Energy Conversion and Management 142 (2017) 153–175

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Approaches to enhance the energy performance of a zero-energy building integrated with a commercial-scale hydrogen fueled zero-energy vehicle under Finnish and German conditions

Sunliang Cao [a,*,1], Konstantin Klein [b], Sebastian Herkel [b], Kai Sirén [a]

[a] Department of Mechanical Engineering, School of Engineering, Aalto University, PO Box 14400, FI-00076 Aalto, Finland (Dr. Sunliang Cao will start his Assistant Professorship in the Department of Building Services Engineering at the Hong Kong Polytechnic University, Hong Kong, from March 20th 2017)
[b] Solar Building Department, Fraunhofer-Institute for Solar Energy Systems, Heidenhofstrasse 2, 79110 Freiburg, Germany

ARTICLE INFO

Article history:
Received 25 November 2016
Received in revised form 7 March 2017
Accepted 11 March 2017

Keywords:
Zero-energy building
Zero-energy vehicle
Hydrogen vehicle
Ground source heat pump
PV
Wind turbine

ABSTRACT

The building and transportation sectors in the EU are progressing towards the zero-energy/emission levels according to the EU 2050 roadmap while the H_2 vehicles have recently started to be commercialized. Based on these backgrounds, this paper focuses on the investigation of a hybrid zero-energy system which consists of a zero-energy building and a H_2 vehicle integrated H_2 system. The focused aspects in this paper are the impact of the ground source heat pump (GSHP), the Finnish and German climate conditions, and the on-site PV and wind turbine capacities and their mix on system performance. The parametric analyses based on these aspects are conducted in the TRNSYS simulation environment. The results show that the use of a GSHP helps realize the net zero-energy balance with less local generation, while improving the overall matching capability with marginal influence on the utilization of the cogenerated heat. Moreover, the Finnish condition has a clear preference on the wind based net zero-energy system, whereas the German condition has a preference on the solar based system. Correspondingly, the optimal mix of PV and wind turbine for the net zero-energy cases occurs when the PV generation percentage reaches 20% and 60% under Finnish and German conditions, respectively.

1. Introduction and background

In the EU, the building and transportation sectors combined account for around 60% of the final energy consumption [1]. Therefore, the efficiency enhancement and energy reduction of these two sectors can play a significant role in meeting the EU 2050 roadmap, which defines that the EU should cut the overall emissions to 80% by 2050 below the 1990 levels [2]. Correspondingly, the EU 2050 roadmap proposes that the building and transportations sectors should cut the equivalent emissions to 90% and 60% below the 1990 levels, respectively [2]. In order to meet these strict targets, the EU parliament has introduced several directives regarding these two sectors: the EU Directive 2010/31/EU regulates that all new buildings built from the beginning of 2021 should be nearly zero-energy buildings [3], while the EU Directive 2009/33/EC [4] regulates that the purchase of the vehicles should take the energy and environmental impacts into account in order to promote the market for clean and energy-efficient vehicles. The ambitious roadmap and the directives also significantly stimulate research activities in the academic world for these two sectors, especially regarding the solutions and the paths towards their continuously reduced energy and emissions [5–9]. Representatively, the so-called “zero-energy/emission building” (ZEB) [10–13] and “zero-energy/emission vehicle” (ZEV) [14–17] have been intensively studied in the recent decade, foreseeing the trend that these two sectors are progressing towards the zero-energy/emission level.

Furthermore, a new recent trend in the transportation sector is the commercialization of the H_2 vehicle (HV), such as the “Toyota FCHV-adv” [18], “Toyota Mirai” [19], “Hyundai Tucson Fuel Cell” [20], and “Honda FCX Clarity” [21]. Their commercialization is mainly based on the mature technology of the 4th generation H_2 storage tank and the fuel cell: the former one is made of the nano-carbon fibre with a thermoplastic liner which can withstand a maximum of 700 bar [22,23], thus significantly enhancing the portability of the H_2 storages, while the latter one is normally a proton exchange membrane fuel cell (PEMFC) for the vehicle which enables a silent and stable oxidation process of the hydrogen fuel

---

* Corresponding author.
E-mail addresses: sunliang.cao@aalto.fi, caosunliang@msn.com (S. Cao).
[1] Assistant Professorship in the Department of Building Services Engineering at the Hong Kong Polytechnic University, Hong Kong.

http://dx.doi.org/10.1016/j.enconman.2017.03.037
0196-8904/

Nomenclature

AHU	air handling unit
AMI	averaged matching index
DHW	domestic hot water
$E_{exp,a}$	annual exported energy to the electrical grid (kWh/m^2·a)
$E_{direct,a}$	annual net direct energy consumption (kWh/m^2·a)
$E_{imp,a}$	annual imported energy from the electrical grid (kWh/m^2·a)
EV	electric vehicle
FSOC	fractional state of charge
$FSOC_{lim}$	a specific FSOC level of the H_2 storage for the control of the fuel cell
GSHP	ground source heat pump
HV	hydrogen vehicle
L_{elec}	the total electric load power (kW)
NOCT	nominal operating cell temperature condition
OEFe	on-site electrical energy fraction
OEMe	on-site electrical energy matching
O&M	operation and maintenance
PEMFC	proton exchange membrane fuel cell
P_{exp}	exported power to the electrical grid (kW)
$P_{FC,home}$	the generated fuel cell power for the domestic usage (kW)
$P_{FC,road}$	the generated fuel cell power for the transportation usage (kW)
P_{gen}	the on-site electricity generation power from wind turbine and/or PV after the regulator/inverter (kW)
P_{HVsys}	the electric power sent to drive the HV integrated H_2 system (kW)
P_{imp}	imported power from the electrical grid (kW)
$Q_{uti,HVsys}$	the utilized cogenerated heat from the H_2 system (kW)
REe	renewable electrical energy
r_{REVst}	the on-site renewable energy ratio for charging the H_2 storages
STC	standard testing condition
ZEB	zero-energy/emission building
ZEV	zero-energy/emission vehicle
η_e	the energy efficiency of the HV integrated H_2 system

[24]. These H_2 vehicles expand the horizons for the ZEVs from the conventional bio-fuel based or battery-based vehicle to a brand-new H_2 based ZEV concept. Similar as the battery-based ZEV [16], the H_2-based ZEV should guarantee that the H_2 fuel needs to be generated by the renewable source, such as the photovoltaic driven electrolysis process [25], rather than the fossil source, in order to be classified as the "zero-energy/emission". Furthermore, the H_2 refueling station should be conveniently accessed to.

Very often, the ZEB(s) and the ZEV(s) are studied separately, whereas limited studies [26–30] have focused on the integration and interaction between the ZEB(s) and the ZEV(s). Among these limited studies, most commonly analysed cases are the integration of the ZEB(s) with the electric vehicle(s), via the so-called "Vehicle to Building (V2B)" or "Building to Vehicle (B2V)" interactions. On one hand, part of the research focused on how the integration of the electric vehicle (EV) alters the load and matching patterns of the ZEB(s). For example, Munkhammar et al. conducted two studies investigating the integration of the EV into the PV supported zero-energy building in Sweden [26] and UK [27], respectively. They showed that by considering the EV load in the zero-energy balance calculation of the ZEB, the self-consumption ratio of the PV and the renewable energy fraction of the local load are respectively enhanced and attenuated due to the escalation effect of the total load during the night-time when the EV is charged and the PV generation is insufficient. On the other hand, some other research treated the electric vehicle(s) as the distributed storage(s) or the additional demand response resource(s) for the smart building energy management system. For example, Erdinc [28] and Aziz et al. [29] integrated the EV(s) into the PV supported building energy management system for one residential [28] and one commercial building [29], respectively, and both of the studies proved the demand response potentials of the EV(s) for shifting or regulating the load and peak power profiles of the building system. Moreover, the advantages of integrating the EV(s) have also been noticed by Wang et al.'s research [30] for enhancing the flexibility of the building energy and comfort management and improving the reliability of the on-site renewable power supply.

Despite of the aforementioned work on the integration of the ZEB(s) and the EV(s), almost no research has focused on the integration between the ZEB(s) and the H_2 vehicle(s), except two former studies presented by the first author of this paper in [31,32]. Cao and Alanne [31] investigated the technical feasibility to integrate one H_2 vehicle with one 150 m^2 zero-energy single family house in Helsinki. The principle is to send the surplus PV or wind turbine generation to the H_2 system for charging the H_2 storages, while the vehicle fuel cell has an option to discharge the H_2 storages for covering the domestic electrical energy shortage. Meanwhile, the cogenerated heat from the H_2 system can be used for domestic heating. With this principle, all the generated H_2 fuel is originated from the renewable source, and the H_2 refueling station is home-based and thus can be conveniently accessed to. The results show that by a 14 kW wind turbine, the nearly ZEB can be met with annual full availability of the HV, whereas by a 178 m^2 PV (19.2 kW NOCT power), although the ZEB can be met, there are 48 days' annual unavailability for the HV due to the insufficient solar resource during the winter season in Helsinki. In a following study, Cao [32] refined the control strategy used in [31], and allowed the use of grid electricity as a backup for the H_2 system in case the surplus on-site renewable generation is insufficient. This refined control is particularly beneficial for the PV supported system in Helsinki where the solar resource is insufficient in winter. Cao [32] also compared the system performances when the ZEB respectively integrates an HV and an EV. The results in [32] show that the building with the HV will be more demanding in meeting the net zero-energy balance which requires a 4 kW higher wind turbine or a 35.6 m^2 (3.85 kW NOCT power) larger PV, resulting from the less efficient HV integrated system (at the magnitude of 45–65%) than that of the EV integrated system (at the magnitude of 88–90%).

Despite of the novelty for investigating the integration of the ZEB with the HV in the first author's former studies in [31,32], there are still several limitations. First, the building heating system was based on the direct electric heaters and the cogenerated heat from the H_2 system. Although around 20% of the heating demand could be covered by the cogenerated heat from the H_2 system with the 14 kW turbine or the 178 m^2 PV (19.2 kW NOCT power), the remaining 80% of the heating demand should be still entirely covered by the direct electric heaters, which is a very inefficient solution. Therefore, in this study, the authors are keen to further expand the hybrid system with a ground source heat pump (GSHP)