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Evaluation on distributed renewable energy system integrated with a Passive House building using a new energy performance index

Yang Wang [a, b, *], Jens Kuckelkorn [c], Daoliang Li [a], Jiangtao Du [d]

[a] College of Information and Electrical Engineering, China Agricultural University, Beijing, China
[b] School of the Built Environment and Architecture, London South Bank University, London, UK
[c] Division of Technology for Energy Systems and Renewable Energy, Bavarian Centre for Applied Energy Research (ZAE Bayern), Munich, Germany
[d] School of the Built Environment, Liverpool John Moores University, Liverpool, UK

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ABSTRACT

The newly built Passive House school buildings have broadly employed a novel distributed renewable energy system for heating energy supply in Germany. This article proposed a distributed renewable energy system and investigated its performances (energy and thermal comfort) through numerical simulations in a school building. A new energy performance index has therefore been defined to evaluate this renewable energy system in the school. The energy system simulation (ESS) methodology and numerical models were validated by typical on-site measurements, including borehole outlet temperature and COP of heat pump. In addition, more numerical simulations relevant to energy performance of the proposed renewable energy system have been conducted based on the effects of the borehole outlet temperature and heat recovery efficiency. Several important findings can be achieved as follows. 1) Increasing the heat recovery efficiency of water-water heat exchanger facility would not only significantly improve COP, but also reduce obviously electricity use and energy costs. 2) A comparison, between the systems with heat recovery efficiency of 0.9 and without heat recovery, demonstrated the reduction of CO_2 emissions up to 5.3 kg per typical winter day in Germany. 3) There is a significant correlation between the heat pump COP and the heat recovery efficiency. 4) In addition, most environmental measurements in the reference rooms in the school building fall in the comfort zone in winter, which indicates the heating energy supply based on this distributed renewable energy system could support a proper level of thermal comfort.

1. Introduction

The energy challenge, climate change and reduction of carbon emissions have substantially exerted high pressure on the building energy reductions [1,2]. In Germany, currently, buildings are responsible for approximately 40% of total annual national energy consumption and one third of national carbon emissions [3–5].

Distributed renewable energy technology used in buildings is a critical approach to effectively reduce the carbon emissions and improve energy efficiency and performance, from the both sides of energy supply and demand. Small and micro-scale distributed renewable energy systems (including building, neighbourhood or community scale), recently, have been increasingly applied in buildings due to the introduction of attractive incentives through the beneficial feed-in tariffs and government subsidies on investments [6]. Recently, Stadler enhanced the potential of renewable energy resources application in buildings, and the importance of managements of diverse energy systems, as well as the opportunities of design optimizations [6]. This study particularly discussed a small-scale distributed renewable energy system in a residential building, including several conversion and storage units. In addition, a two-step multi-objective optimization method has been proposed in order to size both electrical and thermal energy systems, which considers thermoeconomic performance indicators to fit grid operator and consumer interests [6]. Guen et al. investigated the integration of renewable energy technologies and building renovation to improve neighbourhood-scale building energy sustainability in Hemberg, Switzerland [7]. The energy performance (thermal) in the building studied was

* Corresponding author. College of Information and Electrical Engineering, China Agricultural University, Beijing, China.
E-mail addresses: wanghongyang1767@gmail.com, wangy47@lsbu.ac.uk (Y. Wang).

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remarkably improved through this integrated renewable system. Wind and solar energy systems could supply more than 14% of total energy demand concerning rigorous grid restrictions based on the base line, i.e., the integration of both PV panels and wind turbines along with energy storage [7]. Panchal et al. designed and developed a solar-based Rankine cycle and geothermal-based system for multi-generation of renewable energy system in residential buildings, which was applied at a community scale [8]. The energy efficiency of this multi-generation systems are higher than the single one by 20%. Using TRNSYS and an operational simulator in a building complex (Korea Institute of Energy Research (KIER)) Liu et al. [9] built the building load models used for predicting the electricity consumption with the integration of both multi-type engines and renewable energy systems including photovoltaic (PV) cells and solar collectors, fuel cells, and bio-ORC (organic Rankine cycle). This model is capable of calculating the energy consumption based on the number of running engines and their thermal efficiency, as well as the fuel consumption relevant to heating energy and the efficiency [9]. The result shows that around 5% of the produced electricity was used for the system operation, and the tool brings in reasonable predication of electricity production, fuel consumption and working performances of systems [9]. Ikeda and Ooka proposed a new optimization strategy for the operating schedule of energy system, taking into consideration uncertainty of renewable energy sources and demand variations [10]. Implemented in an office building with a floor space of 20000 m^2, this study [10] illustrated that two-time steps recalculation strategy (TtsR) needed less computational time than all-time steps recalculation strategy (AtsR) to gain a quasi-optimal approach in terms of unpredicted changing conditions in the power generation and requirement. Using several case study buildings (semi-detached two-storey house, 106 m^2 floor area) in Ireland, Moran et al. presented investigations of life cycle cost and environmental performances using the indicators for net zero energy buildings [11]. Based on the global warming potential and energy consumption, these indicators were produced for buildings with diverse heat sources including a gas boiler, biomass boiler, a domestic gas fired CHP, heat pump and renewable technologies [11]. The results showed that the future buildings should be installed with well-insulated envelopes and high-level air-tightness in order to minimize the heating load; meanwhile, the heating systems used should have deliver the minimum impact on the natural environment through adopting low carbon technologies, e.g. using heat pump or biomass boiler.

For the integrated energy systems in buildings, a proper energy performance indicator is crucial in order to effectively evaluate their energy performances and seek possible approaches to improve the performances [4,5,12–14]. It has been regarded as a big challenge to produce a novel energy performance indicator capable of minimizing energy consumption and without compromising comfort levels. Marta and Panao proposed a methodology for calculating the overall renewable energy fraction (OREF) used for net zero energy building, which included two performance indicators: the renewable energy ratio (RER) and the on-site energy fraction (OsEF) [12]. The results revealed that the payback credit option without considering embodied energy would theoretically generate OREF higher than 100%. OREF could be an independent indicator from direct use, fossil fuels energy carriers, other fossils fuels energy carriers [12]. Compared with the exported fraction, in addition, it will provide buildings with higher capabilities of self-consumption of on-site produced energy [12]. Bakar et al. conducted a review of the energy efficiency index (EEI) in buildings, which was used as an indicator to evaluate and measure the energy consumption [4]. In order to establish a universal index based on the standardized procedures, however, more work could be still required [4]. Guillermo et al. developed a new index of energy rating factor (ERF) in terms of building energy consumption across different seasons [13]. It has been found that buildings with distributed air conditioning (AC) units have better energy performances than those with centralized AC [13]. This could be explained by the fact that centralized units need much higher energy input, which would lead to adaptation difficulties to inconstant outdoor temperatures; at the same time, users could not effectively control those units. Another new index EEI_B proposed by Gonzalez et al. can measure the energy efficiency of both old and newly built buildings [5]. Updated in time and using real data, this index stands for a real measure for the efficiency and therefore boosts the improvement of energy performance. Wang et al. defined a novel factor named as energy conservation ratio (ECR), targeting at the evaluation of energy performance of air conditioning unit combined with mechanical ventilation heat recovery system in Passive House buildings [14]. A higher ECR value means more energy savings. Based on CFD simulations and on-site measurements, ECR would increase with the increasing heat recovery efficiency and the reduction of temperature difference between the supply and external air.

In summary, a number of studies are currently available based on the optimization of renewable energy systems and the strategy of their operations in buildings. However, few studies focused on performance evaluations and energy indicators of the distributed renewable energy system in Passive House school buildings. In this article, a new performance assessment index to justify the renewable energy system in Passive House buildings, namely Energy Performance Ratio (EPR), has been proposed and applied. The objective of this study is to evaluate the application of this new index. The unique purpose of this study is to establish a new way to reflect energy performance of the renewable energy system based on correlations between the heat transfer level of heat pump, the energy demand, and the new index in Passive House or other similar buildings. In the following sections, the distributed renewable energy system was first introduced. Second, numerical modelling methodology and models were validated by typical on-site measured data, an energy performance ratio was proposed. Third, energy performances of one improved distributed renewable energy system were numerically simulated, taking into account the effects of borehole outlet temperature and heat recovery efficiency. Finally, the energy performance ratio was applied and its correlations to functions of the heat pump were tested.

2. System description of distributed renewable energy system

Combined with a renewable energy system including GSHP unit, a pilot project of Passive House school building has been established at a location of southern Germany (Lat.: 48°18′40″, Long.: 11°53′49″, Fig. 1). The GSHP system integrated in the Passive House building employs Heliotherm heat pump unit, which has a nominal capacity of 120 kW for heating. The heat is transferred from the ground through a closed loop system, which is buried underground. Fig. 2 demonstrates the schematic diagram of GSHP system and Passive House building. The actual building heating load profile and sorted annual heating load for 2014 as well as the sorted annual heating load profile for 2012 and 2013 have been measured (Fig. 3). It has been found that the building demand is normally fulfilled by the GSHP system due to the sorted heating load lying within 90 kW except those discrete peak loads. Meanwhile, the back-up heating energy is provided by a geothermal district heating when the local distributed renewable energy system failed to meet the heating energy demand.