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Transient simulation modelling and energy performance of a standalone solar-hydrogen combined heat and power system integrated with solar-thermal collectors

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HIGHLIGHTS

- A solar-hydrogen (SH) CHP system integrated with thermal collectors (ST) modelled.
- Complementary operational aspect of the two heat sources (SH CHP and ST).
- Heat matching capability of SH CHP with the un-supplied demand from ST in winter.
- System meets 100% power load and 95% of the annual hot water demand (case study).
- Attractiveness of this renewable system in household applications in remote areas.

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ABSTRACT

A computer simulation model of an integrated solar-hydrogen combined heat and power system with solar-thermal collectors (SH CHP-ST) is developed in TRNSYS to supply both power and heat (i.e. hot water demand) for a standalone application. The model is applied to a case study of a remote household in southeast Australia with conservative loads. Two possible configurations of the integrated system are studied and the optimal one is selected. The simulation results show that the system (i.e. designed to meet the full power demand) with the adopted configuration can supply 95% of the annual hot water demand, with more than 90% of this demand met in winter compared to 54% met from the collectors of the solar-thermal (ST) only. The fuel cell heat that is transferred for utilisation is evaluated in this integration along with that of the solar collectors. An important aspect about the heat matching capability of the fuel cell with the un-supplied demand from the ST throughout the year is concluded. This presents an advantageous characteristic of this integration and permits the system to be effectively used to supply full power and almost the entire hot water demand in the standalone remote domestic case (i.e. in southeast Australia) studied in this paper.

1. Introduction

1.1. Solar-hydrogen combined heat and power systems

Solar energy, that is seen to be a major renewable source of energy, is abundantly available in many geographical locations around the world. With current technologies, it can be transformed into electricity and heat through photovoltaics (PVs) and solar thermal collectors respectively. However, the intermittent supply of solar energy – e.g. during the night-time or cloudy periods – as well as its seasonal variability, offer some challenges to maintain a continuous supply in systems relying on the solar sources [1]. This suggests the need for employing reliable energy storage systems in conjunction with such intermittent renewable energy sources.

Hydrogen has been seen to be a promising energy carrier suitable to store energy [2]. Renewable hydrogen systems can be employed to store the electrical energy generated through renewables (e.g. by using PVs or wind turbines) in the form of chemical energy in the hydrogen molecules for later re-electrification when needed [3]. A renewable hydrogen system comprises an electrolyser, a hydrogen storage tank and a fuel cell as their main compo-

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nents. The electrolyser is powered by the excess electricity generated by the renewables and produces hydrogen through the electrolysis of water [4,5]. The hydrogen produced by the electrolyser gets stored conveniently in a storage tank for example. A fuel cell fed by the stored hydrogen can generate electricity and water with no emissions through the chemical reactions between hydrogen and oxygen (i.e. usually taken from air). This thus covers the deficit in the power supply to the load during the periods that the renewable energy source in use, such as solar, is not available or cannot provide enough supply to fully meet the demand. This system ensures a continuous year-round power supply [6]. The efficiency and energy-carrying capacity of hydrogen do not degrade with time, as opposite to batteries [7], and such systems are thus highly suitable for long-term energy storage (i.e. in places with highly seasonal variations in renewable energy inputs) [8]. While the low maintenance cost of such a system and its capability to act as a long-term energy storage system are its key advantages, further improvement in its capital cost and its overall round-trip energy efficiency can make it even more attractive [9]. When the renewable energy source is purely solar, the system is referred to as solar-hydrogen (SH) system (Fig. 1a) [10].

Photovoltaics/wind turbines hybrid power supply systems, together with a hydrogen-based energy storage solution, were demonstrated and optimised through different methods by many researchers for stand-alone applications [11–17]. Petrollese et al. [18] used real-time predictions of renewable resources and load demand to develop a control strategy to achieve both long and short-term optimal planning of a grid-connected renewable hydrogen energy system. Standalone solar-hydrogen systems were successfully implemented and tested for renewable power supply in residential family houses in Freiburg, Germany [19], Zollbruck, Switzerland [20], China [21], Madrid, Spain [22] and in other twelve case studies. More details about these case studies can be found in reference [23]. Recently, Sir Samuel Griffith Centre, Australia's first zero-emission teaching and research building, has been entirely powered by solar-hydrogen energy via a system aimed to be a pilot for remote off-grid communities [24].

In fact, the production of hydrogen and its subsequent use in fuel cells was proven to be technically viable under dynamic solar irradiance and dynamic load conditions [25]. For instance, the proton-exchange membrane (PEM) fuel cell technology emerged to be one of the promising technologies that can be favourable for use in residential applications, due to the fact that it is quite simple, is easy to start up, can adjust efficiently to variable power demands, operate silently at low temperatures (i.e. 50–100 °C), and require low maintenance [26,27]. The electrical energy efficiency of the PEM fuel cell is in the range of ~30–50% (based on the high heating value (HHV) of hydrogen), depending on the current drawn from the FC (e.g. the load) [28]. In other words a substantial portion of the energy content of hydrogen entering the fuel cell converts to heat rather than electricity and the fuel cell needs to be cooled by removing this heat [29,30]. Recovering the heat generated by the fuel cell and supplying it to an on-site thermal load could enhance the overall energy efficiency of the fuel cell, in heat and power supply applications, to around 70% or more [28,31]. For instance, combined heat and power (CHP) fuel cell systems have been studied to supply power and heat for residential applications [32,33], and the integration of the fuel cell heat with an auxiliary boiler [34] or an electric heat pump [35] have been examined. However, hydrogen in such cases was produced on-site from natural gas in a steam

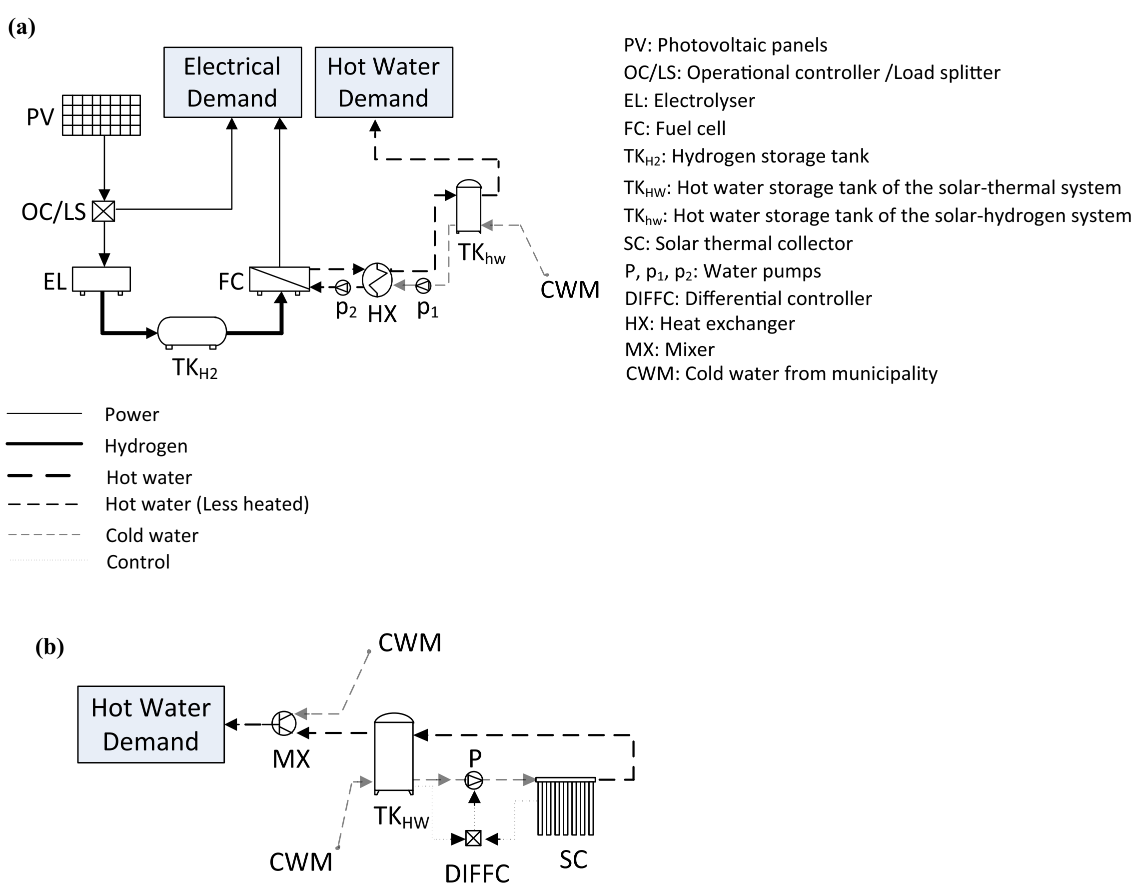

Fig. 1. (a): A schematic diagram of a solar-hydrogen (SH) CHP system; (b): A schematic diagram of a solar-thermal (ST) system.