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Dimensionless analysis of the global techno-economic feasibility of solar-hydrogen systems for constant year-round power supply

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ABSTRACT

A novel dimensionless approach to analysing the capability of a solar electricity supply system with seasonal hydrogen storage to supply a constant load throughout the year is presented. The only input required specific to the location is its solar ratio, defined as the minimum daily solar energy input during the year divided by the maximum. As well as yielding an estimate of the saving in installed primary solar electricity generating capacity, the approach gives an indicative evaluation of the economic viability of adding the hydrogen storage to a photovoltaic-based solar supply, either for a large-scale grid or small scale autonomous application. The model has been validated using the results obtained from the more comprehensive RSHAP simulation model (RMIT Solar-Hydrogen Analysis Program). The dimensionless model is applied to a selection of 78 cities with varying latitudes across all five continents. For a round-trip storage efficiency of around 45% and the base-case unit costs of components assumed, solar-hydrogen systems would be economic in 55% of these cities. At 50% storage efficiency and/or lowered unit costs, solar-hydrogen systems would become viable in the vast majority of the cities, excepting those near the equator where the net benefits of adding storage are lower because of the more constant solar radiation over the year.

1. Introduction

A particularly attractive, if not unique, capability of hydrogen storage is its likely ability to provide secure long-term energy storage in electricity supply systems relying substantially on renewable energy sources that are inherently variable, intermittent, and seasonal, such as solar radiation, hydroelectric, wind and wave power. Especially important here is the ability to store energy with low losses and degradation from season to season, that is, for periods up to six months, given the strong seasonality of the principal renewable supply sources in most locations around the world. This capability renders hydrogen storage highly suitable for employment in solar and wind systems for remote, stand-alone or back-up electricity power supplies, as many authors have described using a system configuration similar to that in Fig. 1 [1–11]. Moreover, the very same capability and basic system configuration has the even more significant prospect of allowing continuous supply from renewables on medium- and large-scale electricity grids [12,13].

The advantageous role played by hydrogen storage in renewable electricity supply systems is threefold in nature.

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Nomenclature

A	PV power correction factor
B	Efficiency improvement factor for fuel cell
C	Unit cost of a component
C_0	Unit cost of a new component at the beginning of the assessment period
C_f	Unit cost of a new component at the end of the assessment period
CR	Capacity ratio
d	Real discount rate
D	Number of days of autonomous operation
DOD	Depth of discharge of the batteries
G	Amplitude of sine wave approximation for PV output
HHV	Hydrogen high heating value
L	The continuous load to be met throughout the year
LR	Load ratio
N	Lifetime of a system component
NPV	Net present value
S	Size, for example, the rated capacity of a component
SR	Solar ratio
P_{PV} (t)	Average daily PV power output profile throughout the year
P_{PV}	The average daily output of the PV array
P_{PV}^{min}	The minimum average daily power output of the PV array throughout the year
P_{PV}^{max}	The maximum average daily power output of the PV array throughout the year
Y	Assessment period (years)
ΔP_{PV}	The difference between the required PV outputs considering actual (<100%) and ideal (100%) round-trip energy efficiencies for the hydrogen energy storage system
ΔP_{PV}^{max}	The difference between the required PV output with and without hydrogen storage
η	efficiency

Subscripts

B	Battery
EL	Electrolyser
FC	Fuel cell
I/C	Inverter/Converter
PV	PV array
T	Hydrogen tank

Firstly by storing excess renewable energy supply over the load in periods of high supply (that is, the summer months in solar-based systems) for reuse to meet the demand in low-supply periods (winter for solar systems), a lower-capacity renewable energy system can be installed than would be the case without storage [14]. Secondly, the addition of hydrogen storage permits the overall system to provide continuous supply throughout the year at a constant level – that is, base load supply – which the renewable energy plant would not be able to do alone, either in the short term (daily or even hourly) or longer term (season to season). Thirdly, the bulk hydrogen storage provides a high degree of energy security, since energy is stored and hence is available to meet demands in the event of unforeseen situations, such as damage to the primary supply after extreme climatic events like cyclones or floods [14,15]. The ability of hydrogen storage, particularly if distributed geographically throughout a country or region, to enhance energy security within a predominantly renewables-based primary energy supply system may indeed prove to be its decisive advantage in the future [12].

In a solar-based electricity supply system, the viability of hydrogen storage depends on a number of factors:

- The degree of seasonal variation in solar radiation, that is, the difference between the maximum and minimum daily solar irradiance over the year. Such seasonal variation in turn depends on latitude and the local climate.
- The annual load profile to be met and how closely this matches the annual profile of solar radiation. If this load is fairly constant throughout the year, or has a winter peak, clearly the need for storage is enhanced.
- The relative costs of increasing the solar supply capacity and the costs of the hydrogen storage sub-system – typically an electrolyser, hydrogen storage, fuel cell and associated balance of system, as shown in Fig. 1.

Solar irradiance at a large proportion of locations on the earth follows a sinusoidal profile over an annual cycle to a reasonable degree of approximation (as will be shown later). In many applications it is desirable for a solar energy supply

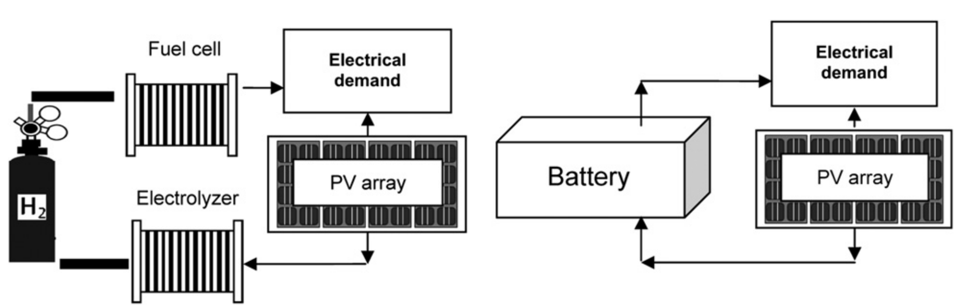

Fig. 1 – Schematic of a hydrogen-based energy storage sub-system used with a PV array to provide continuous year-round power supply (left), compared to the more common PV-battery system (right).