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Techno-economic assessment of dispatchable hydrogen production by multiple electrolysers in Libya

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ABSTRACT

With the worldwide growth of renewable energy generation, the value of hydrogen production by electrolysis as a demand management tool for electricity networks is likely to increase. Electrolytic hydrogen can be sold as a fuel, chemical feedstock or injected into pipelines to lower the carbon content of natural gas. The main obstacle to hydrogen's use as a fuel or energy storage method is the price. The highest costs are in the capital expenditure and the consumption of feedstock (electricity and water). In this paper, three major techno-economic aspects of the system are investigated, including technical analyses of both the energy absorbed by the process in the provision of electricity demand management services and in its meeting of fuel demand, plus an economic assessment of the hydrogen price at the at the point of sale. Thus, the study investigates how only off-peak electricity is used to produce hydrogen via onsite electrolysis at a number of garage forecourts. In a simulated case study, six garage forecourts are assumed to be sited in Darnah, a small city on the east coast of Libya. An electricity pricing mechanism is devised to allow the energy producer (utility company) and energy consumer (garage forecourt operator) to make a profit. Short term (2015) and long term (2030) cost scenarios are applied. Matlab software was used to simulate this process. Without any government support or changes in regulation and policy, hydrogen prices were £10.00/kg, £9.80/kg, £9.60/kg, £10.00/kg, £9.40/kg and £10.30/kg for forecourts 1–6 respectively under the 2015 cost scenario. The electricity price represents around 17% of the total hydrogen cost, whereas, due to the investment cost reduction in 2030, the average prices of hydrogen dropped to £6.50/kg, £6.60/kg, £6.30/kg, £6.40/kg, £6.20/kg and £6.50/kg for stations 1–6 respectively. The feedstock cost share became 44% in the 2030 cost scenario. Nearly 53.91% and 53.77% of available energy is absorbed in short and long term scenarios respectively. Under the long term cost scenario, 65% of hydrogen demand can be met, whereas less than 60% of hydrogen demand is met under the short term scenario. The system reliability (i.e. the meeting of hydrogen fuel demand) is quite low due to the operational mode of the system. Increasing the system size (mainly electrolyser production capacity) can clearly improve the system reliability.

1. Introduction

Many studies have analysed the concept of applying electrolysers to counteract variable renewable energy generation, to supply grid services, and derive revenue from differences in peak and off-peak electricity prices [1–3]. These studies reveal that there are possibilities for electrolysers to absorb off-peak (lower cost) electricity for hydrogen production through the use of different electricity markets and electricity rate structures, as well as consuming surplus renewable energy. Hydrogen production from electricity systems with high wind energy penetration has been widely investigated, since such systems require a high level of flexibility to accommodate the fluctuations of wind power generation [4,5].

Hydrogen is commonly proposed as a means of energy storage that can support the integration of renewable power sources into electricity networks [6,7]. Producing hydrogen from surplus energy was investigated for use in Ireland by Troncoso and Newborough and Gonzalez et al. [8,9]. Gonzalez et al. indicated that a low electricity tariff and an high hydrogen sale price is required to create a profit, whereas Troncoso and Newborough point out that profitability can be achieved if a certain amount of on-peak electricity is also absorbed to better amortize the device's costs [10]. Mansilla et al. noted the potential for hydrogen price reduction when operating alkaline electrolysers intermittently in order to exploit the benefits of lower electricity tariffs [11].

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Nomenclature

D_{HP}	Daily hydrogen production (kg/day)
E_F	Electricity usage (kWh/kg)
R_E	Required power (kW/day)
E_{TC}	Total electrolyser cost (£)
E_C	Electrolyser cost (£/kW)
S_{TC}	Total storage cost (£)
S_C	Storage cost (£/kW)
S_S	Storage size (kg)
C_{Tc}	Total compressor cost (£)
Cm_c	Compressor cost (£/compression system)
C_S	Compressor size (kg/day)
D_C	Dispenser cost (£)
I_{DC}	Total investment cost for 7 years (£)
C_C	Capital cost (£)
F_C	Fixed cost (£)
i_r	Interest rate (5%)
Y_P	Yearly payment (£)
D_P	Daily payment (£)
W_C	Water cost (£)
EL_C	Electricity cost (£/day)
Req_H_2	Daily required hydrogen (kg/day)
max_H_2	Maximum storage size (kg)
$Curr\_H_2$	Current amount of hydrogen in tank (kg)
CH_2	Assumed cost of hydrogen (£/kg)
R_{EC}	Required energy price (£/kWh)

Advances in modelling intermittent electrolyser operation are suggested in this paper, which uses Libya as an example of a country with good renewable resources and a need to modernize its energy system to a more sustainable model. Floch et al. investigated hydrogen production using an alkaline electrolyser with power consumption restricted to off-peak times. From this, they concluded that a wide disparity between high peaktime tariffs and low off-peak tariffs can lower the cost of hydrogen production, despite the difficulty in quantifying such volatility that otherwise acts as a complicating factor in electrolyser operation [12]. A 563 MW wind-hydrogen and storage model was tested in Canada. The price extracted from this scenario is \$9.00/kg H_2, if the wind turbine capital cost is added to the total cost, and \$3.37/kg H_2 if the turbine cost is excluded [13]. Hydrogen electrolysis was involved as a technology option within an operational optimisation system of a combined electricity and gas network in Great Britain [14]. The results reveal that hydrogen production from electricity can effectively reduce wind curtailment in a network with high wind penetration and also lower the overall cost of electricity and gas in the GB energy system. Stand-alone (or off-grid) systems have been widely investigated in several regions [15–17] and a variety of techniques were used for optimization of such systems. For example, Particle Swarm Optimization (PSO) was applied for optimal sizing of wind and photovoltaic generation systems and compared with Genetic Algorithm (GA) optimization. The results reveal that PSO is better than GA in many respects, such as accuracy and speed [18]. A multi-objective system has been applied to achieve certain targets in stand-alone networks consisting of wind, photovoltaic and fuel cell power generators. The target for these is reliable supply under different weather conditions. A hydrogen tank was used as an energy store. A Multi-Objective Particle Swarm Optimization (MOPSO) was applied to meet these goals and the Single-Objective Optimisation (SOO) algorithms. The results reveal that this optimization can offer a better configuration with lower reliability indices. Generally, the suggested algorithm can provide a reliable and cost–effective solution for any hybrid energy system [16]. In this paper, hydrogen storage will be applied as a demand management tool and the hydrogen thereby produced will be exploited as a clean fuel. The optimization in this paper is based on the price of 'excess energy', i.e. that which is available due to temporary surpluses of supply (see Section 5).

In coming years, it is expected that there will be a transition from the combustion engine, fuelled by conventional fuels, to electrically powered vehicles [19,20]. These would include both Battery-only Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs), so hydrogen will have an important role in this emerging market. Automobile manufactures have made substantial progress in the improvement of FCEVs, with a smattering of pre-commercial, market-ready (in a technical sense) models launched from 2015 onwards [21]. As an anticipated fuel for the transportation sector, hydrogen eliminates greenhouse gas emissions from vehicles, while allowing fast fuelling, which is not possible with BEVs, longer range and greater carrying capacity [22,23]. The work in this paper creates a new method of electricity pricing, which aims to simultaneously satisfy the needs of the power supplier (the utility company) with the fuel supplier (the forecourt operator) and end users (FCEV drivers). A settlement is reached between the utility company and forecourt operators that aims to optimise electricity demand management while lowering fuel prices for drivers. The proposed mechanism produces a daily electricity price (based on temporary surpluses in energy yield resulting from the variability of renewable energy harvest) that strikes a balance between the utility company obtaining some income for energy generation that would otherwise be curtailed and the electrolyser operators who seek the lowest possible price for electricity, which is their most expensive feedstock. Most previous work focuses predominantly on the satisfaction of grid electricity demand, with excess energy being absorbed by battery or electrolysis so that temporary energy surpluses are used to compensate for a shortage of renewable energy production at a later time [16,18,24]. In such cases, the energy stored in hydrogen is converted back into grid electricity, which entails prohibitive round-trip losses and is therefore not considered in this study. Instead, the optimisation in this paper focuses on the use of excess renewable energy for the production of hydrogen for use as transport fuel to replace the fossil fuel use in vehicles, not for the re-electrification of stored energy.

2. Methodology

2.1. Data collection

2.1.1. Wind speed

Hourly wind speed data was used for this paper. There are a large number of weather stations in Libya that not only record wind speed but also air pressure, ambient temperature, rainfall, and so on. The wind data were collected at a height of 10 m above ground level [25]. However, wind turbine hubs are much higher than this, and wind speed changes with height and due to friction from the terrain, buildings, etc., that can cause a slowing of airflow.

2.1.2. Fossil fuel data

Because of the absence to data for an extensive hydrogen market, the hydrogen demand calculation cannot be computed with any great accuracy. The widespread uptake of hydrogen markets will rely initially on the availability of hydrogen-based infrastructure, particularly the deployment of Hydrogen Refuelling Stations (HRSs) and hydrogen-fuelled cars [26]. Due to this uncertainty, scenario planning can be deemed as the only systematic method of assessing the future hydrogen supply chain. In this paper, estimates of hydrogen demand (and thus the number