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Multi-objective sizing optimisation of a solar-thermal system integrated with a solar-hydrogen combined heat and power system, using genetic algorithm

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ABSTRACT

A sizing multi-objective optimisation using the genetic algorithm is performed on a solar-hydrogen combined heat and power system integrated with solar-thermal collectors (SH CHP-ST) to supply both power and heat (i.e. hot water demand) to an application. A solar-hydrogen system is a renewable system with hydrogen-based storage consisting of an electrolyser, a hydrogen tank, and a fuel cell. The fuel cell generates heat while producing power that can be recovered. The heat collected from the fuel cell can be integrated with the heat supply of a renewable solar-thermal system consisting of an evacuated tube collector and a hot water storage tank. A simulation module to model the operation of the whole system is implemented in MATLAB. Energy demands and meteorological data for a remote household located in southeast Australia are considered. The sizes of the main components of the system are optimised with the objectives of maximising the overall reliability of the system, minimising the levelised cost of energy, and minimising the percentage of excess energy from the PV that is not utilised. The results show that the electric reliability of the optimal solutions in favour is always equal to 100%. The maximum thermal reliability that could be obtained is around 96%. A trade-off between the cost of energy and percentage of wasted power from PV is found.

1. Introduction

Renewable systems with hydrogen-based storage have received increasing attention in recent years [1–3]. One of the promising areas of applications (i.e. as energy storage) is to support intermittent photovoltaic (PV)-based standalone power supply systems in standalone applications: i.e. known as Solar-Hydrogen (SH) system. In a SH system, as considered in this paper and illustrated in the top section of Fig. 1, the PV panels that are equipped with a maximum power point tracking device, supply renewable electricity to the load. The excess of the electricity generated by the PVs, energises an electrolyser unit that produces hydrogen [4]. The hydrogen produced by the electrolyser is stored in the hydrogen storage tank (TK_{H2}) for a later use by the fuel cell (FC). For both electrolyser and the FC, Proton Exchange Membrane (PEM) technology is considered. The FC operates when the photovoltaic panels fall short to meet the demand alone due to low or no solar radiation. In this case, the FC kicks in and draws on hydrogen from TKH_2 to produce electricity [5,6]. The key advantage of this arrangement is its capability to be used as long-term energy storage as opposed to more conventional technologies such as battery systems [7,8]. This makes it suitable for areas with considerable seasonal variations in solar radiation [9] or a good option for large-scale (e.g. utility scale) energy storage applications [10].

The fuel cell electrical energy efficiency is in the range of ~30–55%, depending of the current withdrawn from the FC [11]. Hence a substantial amount of energy entering the cell (i.e. the chemical energy content of hydrogen) converts to heat (that is about 50–70% of the total energy input) [12]. Cooling the fuel cell (i.e. to a temperature between 60 °C and 80 °C) by removing this heat is an essential operating requirement for the PEMFC [13,14]. An earlier study, conducted by Shabani, Andrews [15] for a conservative standalone household, indicated, that recovering this heat and making a solar-hydrogen combined heat and power (SH CHP) system, could offer up to over 30% of saving in the energy normally required for hot water supply, that is usually supplied through a transported fuel such as LPG.

On the other hand, for supplying thermal energy, a renewable alternative to fossil-fuel-based technologies for hot water supply is using Solar-Thermal (ST) systems. An ST system consists mainly of solar-thermal collectors (i.e. flat plat or evacuated tube collectors) and a hot water storage tank. However, this system, when operating by itself, was found to be able to supply in its best design only about 60–70% of the total annual hot water demand of a standalone household in Australia

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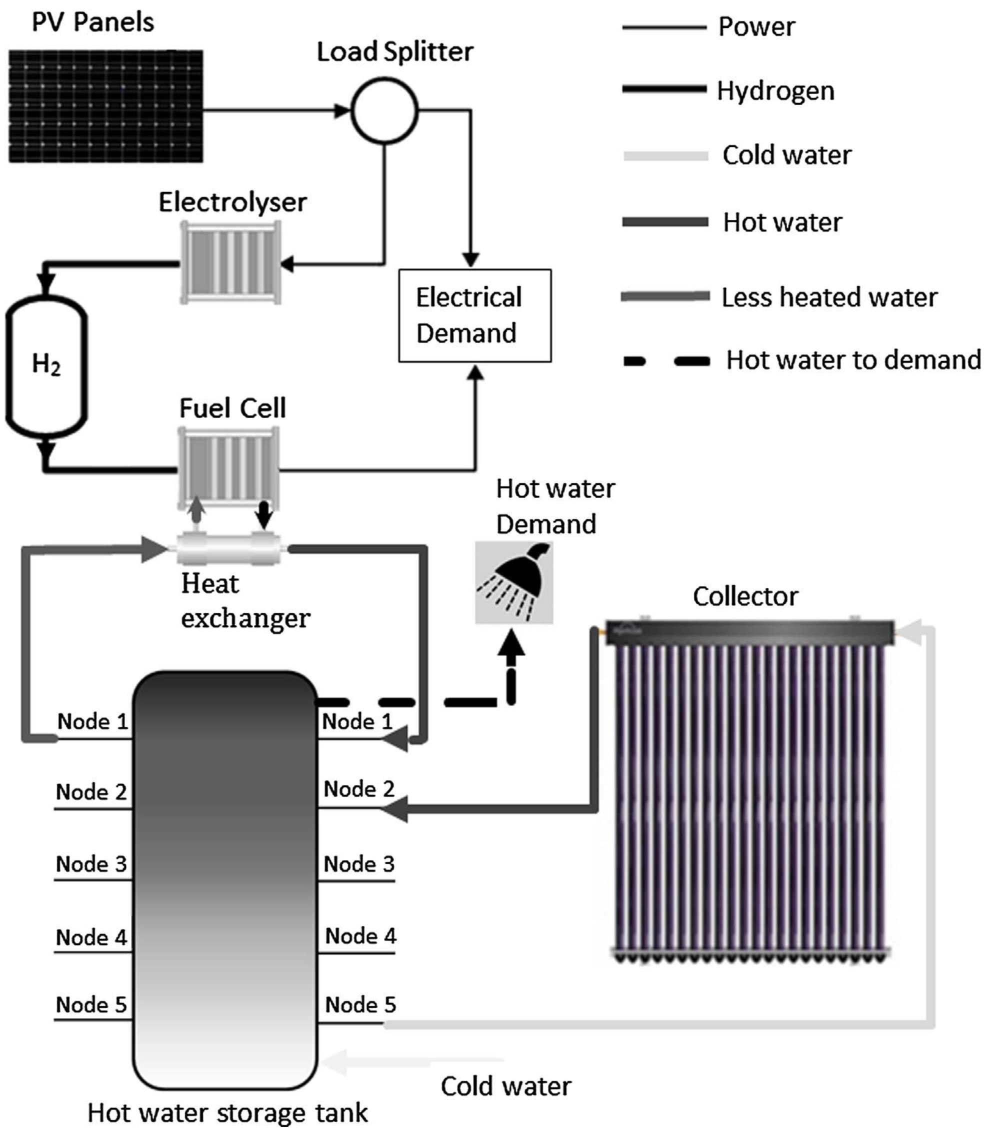

Fig. 1. Schematic diagram of the integrated SH CHP-ST system.

[16], with only around 54% of the hot water demand met in winter [17].

When integrated, ST and SH CHP systems can effectively complement each other in terms of heat supply to the kind of standalone applications focused by this paper (e.g. a household of a few people located in a remote area) [17]. It is because during the absence of sufficient solar radiation, when the electrical output of the PV system is insufficient, the thermal output of the ST system is supposed to be insufficient as well. This is when the fuel cell kicks into cover the PVs' shortage in supplying power. While the FC is in operation, its heat can be recovered in the SH CHP system, thus, greatly covering the shortage of supply from the ST collectors [17].

In an integrated solar-hydrogen combined heat and power/solar-thermal system (SH CHP-ST) (Fig. 1), the fuel cell heat is recovered through a heat exchanger (HX) that is used to cool down the FC. This cooling load (i.e. the heat recovered from the FC) is transferred at best through the HX to the top part of the hot water tank (TK_{HW}) of the ST subsystem (Fig. 1). The temperature in the TK_{HW} is limited to 65 °C for domestic use and safety [18,19]. The remaining of the FC cooling load that cannot be transferred to the tank is dumped to environment. The integration between the SH CHP and ST was found to be well effective in covering the shortfall of the ST system, and increased the annual capacity of the system for meeting the total thermal demand (i.e. hot water demand in this case) of a typical standalone household, from about 60–70% to well around 95%, while the SH CHP is sized to fully meet the electrical demand of the site [17]. The fuel cell heat (cooling load) that was transferred to the tank was annually on average 83%, which showed the benefit of this integration. The wasted heat of the fuel cell (not transferred to the tank) occurred mainly during periods (i.e. in relatively warm or hot weather), when the hot water demand could be met at large part from the solar-thermal collector, and the fuel cell heat was needed partly [17].

2. The focus of this study

In the previous study conducted by the authors on the feasibility of the SH CHP-ST system, the system was modelled and simulated theoretically in TRNSYS [17]. This was followed by a detailed study on the economics of this integrated system [20]. The sizing strategy adopted by the authors in those studies was based on an objective to fulfil 100% of the power load, and by having close to zero-power wasted from the PVs. This was done by performing repetitive simulations of the system with different sizes. For instance, the electrolyser was sized to accommodate all the excess power from the PVs. A hydrogen tank of unconstrained size was considered. The PV array was sized in such a way that all the hydrogen produced by the electrolyser was consumed by the