The SOLCER Energy Positive House: Whole System Simulation

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Abstract

There is a global trend to deliver zero carbon buildings, with European countries required to deliver near zero energy housing by 2020. This paper presents the results of the simulation of the energy performance of the SOLCER house. The house was designed using a 'systems' approach to integrate the building technologies for thermal and electrical energy systems, based on the concept of buildings as power stations, using the renewable energy systems as part of the building envelope. The aim was to produce a house that achieves an 'energy positive' performance, which, on an annual basis, generates more energy than in consumes. The house is designed for wide-scale application, so, in addition to energy performance, the focus was also on affordability and ease of build. In order to assess the performance of the house a model was needed to assess the whole building energy performance of the building and its integrated energy systems. The paper describes the development of a simulation model based around the building thermal model, HTB2 (Heat Transfer in Buildings: version 2). A number of sub-models were constructed to simulate the innovative heating, ventilation and power systems. Results are presented relating to seasonal performance of the building, which demonstrate that on an annual basis the building is around 70% self-sufficient in its energy needs, with a grid export to import rate is 1.75.

Introduction

European countries are required to deliver near zero energy housing by 2020 (European Union, 2010). This is however typical of a global trend towards a low carbon built environment. In recent years there have been a number of examples of low to zero energy housing, and more recently energy positive housing. In general, an energy positive performance is achieved when the total energy generated over the year from building integrated renewables is greater than the energy used; such buildings could also be regarded as zero carbon or carbon neutral. For example, Ireland's first energy positive house, Ileeid House, was built by integrating low energy and environmental design strategies, achieving a primary energy score of -25 kWh/m^2/yr (Daly, 2011). A family home in southeast Queensland, Australia, constructed through an integrated systems approach, was demonstrated to be energy positive with high levels of thermal comfort (Miller and Buys, 2012). Measured energy data from the Lincoln Farmhouse in MA, USA, showed 42% net positive energy performance over 2014-2015 (Zero Energy Design, 2015).

As we move towards energy positive buildings there is a need to fully understand their performance in order to optimize their operation. This paper presents the simulation of the energy performance of the SOLCER house, whose construction was completed in March 2015, and which is located in South Wales, UK. The aim was to design and construct an energy positive house that would be up-scalable for wide-scale application. It therefore needed to be affordable and buildable with existing technologies and skills. It is specifically targeted at the social housing market.

The design of the SOLCER house adopted a number of technologies and design approaches developed within the LCRI Low Carbon Buildings Programme (Jones, P. et al., 2015). These technologies have been optimized through a systems approach, integrating reduced energy demand, renewable energy supply and energy storage. Firstly, the electrical and thermal technologies were combined. The electrical system includes a 4.3kWp solar PV array of 34m^2, a 6.9kWh lithium-ion-phosphate battery storage system. This powers the thermal system, which includes a 585W electric heat pump (COP of 3.2), which together with the Transpired Solar (air) collector (TSC) and mechanical ventilation heat recovery system (MVHR) provide space heating, ventilation and thermal storage. Secondly, the renewable energy systems have been fully integrated into the design of the building, with the PV panels providing the south facing roof element, and the thermal air collector providing the external layer of the south facing first floor (see figure 1). The priority is to use as much of the renewable energy in the building, before exporting to the grid.

Figure 1. SOLCER House featuring its PV roof and 1st floor transpired solar air collector (TSC)

This paper describes how energy simulation was carried out to analyse the performance of the building in use. The house was constructed with readily available technologies, using local supply chains, and for a replication cost of around £1,200/m^2. This cost is comparable with social housing costs in the region, and also with high quality private sector homes, especially those that provide a low to zero energy performance (Land Registry, 2016).

Method

The simulation used the dynamic thermal model, HTB2 (Lewis, P.T. et al., 1990). This model is able to simulate the thermal performance of a building, using local weather data, building construction details and occupancy profiles. The main thermal and energy related components and systems of the building have been added to the model, either through the sub-models using the HTB2 input files, or through separate external plug-in sub-models applied during the post-processing stage.

The total heating demand was calculated by adding the space heating to the domestic hot water heating, which can be calculated according to measured hourly hot water usage profile for household with children (Energy Monitoring Company, 2008). The electrical demand was calculated from hourly user profiles for equipment and lighting use by a couple with two children, together with the heat pump and TSC/MVHR fan system, and the electricity usage profile was derived from published survey sample (Zimmermann, J. et al., 2012) and the available energy-efficient products in the market.

The paper focuses on two aspects of simulation:

(i) Comparisons are made with monitored data from the detailed measurement of the building in use, for specific items of equipment, such as the TSC and MVHR systems.

(ii) Seasonal energy simulation to analyse the whole house performance (comparison with seasonal energy data will be published separately).

The house is currently occupied as a test facility with daily office-type use profiles.

System Modelling

The overall energy system is illustrated in figure 2.

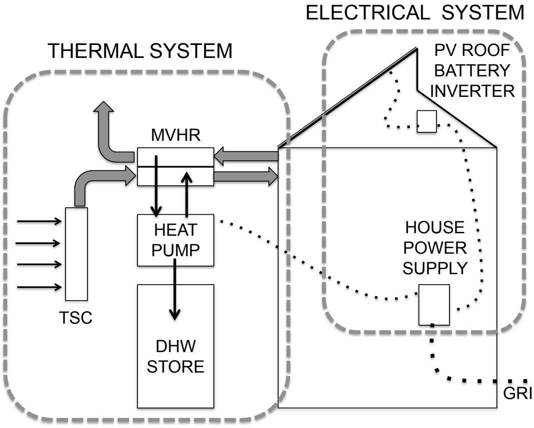


Figure 2. Diagram illustrating the energy systems.

Transpired Solar Collector (TSC)

The TSC is modelled as a set of four vertical spaces within HTB2. The performance of the TSC sub-model has been compared to measured data in relation to the temperature rise between external air temperature and the outflow TSC air temperature (figure 3). There is good agreement between the predicted hourly values and the measured data.

Mechanical ventilation heat recovery (MVHR)

The MVHR has been modelled explicitly in HTB2 by setting up two spaces, one for the supply air and the other for the exhaust air. The spaces are separated by a metal 'wall' with the same surface area as the sum of the heat exchange plates within the actual MVHR unit. A surface heat transfer coefficient 100Wm^{-2}K^{-1} was used, representing the nature of airflow through a narrow cavity (CIBSE, 2007). HTB2 then simulates the hourly heat exchange between the exhaust air and the supply air, passing through the two spaces separated by a wall.

The combined performance of the TSC and MVHR is presented in figure 4, in terms of an hourly distribution of overall temperature rise, again comparing measured and predicted data.

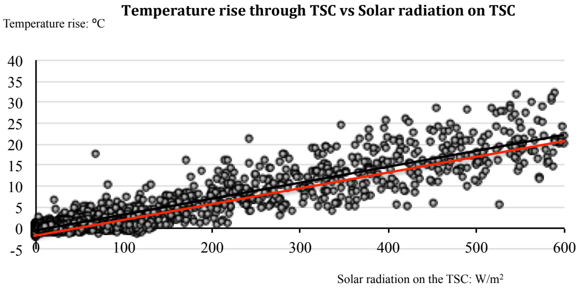


Figure 3. Temperature rise versus solar radiation incident to the TSC panel. Measured data available form Oct. 2015 to Mar. 2016 (black markers and trend line); Predicted data (red trend line).

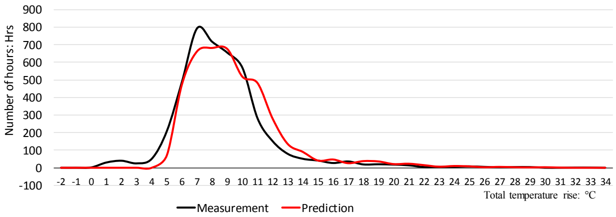


Figure 4. Seasonal hourly distribution of overall temperature rise through the TSC and MVHR (Oct. 2015 to Mar. 2016), comparing measured (black) and predicted (red) data.

Heat pump

The 585W heat pump with a COP of 3.21 provides heat to top-up the incoming supply air and thermal water store as required. The heat pump takes heat from the exhaust air after it has passed through the MVHR.

The heat pump has one condensing coil wrapped around the DHW tank and the other is located in the supply airflow. It prioritises DHW heating, once the tank is up to temperature the unit will automatically switch to heating the air if required.

DHW thermal store

The DHW thermal store operates between a temperature of 52^{o}C and 65^{o}C. The heat pump raises the temperature to 52^{o}C, when the thermal store requires heat input. When there is excess PV electricity generated in relation to the demand of the battery storage and heat pump and small power demand, electricity will be used to heat the thermal store. It raises the temperature up to a maximum of 65^{o}C. Storage heat loss is considered to contribute to space heating.

Solar PV and battery storage, inverter and grid electricity supply

The electrical power system includes the 34m^2 4.3kWp solar PV array, which covers the whole of the south-facing roof. This is combined with the 6.9kWh lithium-ion-phosphate battery storage. The PV array is simulated within HTB2 as a solar energy collector. Energy is supplied to the grid once the house power needs are met, and imported when needed.

Results

The model has been used to simulate the performance of the house over a whole year, and for the analysis in this paper, typical days have been selected to demonstrate the detailed energy performance of the building and its integrated energy systems for winter, mid-season and summer periods.

Daily profiles for a sunny and cloudy winter days

Figure 5a present temperature data for the supply air as it travels through the components of the ventilation system. The TSC adds a considerable amount of heat during the sunny period, boosting the air temperature by up to 25^{o}C. When there is little or no solar, the MVHR provides up to 10^{o}C temperature rise, and when needed heat is added from the heat pump. Figure 5b presents data for space and DHW heating. DHW takes energy from the thermal store as indicated by its reduced temperature. Excess PV energy is input to the thermal store during the afternoon period of sunny days. On a sunny day, power from grid is only needed during the night or early morning hours. A more detailed analysis of the solar PV, battery storage, and grid energy supply is presented in figure 5c, accompanied by thermal and electrical demands. The thermal store temperature ranges between 39 to 52^{o}C, with energy being drawn from the grid to heat the thermal store. Electricity is exported to the grid when the PV system is producing more than the building demands.

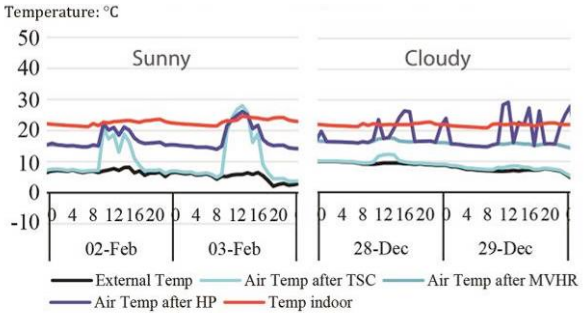


Figure 5a. Winter temperature variations

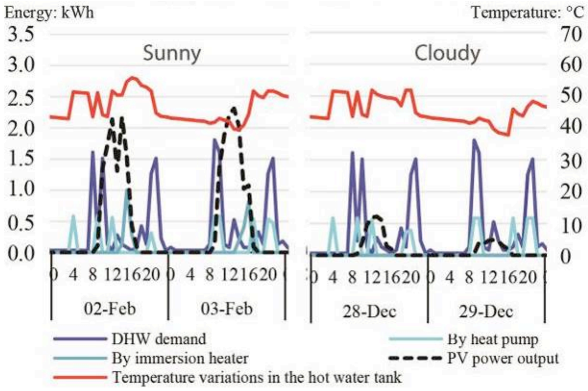


Figure 5b. Winter DHW temperature and energy

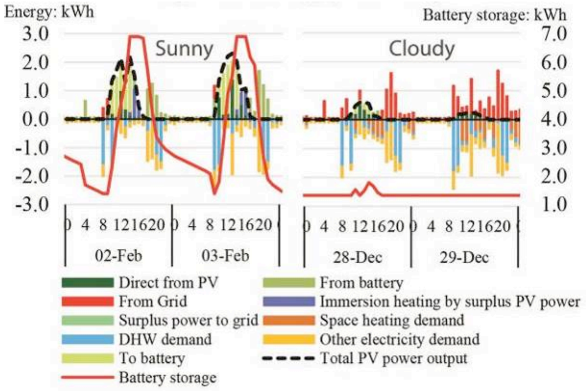


Figure 5c. Winter energy demand, supply and storage

Daily profiles for mid-season days

Figure 6a indicates that for sunny days the TSC adds a considerable amount of heat during the sunny period, boosting the supply air temperature by up to 23^{o}C. At night the MVHR provides up to 10°C temperature rise and with no heat needed from the heat pump. Figure 6b indicates that the DHW thermal store is mainly heated from excess PV. The thermal store temperature ranges averagely between 42 to 52°C. In figure 6c the PV power is able to supply all energy uses, almost no power is imported from grid and the potential grid export of electricity from the PV system is relatively high. During cloudy days grid is needed to supplement the heat pump energy needs.

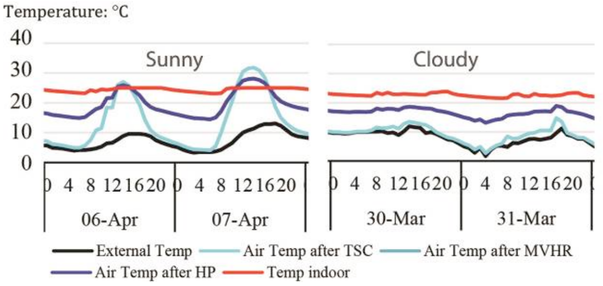


Figure 6a. Mid-season temperature variations

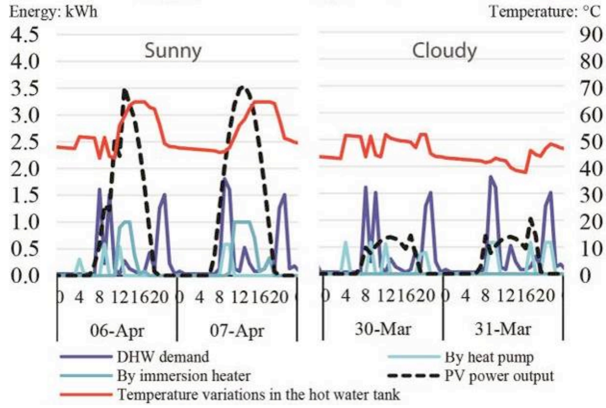


Figure 6b. Mid-season DHW temperature and energy

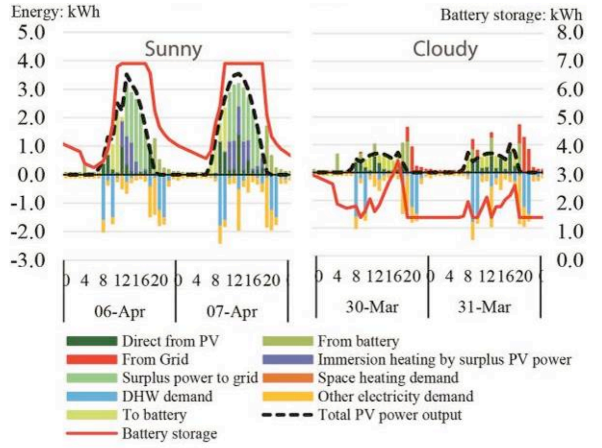
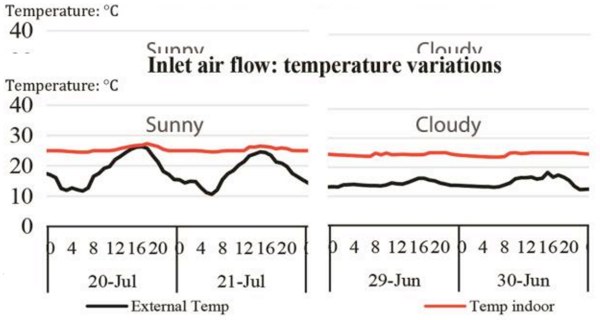
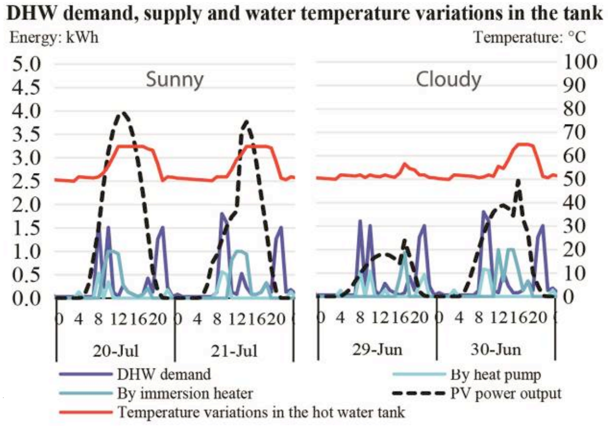


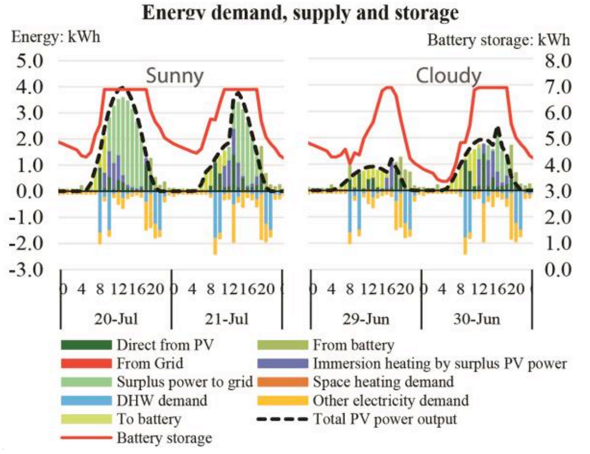
Figure 6c. Mid-season energy demand, supply and storage

Daily profiles for summer days

In figure 7a the indoor air temperature peaks at between 23 to 26ºC. During summer time, the TSC is not in use, and the MVHR changes to the summer mode, bypassing heat recovery. Figure 7b indicates the DHW demand and the corresponding temperatures in thermal store, ranging between 50ºC and 65ºC, which is heated by both heat pump and excess PV energy. In figure 7c the PV power is able to supply all the building energy needs, no power is imported from grid. A relatively large amount of electricity is exported to the grid. The majority of PV power generation is used to charge the battery in the morning, to heat thermal store during midday and the remainder is exported to grid in the afternoon.







Annual energy performance

Figure 8 summarises the annual simulated energy performance, indicating that the building has the potential to be about 70% autonomous (that is, independent of grid supply), whilst over the year its grid export to import rate is 1.75:1.

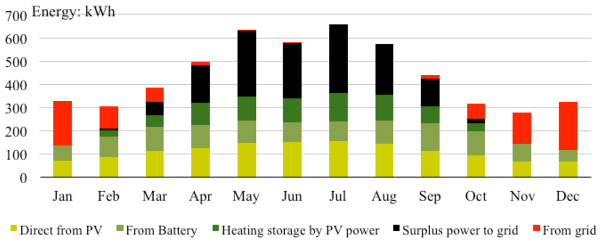


Figure 8: Monthly energy performance.

Conclusion

The paper has described the development of an energy modelling framework to simulate the SOLCER house based on the building energy model HTB2 with sub-models for the house's innovative energy systems.

There is good agreement between simulated and measured performance for thermal environmental systems, which includes the Transpired Solar Collector (TSC) and Mechanical Ventilation Heat Recovery System (MVHR). This indicates that the sub-models developed for the thermal system are operating as designed.

The annual simulation of energy use indicates that an energy positive performance is possible achieving some 70% autonomous operation independent of grid supply, whilst over the year its grid export to import rate is 1.75:1.

A fundamental aim of the design was to construct the building at costs comparable to market costs for this type of house, whilst using off-the-shelf technology and local supply chains.

The modelling framework is now being used to explore variations to the design of the SOLCER house, including orientation, size and alternative energy systems.

Acknowledgement

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