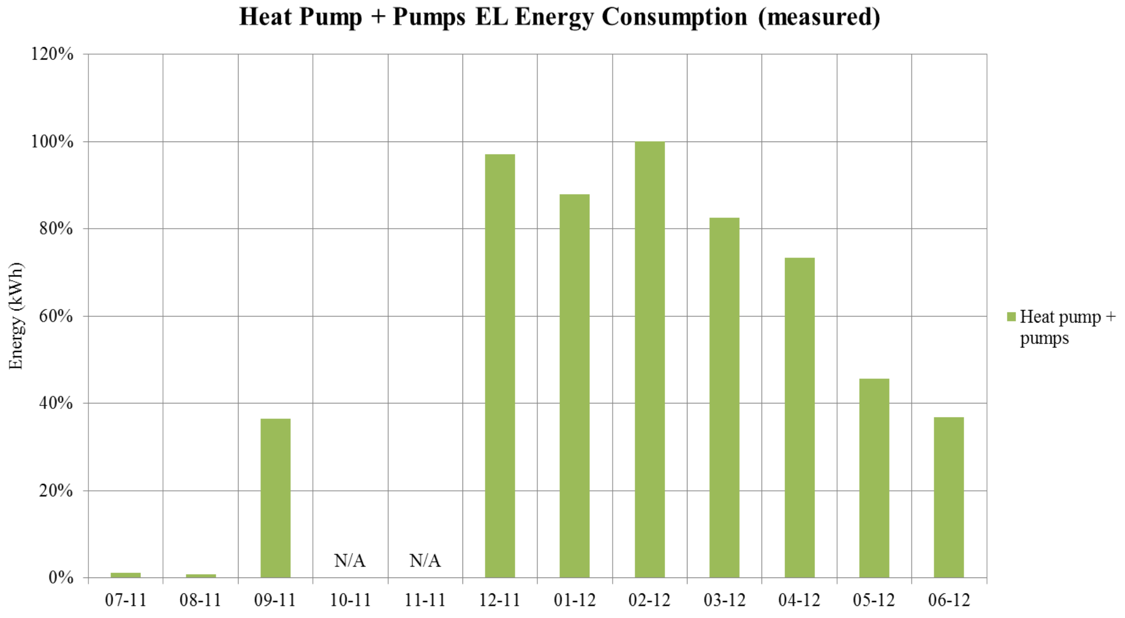

Fig. 64 Heat pump and pumps electrical energy consumption

5.6.5 Solar assisted domestic hot water system

Solar assisted domestic hot water system was monitored in two parameters. Solar collector heat energy generation and total solar radiation (direct and diffuse) incident on horizontal surface are shown in Fig. 65. The energy generation peak is reached in May 2012 with an average monthly solar radiation rate of 325 W/m^2.

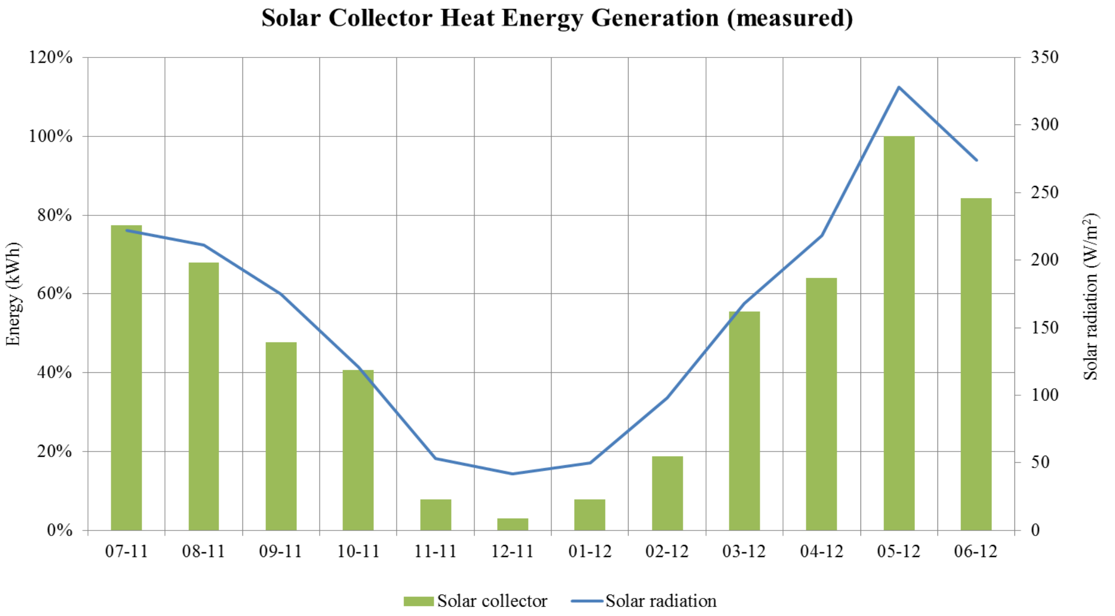

Fig. 65 Solar collector heat energy generation

The energy needed to heat DHW in the water tank by the GSHP heat exchanger and additional auxiliary electric water heater is shown in Fig. 66. The highest energy heat demand is in the months of December 2011. The lowest energy demand should be during the summer period with the expected delivered monthly energy nearly 0 kWh.

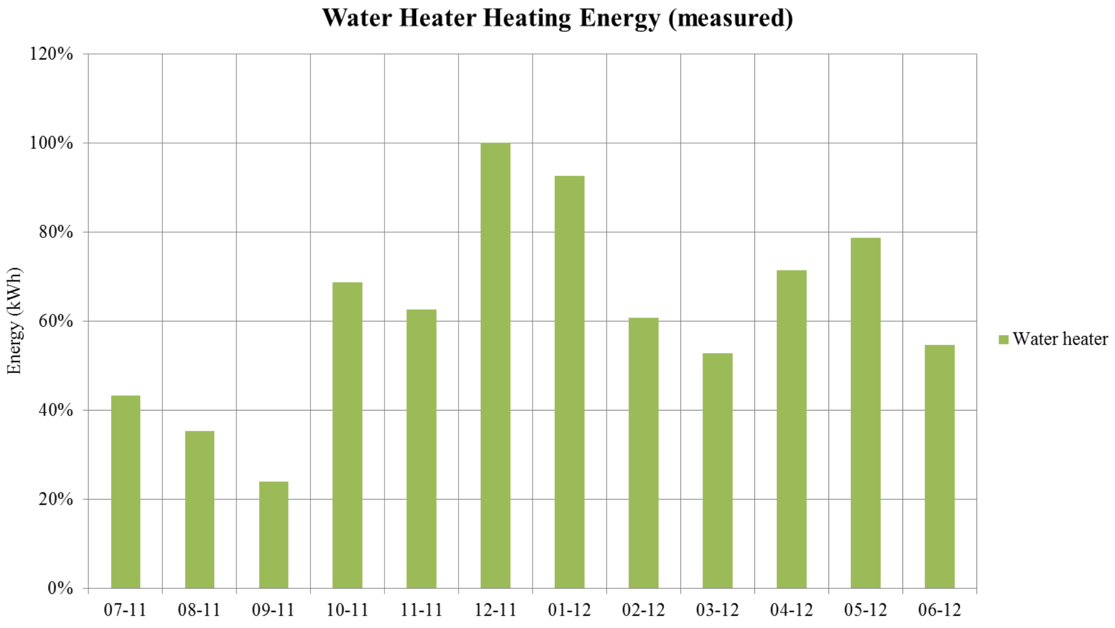

Fig. 66 Auxiliary water heater heating energy

5.6.6 Photovoltaic system

Photovoltaic system is used to generate energy to operate the house. Fig. 67 shows the energy generation from PV cells mounted on the prefabricated element. The highest electricity energy generation is during the summer months of June 2010 and July 2011. The lowest energy generation is during the winter period.

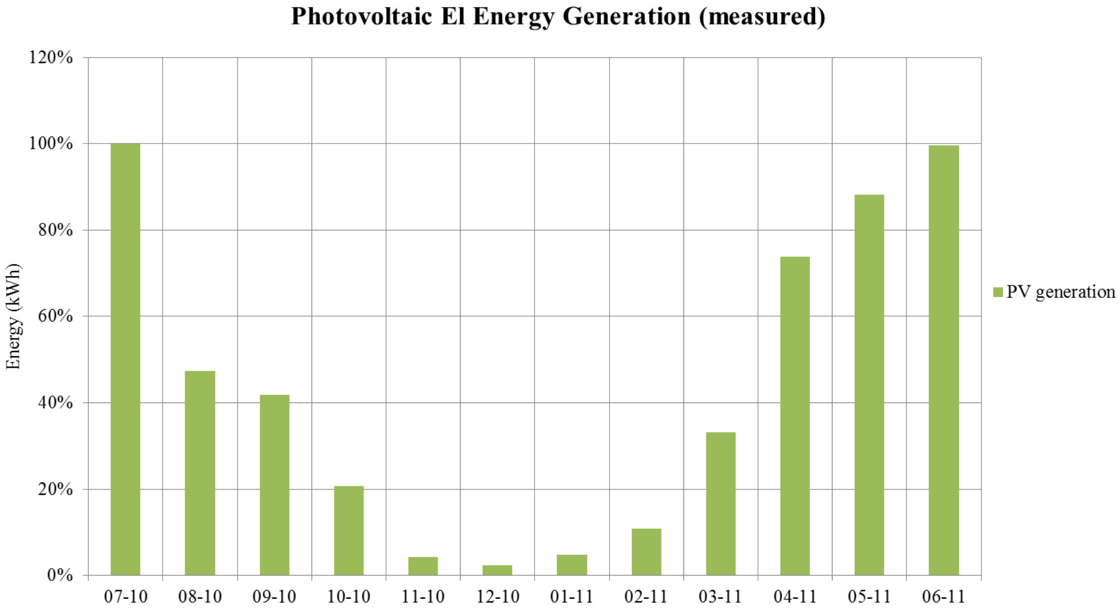

Fig. 67 Photovoltaic energy generation

5.6.7 Household and artificial lighting

Household appliances and artificial lighting energy consumption is presented in Fig. 68. During the winter period (from November 2010 to February 2011) the energy consumption increased rapidly.

This can be caused by using extra electric heating appliances in the dwelling and partially by the lengths of the day in Denmark. The lengths of the day can vary from 7 hours a day in December to nearly 17.5 hours a day in June.

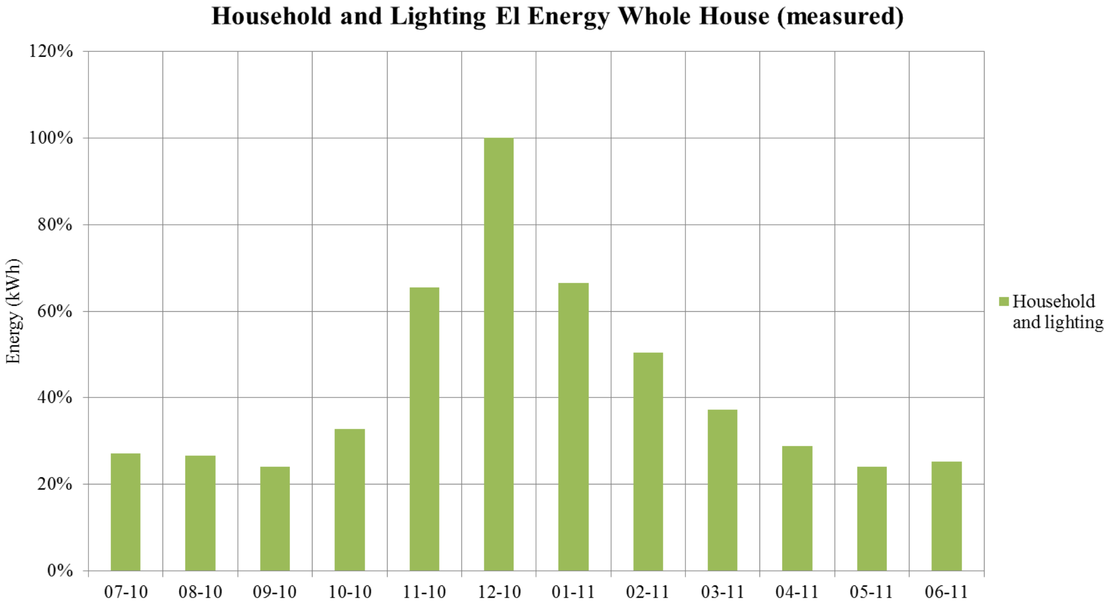

Fig. 68 Household and artificial lighting energy consumption

5.6.8 Auxiliary Energy

Auxiliary energy is the electric energy consumption of the pumps, control gears and other HVAC equipment not described in chapters above. Most of the auxiliary system energy is used in winter period as it is presented in Fig. 69.

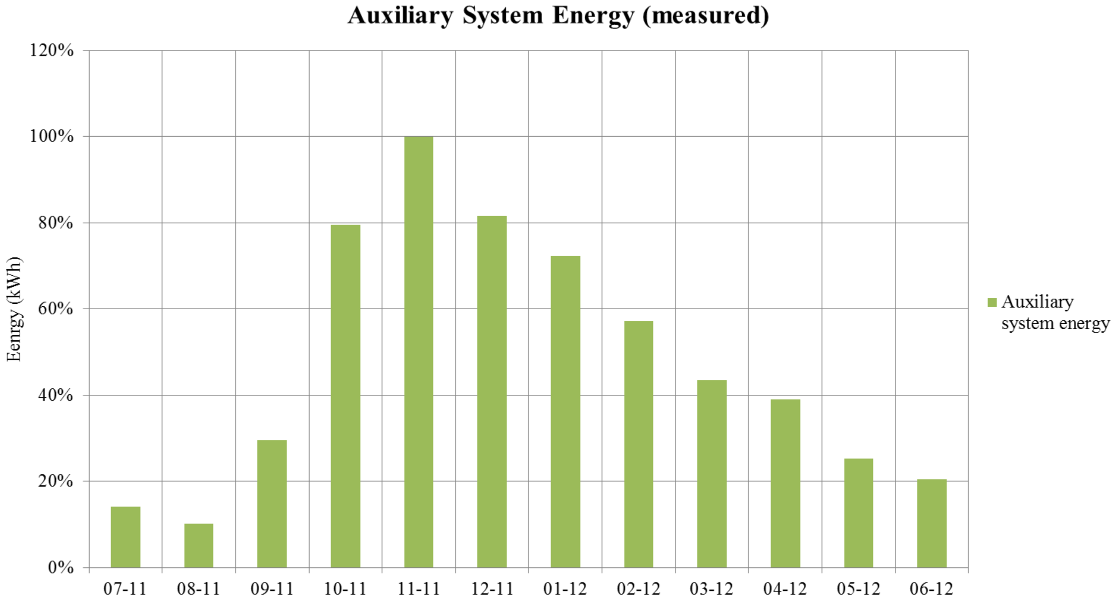

Fig. 69 Auxiliary system energy consumption

5.6.9 Results and discussion

Intensive long term energy and thermal comfort 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. More detailed information about measured building service systems, indoor and outdoor climate values are described in chapters above (from subsection 5.6.1 to 5.6.8).

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 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. 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. 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.

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. 70 and Fig. 71. 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.

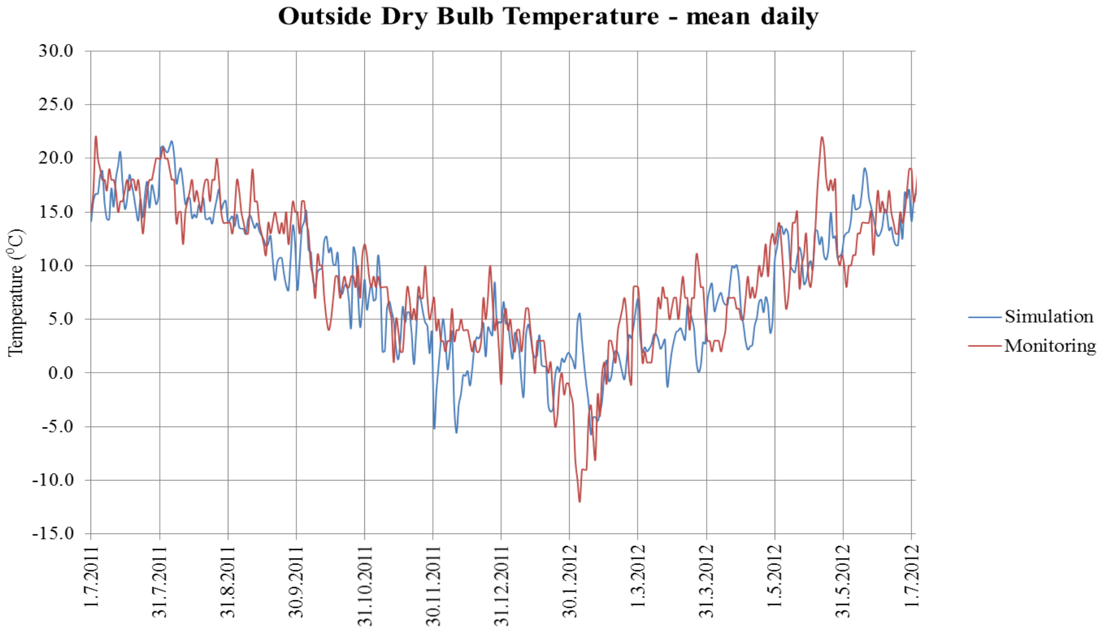

Fig. 70 Simulated and monitored outside dry-bulb temperature

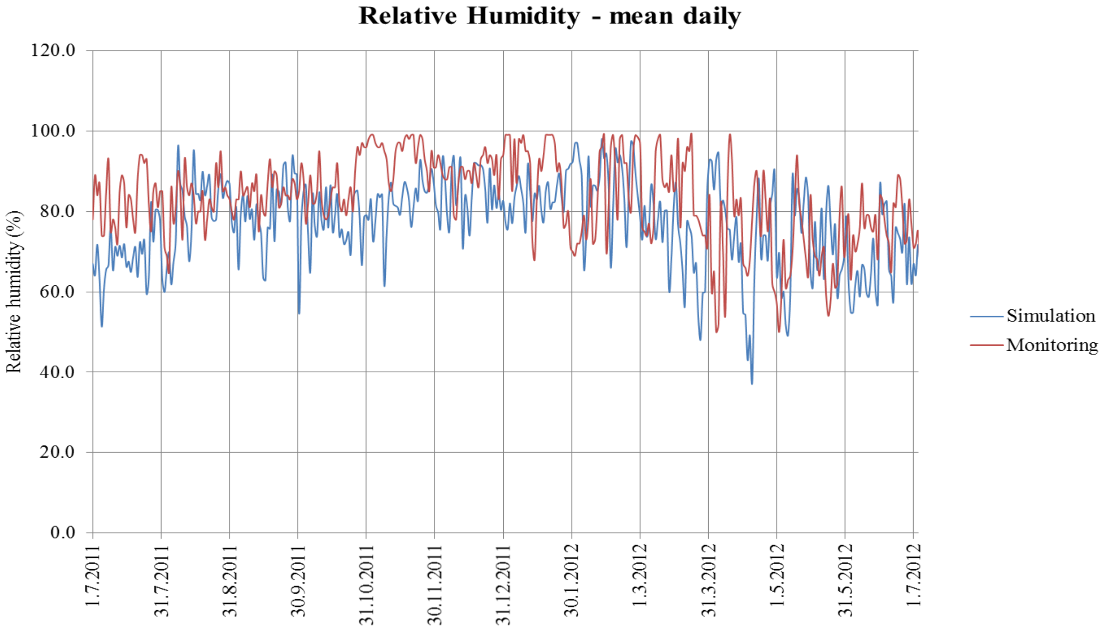

Fig. 71 Simulated and monitored outside relative humidity

Global solar radiation on horizontal surface (Fig. 72) shows no significant deviation between typical meteorological year and measured data. Mean monthly solar radiation in W/m^2 for different months during the year are shown in Fig. 73. 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.

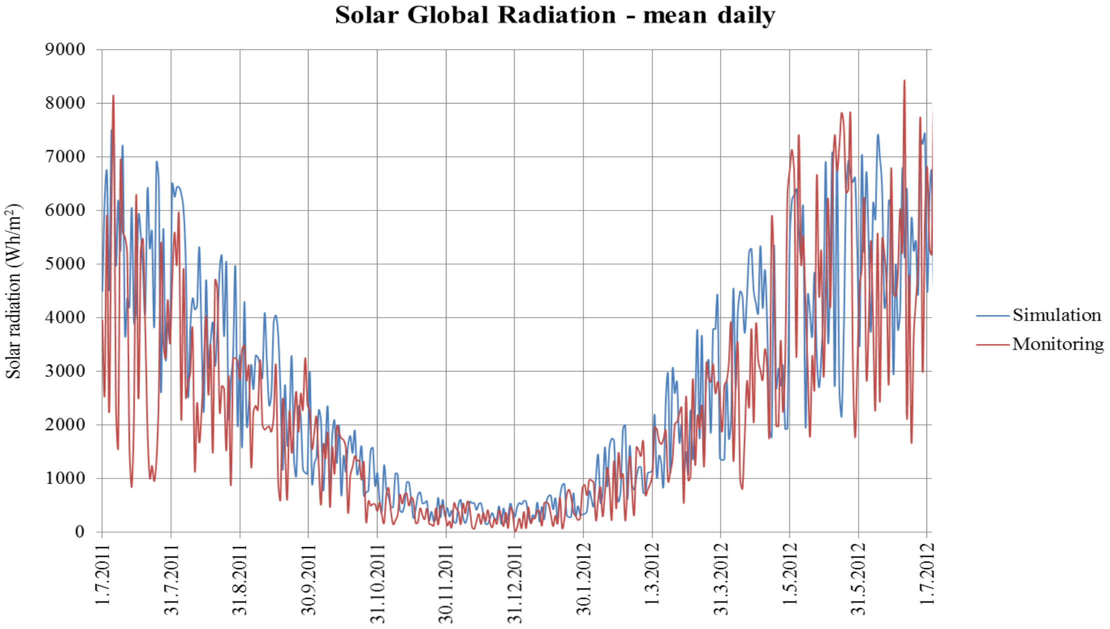

Fig. 72 Simulated and monitored solar global radiation

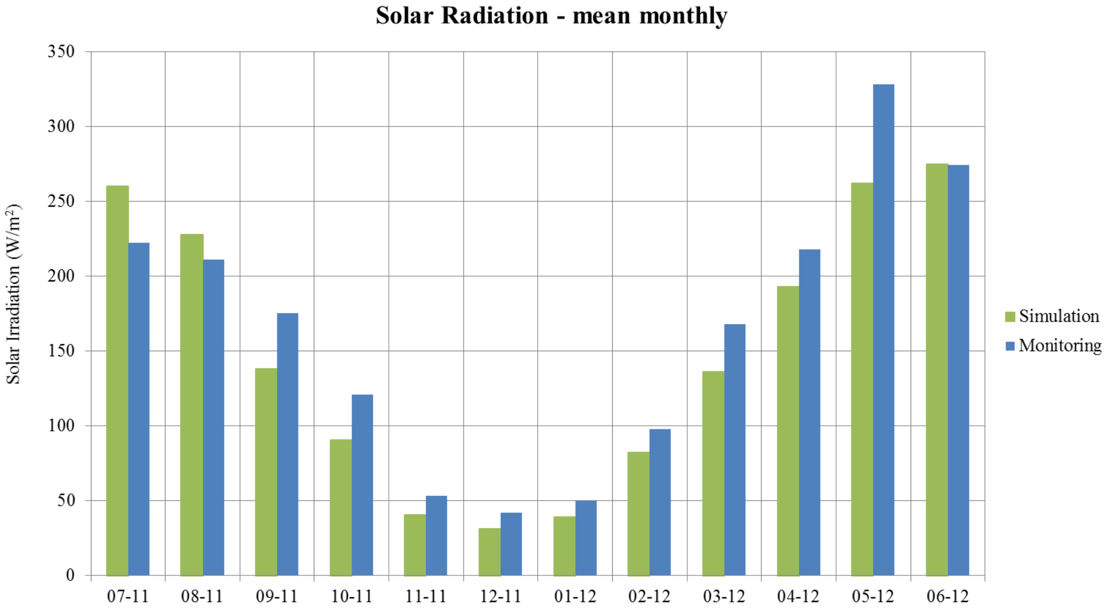

Fig. 73 Simulated and monitored mean monthly solar global radiation in W/m^2

5.7.2 Thermal comfort

Thermal comfort verification process represents two main areas in the dwelling. The ground floor – living room and kitchen daily indoor air temperature gradient is shown in Fig. 74. It is apparent that the space was overheated during the heating period. During the selected period of 1st October 2011 to 31st March 2012, the average simulated air temperature in the living room with kitchen was 21.8 °C compared to monitored 23.0 °C. The other days of the year do not show any significant air temperature fluctuation. Air relative humidity for the same space is presented in Fig. 75. The average annual simulated air relative humidity is about 34 % in comparison to 51 % from the monitoring.

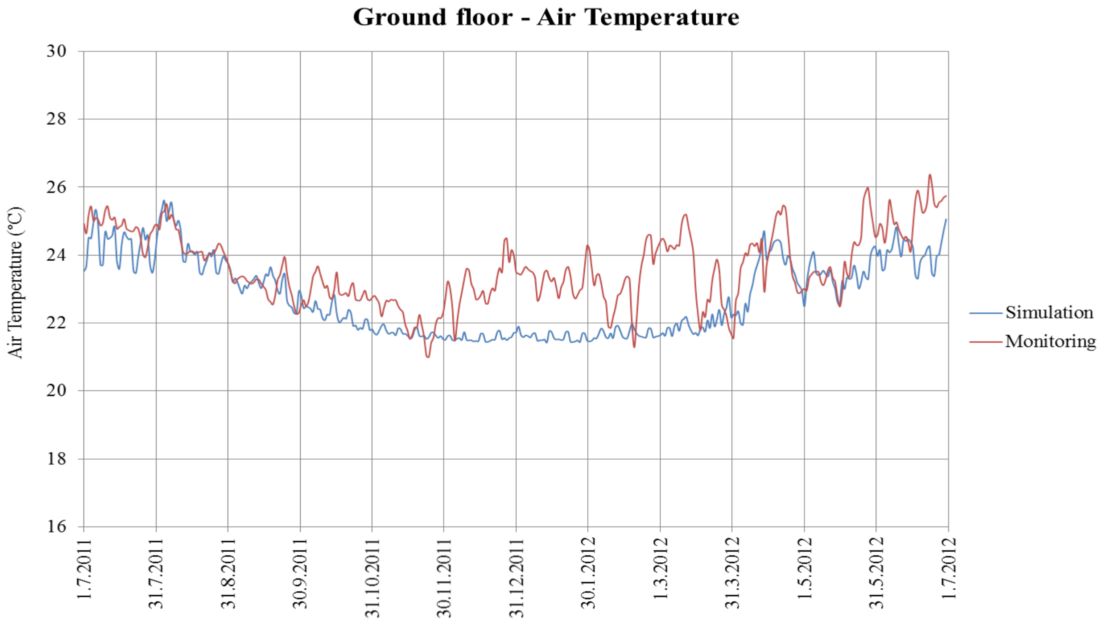

Fig. 74 Simulated and monitored indoor air temperature on ground floor

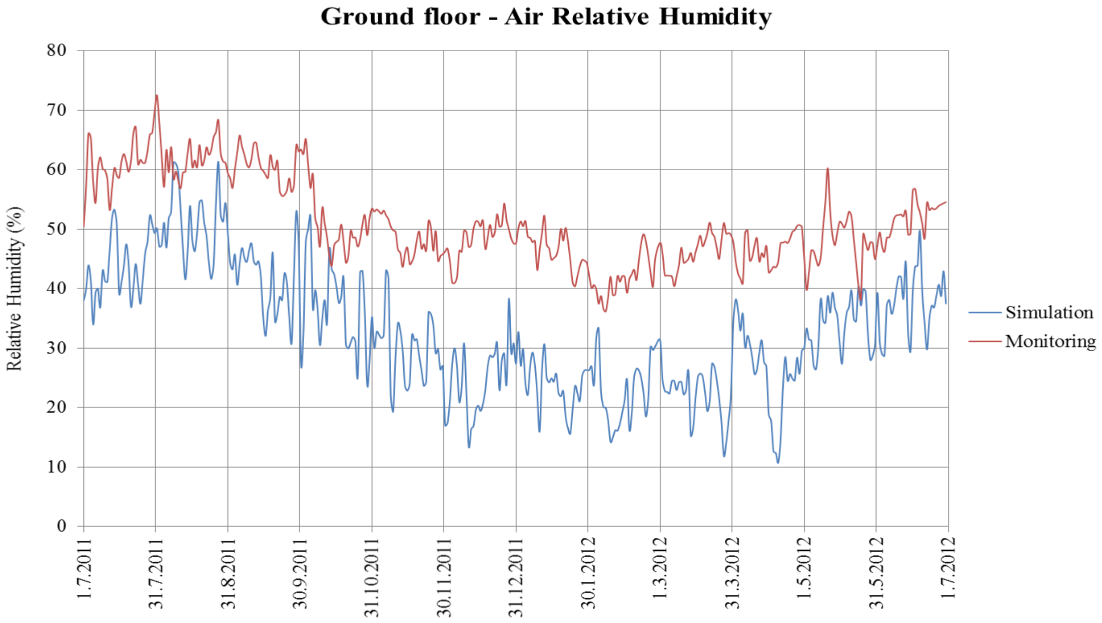

Fig. 75 Simulated and monitored indoor air relative humidity on ground floor

Air temperature on the first floor has curve similar to the ground floor expected an average air temperature height. Air temperature on the first floor is higher than on the ground floor for monitored and simulated case, due to the overall glazed area for this space (Fig. 76). In winter period the monitored air temperature fluctuation is more significant which was probably caused by tenant's natural ventilation requirements in the bedroom. The average simulated air temperature for the period of 1st October to 31st March is 22.7 °C and 22.0 °C the monitored one. Air relative humidity for bedroom is shown in Fig. 77 and it has almost the same parameters as in the ground floor. The average annual simulated relative humidity value is 32 % compared to 52 % from monitoring.

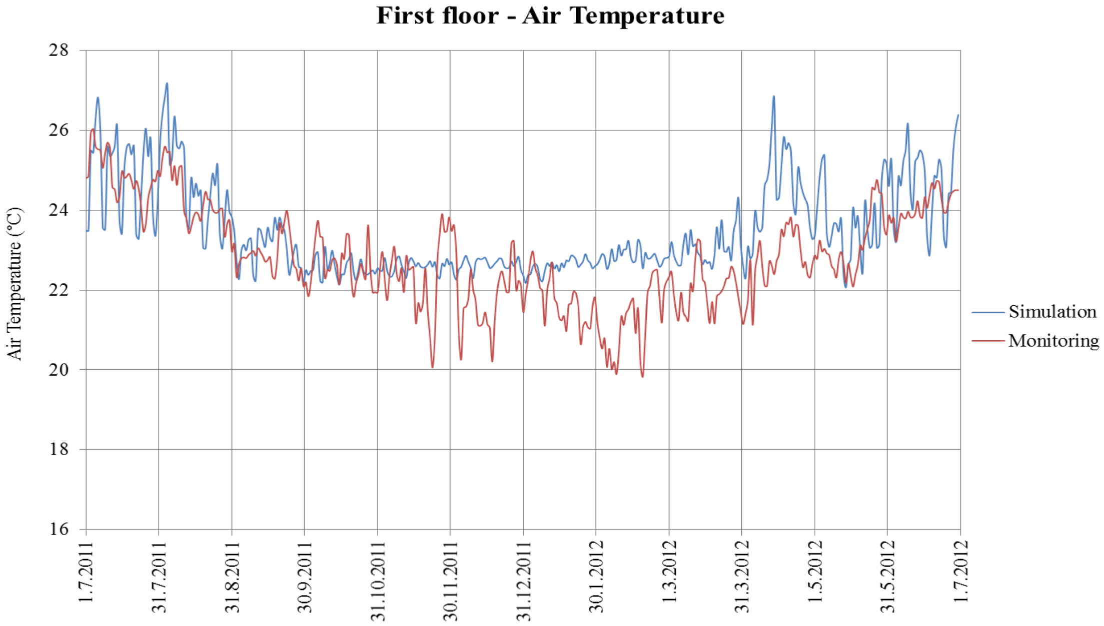

Fig. 76 Simulated and monitored indoor air temperature on first floor

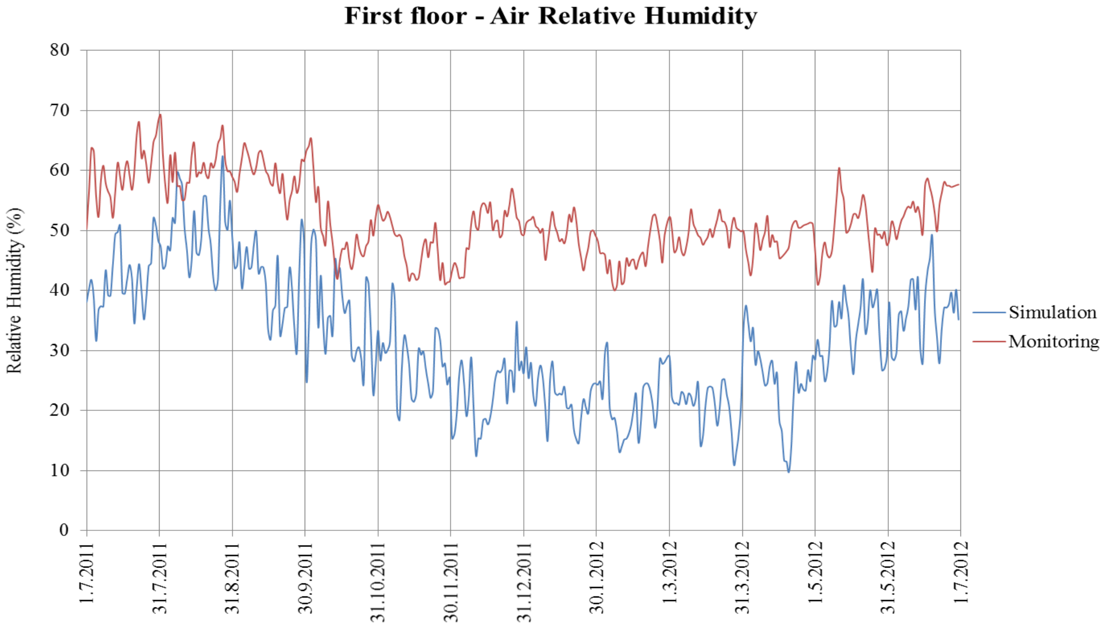

Fig. 77 Simulated and monitored indoor air relative humidity on first floor

5.7.3 Mechanical ventilation with heat recovery

Mechanical ventilation with heat recovery energy consumption during the winter period is shown in Fig. 78. 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.

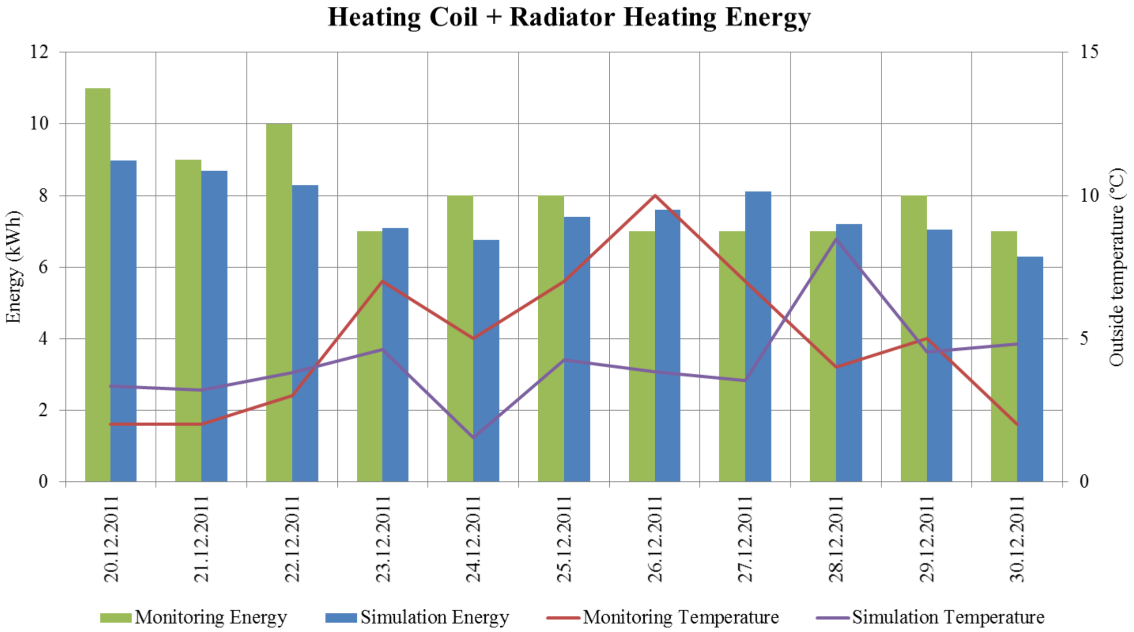

Fig. 78 Simulated and monitored heating coil and radiator energy consumption

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. 79. 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.

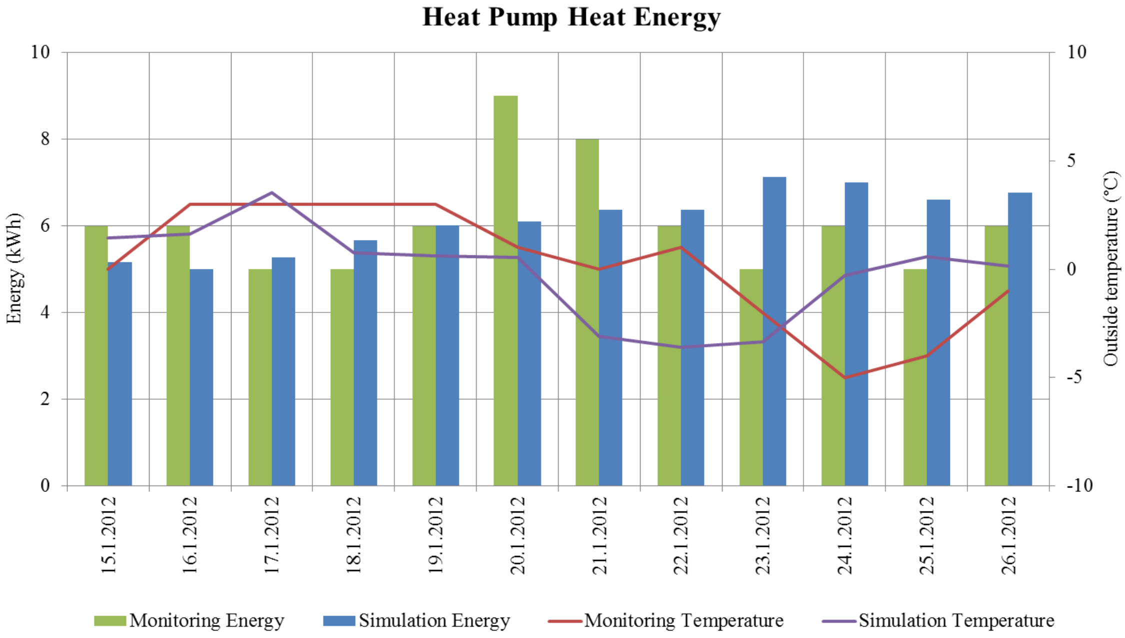

Fig. 79 Simulated and monitored ground source heat pump energy generation

5.7.5 Solar assisted domestic hot water system

Partial contribution of renewable energy into the system represents solar assisted domestic hot water system. The comparison of a solar collector heat energy production for a daily period is considerably misleading. The typical reference year weather data provide reliable information for longer studied period, for example one month due to the daily weather data deviation (rain, sunny, overcast sky, etc.)

Fig. 80 shows a detail daily solar collector heat energy production for twenty days in June. Differences in the global solar radiation energy production for each day are noticeable from the chart. If the values are averaged for selected period then the daily 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 due to the complexity of boundary conditions.

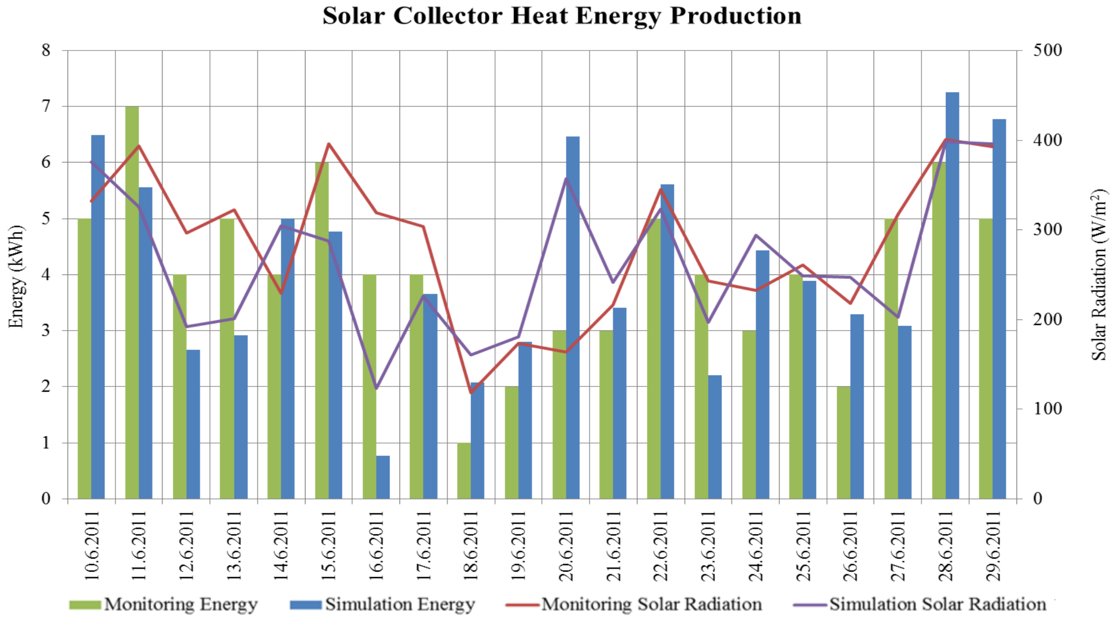

Fig. 80 Solar collector heat energy production and global solar radiation

5.7.6 Photovoltaic system

Photovoltaic system production verification during short term period has not predicative information. Fig. 81 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.).

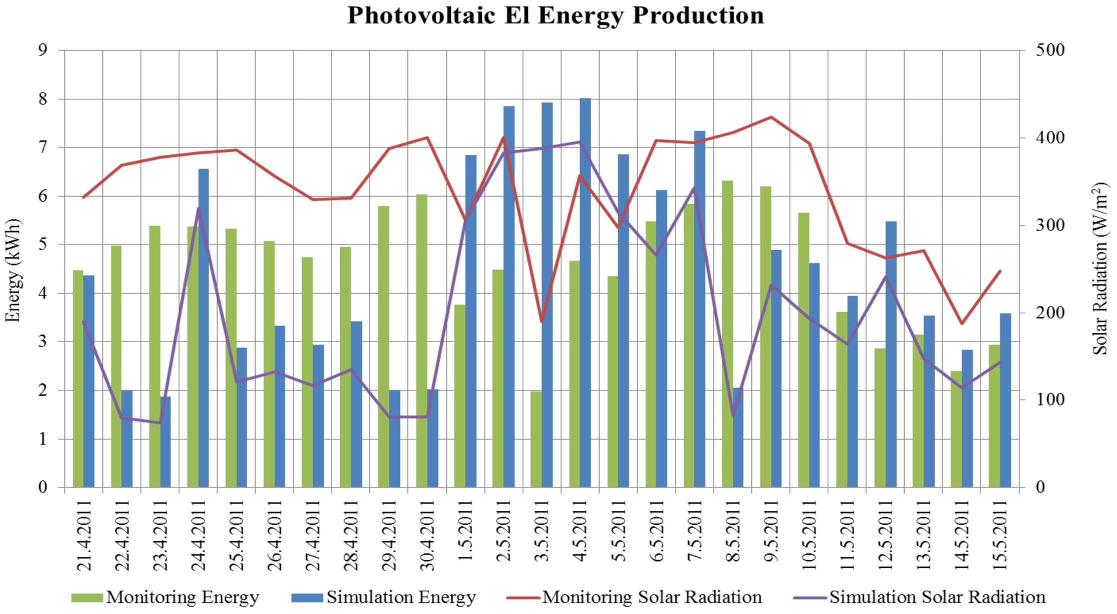

Fig. 81 Photovoltaic EL energy generation and global solar radiation

5.7.7 Household and artificial lights

The last verified area covers household appliances and artificial lights. The period of 14 days in August 2011 was selected and is shown in Fig. 82. The monitored energy consumption for selected period is around 11 % higher than the results from simulation.

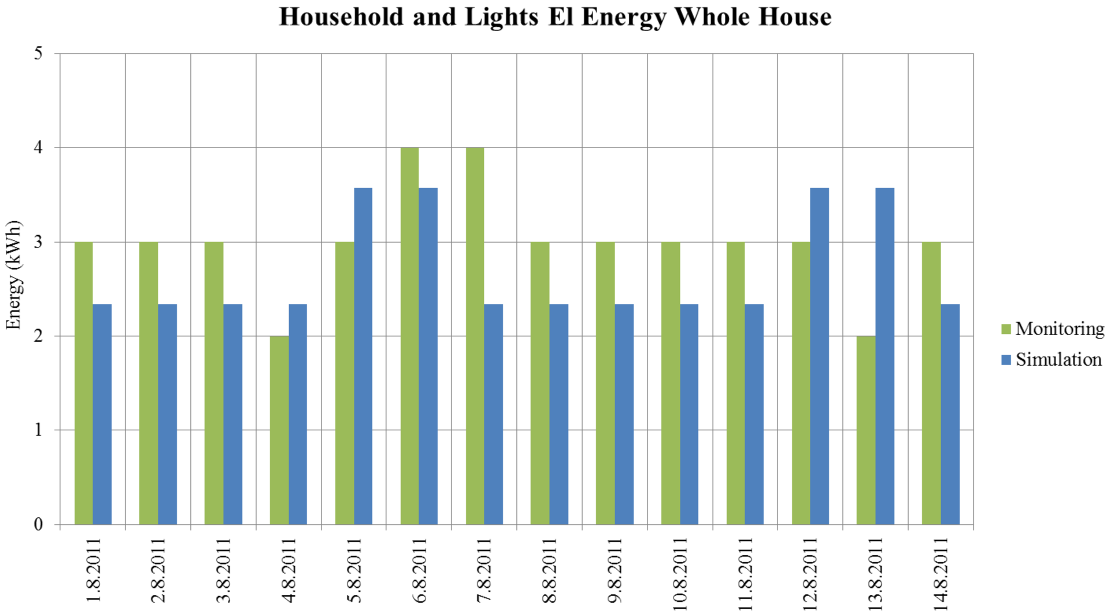

Fig. 82 Simulated and monitored household and artificial lights energy consumption

5.7.8 Results and discussion

The simulated and measured building energy consumption and production, thermal comfort and weather data were verified. The annual weather data verification shows small deviation between reference meteorological year compared to measured weather data; for example outside dry bulb temperature and relative humidity from simulation is 8.3 °C and 77 % compared to 9.1 °C and 83 % from monitoring.

The indoor air temperature 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).

Most of the building service systems had energy consumption values within the acceptable limits in verified time period. For example MVHR had in the second half of December 2011 (from 20th December to 30th December) daily simulated energy consumption of 7.2 kWh/day and outside dry bulb temperature of 4.2 °C compared to monitored values of 8.1 kWh/day and 4.9 °C. The GSHP verification showed no differences in measured and simulated energy production values for selected period (from 15th January 2012 to 26th January 2012).

To perform the verification of solar energy generation systems 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 (especially global solar radiation) in a selected daily period was significant due to the different reference meteorological year and actual measured weather data. The appropriate period for solar energy generation systems verification was in our cases at least twenty consecutive days to get an adequate data set for verification. In case of solar assisted DHW system the mean daily measured global solar radiation and heat energy production in the period from 10th June 2011 to 29th June 2011 was 284 W/m^2 and 82.0 kWh in comparison to 264 W/m^2 and 83.1 kWh from energy simulation. The photovoltaic system electric energy production was verified during four weeks period (from 21st April 2011 to 15th May 2011). 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 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 details. 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 5.7.3) 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.

Literature

[1] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC [online]. OJ L 315. p 56. [Accessed 10 November 2014]. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=EN

[2] The Ministry of Industry and Trade. *National Energy Efficiency Action Plan of the Czech Republic pursuant to Article 24(2) of Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency* [online]. April 2014. [Accessed 12 November 2014]. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/NEEAPCzechRepublic_en2014.pdf

[3] The Ministry of Climate, Energy and Building. *Strategy for energy renovation of buildings. The route to energy-efficient buildings in tomorrow's Denmark* [online]. May 2014. [Accessed 18 November 2014]. ISBN 978-87-93214-02-6. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/2014_article4_en_denmark.pdf

[4] The Government of the Federal Republic of Germany. *Report on the long-term strategy for mobilising investment in the renovation of the national building stock pursuant to Article 4 of the Energy Efficiency Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012* [online]. April 2014. [Accessed 18 November 2014]. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/2014_article4_en_germany.pdf

[5] Ministry of Economy. *National Energy Efficiency Action Plan for Poland 2014.* Warsaw [online]. October 2014. [Accessed 18 November 2014]. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/NEEAP_Poland_ENG_2014.pdf

[6] Italian Energy Efficiency Action Plan. [online] July 2014. [Accessed 18 November 2014]. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/ItalyNEEAP2014en.pdf

[7] Europe 2020. A strategy for smart, sustainable and inclusive growth. Communication from the Commission [online]. COM (2010) 2020 final, 3 March 2010. [Accessed 18 November 2014]. Available from: http://aei.pitt.edu/42633/1/com2010_2020en01_straetry.pdf

[8] HUOVILA, Pekka. *Buildings and climate change: status, challenges, and opportunities* [online]. Paris, France: UNEP DTIE, Sustainable Consumption and Production Branch, 2007. [Accessed 27 November 2014]. ISBN 92-807-2795-8. Available from: http://www.unep.fr/shared/publications/pdf/DTIx0916xPA-BuildingsClimate.pdf

[9] Directive 2010/31/EU of the European Parliament and of the Council on 19 May 2010 on the energy performance of buildings [online]. OJ L 153, 18 June 2010, p. 13–35 [viewed 15 November 2014]. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN

[10] EUROPEAN MANUFACTURERS OF EXPANDED POLYSTYRENE. *Low and net zero energy buildings with EPS Insulation* [online]. Belgium. [Accessed 16 November 2014]. Available from: http://www.eumeps.construction/show.php?ID=4717&psid=hmotjteo

[11] ECONOMIDOU, Marina, ATANASIU, Bogdan, DESPRET, Chantal, MAIO, Joana, NOLTE, Ingeborg, RAPF, Oliver. *Europe's buildings under the microscope* [online]. Buildings Performance Institute Europe (BPIE), 2011, no. 16 p. [Accessed 28 November 2014]. ISBN 9789491143014. Available from: http://www.bpie.eu/uploads/lib/document/attachment/20/HR_EU_B_under_microscope_study.pdf

[12] SARTORI, Igor, NAPOLITANO, Assunta and VOSS, Karsten. Net zero energy buildings: A consistent definition framework. *Energy and Buildings* [online]. 2012. Vol. 48, p. 220-232. [Accessed 27 November 2014]. DOI 10.1016/j.enbuild.2012.01.032. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778812000497

[13] TORCELLINI, P., PLESS, S., DERU, M. and CRAWLEY, D. Zero Energy Buildings: A Critical Look at the Definition. *Less is more: en route to zero energy buildings proceedings, 2006 ACEEE Summer Study on Energy Efficiency in Buildings* [online]. Washington, D.C.: American Council for an Energy-Efficient Economy, 2006, no. 12p. 275-286. [Accessed 28 November 2014]. ISBN 09-182-4956-2. Available from: http://www.eceee.org/library/conference_proceedings/ACEEE_buildings/2006/Panel_3/p3_24/paper

[14] MARSZAL, A.J., HEISELBERG, P., BOURRELLE, J.S., MUSALL, E., VOSS, K., SARTORI, I. and NAPOLITANO, A. Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings* [online]. 2011. Vol. 43, no. 4p. 971-979. [Accessed 27 November 2014]. DOI

10.1016/j.enbuild.2010.12.022. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778810004639

[15] VOSS, Karsten, SARTORI Igor, LOLLINI Roberto. Nearly-zero, Net zero and Plus Energy Buildings – How definitions & regulations affect the solutions. *The REHVA European HVAC Journal* [online], Volume 49, Issue 6, December 2012, no. 5p. 23-27 ISSN 1307-3729. [Accessed 27 November 2014]. Available from: http://www.rehva.eu/fileadmin/hvac-dictio/06_2012/RJ1206_WEB.pdf

[16] LAUSTSEN, Jens. *Energy efficiency requirements in building codes, energy efficiency policies for new buildings*. International Energy Agency (IEA) [online]. 2008. [Accessed 29 November 2014]. Available from: https://www.iea.org/publications/freepublications/publication/Building_Codes.pdf

[17] ERHORN-KLUTTIG, Heike, ERHORN, Hans, THOMSEN, Kirsten Engelund and NYFFENEGGER, Ulrich. Trends in National Nearly Zero-Energy Building Approaches. *In Joint Conference 32nd AIVC Conference and 1st TightVent Conference Towards Optimal Airtightness Performance: Proceedings* [online]. Brussels: AIVC, 2011. [Accessed 04 December 2014] Available from: http://vbn.aau.dk/files/58112422/AIVC_Trends_in_NZEBs_Erhorn_Kluttig_02_10_11.pdf

[18] LEPKOVA, Natalija, ZUBKA, Domantas and JENSEN, Rasmus Lund. Financial Investments for Zero Energy Houses. *Global Sustainable Communities Handbook* [online]. 2014. P. 217. [Accessed 04 December 2014]. DOI 10.1016/B978-0-12-397914-8.00010-2. Available from: http://linkinghub.elsevier.com/retrieve/pii/B9780123979148000102

[19] DALL'O', Giuliano, BRUNI, Elisa and SARTO, Luca. An Italian pilot project for zero energy buildings: Towards a quality-driven approach. *Renewable Energy* [online]. 2013. Vol. 50, p. 840-846. [Accessed 04 December 2014]. DOI 10.1016/j.renene.2012.08.035. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0960148112005058

[20] SILVA, Pedro C.P., ALMEIDA, Manuela, BRAGANÇA, Luís and MESQUITA, Vasco. Development of prefabricated retrofit module towards nearly zero energy buildings. *Energy and Buildings* [online]. 2013. Vol. 56, p. 115-125. [Accessed 05 December 2014]. DOI 10.1016/j.enbuild.2012.09.034. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778812004884

[21] KAPSALAKI, M., LEAL, V. and SANTAMOURIS, M. A methodology for economic efficient design of Net Zero Energy Buildings. *Energy and Buildings*

[online]. 2012. Vol. 55, p. 765-778. [Accessed 10 December 2014]. DOI 10.1016/j.enbuild.2012.10.022. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778812005312

[22] MWASHA, Abraham, WILLIAMS, Rupert G. and IWARO, Joseph. Modeling the performance of residential building envelope: The role of sustainable energy performance indicators. *Energy and Buildings* [online]. 2011. Vol. 43, no. 9p. 2108-2117. [Accessed 10 December 2014]. DOI 10.1016/j.enbuild.2011.04.013. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778811001666

[23] CANADA MORTGAGE AND HOUSING CORPORATION. Highly Energy Efficient Building Envelope Retrofits for Houses. *Research Highlights* [online]. 2012. Technical series 12-103, no. 6p. [Accessed 10 December 2014]. Available from: http://www.cmhc.ca/odpub/pdf/67629.pdf

[24] THE PASSIVE HOUSE INSTITUTE (PHI). *Passive House requirements* [online]. ©2014 [Accessed 11 December 2014]. Available from: http://www.passiv.de/en/02_informations/02_passive-houserequirements/02_passive-house-requirements.htm

[25] PEREZ-LOMBARD, Luis, ORTIZ, Jose and MAESTRE, Ismael R. The map of energy flow in HVAC systems. *Applied Energy* [online]. 2011. Vol. 88, no. 12p. 5020-5031. [Accessed 10 December 2014]. DOI 10.1016/j.apenergy.2011.07.003. Available from: http://linkinghub.elsevier.com/retrieve/pii/S030626191100448X

[26] SATTARI, S. and FARHANIEH, B. A parametric study on radiant floor heating system performance. *Renewable Energy* [online]. 2006. Vol. 31, no. 10p. 1617-1626. [Accessed 16 December 2014]. DOI 10.1016/j.renene.2005.09.009. Retrieved from: http://linkinghub.elsevier.com/retrieve/pii/S0960148105002624

[27] BS EN 1264-1:2011. *Water based surface embedded heating and cooling systems. Definitions and symbols*. British Standards Publications (BSI). 2011. ISBN 978 0 580 73043 6.

[28] EL FOUIH, Younness, STABAT, Pascal, RIVIÈRE, Philippe, HOANG, Phuong and ARCHAMBAULT, Valérie. Adequacy of air-to-air heat recovery ventilation system applied in low energy buildings. *Energy and Buildings* [online]. 2012. Vol. 54, p. 29-39. [Accessed 20 December 2014]. DOI 10.1016/j.enbuild.2012.08.008. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778812003945

[29] MARDIANA-IDAYU, A. and RIFFAT, S.B. Review on heat recovery technologies for building applications. *Renewable and Sustainable Energy Reviews* [online]. 2012. Vol. 16, no. 2p. 1241-1255. [Accessed 20 December 2014]. DOI 10.1016/j.rser.2011.09.026. Available from: http://linkinghub.elsevier.com/retrieve/pii/S136403211100476X

[30] DODOO, Ambrose, GUSTAVSSON, Leif and SATHRE, Roger. Primary energy implications of ventilation heat recovery in residential buildings. *Energy and Buildings* [online]. 2011. Vol. 43, no. 7p. 1566-1572. [Accessed 20 December 2014]. DOI 10.1016/j.enbuild.2011.02.019. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778811000636

[31] PAPAKOSTAS, K.T., PAPAGEORGIOU, N.E. and SOTIROPOULOS, B.A. Residential hot water use patterns in Greece. Solar Energy [online]. 1995. Vol. 54, no. 6p. 369-374. [Accessed 27 December 2014]. DOI 10.1016/0038-092X(95)00014-I. Available from: http://linkinghub.elsevier.com/retrieve/pii/0038092X9500014I

[32] ENERGY SAVING TRUST. *Measurement of Domestic Hot Water Consumption in Dwellings* [online]. ©2008. [Accessed 27 December 2014]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48188/3147-measure-domestic-hot-water-consump.pdf

[33] FABRIZIO, Enrico, SEGURO, Federico and FILIPPI, Marco. Integrated HVAC and DHW production systems for Zero Energy Buildings. *Renewable and Sustainable Energy Reviews* [online]. 2014. Vol. 40, p. 515-541. [Accessed 28 December 2014]. DOI 10.1016/j.rser.2014.07.193. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032114006455

[34] PARDO, Nicolas and THIEL, Christian. Evaluation of several measures to improve the energy efficiency and CO2 emission in the European single-family houses. *Energy and Buildings* [online]. 2012. Vol. 49, p. 619-630. [Accessed 07 January 2015]. DOI 10.1016/j.enbuild.2012.03.006. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778812001545

[35] BAÑOS, R., MANZANO-AGUGLIARO, F., MONTOYA, F.G., GIL, C., ALCAYDE, A. and GÓMEZ, J. Optimisation methods applied to renewable and sustainable energy: A review. *Renewable and Sustainable Energy Reviews* [online]. 2011. Vol. 15, no. 4p. 1753-1766. [Accessed 07 January 2015]. DOI 10.1016/j.rser.2010.12.008. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032110004430

[36] BADESCU, Viorel and SICRE, Benoit. Renewable energy for passive house heating. *Energy and Buildings* [online]. 2003. Vol. 35, no. 11p. 1077-1084. [Accessed 10 January 2015]. DOI 10.1016/j.enbuild.2003.10.001. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778803001166

[37] STICKNEY, Bristol, SOIFER Boaz. Solar Thermal Hydronics: Collector Comparison and Selection. *SolarPro* [online]. 2009. Issue 2.6, Oct/Nov 2009. ©2009. [Accessed 10 January 2015] Available from: http://solarprofessional.com/articles/products-equipment/solar-heating/solar-thermal-hydronics?v=disable_pagination

[38] CARBONI, Christian and MONTANARI, Roberto. Solar thermal systems: Advantages in domestic integration. *Renewable Energy* [online]. 2008. Vol. 33, no. 6p. 1364-1373. [Accessed 11 January 2015]. DOI 10.1016/j.renene.2007.07.004. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0960148107002388

[39] U.S. DEPARTMENT OF ENERGY. Solar Energy Technologies Office. *SunShot Vision Study* [online]. February 2012. [Accessed 11 January 2015]. Available from: http://energy.gov/sites/prod/files/2014/01/f7/47927_chapter4.pdf

[40] GÜNES, Serap and SARICIFTCI, Niyazi Serdar. Hybrid solar cells. *Inorganica Chimica Acta* [online]. 2008. Vol. 361, no. 3p. 581-588. [Accessed 11 January 2015]. DOI 10.1016/j.ica.2007.06.042. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0020169307004343

[41] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. OJ L 140. p. 16-62. [Accessed 15 January 2015]. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN

[42] MUSTAFA OMER, Abdeen. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews* [online]. 2008. Vol. 12, no. 2p. 344-371. [Accessed 15 January 2015]. DOI 10.1016/j.rser.2006.10.003. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032106001249

[43] SUSTAINABLE ENERGY AUTHORITY OF IRELAND. *Best Practice Guide: Heat Pump Technologies* [online]. 2012. [Accessed 15 January 2015]. Available from: http://www.seai.ie/Publications/Your_Home_Publications_/Heating/Best_Practice_Guide_Heat_Pump_technologies.pdf

[44] ERTESVÅG, Ivar S. Uncertainties in heat-pump coefficient of performance (COP) and exergy efficiency based on standardised ised testing. *Energy and Buildings* [online]. 2011. Vol. 43, no. 8p. 1937-1946. [Accessed 15 January 2015]. DOI 10.1016/j.enbuild.2011.03.039. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778811001484

[45] AL-BAHADLY, Ibrahim. Building a wind turbine for rural home. *Energy for Sustainable Development* [online]. 2009. Vol. 13, no. 3p. 159-165. [Accessed 18 January 2015]. DOI 10.1016/j.esd.2009.06.005. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0973082609000489

[46] MESSINEO, Antonio and CULOTTA, Simona. Evaluating the Performances of Small Wind Turbines: A Case Study in the South of Italy. *Energy Procedia* [online]. 2012. Vol. 16, p. 137-145. [Accessed 18 January 2015]. DOI 10.1016/j.egypro.2012.01.024. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1876610212000343

[47] CARBON TRUST. *Small-scale wind energy: Policy insights and practical guidance* [online]. ©2008. [Accessed 18 January 2015]. Available from: http://www.wind-power-program.com/Library/Policy%20and%20planning%20documents/Carbon-Trust-Small-Scale-Wind-Report.pdf

[48] TABRIZI, Amir Bashirzadeh, WHALE, Jonathan, LYONS, Thomas and URMEE, Tania. Rooftop wind monitoring campaigns for small wind turbine applications: Effect of sampling rate and averaging period. *Renewable Energy* [online]. 2015. Vol. 77, p. 320-330. [Accessed 18 January 2015]. DOI 10.1016/j.renene.2014.12.037. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0960148114008647

[49] HOSSAIN, Md Maruf and ALI, Mohd. Hasan. Future research directions for the wind turbine generator system. *Renewable and Sustainable Energy Reviews* [online]. 2015. Vol. 49, p. 481-489. [Accessed 18 January 2015]. DOI 10.1016/j.rser.2015.04.126. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032115003962

[50] WALKER, Sara Louise. Building mounted wind turbines and their suitability for the urban scale - A review of methods of estimating urban wind resource. *Energy and Buildings* [online]. 2011. Vol. 43, no. 8p. 1852-1862. [Accessed 19 January 2015]. DOI 10.1016/j.enbuild.2011.03.032. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778811001101

[51] SIMIC, Zdenko, HAVELKA, Juraj George and BOZICEVIC VRHOVCAK, Maja. Small wind turbines - A unique segment of the wind power market. *Renewable Energy* [online]. 2013. Vol. 50, p. 1027-1036. [Accessed 20 January 2015]. DOI 10.1016/j.renene.2012.08.038. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0960148112005083

[52] U.S. ENVIRONMENTAL PROTECTION AGENCY. ENERGY STAR. *Portfolio Manager Technical Reference: Green Power* [online]. July 2013. [Accessed 20 January 2015]. Available from: https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf

[53] MOLENBROEK, E., STRICKER, E. and BOERMANS, T. *Primary energy factors for electricity in buildings: Toward a flexible electricity supply* [online]. Ecofys Netherlands. 2011. [Accessed 20 January 2015]. Available from: http://www.leonardo-energy.org/sites/leonardo-energy/files/documents-and-links/pef-finalreport.pdf

[54] ČSN 73 0540-2. *Thermal protection of buildings – Part 2: Requirements*. Prague: Czech Office for Standards, Metrology and Testing, 2011.

[55] ZIRNGIBL, Johann. *European energy standards related to the EPBD: Fundamental definitions for the assessment of the energy performance (prEN 15603:2013)* [online]. EUSEW Brussels: European Union – Sustainable Energy Week (EUSEW). June 2013. [Accessed 20 January 2015] Available from: http://iet.jrc.ec.europa.eu/energyefficiency/sites/energyefficiency/files/events/High-Performance-Buildings-June-2013/Presentations/session3/32_zirngibl_eusew_2013_session_3.pdf

[56] MARSZAL, Anna Joanna, BOURRELLE, Julien S., MUSALL, Eike, HEISELBERG, Per, GUSTAVSEN, Arild and VOSS, Karsten. Net Zero Energy Buildings: Calculation Methodologies versus National Building Codes. In *EuroSun 2010: Book of Abstracts* [online]. EuroSun 2010, p. 22. [Accessed 21 January 2015] Available from: http://task40.iea-shc.org/data/sites/1/publications/Task40a-Net_Zero_Energy_Buildings_Calculation_Methods_and_Input_Variables.pdf

[57] U.S. DEPARTMENT OF ENERGY. *EnergyPlus Energy Simulation Software: Weather Data for Simulation* [online]. [Accessed 21 January 2015]. Available from: http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_simulation.cfm

[58] CRAWLEY, Drury B. Which Weather Data Should You Use for Energy Simulations of Commercial Buildings? *ASHRAE journal* [online]. 1998. Vol. 104, pt. 2, p. 498-515. Available from: http://www.climate.onebuilding.org/papers/1998_06_Crawley_Which_Weather_Data_Should_You_Use_for_Energy_Simulations_of_Commercial_Buildings.pdf

[59] JYLHÄ, Kirsti, RUOSTEENOJA, Kimmo, JOKISALO, Juha, PILLI-SIHVOLA, Karoliina, KALAMEES, Targo, MÄKELÄ, Hanna, HYVÖNEN, Reijo and DREBS, Achim. Hourly test reference weather data in the changing climate of Finland for building energy simulations. *Data in Brief* [online]. 2015. Vol. 4, p. 162-169. [Accessed 01 October 2015]. DOI 10.1016/j.dib.2015.04.026. Available from: http://linkinghub.elsevier.com/retrieve/pii/S2352340915000682

[60] KIKUMOTO, Hideki, OOKA, Ryozo, ARIMA, Yusuke and YAMANAKA, Toru. Study on the future weather data considering the global and local climate change for building energy simulation. *Sustainable Cities and Society* [online]. 2015. Vol. 14, p. 404-413. [Accessed 23 January 2015]. DOI 10.1016/j.scs.2014.08.007. Available from: http://linkinghub.elsevier.com/retrieve/pii/S2210670714000936

[61] BEN-NAKHI, Abdullatif E and AASEM, Essam O. Development and integration of a user friendly validation module within whole building dynamic simulation. *Energy Conversion and Management* [online]. 2003. Vol. 44, no. 1, p. 53-64. [Accessed 23 January 2015]. DOI 10.1016/S0196-8904(02)00039-0. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0196890402000390

[62] JUDKOFF, R., WORTMAN, D., O'DOHERTY, B., BURCH, J. *Methodology for Validating Building Energy Analysis Simulations* [online]. 2008. United States. [Accessed 23 January 2015]. DOI 10.2172/928259. Available from: http://www.osti.gov/scitech/servlets/purl/928259

[63] CRAWLEY, D. B., LAWRIE, L. K., PEDERSEN, C.O. LIESEN, R. J., FISHER D. E., STRAND, R. K., TAYLOR, R. D., WINKELMANN, R. C., BUHL, W. F., HUANG, Y. J., ERDEM, A. E. EnergyPlus, A New-Generation Building Energy Simulation Program. *Proceedings of Building Simulation '99* [online]. 1999. Vol. 1, p. 81-88. [Accessed 01 February 2015]. Available from: http://www.hvac.okstate.edu/sites/default/files/pubs/papers/pre_2000/01-Crawley_Lawrie_Pedersen_Liesen_Fisher_Strand_Taylor_Winklem.pdf

[64] HENNINGER, Robert H, WITTE, Michael J and CRAWLEY, Drury B. Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST

E100–E200 test suite. *Energy and Buildings* [online]. 2004. Vol. 36, no. 8p. 855-863. [Accessed 01 February 2015]. DOI 10.1016/j.enbuild.2004.01.025. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778804000362

[65] FUMO, Nelson, MAGO, Pedro and LUCK, Rogelio. Methodology to estimate building energy consumption using EnergyPlus Benchmark Models. *Energy and Buildings* [online]. 2010. Vol. 42, no. 12p. 2331-2337. [Accessed 01 February 2015]. DOI 10.1016/j.enbuild.2010.07.027. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778810002574

[66] CRAWLEY, Drury B., LAWRIE, Linda K., WINKELMANN, Frederick C., BUHL, W.F., HUANG, Y.Joe, PEDERSEN, Curtis O., STRAND, Richard K., LIESEN, Richard J., FISHER, Daniel E., WITTE, Michael J. and GLAZER, Jason. EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings* [online]. 2001. Vol. 33, no. 4p. 319-331. [Accessed 02 February 2015]. DOI 10.1016/S0378-7788(00)00114-6. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778800001146

[67] BOYANO, A., HERNANDEZ, P. and WOLF, O. Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations. *Energy and Buildings* [online]. 2013. Vol. 65, p. 19-28. [Accessed 02 February 2015]. DOI 10.1016/j.enbuild.2013.05.039. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778813003277

[68] PEREIRA, Welma, BÖGL, Andreas and NATSCHLÄGER, Thomas. Sensitivity Analysis and Validation of an EnergyPlus Model of a House in Upper Austria. *Energy Procedia* [online]. 2014. Vol. 62, p. 472-481. [Accessed 03 February 2015]. DOI 10.1016/j.egypro.2014.12.409. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1876610214034407

[69] INTEGRATED ENVIRONMENTAL SOLUTIONS LIMITED. *Virtual Environment by Integrated Environmental Solutions (IES-VE)* [online]. ©2011-2015. [Accessed 08 February 2015]. Available from: https://www.iesve.com/

[70] AL-TAMIMI, Nedhal A. and FADZIL, Sharifah Fairuz Syed. The Potential of Shading Devices for Temperature Reduction in High-Rise Residential Buildings in the Tropics. *Procedia Engineering* [online]. 2011. Vol. 21, p. 273-282. [Accessed 08 February 2015]. DOI 10.1016/j.proeng.2011.11.2015. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1877705811048491

[71] ALDOSSARY, Naief A., REZGUI, Yacine and KWAN, Alan. Domestic energy consumption patterns in a hot and humid climate: A multiple-case study

analysis. *Applied Energy* [online]. 2014. Vol. 114, p. 353-365. [Accessed 08 February 2015]. DOI 10.1016/j.apenergy.2013.09.061. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0306261913008088

[72] ZHUN MIN ADRIAN, Chong, NYUK HIEN, Wong, MARCEL, Ignatius and STEVE KARDINAL, Jusuf. Predicting the envelope performance of commercial office buildings in Singapore. Energy and Buildings [online]. 2013. Vol. 66, p. 66-76. [Accessed 12 February 2015]. DOI 10.1016/j.enbuild.2013.07.008. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778813003964

[73] MAILE, Tobias, FISCHER, Martin and BAZJANAC, Vladimir. *Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective* [online]. CIFE Working Paper. 2007. [Accessed 15 February 2015]. Available from: http://cife.stanford.edu/sites/default/files/WP107.pdf

[74] ANDARINI, Rahmi. The Role of Building Thermal Simulation for Energy Efficient Building Design. *Energy Procedia* [online]. 2014. Vol. 47, p. 217-226. [Accessed 15 February 2015]. DOI 10.1016/j.egypro.2014.01.217. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1876610214002331

[75] TRONCHIN, Lamberto and FABBRI, Kristian. Energy performance building evaluation in Mediterranean countries: Comparison between software simulations and operating rating simulation. *Energy and Buildings* [online]. 2008. Vol. 40, no. 7p. 1176-1187. [Accessed 15 February 2015]. DOI 10.1016/j.enbuild.2007.10.012. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778807002447

[76] WANG, Xi, ALTAN, Hasim and KANG, Jian. Parametric study on the performance of green residential buildings in China. *Frontiers of Architectural Research* [online]. 2015. Vol. 4, no. 1p. 56-67. [Accessed 19 February 2015]. DOI 10.1016/j.foar.2014.06.007. Available from: http://linkinghub.elsevier.com/retrieve/pii/S2095263514000442

[77] PICCO, Marco, LOLLINI, Roberto and MARENGO, Marco. Towards energy performance evaluation in early stage building design: A simplification methodology for commercial building models. *Energy and Buildings* [online]. 2014. Vol. 76, p. 497-505. [Accessed 19 February 2015]. DOI 10.1016/j.enbuild.2014.03.016. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778814002369

[78] EGUARAS-MARTÍNEZ, María, VIDAURRE-ARBIZU, Marina and MARTÍN-GÓMEZ, César. Simulation and evaluation of Building Information Modeling in

a real pilot site. *Applied Energy* [online]. 2014. Vol. 114, p. 475-484. [Accessed 20 February 2015]. DOI 10.1016/j.apenergy.2013.09.047. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0306261913007940

[79] COLE, Wesley J., POWELL, Kody M., HALE, Elaine T. and EDGAR, Thomas F. Reduced-order residential home modeling for model predictive control. *Energy and Buildings* [online]. 2014. Vol. 74, p. 69-77. [Accessed 20 February 2015]. DOI 10.1016/j.enbuild.2014.01.033. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778814000711

[80] COMPAGNON, R. The RADIANCE simulation software in the architecture teaching context. *2nd Florence International Conference for Teachers of Architecture* [online]. Italy, Firenze. 16-18 October 1997. [Accessed 25 August 2015]. Available from: http://radsite.lbl.gov/radiance/papers/rctia97/rct97.htm#fig1

[81] FATH, Karoline, STENGEL, Julian, SPRENGER, Wendelin, WILSON, Helen Rose, SCHULTMANN, Frank and KUHN, Tilmann E. A method for predicting the economic potential of (building-integrated) photovoltaics in urban areas based on hourly Radiance simulations. *Solar Energy* [online]. 2015. Vol. 116, p. 357-370. [Accessed 25 August 2015]. DOI 10.1016/j.solener.2015.03.023. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0038092X15001413

[82] WARD, Gregory J. The RADIANCE Lighting Simulation and Rendering System. *Computer Graphics (Proceedings of '94 SIGGRAPH conference)* [online]. July 1994. p. 459-472. [Accessed 27 February 2015]. Available from: http://radsite.lbl.gov/radiance/papers/sg94.1/abstract.html

[83] REINHART, Christoph F. and HERKEL, Sebastian. The simulation of annual daylight illuminance distributions — a state-of-the-art comparison of six RADIANCE-based methods. *Energy and Buildings* [online]. 2000. p. 167-187. [Accessed 27 February 2015]. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0378778800000426

[84] RUBOW ARKITEKTER A/S [online]. Available from: http://www.rubowarkitekt.dk/

[85] DANISH BUILDING REGULATIONS (BR-08) [online]. Copenhagen: The Danish Ministry of Economic and Business Affairs, Danish Enterprise and Construction Authority, 2007. ISBN 978-87-91769-32-0. Available from: http://energycodesocean.org/sites/default/files/Bygningsreglementet_englesk.pdf

[86] CENERGIA ENERGY CONSULTANTS [online]. Available from: http://www.cenergia.dk/

[87] BREEAM UK NEW CONSTRUCTION. *Non-Domestic Buildings, Technical Manual SD5076: 0.1 (Draft) – 2014, Hea 01 Visual comfort* [online]. 2014. p. 61. [Accessed 28 February 2015]. Available from: http://www.breeam.org/BREEAMUK2014SchemeDocument/content/05_health/hea01_nc.htm