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Sustainability of a wind-hydrogen energy system: Assessment using a novel index and comparison to a conventional gas-fired system

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ABSTRACT

This study applies a previously developed methodology to assess the sustainability of a wind-hydrogen system designed to meet the energy needs of a small community in southern Ontario. A thermodynamic analysis demonstrates that the energy system can meet the heating, cooling, and electrical energy needs of the 50-household community with a wind turbine rotor radius of 28 m and hydrogen storage capacity of 8550 kg. A subsequent multi-criteria assessment reveals that the Integrated Sustainability Index (ISI) is particularly sensitive to weighting factors associated with Affordability, Global Warming Potential, and Stratospheric Ozone Depletion Potential sub-indicators. Although the individualist ISI only varies from 0.77 to 0.90, the egalitarian ISI varies from 0.30 to 0.75 over a range of weighting factors. A comparative assessment of a wind-hydrogen and traditional gas-fired system shows that there is very little difference in the ISI of each system. The individualist ISI is 0.84 and 0.86 and the egalitarian ISI is 0.56 and 0.52 for the wind-hydrogen and gas-fired system, respectively. This suggests that superficial assessments of sustainability should be avoided and that multi-criteria analysis is essential.

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Introduction

The struggle to achieve a sustainable society is not unique to the modern age. Sustainability has been important since the earliest human civilizations. Ever since the Neolithic Revolution approximately 10,000 years ago, when human beings transitioned from mobile hunter-gatherers to agriculture and settlements, the sustainability of the local lifestyle has been essential to avoid societal collapse. Although sustainable development is generally regarded as a positive evolutionary course, making the concept of sustainability operational is a challenge. Before a system can be declared sustainable, a method for measuring and assessing sustainability has to be in place. Otherwise, the practical value of sustainability and sustainable development diminishes.

Although there are numerous methods of assessing the sustainability of energy systems, a standard and universally accepted approach does not exist. Some studies comment on the sustainability of an energy system from a thermodynamic [1–5]

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or environmental [6–8] perspective. More comprehensive approaches that consider different aspects of sustainability but rank indicators without normalization with respect to sustainability target values are better suited to relative assessments of energy systems [9,10]. Other studies develop quantitative sustainability assessment tools that address technical, economic, social, and environmental criteria [11–14]. However, sustainability indicators are not normalized with respect to a reference state that represents limits on, for example, emissions of pollutants.

A novel Integrated Sustainability Index (ISI) for energy systems that considers critical multidimensional sustainability criteria is developed in Ref. [15]. This constitutes a novel contribution to efforts to develop measures of sustainability in a unified manner, in that it builds on previously developed measures, which tend to focus on aspects of sustainability separately. The novelty of this new index is that it incorporates fundamental thermodynamic, economic, and environmental constraints to combine indicators from multiple dimensions into a single-score evaluation of sustainability. The index is therefore unique because it can assess sustainability relative to an ideal reference state instead of being limited to ranking systems via relative assessments.

The integrated sustainability index achieves this by considering the following main factors:

- an efficiency ratio (including energy and exergy efficiency ratios),
- an economic factor (accounting for affordability and commercial viability),
- a size factor (considering relevant parameters like mass, area and volume),
- global environmental impact potential (including potentials for global warming, stratospheric ozone depletion, and abiotic depletion),
- air pollution potential (considering fine and coarse particulate matter, sulphur dioxide, carbon monoxide, nitrogen dioxide, ground-level ozone and lead), and
- water pollution potential (accounting for potentials for eutrophication, freshwater aquatic ecotoxicity and marine aquatic ecotoxicity).

Various investigations have been carried out of techno-economic factors related to energy systems for electricity in general [16] and for wind energy conversion systems [17–20] and diesel systems [20]. Research has also been carried out on wind energy systems incorporating electrolyzers [20] and fuel cells [4,18]. Although these articles focus on technical and economic aspects, they do not directly and extensively address sustainability, even though a good understanding of sustainability is increasingly viewed as important and necessary. The present work seeks to address this need.

The objective of this research study is to apply the methodology developed in Ref. [15] to assess the sustainability of a wind energy system with hydrogen-based storage. Such an application has not been attempted previously, and thus provides a novel contribution and advance. The ISI of the wind-hydrogen system is also compared to the ISI of a conventional gas-fired system for comparative purposes.

System description

Each system considered here is designed to meet the heat, cold, and electrical energy needs of a 50-household community in southern Ontario. The daily average cooling, electricity, and hot water demands of a household are predicted based on a measurement campaign to record the electrical demands of a sample of 12 houses in Ontario at 1-min intervals for one year [22]. The demand for space heating is derived using an empirical correlation [15]. The energy demands of a household over the course of a year are illustrated in Figs. 1 and 2, and the systems are illustrated in Figs. 3 and 4.

Wind-hydrogen system

A wind turbine that converts the kinetic energy of wind to electricity is proposed to meet the energy needs of a 50-household community in southern Ontario. The wind turbine is integrated with a hydrogen storage subsystem and heat pump (Fig. 3) to ensure the community has a reliable supply of energy during periods of low wind activity. In Fig. 3, the wind turbine is seen to be able to satisfy an electrical load directly (centre of diagram), or to drive a heat pump for heating or cooling (top portion of diagram), or to drive an electrolyser, which is linked to a hydrogen storage tank and a fuel cell system that can generate electricity (bottom portion of diagram). Further details on the system in Fig. 3 are provided in Ref. [15]. When the power delivered by the wind turbine is greater than the load the electrolyser is activated to charge the hydrogen storage tanks. When there is unmet demand hydrogen is discharged to the fuel cell.

The size of the wind turbine is selected such that the year-end net change of hydrogen in the storage tanks is positive. Long-term mean wind velocity data are employed that are typical of the region where the wind turbine is located in southern Ontario, based on standard databases, as outlined in Ref. [15].

A thermodynamic model of the system was developed using the Engineering Equation Solver (EES) software and

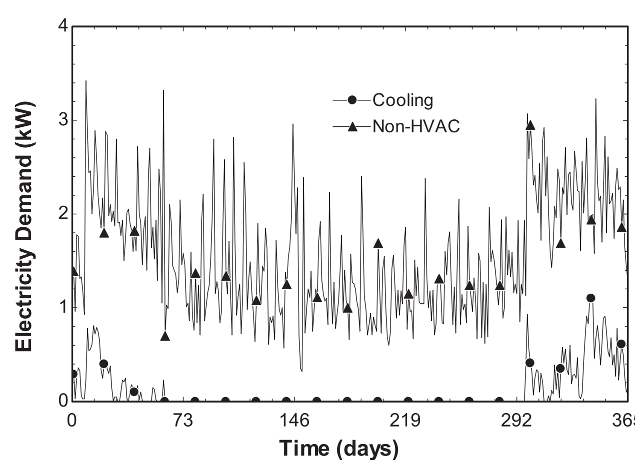

Fig. 1 – Cooling and non-HVAC electricity demand over one year for a typical household in Ontario (day "1" corresponds to August 1, 2009).

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