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The interplay between renewables penetration, costing and emissions in the sizing of stand-alone hydrogen systems

*Adel Brka**, *Yasir M. Al-Abdeli*, *Ganesh Kothapalli*

School of Engineering, Edith Cowan University, 270 Joondalup Drive, Joondalup, WA 6027, Australia

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ABSTRACT

Multi-objective Genetic Algorithms are used to optimise three stand-alone hydrogen systems (WG-H_2, WG/PV-H_2 and PV-H_2) under three different objective functions: minimising (hardware) Net Present Cost – NPC ($), whole Life Cycle Emissions – LCE (CO_2-eq/yr) and dumped/Excess Energy –EE (%) at low demand. Optimisations considering Excess Energy haven't been reported before. Simulations are implemented using MATLAB, incorporate experimentally resolved fuel cell start-up transients, and dynamic profiles for wind speed, solar irradiance as well as electric load demand.

Results indicate the significance of integrating fuel cell start-up into the LPSP when optimising systems, another aspect not reported before and a modified LPSP is introduced. Furthermore, when sizing energy systems by reducing LCE, EE, and NPC, the favoured hybrid architecture appears to be WG-H_2 over the others studied. For the same LPSP, an interesting finding is that increased renewables penetration (reduced dumped loads) affects the optimised solution but comes at a cost.

Introduction

Because renewable energy resources are unpredictable and intermittent in nature, research has been conducted to better forecast renewables (wind, solar-PV) and their integration into stand-alone [1] and hydrogen systems [2]. Consequently, these technologies are sometimes perceived as having poor reliability compared to traditional decentralised power such as diesel generators [3,4]. Although there are no greenhouse gases generated by hardware during renewable energy conversion, these devices are still responsible for greenhouse gas emissions during their lifetime (cradle-to-grave) [5–7]. Other problems cited with adopting renewable energy systems relate to the high cost of conversion technologies and the need to sometimes dump "excess" power generated [8].

Several approaches have been followed to tackle the drawbacks of renewable energy systems. Combining more than one energy source (hybridising) and incorporating means of energy storage are used to increase system reliability [9,10] and provide limited excess storage. In this regard, batteries, capacitors and hydrogen technology (electrolyser, hydrogen storage and fuel cell) are amongst the most cited (non-thermally based) energy storage means. Lead-acid batteries are traditionally used as short-term energy storage because of low capital cost. However, there are many environmental concerns with using batteries [8] in addition to having relatively small lifespans and appreciable operational and maintenance

* *Corresponding author*. Tel.: +61 432611745.
E-mail address: abrka@our.ecu.edu.au (A. Brka).
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costs [11]. In contrast, hydrogen storage is perceived as being more eco-friendly and more easily expandable but suffers from relatively high capital cost [12] as hybridisation of storage technologies can increase overall system complexity and, in turn, the cost of the energy system. In addition, a well-founded compromise between the cost of energy storage (battery-vs-hydrogen) and their associated lifetime environmental impact must be made. This makes it important to choose a combination of components which results in a systematic compromise between design objectives, operational reliabilities and environmental considerations.

Studies have been conducted to optimally size hybrid renewable energy systems with the (sole) objective of minimising system cost. In this regard, Particle Swarm Optimisation (PSO), Tabu Search (TS), Simulated Annealing (SA), Harmony Search (HS) and Artificial Bee Swarm Optimisation (ABSO) have been recently used to minimise energy system cost [13–15]. These good works do not however account for transient device characteristics and only use single objectives. Even so, PSO is found to be the most robust between the aforementioned techniques [14], but its performance subject to the choice of acceleration parameters [16]. Additionally, comparative studies between PSO and Genetic Algorithms (GA's) applied to hydrogen energy systems are not widespread in the literature. The reliability of the system in Ref. [13] was evaluated using several indices such as the Loss of Load Expected (LOLE) and Loss of Power Supply Probability (LPSP), both considering only steady state (nominal) power characteristics. A hybrid sizing (Net Present Cost) procedure that combines PSO and Harmony Search has also been proposed by Dehghan et al. [17] to optimally size a hydrogen-based energy system and the resulting reliability evaluated via the Equivalent Loss Factor (ELF) index. Other research [18] has used battery storage and diesel generators with solar-PV and wind turbines to build small-scale stand-alone hybrid renewable energy systems for remote regions in India, but only considered life cycle cost and environmental impact.

Although cost is an important aspect in the sizing of any energy system, other considerations such as consequential emissions or the reliability of meeting external (electric) loads are also important. To design hybrid energy systems which consider more than one sizing objective (i.e., not just cost, \$/kW-h), multi-objective optimisation based Genetic Algorithms (GAs) have been used. Examples include sizing a small autonomous renewable energy system with a diesel generator [7] by considering economic and environmental objectives. In such cases, economic objectives are generally to minimise the Cost of Energy (COE, \$/kW-h) whereas environmental objectives may be to minimise the CO_2 (equivalent) emissions over the project lifetime. In addition to the economic and environmental objectives, Dufo-Lopez and Bernal-Agustin [19] have considered reducing the unmet load as a third objective, thereby including operational (reliability) into their design objectives. However, they only considered steady state characteristics of primary movers (e.g fuel cells) and did not include maximising renewable energy penetration in their optimisation algorithm. The output of multi-objective optimisation algorithms is however not a single solution, but a group of non-dominant solutions where each individual solution cannot be optimised towards one objective without detracting from at least one of the other objectives. This constitutes the third aspect which Dufo-Lopez and Bernal-Agustin and others [7,19,20] have not addressed and have left these decisions to system designers to choose. Such optimisation methodologies may not only be considered subjective, but also do not guarantee consistency or that selected solutions are indeed optimal. The approach used in the present paper overcomes these earlier limitations by applying a fuzzy membership function [21,22] to decide which of the non-dominant solutions represents the optimal compromise between all system design objectives. Moreover, the solutions reached also analyse the effects of integrating experimentally resolved transient start-up characteristics of fuel cells.

Additionally, the percentage of waste converted (renewable) energy diverted to dump loads could reach 50% of total power generated [23]. Excess energy conversion may not only indicate oversized devices (e.g. fuel cells, solar-PV panels and wind turbines) but also has flow-on effects onto operational, maintenance and decommissioning costs and a systems associated lifetime environmental impact. All these factors affect the techno-economic viability of stand-alone (hybridised) energy systems. This paper also addresses such shortfalls by investigating the sizing of hydrogen based renewable energy systems in the context of multiple objectives. For a predetermined reliability of meeting a load, the factors considered are Net Present Cost (NPC, \$), Excess Energy delivered to dump loads (EE, %) and Life Cycle Emissions (LCE, CO_2-eq/yr). The relative impact of the above optimisation is studied using a Multi-objective Genetic Algorithm in the context of three stand-alone hybrid renewable energy system configurations. These configurations also consider two energy storage technologies namely, hydrogen and battery. For the first time, a modified formula for the Loss of Power Supply Probability (LPSP) index, which considers load losses during fuel cell transient start-up, is also introduced to assess its effect on system reliability and its significance if the transient (start-up) characteristics of fuel cells are ignored. This is developed with practical testing to resolve fuel cell (transient) characteristics.

In summary, the contributions of the present work focus not only on applying multi-objective optimisation (i.e., the consideration of emissions, cost and renewables penetration) to stand-alone hydrogen systems, but go further. Specifically, the impact of transient fuel cell characteristics on the loss of power supply is seen to be significant in systems which had been sized with these transients neglected. Additionally, a modified LPSP measure is presented and the effects of battery storage, in the context of multi-objective optimisations, are studied for three types of hydrogen systems.

The paper is structured as follows: Section 2 presents a description of the energy system components. Section 3 describes the Power Management Strategies used and Section 4 explains the optimisation algorithm. The results are presented and discussed in Section 5 followed by the conclusions in Section 6.

Systems model

A block diagram of hydrogen based hybrid renewable energy system with (and without) battery is shown in Fig. 1. The key