Energy and Buildings 41 (2009) 1215–1222

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Case study of zero energy house design in UK

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ARTICLE INFO

Article history:
Received 10 March 2009
Received in revised form 11 July 2009
Accepted 13 July 2009

Keywords:
Zero energy building
TRNSYS
EnergyPlus

ABSTRACT

Possible solutions for zero energy building design in UK are discussed in this paper. Simulation software (EnergyPlus and TRNSYS 16) are employed in this study, where EnergyPlus simulations are applied to enable facade design studies considering building materials, window sizes and orientations and TRNSYS is used for the investigation of the feasibility of zero energy houses with renewable electricity, solar hot water system and energy efficient heating systems under Cardiff weather conditions. Various design methods are compared and optimal design strategies for typical homes and energy systems are provided.

1. Introduction

The scientific evidences for climate changes and the associated impacts of greenhouse gas emissions are becoming increasingly obvious. In UK, buildings are responsible for 47% of national energy consumption [1]. Scientists and built environment professionals are trying to find advanced technologies, renewable energies, and useful strategies to reduce carbon dioxide emission.

Zero energy building design has become a high priority for architects and multi-disciplinary researchers related to architectural engineering and building physics. A zero energy building refers to a building with a net energy consumption of zero over a typical year. It implies that the energy demand for heat and electrical power is reduced, and this reduced demand is met on an annual basis from renewable energy supply. The renewable energy supply can either be integrated into the building design or it can be specifically provided for the building, for example as part of a community renewable energy supply system. It also normally implies that the grid is used to supply electrical power when there is no renewable power available, and the building will export power back to the grid when it has excess power generation. This 'two way' flow should result in a net positive or zero export of power from the building to the grid. The zero energy building design concept is a progression from passive sustainable design. The object of a zero energy building is not only to minimize the energy consumption of the building with passive design methods, but also to design a building that balances energy requirements with active techniques and renewable technologies (for example, solar photovaltics, solar thermal or wind turbines). It can be measured in terms of primary energy consumption or carbon emissions.

The UK government has proposed sustainable house design in the consultation document Building a Greener Future: Toward a Zero Carbon Development which was published in December, 2006. This publication proposed that by 2016 all new homes in UK are to be zero carbon. In Wales, the Welsh Assembly Government has proposed that, not just housing, but all new building must be zero carbon by 2011. Most of the current houses are designed based on the building regulations 2006: Part L (conservation of fuel and power), in which the detailed procedures for achieving a zero carbon design are not addressed. It is a big challenge for both architects and researchers to develop zero carbon standards and achieve the zero carbon designs.

There are several advanced sustainable building design standards such as Ecohomes (BRE, UK), PassivHaus (Germany), AECB (UK), and LEED (USA). These standards provide different ranking criteria to evaluate energy efficiency and/or zero energy buildings. However, there are no specific strategies or design guidelines provided for achieving zero energy building designs. Specific design guidelines and strategies are extremely important for architects or engineers to popularize zero energy buildings. The purpose of this study to investigate the feasibility of zero energy house design in UK, and provide specific design methods to achieve zero energy house design in UK.

2. Literature review

Clarke et al. [2] applied an established integrated software environment, with building simulation software ESP-r, a RE modeling and matching tool Merit and a fuel use information management program EnTrak, for a case study of hybrid renewable energy systems for residential building in Korea to evaluate the

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doi:10.1016/j.enbuild.2009.07.001

feasibility of new technologies using a simulation based decision support system. The integrated software environment can help identify suitable technology types and capacities at an early design stage. Biaou et al. [3] simulated a zero net energy home in Montreal with TRNSYS. The home is equipped with photovoltaic (PV) panels and a geothermal heat pump for heating and cooling. The results indicated that it is possible to achieve a zero net energy for a R-2000 type home with PV and ground source heat pump. Bolling and Mathias [4] compared four heating and cooling systems in the aspects of the entire life cost, energy usage, exergetic efficiency and exergy destruction for the same residential house located in four different cities in America. The four systems include a high efficiency furnace and electric air conditioner, a ground source heat pump, an absorption air conditioner and direct heating and a thermally driven heat pump; the last two systems use solar thermal energy and backup non-renewable energy. The results showed that vertical ground source heat pump paid back in the shortest time. Norton and Christensen [5] presented the full year of energy performance data on the 3-bedroom Denver zero energy home combining envelope efficiency, efficient equipment, appliances and lighting, a photovoltaic system, passive and active solar thermal features. This case study demonstrates that it is possible to build efficient affordable zero energy homes in cold climates.

3. Methodology

The construction and laboratory experiments on zero energy houses are a costly method to explore potential variations in building designs. Without the experience of the design of energy efficient building systems, the outcomes of zero carbon house design in the aspects of thermal comfort, and energy usage are likely to be questionable. Computer simulations of building systems can provide convenient and quick prediction for zero energy house design and avoid large costs due to building construction and experiments. EnergyPlus and TRNSYS 16.0 are used in the study. EnergyPlus models hourly energy consumption in multi-zone buildings based on detailed designs and weather data, while TRNSYS has been widely applied for both energy efficiency and renewable energy analyses. The latter models each component in the system as a module and allows access to the source code for appropriate adaptation. In this study, EnergyPlus simulations are used for building envelope design and TRANSYS is used for building systems and renewable energy systems design.

4. Weather data analyses

Weather data analyses should be the primary step for any energy efficient building or zero energy building design. The analyses can provide important guides for building energy systems design and renewable energy system selections. Representative Cardiff weather data are analyzed in the aspect of wind, solar radiation and ambient temperature.

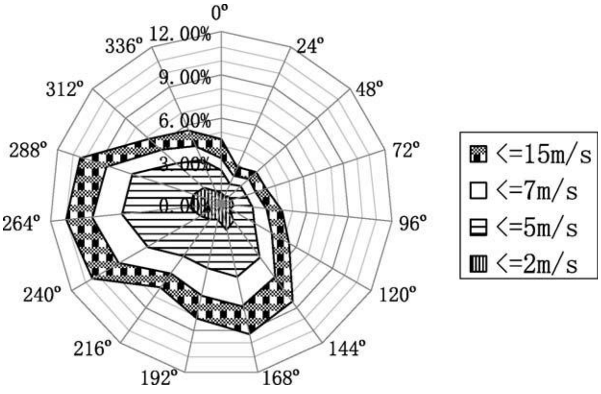

Fig. 2. Yearly wind rose profile for Cardiff, UK.

Wind frequency profile for Cardiff, UK is illustrated in Fig. 1. About 60% wind speed in Cardiff ranges from 3 m/s to 7 m/s. Small wind turbine with high-efficiency at 3–7 m/s band for domestic usage is applicable for zero energy buildings. Fig. 2 shows the yearly wind rose profile. It is observed that the main wind direction in Cardiff for the whole year is southwest. Fig. 3 shows the monthly distribution of direct solar radiation and diffuse solar radiation. It is found that the amount of solar radiation is generally high throughout March–October. Annual total solar radiation in Cardiff is 1337 kWh/m^2 with approximately 3029 h sunshine. Fig. 4 illustrates the average, maximum, and minimum monthly dry bulb temperature distribution. The annually highest statistic temperature is 24.7 °C and lowest statistic dry bulb temperature is −4.8 °C. Annual cooling degree-days (CDDs) base 10 °C (50 °F) is 719, CDDs base 27 °C is 0, and annual heating degree-days (HDDs) base 18 °C (65 °F) is 3015. The CDD and HDD indices reflect the high demands of heating for buildings in Cardiff, UK and the absence of cooling demands for building with no large amounts of internal heating gains.

5. Passive building designs

Facade design studies, undertaking the manipulation of façade details, can be effective in determining their relationship with heating and cooling loads of a building as well as the associated indoor thermal environment. The building model used for the facade design studies in EnergyPlus is shown in Fig. 5 and the first floor plan in Fig. 6. Construction properties for the house are listed in Table 1. These reflect typical practice in UK domestic mass housing market.

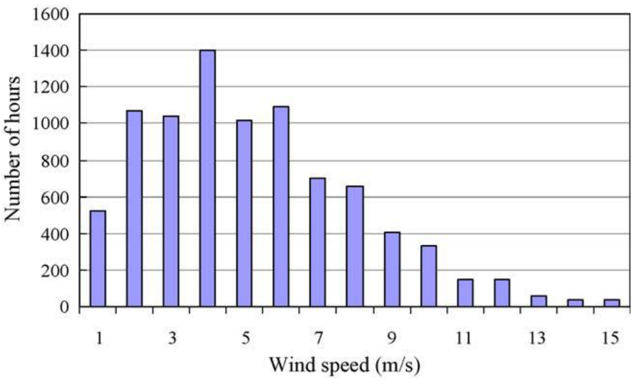

Fig. 1. Wind frequency profile for Cardiff, UK.

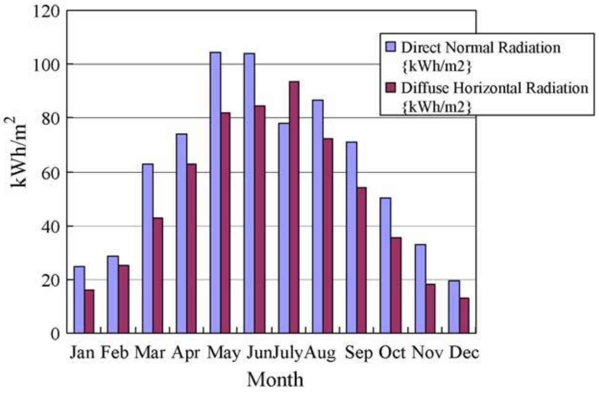

Fig. 3. Monthly solar radiation distribution profile for Cardiff, UK.

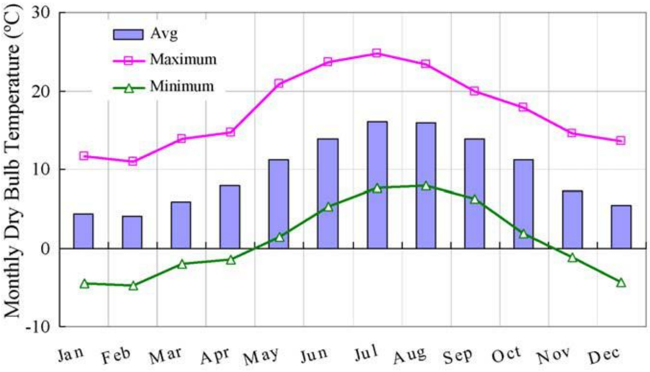

Fig. 4. Monthly dry bulb temperature distribution for Cardiff, UK.

Various parameters including *U* values of external walls, window to wall ratios (WWR), and orientations (indicated by large area window facing orientation) are investigated in this parametric study. Four different *U* values of external wall: 0.1 W/m^2 K; 0.2 W/m^2 K; 0.3 W/m^2 K; 0.4 W/m^2 K are employed to analyze heating and cooling loads for the residential house. (For comparison: Part L [8], $\leq$0.35 W/m^2 K; AECB standards [12], Silver—$\leq$0.24 W/m^2 K and gold—$\leq$0.14 W/m^2 K, PassivHaus [13]—$\leq$0.1 W/m^2 K). Facade orientation is another important factor to determine energy consumption of the building. Four orientations N, S, W, E have been investigated in this study. Various WWR (0.1–0.4) for bedroom1 shown in Fig. 6 have been investigated. In total, sixty-four different cases were simulated with EnergyPlus for facade design study.

In the simulation, the heating setpoint is 20 °C and cooling setpoint is 24 °C. Single setpoint controls are used for heating and cooling. Heating is made available from January to March and October to December, and cooling from April to September. The energy consumption of the house is taken as the criteria for the optimal sustainable facade design.

The results of cooling and heating loads with the variation in *U* value for WWR = 0.1, south orientation are demonstrated in Fig. 7. The simulation results indicate that with the increase of *U* values of external wall, cooling loads decrease while heating loads increase. The same conclusion can be obtained for other window to wall ratios and orientations. It can be attributed to insulation‘s double-edged effects on HVAC loads. Insulation, on the one hand, promotes the ability of a building to retain heat during the heating seasons; on the other hand it prevents the release of unwanted heat through the building envelope during the cooling seasons. As can be seen from the results shown in Fig. 7, the total energy consumption is reduced with the increase of thermal insulation. When the *U* value of the external wall is equal to 0.1 W/m^2 K, the lowest heating loads and total energy consumption are predicted.

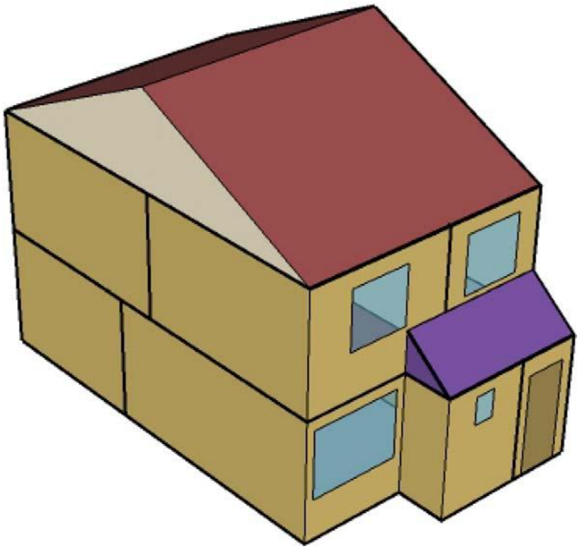

Fig. 5. EnergyPlus model for domestic house in UK.

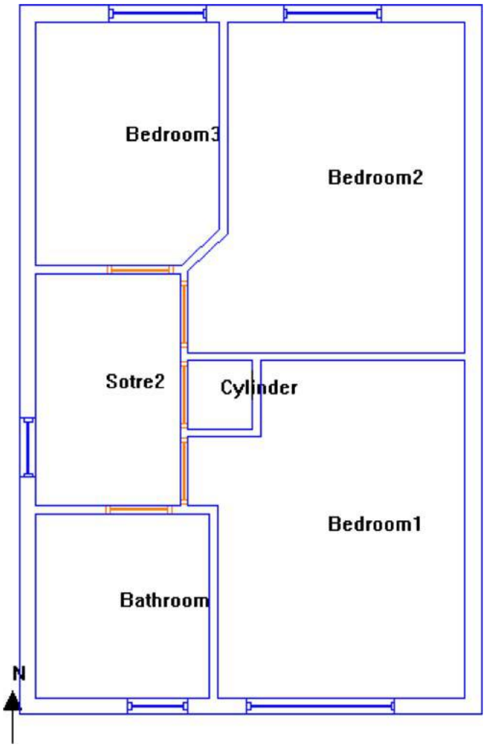

Fig. 6. First floor plan for domestic house.

Orientation is another important factor for the performance of both indoor thermal environment and energy consumption. The house orientation refers to the direction in which the entrance façade is facing. From the simulation results shown in Fig. 8(a)–(d), it can be found that annual heating loads with south facing orientation are generally lower than other orientations except for large WWR scenarios. During heating periods, large amounts of useful solar heat gains can be obtained through south facing windows. However, the heating loads of south facing cases tend to increase with the increase of WWR. This can be attributed to the fact that the increase of solar heat gain with large window areas is offset by increased heat losses with large windows due to their with relatively low insulation. Since north oriented facades receive the least solar heat gain among all the orientations, it seems confused that the annual heating loads for north orientation cases are a bit lower than the loads for west and east orientation cases. Actually, the annual heating loads here refer to the heating loads for the whole house (including bedrooms, dinning rooms, kitchen and lounge). In other words, in each north facing case, there are

Table 1
Building construction materials.

Building Elements	Material	*U* value
External wall	Concrete block and brick	0.4 W/m^2 C
Glazing	24 mm double glazing	1.78 W/m^2 C
Internal partition	Plasterboard and insulation	0.71 W/m^2 C
Roof construction	Concrete tiles, felt/underlay	4.298 W/m^2 C

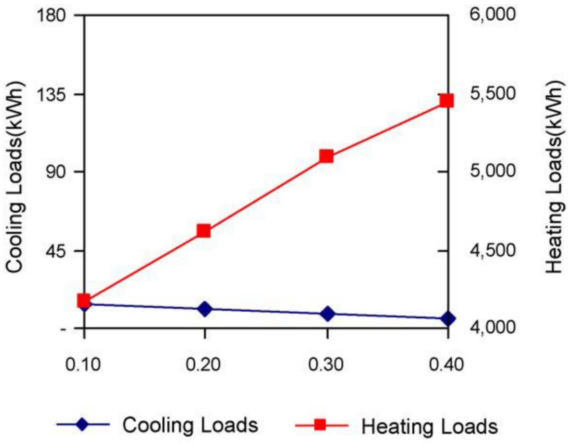

Fig. 7. Cooling load and heating load plots for WWR = 0.1, south orientation.

both conditioned rooms facing north and south. Therefore, the total heating loads for both north facing and south facing rooms can be lower than heating loads for west and east orientations. Cooling loads for west and east facing cases are higher than those for north and south facing cases. This is attributed to the high level of solar heating gains obtained through west and east facing windows.

WWR is another important parameter to affect indoor thermal environment and energy consumption. The relatively low insulation levels afforded by windows will have an impact on the internal thermal performance of a home during the winter, while larger windows will increase internal solar heat gains. An interesting study would therefore be to identify the optimal proportion of glazing in a wall to provide reductions of energy loads. Various WWR (0.1–0.4) have therefore been investigated for various orientations and *U* values. Fig. 9(a)–(d) demonstrate the cooling and heating loads for bedroom1 (referred to Fig. 6) with various room facing orientations and WWR under *U* value = 0.1 W/m^2 K. It should be noted that the indicated orientations (room facing orientations) in Fig. 9(a)–(d) are different from the house orientations in Figs. 7 and 8. The room orientations refer to the window orientation in the bedroom, while the house orientations refer to the facing of entrance facade. In this study, bedroom1 orientation is the opposite orientation of house orientation. From the results, it is clear that the cooling loads of the bedroom are increasing with the increase of WWR for all the orientations. North facing cases have the lowest cooling energy requirements. Also, it is interesting to find that the heating loads of the bedroom are decreasing with the increase of WWR for south facing cases, while the heating loads are increasing with the increase of WWR for other facing cases. Solar heat gains are admitted through the window for both beneficial heat, during the winter and unwanted heat, during the summer. Therefore, the optimum WWR for north, east and west is the 10% to reduce heating and cooling loads, while for south orientation, the optimum WWR is 10% for lowest cooling loads but 40% for lowest heating loads.

Therefore, the modified house design after the parametric facade design studies is south facing, WWR = 0.4 (south facade), WWR = 0.1 or less (other oriented facades), and *U* value = 0.1. Compared with original house design, the energy saving in heating with optimum design guide is about 26.5% reduction of the original heating requirements. There is a little increase in annual cooling energy from 8.33 kWh to 61.1 kWh.

The *U* value for glazing was then further improved from 1.78 W/m^2 K to 1.367 W/m^2 K resulting in a further heating demand reduction of 55.6 kWh and cooling demand reduction of 33.3 kWh. When *U* value of roof construction is reduced from 4.298 W/m^2 K (ventilated roof) to 0.2 W/m^2 K (insulated roof), annual heating demand is further reduced by 197.2 kWh, while annual cooling demand is reduced by 8.3 kWh.

Regarding the cooling loads, natural ventilation should be firstly considered to reduce the demands for cooling in passive designs. Therefore, natural ventilation is used for cooling seasons

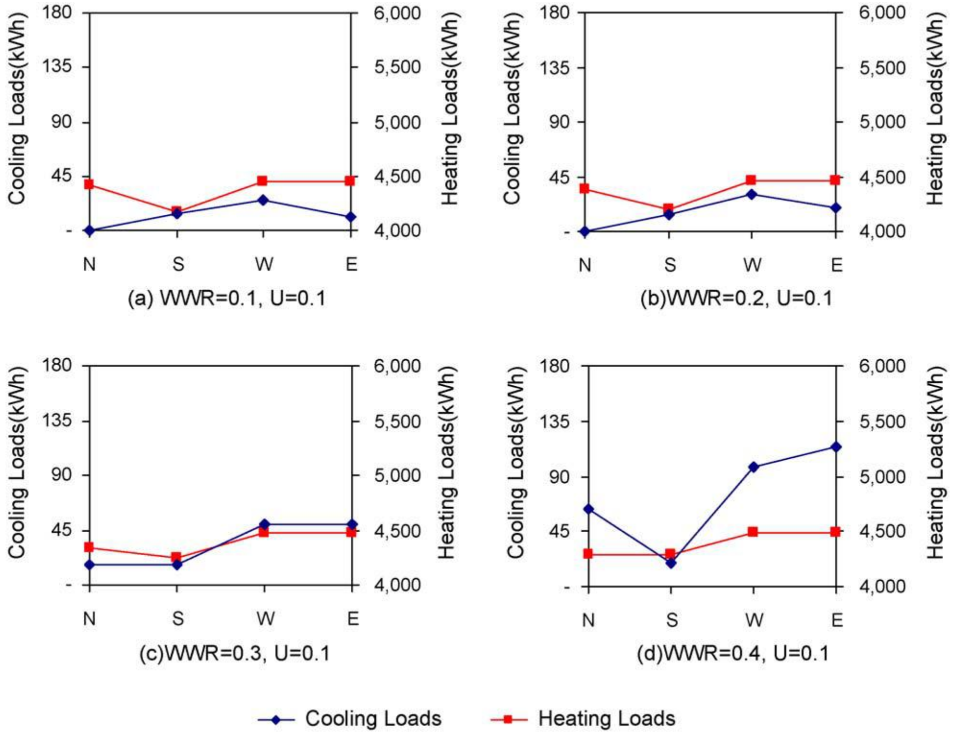

Fig. 8. (a–d) Cooling load and heating load plots for WWR = 0.1–0.4, *U* value = 0.1 W/m^2 K with different house orientations.

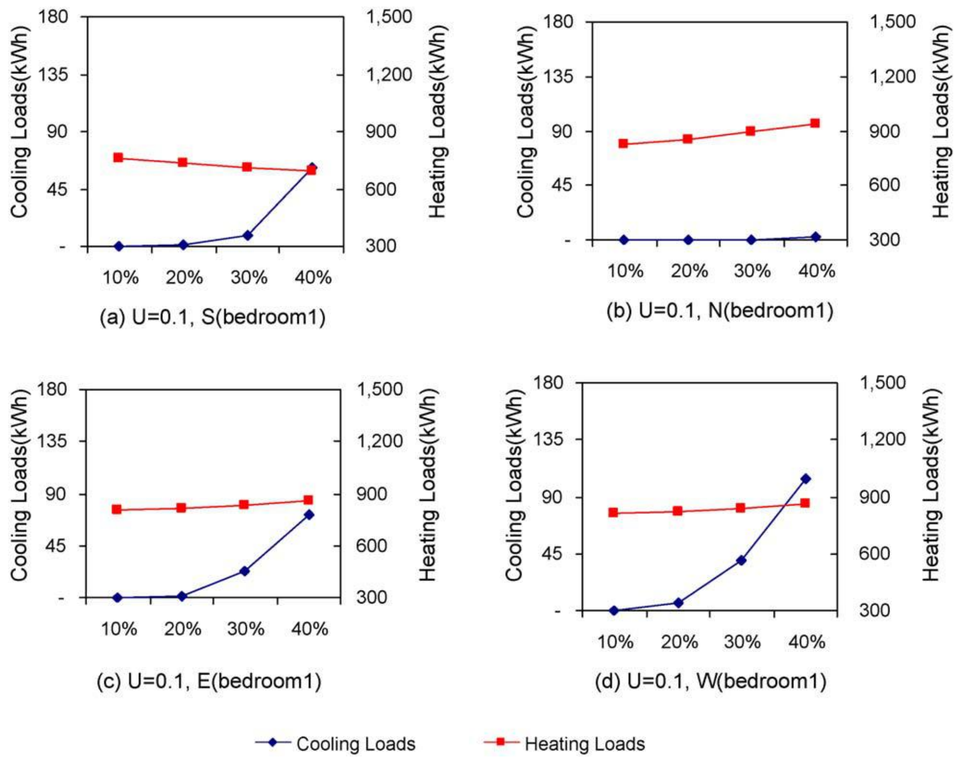

Fig. 9. (a–d) Cooling load and heating load plots for WWR = 0.1–0.4, *U* value = 0.1 W/m^2 K with various orientations of bedroom1.

in the simulation based on the optimum design. In the simulation, when the indoor air temperature reaches above 28 °C, the air change rate is 5 ACH, which is a reasonable assumption for naturally ventilated rooms. The maximum room temperature (28.01 °C) in summer with natural ventilation occurs in south facing bedroom2. With natural ventilation, the indoor comfortable room temperature can be up to 30 °C. Therefore, it is concluded that no cooling energy is needed for summer time.

So far, the optimum passive facade design to minimize the requirements of energy has been identified. The improved construction properties for the house are listed in Table 2. Compared with the original design, there is about 31% heating energy saving with the finalized optimum passive house design.

6. Building systems

In this typical home in UK, three building service systems-hot water system, space heating system, and electricity for lighting and appliance are discussed in the paper. To achieve zero energy home, we need to utilize energy efficient heating and renewable energy systems.

6.1. Solar hot water system

Solar domestic hot water systems are widely considered to be one of the most promising systems in the delivery of zero energy homes. Currently, the vast majority of the domestic hot water system in UK is supplied by gas or electricity, consuming large amounts of conventional energy, where in particular the application of high quality energy (e.g. electrical energy) to low quality heat energy may be considered wasteful. The applicability of domestic solar hot water system in UK is discussed in the following section. TRNSYS 16.0 is used for modeling this domestic solar hot water system.

Table 2
Optimum passive house design.

Building Elements	Material	*U* value
External wall	Concrete block and brick	0.1 W/m^2 C
Glazing	19 mm double glazing with low E coating Suspended plaster board	1.367 W/m^2 C
Roof construction	Ceiling, insulation, reflective foil, air gap, building	0.2 W/m^2 C

Fig. 10 shows the scheme of a solar domestic hot water including flat-plate solar collectors, circulation pumps, heat exchanger, fully stratified storage tank (with an auxiliary heater), and controller. Solar collector is south facing with 50° tilted angle, which is equivalent to the latitude of Cardiff, UK. Considering daily minimum temperature of -4.8 in Cardiff, 25% glycol–water

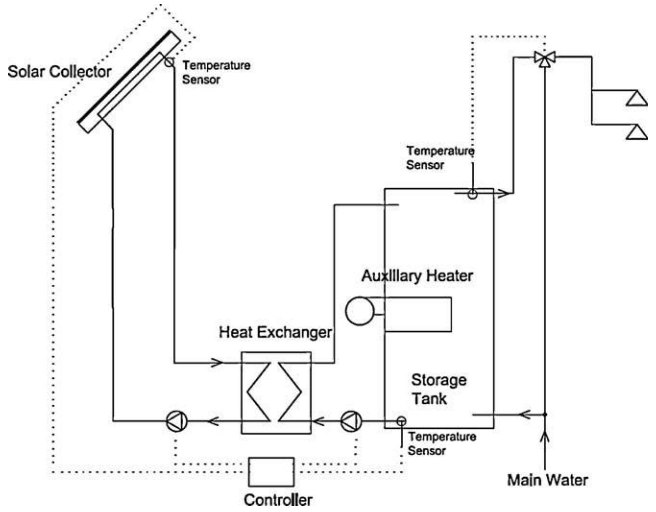

Fig. 10. Scheme of the DHW system.

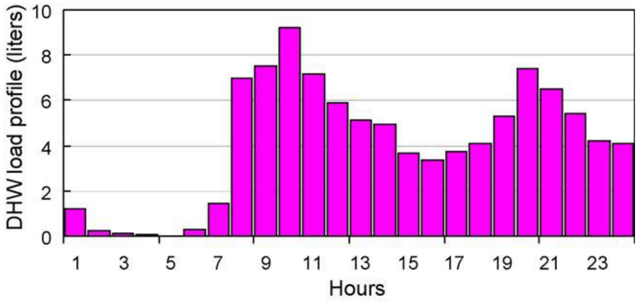

Fig. 11. Hourly DHW profile.

solution is used to make sure that the system can operate normally under freezing conditions. The specific heat capacity is 3.9 kJ/(kg K). The storage tank volume is 0.3 m^3, which is the typical size for a family. The feedback controls (type 22) are used in the simulation to control the pump in the solar collector loop. The controller sets the flow rate so that the collector outlet temperature is 10 °C warmer than the return water temperature to the solar collector. This feedback controller can model a real feedback controller (e.g. PID) and adapt its control signal continuously [11].

The current total average UK individual domestic hot water usage is 49 L/day [10]. Two occupants are assumed in a typical house in UK. Therefore, the total domestic hot water consumption is 98 L/day. Hourly DHW profile [6,7] is illustrated in Fig. 11. The mains water is assumed to be a constant 5 °C and the set point for the DHW is 50 °C.

Parametric simulations with TRNSYS have been undertaken with different solar collector areas (2 m^2, 4 m^2, 5 m^2, 6 m^2, 8 m^2), and different mass flow rate (20 kg/h, 30 kg/h, 40 kg/h, 50 kg/h). The solar collector's mean annual efficiency and solar fractional energy saving are used to optimize the design parameters.

The results for solar collector efficiency are shown in Fig. 12. There is optimum mass flow rate for each solar collector area. For solar collector with 2 m^2, the optimum mass flow rate is 20 kg/h and solar collector efficiency decreases drastically with the increase of mass flow rate. For solar collector with 4 m^2, 5 m^2, 6 m^2 and 8 m^2, the optimum mass flow rate is 20 kg/h, 30 kg/h, 30 kg/h, 40 kg/h respectively and the changes of efficiency with the variation of mass flow rate tends to be slow. The maximum solar collector efficiency decreases with the increase of solar collector areas.

The results of annual solar fraction are shown in Fig. 13. From the results, it can be found that the solar fractional energy saving increases when solar collector increases from 2 m^2 to 8 m^2. Annual solar fraction varies with different mass flow rates. For solar collector area 2 m^2, 4 m^2 and 5 m^2, the optimum mass flow rate is 20 kg/h; for solar collector area 6 m^2, the optimum mass flow rate is 30 kg/h; for solar collector area 8 m^2, the optimum mass flow rate is 40 kg/h.

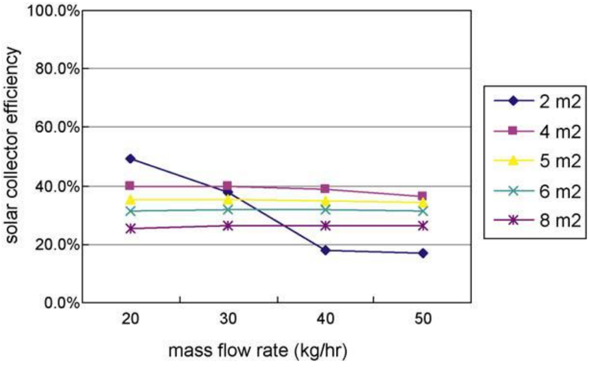

Fig. 12. Solar collector efficiency with the variation of solar collector areas and mass flow rate.

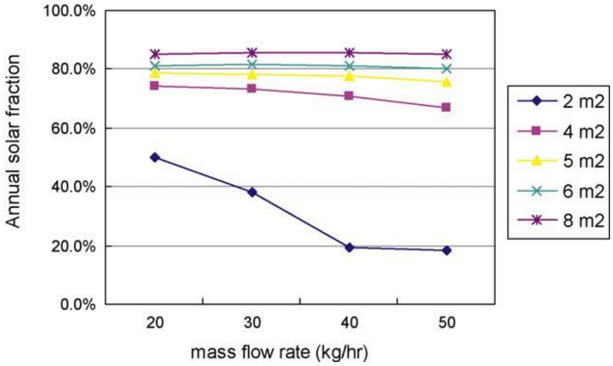

Fig. 13. Annual solar fraction with the variation of solar collector areas and mass flow rates.

Considering both factors: solar collector efficiency and solar fractional energy saving, 5 m^2 solar collector with mass flow rate 20 kg/h are selected for solar domestic hot water system. The flat-plate solar collector efficiency is 35% and the solar fractional energy saving is 78.5%. The annual required auxiliary energy is 401.7 kWh, which is about 21.5% of domestic hot water load.

6.2. Underfloor heating system

Underfloor heating system offers great potential to reduce heating energy consumption. The mean supply water temperature of underfloor heating system can be reduced to 35–40 °C compared with common radiators as the floor size is generally large. The rate of heat output from the system is determined by mean water temperature, spacing and diameter of pipework, floor finish and floor construction. The supply water temperature of underfloor heating is much lower than the water supply temperature in conventional radiant heating systems (55–60 °C). As the heating source is from the floor, the air temperature at the lower level is warm and the temperature tends to be cool at the higher level. Therefore, it can provide occupant ideal thermal comfort conditions (warm feet and cool head). As a result, for the same comfort level, the average room air temperature can be 2 °C lower than that for conventional heating systems. In the study, the setpoint for room temperature is 20 °C during the heating season (January–March and October–December).

The house is modeled with TRNSYS type 56 as a simplified one-zone model. The design parameters are based on the optimum passive house design in previous section. Infiltration is set as 0.5 ACH. The worst scenario is considered with no specific internal heat gain except solar radiation. The heating floor is supplied with hot heating fluid and directly modeled in the definition of the floors of the building. The pipe grid is an active layer of the floor. The pipe spacing from centre to centre is 100 mm, the outside diameter of the pipe is 20 mm.The pipe wall thickness is 2 mm and pipe wall conductivity is 1.26 kJ/h m K. When indoor air temperature is higher than 20 °C, the underfloor heating system is turned off. The annual required energy input by floor heating is 3666.7 kWh for heating seasons. From the thermal comfort point of view, the setpoint of indoor air temperature can be 18 °C. In this case, the annual required energy input by floor heating can be reduced to 2805.6 kWh. If air source heat pump is used to provide 40 °C water to heat screed floor, the required work consumed by the heat pump is 935.2 kWh with the assumption of COP 3.0. The energy

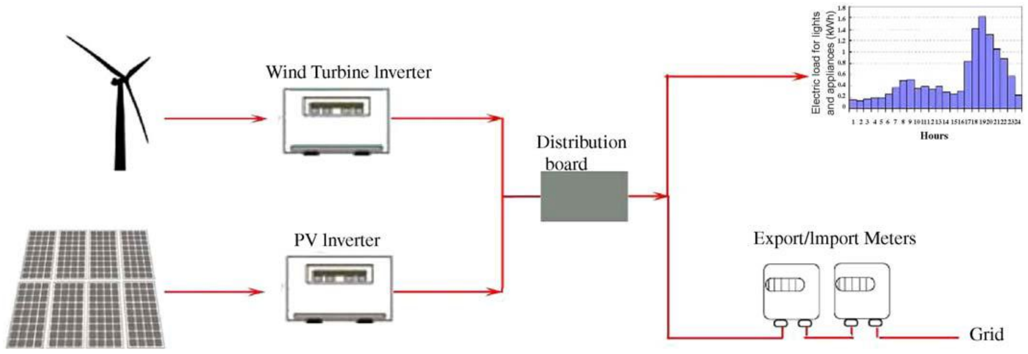

Fig. 14. Scheme of grid-connected renewable electricity system.

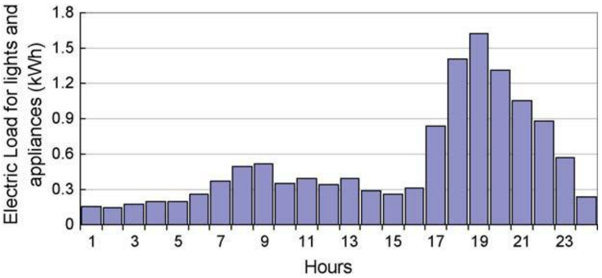

Fig. 15. Hourly domestic electric load profile.

consumption could be further reduced if ground coupled heat pump is applied. The efficiencies for ground source heat pumps are generally higher as the ground maintains a relatively stable source/sink temperature, allowing the heat pump to operate close to its optimal design point.

6.3. Renewable electricity systems

Systems designed to supply a renewable source of electricity systems are indispensable in the delivery of zero energy building designs. The scheme of a grid connected renewable electricity system is shown in Fig. 14. It is comprised of PV, small wind turbines, inverters for PV and wind turbine (from AC to DC), a distribution board, meters for export and import connected to the grid, and electricity loads. Hourly domestic electric load profile for light and appliances is shown in Fig. 15 [9]. The daily electric load is therefore considered to be 12.8 kWh.

Photovoltaic array (Type 194), wind turbine (Type 90) and DC/AC inverter (Type 48) are used to simulate a utility grid connected renewable energy system under Cardiff weather conditions. The inverter will convert the direct current (DC) electricity produced by the PV array into alternating current (AC) electricity typically required for light and appliance loads with the efficiency of 0.78. The designed PV array is composed of 2 strings in parallel with 4 modules in one string. The array slope is set to 50° in accordance with local latitude (51.4 N). The PV parameters are listed in Table 3. The wind turbine model calculates the power output of a WECS (wind energy conversion system) based on a power versus wind speed characteristic. The impact of air density changes and wind speed increases with height is also modeled. 2 no. 2.5 kW wind turbines with the hub height 15 m are selected for this study. The performance profile of wind turbine is show in Fig. 16.

The renewable electricity system is simulated with TRNSYS. In the study, annual lighting and appliance electricity consumption is 4672.0 kWh. Annual power output from the inverter is 7305.9 kWh.

The wind turbine and PV output profile on typical spring day March 21st are shown in Fig. 17. The wind turbine and PV outputs indicate that in those seasons such as spring, fall and winter, most of the electricity is generated by wind turbines. In summer, PV can generate large amount of electricity, which is comparable to the amount generated by wind turbine in summer. From the annual electricity generation results, the power output from photovoltaic is only 9% of annual power generated, while the annual power output from wind turbines is 91% of annual power generated.

Table 3
PV parameters in the electricity system.

Parameters	
Rated power	165 W
Area	1.26 m^2
Short circuit current	4.7 A
Open circuit voltage	44.2 V
Modules	4 × 2
Total rated power	1.32 kW

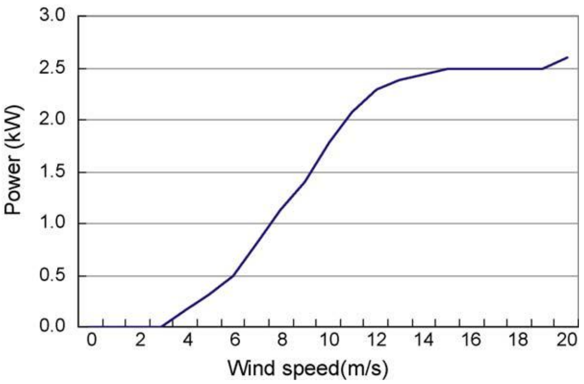

Fig. 16. Wind turbine performance profile.

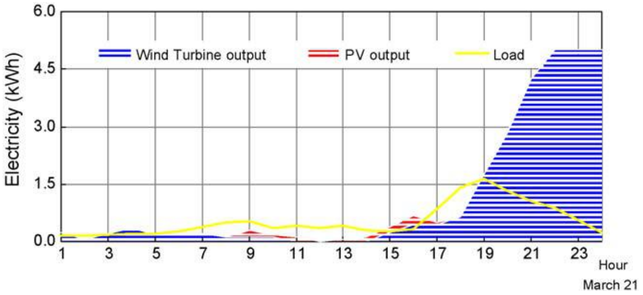

Fig. 17. Wind turbine and PV output profile on kJ/h typical spring day March 21st.

Table 4
Annual electricity consumption and generation.

Annual electricity	kWh
Lighting and appliance	(4672.0)
Auxillary heating in SDHW	(401.7)
Energy consumption with floor heating	(935.2)
Annual electricity generated with PV	687.8
Annual electricity generated with wind turbines	6618.1
Sum	1297.0

7. Conclusion

From the above study, it can be found out that it is theoretically possible to achieve the zero energy homes in the UK. The annual electricity consumption and generation is summarized in Table 4. The annual electricity generated with PV and wind turbine is predicted to be 7305.9 kWh. The electricity consumption from lighting, appliance, auxiliary heating for SDHW and energy consumption in floor heating system is 6008.9 kWh. The remaining electricity (1297.0 kWh) can be used for pump circulation in the system and electrical charging of vehicles for transport and financial gain from sale back to the grid.

This study aims to identify solutions for zero energy house design in the UK. The optimum house design in the UK is south facing, WWR = 0.4 (south facade), WWR = 0.1 or less (other oriented facades), and U value = 0.1 for external walls and roof. For solar domestic hot water system with 98 L/day hot water load, the optimum solar collector area is 5 m^2 with mass flow rate 20 kg/h. The flat-plate solar collector efficiency is 35% and the solar fractional energy saving is 78.5%. The combined underfloor heating and heat pump system can significantly reduce the energy consumption compared with other electric heating or typical radiant heating systems. For electricity generation systems, two small wind turbines, with a total rated power of 5.0 kW in total contributed to 91% of annual electricity generation, while a 1.3 kW PV array contributed to 9% of annual electricity generation.

The whole design process can be summarized into three steps. Firstly, an analysis of local climate data is of primary importance in order to make use of the local climate condition for promoting zero energy homes. Secondly, the application of passive design methods and advanced facade designs to minimize the load requirement from heating and cooling through building energy simulations. Finally, through the use of TRNSYS to investigate various energy efficient mechanical systems and renewable energy systems including photovoltaic, wind turbines and solar hot water system to enable system design optimizations.

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