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Hydrogen energy system with renewables for isolated households: The optimal system design, numerical analysis and experimental evaluation

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ABSTRACT

One potential solution for stand-alone power generation is to use hybrid energy systems with hydrogen storage. In this paper, the physical behaviour of a hydrogen energy system with renewables has been numerically simulated and experimentally re-enacted. A reference household in Slovenia's coastal region was used to identify the optimal energy system design, by considering the geographical location, availability of energy sources, actual load dynamics, and components' technical and economical characteristics. The results show that optimal electricity supply is technically feasible with a 100% renewable system, consisting of wind turbines and solar photovoltaic arrays, including hydrogen technologies (electrolyser, hydrogen tank, fuel cell). The optimal feasible system capacity (33 kW), with the lowest total net present cost (€136,063), is approximately eight times larger than the peak power demand (3.8 kW). The experimental work was performed at hydrogen laboratory facilities. Experiments proved the possibility of alternative uses of existing industrial hydrogen technology for balancing power supply and demand, with a mere 3% deviation from numerical results

1. Introduction

The increasing needs for energy and the uncertain costs of future fossil fuel supplies, along with the mitigation of climate change effects and natural environment preservation, are the reasons for the increasing interest in renewable (RES), local and distributed energy sources, as opposed to centralised fossil primary energy usage. 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 balancing energy demand and supply due to their variable 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 stand-alone user presents the most challenging case of RES integration, due to its inability to import and export surplus energy.

In coping with the misalignment of energy production and demand, the use of energy storage is usually required [1]. Hydrogen technology is a technically viable storage solution especially in energy systems with high shares of renewables [2–4]. Several technical and economic numerical simulations of stand-alone RES energy systems with hydrogen storage have already been discussed [5–11]. Such hybrid energy systems have also been experimentally demonstrated [12–15] or partially experimentally validated [16].

Although stand-alone RES–hydrogen energy systems have been proposed and studied, common shortcomings of those analyses include (a) a pre-determined system design, (b) optimization of system's performance without preliminary optimising its configuration or design, (c) overgeneralised input parameters, such as using typical daily consumption data sets only, (d) short term simulation only (day, week) and finally (e) numerical models and simulation results not being experimentally evaluated and verified. Studies also show that results are highly dependent on numerous local factors, e.g. meteorological conditions; therefore, a site-specific analysis is needed for credible results [17].

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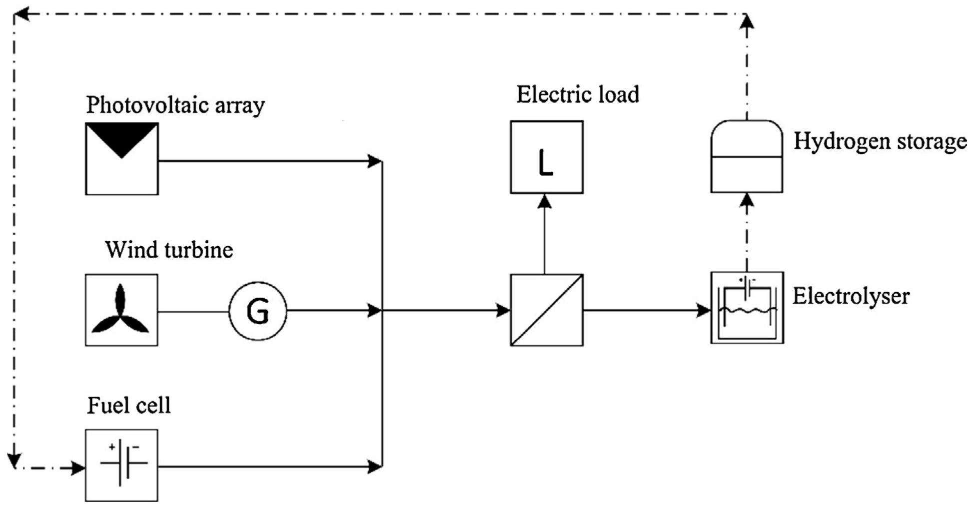

Fig. 1. A schematic of the numerical model of a stand-alone energy system with renewables and hydrogen storage.

This paper aims to overcome the detected shortcomings by considering the topics of optimal hydrogen–RES system design based on relevant, site specific and actual measured input data, hourly system's dynamics analysis for a period of one year, including experimental evaluation of numerical results. An RES–hydrogen energy system for a self-sufficient power supply of a single household is described and analysed in this study, as shown schematically in Fig. 1. In this example, hydrogen is produced (and stored in a tank) by an electrolyser, which is powered by the surplus electricity from renewable energy sources, using solar and wind technologies (specifically at summer daytime). When RES are scarce, or demand is high, additional power is needed; therefore, the fuel cell converts the chemical energy of the stored hydrogen gas directly into electricity (usually at night and in winter).

2. Methodology

The scope of this work is, first, to find an optimal feasible configuration of a self-sufficient energy system based on RES and hydrogen technologies for a remote household located in Slovenia and to numerically model its physical behaviour and, second, to experimentally validate the results of the system's operation. In this study, only electricity is considered. Experimentally, only hydrogen technologies are validated, while renewables are only simulated. A demonstration laboratory system with hydrogen technologies was used for experimental evaluation of the numerical results; its photograph is shown in Fig. 6.

2.1. Numerical model and simulation

The optimal RES–hydrogen energy system structure was determined using the HOMER numerical simulation software, 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. HOMER is a deterministic 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.

In this paper, the power supply of a stand-alone household, located in Slovenia, is considered. In the model (Fig. 1), AC electrical load is supplied, via DC–AC inverter, primarily by wind turbine and photovoltaic array. Excess electricity produced from RES is stored as electrolytically produced hydrogen. When primary RES are scarce or unavailable, the fuel cell system produces power from stored hydrogen.

Here, 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),

$$E_{\text{produced}}(t) - E_{\text{consumed}}(t) - E_{\text{excess}}(t) = 0 \quad (1)$$

where E denotes the total energy at time interval t.

For the conversion of solar radiation to electrical energy, a photovoltaic array (PV) has been used. The power output of the PV array depends on the amount of radiation striking its surface, which is generally not horizontal. Thus, in each time step, the model 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. For converting wind kinetic energy into electricity, a wind turbine (WT) was used. Its power depends on wind speed, adjusted to hub height, and its power curve [18]. The cut-in wind speed of the chosen wind turbine equals 3 m/s, and it reaches peak output power at wind speeds of 13 m/s. The hydrogen production rate is defined by the electrolyser's efficiency and minimum load ratio (technical minimum). Experimentally determined values 72% and 50%, respectively, were used [19]. A hydrogen container is used to store produced hydrogen for later use. A fuel cell system re-powers stored hydrogen when there is not enough RES. Fuel cell hydrogen consumption depends on the fuel curve, shown in Fig. 2, which was experimentally defined [20]. The fuel cell's electric efficiency is based on a lower heating value (LHV): 120 MJ/kg (maximum efficiency is 48%). The DC/AC power converter's energy efficiency of 0.9 has been used in the calculation.

The model simulates different system configurations with several combinations of components (and their sizes), which are specified in the components' inputs. All feasible system configurations are then listed in order from most cost-effective to least cost-effective, based on their net present cost (NPC).

The project's lifetime is assumed to be 20 years, as well as all components' lifetime, except for the fuel cell, which has to be replaced every 20,000 operating hours. The annual real interest rate considered in the model was 6%. Table 1 shows components' parameters as boundary conditions of the model, considered in optimising the configuration of the system. The sizes of the PV array and wind turbine considered in calculation were 10–30 and