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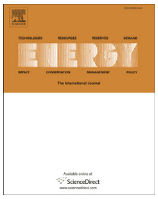

Stand-alone renewable combined heat and power system with hydrogen technologies for household application

R. Lacko [a], [*], B. Drobnič [b], [c], M. Mori [b], [c], M. Sekavčnik [b], [c], M. Vidmar [a], [c]

[a] INEA d.o.o., Ljubljana, Slovenia
[b] Faculty of Mechanical Engineering, University of Ljubljana, Ljubljana, Slovenia
[c] Centre of Excellence for Low-Carbon Technologies, Ljubljana, Slovenia

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ABSTRACT

A hybrid energy system, based on renewable energy sources and with hydrogen storage, can become an alternative for stand-alone electricity and heat supply. The objective of this work is to evaluate the feasibility of a completely renewable supply of power and heat for an isolated household, and a comparison to reference and alternative energy supply scenarios. In this paper, an energy system using fossil and renewable energy sources is compared to a system using only renewable energy sources (solar and wind) with hydrogen-based energy storage technologies. A reference household in Slovenia's coastal region was used for modelling and numerical simulation. Simulations and optimal energy system identification were conducted by considering the geographical location and availability of energy sources, load dynamics, and components' technical and economical characteristics. A household with electricity consumption of 11 kWh/day, hourly peak power demand of 3.8 kW and 660 L of oil-equivalent yearly heat demand was considered as the stand-alone load. The results show that 100% renewable electricity and heat supply of a reference household is technically feasible and is more cost-effective, compared to systems utilising fossil heat.

1. Introduction

Climate change mitigation, natural environment preservation, increasing needs for energy and uncertain costs of fossil fuel supply in the future are the reasons for the increasing interest in local and RES (renewable energy sources), as opposed to fossil energy use. While fully energy self-sufficient dwellings are still rare, solar and wind power units have been widely adopted for private family homes.

The introduction of RES into the energy supply, however, raises certain issues in load balancing due to their intermittent and non-storable nature. This especially applies to wind and solar energy, and (to a lesser respect) to other RES, such as geothermal energy, hydropower and biomass. Furthermore, a single self-sufficient user presents the most challenging case of RES integration, due to its inability to import and export surplus energy.

Electricity supply based on renewable energy sources, coupled with hydrogen storage, has already been proposed as a technically viable solution [1–8]. Several technical and economic analyses of stand-alone RES energy systems with hydrogen storage, focusing on electricity supply only, have already been discussed [9–16]. Such hybrid energy systems have been experimentally demonstrated [17]. Furthermore, studies on RES-hydrogen energy systems considering CHP (combined heat and power) have been reporting on energy and exergy analysis [18], system performance assessment methodology [19] and a mathematical model of a wind-hydrogen CHP system with metal hydride storage [20]. RES-hydrogen CHP systems have also been successfully demonstrated [21–23].

In research undertaken within CONOT (Centre of Excellence for Low-Carbon Technologies),[1] an optimal self-sufficient renewable hydrogen energy system has been numerically determined, based on an actual geographical location (Slovenia's coastal area), the availability of energy sources, electric load dynamics and components' technical and economical characteristics [24]. Numerical results were experimentally proven using a demonstration system with hydrogen technologies [25]. The results of both studies have

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* Corresponding author. Tel.: +386 1 5138109; fax: +386 1 5138170.
E-mail addresses: rok.lacko@inea.si, rok.lacko@gmail.com (R. Lacko), bostjan.drobnic@fs.uni-lj.si (B. Drobnič), mitja.mori@fs.uni-lj.si (M. Mori), mihael.sekavcnik@fs.uni-lj.si (M. Sekavčnik), marijan.vidmar@inea.si (M. Vidmar).

[1] Centre of Excellence for Low-Carbon Technologies, Hajdrihova 19, 1000 Ljubljana, Slovenia.

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shown that the required relatively large production capacity causes excess electricity generation, which is not used by the household.

Although stand-alone RES-hydrogen CHP systems have been proposed and partially studied, further, more detailed hour-by-hour analysis based on actual data is needed. Studies also show that results are highly dependent on numerous local factors, e.g. meteorological conditions; therefore, a site-specific analysis is needed [19,26].

This paper is a continuation of our previous work [24,25] with the scope to investigate the use of excess electricity and waste heat by a stand-alone RES-hydrogen energy system in Slovenia. For that purpose, numerical simulation of a single household's heat and power supply from renewable surplus electricity, together with the electrolyser and fuel cell waste heat was compared to fossil heat production. The energy models considered in this research are composed of photovoltaic panels, wind turbines, electrolyser, hydrogen storage tank, fuel cell, power converter, thermal storage and both electricity and heat demands.

2. Methodology

Three different feasible energy systems (or scenarios) capable of supplying the required electric and thermal demand have been analysed by numerical simulation:

i .a reference energy system in which (renewable) electricity and (fossil) heat are produced entirely separately,
ii .an alternative energy system that utilises a fuel cell's excess heat and converts renewable excess electricity into heat using a resistive heater, saving on fossil fuel used for heating,
iii .the third energy system includes a heat storage capacity, which enables better utilisation of available excess energy produced by renewable excess electricity, as well as the fuel cell's and the electrolyser's available heat.

The first two systems balance heat demand and production within a one-hour period; i.e. the energy produced can only be consumed within the same hour. In the third system, the heat can also be used later.

2.1. Numerical model and simulation

HOMER[2] numerical simulation software was used to determine the optimal energy system configuration based on the lowest net present cost. The energy system's physical behaviour and its life-cycle cost, which is the total cost of installation and operation over its life span, have been modelled. It is an input/output model making annual analyses in steps of one hour. The general inputs are the demands, capacities, component technical characteristics and costs. Outputs or results are the energy balances, capacities, resulting annual production and life-cycle costs. For simulating a totally renewable system (100% RES), a custom-made numerical model (for heat simulation only) was designed.

In this paper, mathematical models of energy systems are not based on differential equations; instead, a quasi-dynamic approach has been used, and stationary conditions within each hourly interval have been assumed. For each time interval, an energy balance has been calculated, presented in general by Eq. (1),

$$E_{\text{produced},t} - E_{\text{consumed},t} - E_{\text{excess},t} = 0 \tag{1}$$

where E denotes energy at time t.

The conversion of solar radiation to electrical energy is achieved with a PV (photovoltaic array). The power output of the PV array depends on the amount of radiation striking its surface, which in general is not horizontal. Thus, in each time step, HOMER calculates the global solar irradiation on the surface of the PV array. In the calculation of the PV's power output, its rated capacity, derating factor, solar irradiation, temperature coefficient of power and PV cell temperature are considered. We have generalized the influences reducing rated cell performance by using a conservative 80% derating factor [27], thus the PV output power has been calculated using Eq. (2),

$$P_{\text{PV}} = Y_{\text{PV}} \cdot f_{\text{PV}} \cdot \left(\frac{G_T}{G_{T,\text{STC}}}\right) \tag{2}$$

where Y_{PV} is the rated capacity, f_{PV} is the derating factor, G_T is the solar radiation incident on the PV array, (also known as the HDKR model, which is elaborated in Ref. [28]) and $G_{T,\text{STC}}$ is the incident radiation at standard test conditions (1 kW/m^2).

A wind turbine converts wind kinetic energy into electrical energy. Its power depends on wind speed, hub height, actual air density and wind turbine power curve [29]. The chosen hub height (10 m) is equal to the anemometer height which simplifies the wind turbine output power calculation, as defined by Eq (3).

$$P_{\text{WT}} = \left(1 - \frac{Bz}{T_0}\right)^{g/RB} \cdot \left(\frac{T_0}{T_0 - Bz}\right) \cdot P_{\text{WT,STP}} \tag{3}$$

where B is the lapse rate (0.00650 K/m), z is the altitude (10 m), T_0 is standard temperature (288.16 K), g is gravitational acceleration (9.81 m/s^2), R is gas constant (287 J/kg K) and $P_{\text{WT,STP}}$ is the wind power output at standard temperature and pressure.

The cut-in wind speed of the chosen wind turbine equals 3 m/s, and at wind speeds of 13 m/s it reaches peak output power.

The hydrogen production rate is defined by electrolyser's efficiency and minimum load ratio (technical minimum). Experimentally determined values, acquired within CONOT research, 72% and 50% respectively, were used [30,31]. We have assumed an ideal (no loss) hydrogen tank as a container used to store produced hydrogen for later use. A fuel cell system is used to re-power stored hydrogen, when there is not enough RES. Fuel cell power production depends on a fuel curve; an experimentally defined fuel curve is shown in Fig. 1. Hydrogen consumption is calculated using a simplified linear fuel curve which is based on measurements and defined by Eq. (4),

$$F = F_1 \cdot P_{\text{FC}} \tag{4}$$

where F_1 is the fuel curve slope (0.066 kg/h/kW) and P_{FC} is the electrical output of the fuel cell. The fuel cell electric efficiency is

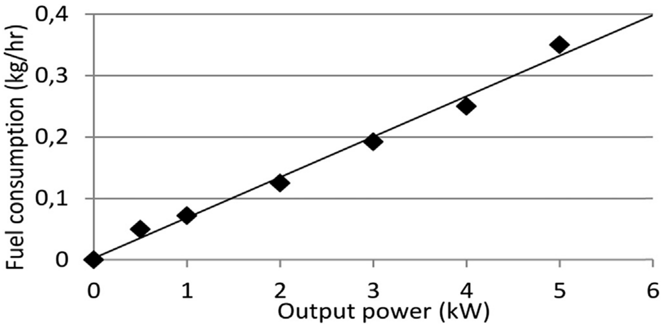

Fig. 1. Experimentally defined fuel cell's fuel curve [31]. Corresponding fuel cell's maximum efficiency is 45%.

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[2] http://homerenergy.com/pdf/homergettingstarted268.pdf.

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