Elsevier Editorial System(tm) for Applied Energy
Manuscript Draft

Manuscript Number:

Title: Technical and economic analysis of hydrogen refuelling

Article Type: SI: Integrated EnergySystems

Keywords: Hydrogen production; Hydrogen economics; PEM; Alkaline; Wind integration

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Technical and economic analysis of hydrogen refuelling

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1. Introduction

Global pressure is continuing to drive methods to reduce our carbon emissions throughout the energy supply chain, from raw fuels to products. The level of reductions required points to a shift in energy sources as well as social habits. This is likely to require a mix of different technologies which may differ between countries based on local needs, context, and resources. Amongst potential technologies, hydrogen is gaining prominence as a crucial part of a low carbon future for a number of countries. A study found that there were 224 working hydrogen stations over 28 countries in 2013 [1]; notably 43% were located in North America and 34% in Europe [1]. In recent years Japan has promoted hydrogen fuel cells as a way to de-risk their energy supply chain as well as creating reserve energy in cases of emergency. A review of UK hydrogen related activity [2] shows the appetite for hydrogen related research and commercialisation with activities ranging from fuel cell technology to socio-economic issues. The paper [2] highlights the need for a collaborative approach into this area in order to realise the commercialisation of hydrogen and fuel cell systems. Taking such technology into commercial operation in a transport context is complicated further as it requires new infrastructure and technology to be adopted in a coordinated fashion [3] leading to the proverbial ‘chicken and egg’ situation.

As a reflection of the development of technology and potential of hydrogen, the European Commission set up the Fuel Cell and Hydrogen Joint Undertaking (FCH JU)[1] in 2008 and renewed the initiative in 2014. The nature of projects suggest that the commercialisation of hydrogen and fuel cell systems are expected to be realised.

This paper aims to explore and analyse the short to medium term feasibility of hydrogen refuelling with onsite hydrogen generation using a pilot project (Island Hydrogen) in the UK as a use case. In particular we analyse the performance (unit cost of hydrogen) current state of hydrogen refueller technology (both PEM and alkali electrolysers) in order to address the present case for hydrogen fuelled transport without relying on reductions in future technology costs. We then evaluate the effectiveness of a refuelling site in terms of serving customers based on primary energy source (wind power versus grid power). Finally, evaluate the commercial impact of R&D funding on the system to reflect the efforts of national policies which direct funding towards such trials (e.g. in the European Commission).

The paper is organised as follows; §2 covers relevant work in the literature, §3 provides system and simulation details, §4 presents Island Hydrogen as a case study and discusses results, and finally §5 makes some conclusions and highlights areas for further work.

2. Relevant Work

This paper looks at technical and economic analysis of a pilot project in order to evaluate feasibility of the system to satisfy demand and to be economically attractive. A study [4] observed that realistic cost estimates coupled with confidence in the technical performance of hydrogen fuel celled electric vehicles (H2 FCEV). The need for government commitment and coordination amongst stakeholders is also highlighted to help create momentum for the sector. In a Californian based study [4], an approach of clustering refueler stations was explored and found to be a better strategy than simply allocating refuelers in proportion to population density. The authors also noted [4] that subsidies and government policy directed at alleviating the high capital cost and long payback period would assist in encouraging private investment and technology adoption.

Previous techno-economic analysis of hydrogen production for FCEV’s has found that the price of electricity is the key driver in cost [5]. The study [5] also found that in addition to electricity costs, key factors with medium to high impact are; storage, compression, volume produced, size, financing, capacity factor and electrolyser efficiency. The work [5] is limited in the depth to which the technical aspects are modelled with the authors noting that a number of couplings are not reflected explicitly in the model. The model [5] assumes that the electrolyser functions at nominal production capacity which in practice is unlikely to happen.

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[1] http://www.fch.europa.eu/

A more recent study [6] has looked at a self-sustaining hydrogen fuelling station where the power to operate the electrolyser is purely from renewable sources. They find that using power from the generation sources to directly run the electrolyser is preferred to using a fuel cell to balance the intermittency. They found that 200 kW wind turbines or 360 kw solar PV could successfully operate in a self-sustaining manner while producing approximately 25 kg of hydrogen [6]. Modelling hydrogen vehicles and refuelling infrastructure using the lens of complementary goods [7] suggests that favorable market conditions are required for FCEV's to penetrate the market. The study analysed four scenarios using system dynamics where the most successful scenario required both investment in infrastructure and fuel subsidies [7]. However, this type of longer term analysis can be very difficult given the high uncertainty of a number of factors such as component life time, manufacturing costs, and maintenance costs [8].

These papers highlight a key issue in the hydrogen refueler domain which is the close linkage between economic and technical factors and the impact on the overall competitiveness of such schemes. There are a number of simulation environments that have started to integrate technical and economic models with which to analyse energy systems more generally. The Department of Energy in the USA have created the hydrogen analysis (H2A) tool[2] which allows analysis of the economics of hydrogen production systems as well as some technical attributes related to this (mainly the electrolyser). The analysis is well suited towards medium-long term system analysis however doesn't allow for detailed technical models and real-time analysis. The National Renewable Energy Labs developed and have now commercialised HOMER, a microgrid simulation tool. HOMER also contains hydrogen related components (electrolyser and storage) and has simulation granularity of 1 minute to 1 hour. The system is proprietary hence customising scenarios and technology performance can be difficult. In the realm of real-time simulation systems, TRNSYS 17 provides real-time analysis capability for technical systems which is suitable for analysing short term scenarios.

The key limitations we find in the available simulation environments is that they are either mainly economic models with limited technical features or detailed technical models with little or no economic and policy views. Hence, the work presented here is based on a customised simulation environment where detailed technical models of the physical processes (e.g. electrolysis, compressors, buffer, and dispenser) are coupled with economic models from the literature. The granularity of the simulation allows for dynamic effects of the system (e.g. generation) to be captured, giving a more realistic representation.

Whilst the studies mentioned have focused predominantly on hydrogen as a transport fuel, there is also research into its use to alleviate grid constraints [9][10][11] which we note as being of relevance and indeed being trialled in Germany [9]. However, for the purpose of this paper we classify these as out of scope in order to focus on the primary case of technical and economic analysis of refuelers with wider grid management analysis being a topic for further work.

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[2] http://www.hydrogen.energy.gov/h2a_analysis.html

The focus of this work is to create analysis methods and tools that focus on the often ignored short to medium term small infrastructure projects [12]. It has been highlighted that there is a lack of focus in this area on technology capacity factors [12] when determining hydrogen prices and hence feasibility. Our aim is to advance the current state of the art in this direction by performing a coupled techno-economic analysis of a hydrogen refueler site and examine the impact of subsidies on such a scenario. This reflects the majority of projects where government or external grants are a key factor. We use costs and prices which are as recent as possible and do not include technology glide path estimates in order to evaluate the system given the current technical and economic conditions. We also investigate the impact of technology parameters on the economic performance through a sensitivity analysis.

3. SIMULATION OF A HYDROGEN REFUELLING STATION

3.1. System overview

An overview of the envisioned system employed for the techno-economic analysis is depicted in Fig. 1. The technical module contains a wind turbine generation model, a hydrogen refueler station model and a hydrogen demand model for fuel cell electric vehicles (FCEVs). For the hydrogen refueler station the modelled components are the electrolyser stacks, storage, dispenser, cooling and rectifier. The model is an improvement from a previous work of the authors [13].

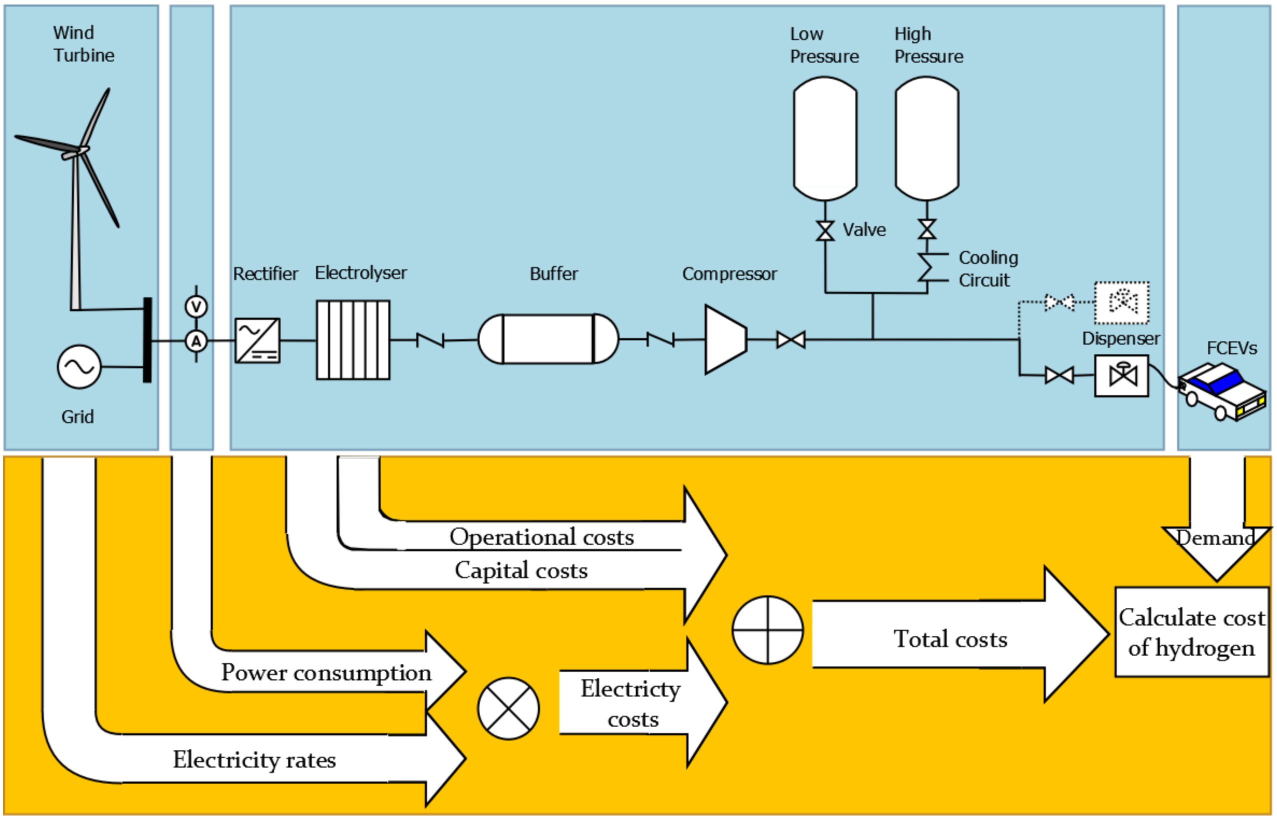

Fig. 1: Process flow diagram

The economic module captures the technical operation of the station and estimates the unit cost of hydrogen. The simulation tool is developed in Matlab® software. The description and values of the parameters found in the next section can be found in Table 4 of the Appendix.

3.2. Technical model

3.2.1. Wind turbine

The model used to obtain the wind turbine power output was proposed in [14], and is given in Eq. (1).

$$P(v) = \begin{cases} 0, & v < v_{CI} \\ P_R \cdot \left(\frac{v - v_{CI}}{v_R - v_{CI}}\right), & v_{CI} \leq v < v_R \\ P_R, & v_R \leq v \leq v_{CO} \\ 0, & v_{CO} < v \end{cases} . \quad (1)$$

Where P_R is the rated power output of the wind turbine generator, v is the wind speed, v_{CI} is the cut-in speed, v_{CO} is the cut-out speed and v_R is the rated wind speed.

3.2.2. Electrolyser

An electrolyser is formed from one or more stacks of electrolytic cells. The flow of hydrogen produced is a result of the passing of current through the cell, also expressed by Eq. (2). The Faraday efficiency, η_F, accounts for the parasitic currents and depends on the temperature and current as shown in Eq. (2). The Faraday efficiency decreases with the increase of temperature and the decrease of the current through the cell.

$$\dot{n}_{H_2} = \eta_F \cdot \frac{I}{z \cdot F} \quad , \quad \eta_F = a_1 \cdot exp\left(\frac{a_2 + a_3 \cdot T + a_4 \cdot T^2}{I/A} + \frac{a_5 + a_6 \cdot T + a_7 \cdot T^2}{(I/A)^2}\right). \quad (2)$$

The electrolytic cell has a current-voltage non-linear characteristics. Two technologies have been considered in this study: alkaline and Proton Exchange Membrane (PEM). The U-I characteristic of the alkaline cell, given by Eq. (3), was found in [15] through experimental data fitting method. The first element of the sum is the reversible cell voltage (U_0), the second models the electrolytes resistance, and the next two model overvoltage on the electrodes.

$$U = U_0 + \frac{r_1 + r_2 \cdot T}{A} \cdot I + (s_1 + s_2 \cdot T + s_3 \cdot T^2) \cdot \log_{10}\left(\frac{t_1 + t_2/T + t_3/T^2}{A} \cdot I + 1\right). \quad (3)$$

For the PEM cell the U-I characteristic, given by Eq. (4), was found in [16] through experimental data fitting method. As in the case of alkaline cell, the first element of the Eq. (4) is the reversible cell voltage (U_0). The second element of the sum, U_1, considers the influence that the pressures of the gases and water have on the overvoltage. The third element, U_2, considers the plates and membrane resistance. Only the membrane resistance was included in this study, as its resistivity is significantly higher than that of plates and electrodes [16]. While the last element of Eq. (4), U_3, models the activation overvoltage. The description and the value of the parameters of both Eq. (3) and Eq. (4) are given in Table 4 of the Appendix.

$$U = U_0 + U_1 + U_2 + U_3\,, \tag{4}$$
$$U_1 = \frac{R \cdot T_{cell}}{F} \cdot ln\left(\frac{p_{H_2} \cdot {p_{o_2}}^{1/2}}{p_{H_2O}}\right),$$
$$U_2 = \left(R_{eq,an} + R_{eq,cat} + \frac{\delta_m \cdot R \cdot T_{cell}}{F^2 \cdot A \cdot C_{H^+} \cdot D_{H^+}}\right) \cdot I,$$
$$U_3 = \frac{R \cdot T_{an}}{\alpha_{an} \cdot F} \cdot arcsinh\left(\frac{I/A}{2 \cdot i_{0,an}}\right) + \frac{R \cdot T_{cat}}{\alpha_{cat} \cdot F} \cdot arcsinh\left(\frac{I/A}{2 \cdot i_{0,cat}}\right).$$

3.2.3. Compressor

Eq. (5) from reference [17] was employed to model the compression process of the hydrogen gas from the buffer to the low and high pressure tanks. The equation describes the operation of a compressor with two stages by modelling a polytropic process. At the first stage the compressor first increases the hydrogen inlet pressure P_1 (bars) to an intermediate value P_2 (bars) and cools the gas to the temperature before the compression, T (^{o}K). The process is repeated at the second stage, the gas leaving at the discharge pressure P_3 (bars) and same temperature T. The energy required for the compression process is situated between the energy required for an isothermal process as a lower boundary and that of an adiabatic process as the upper boundary. The parameter $P_2 = \sqrt{P_1 \cdot P_3}$ is the optimal intermediate pressure. The polytropic index n depends on the nature of the gas and the details of the compression.

$$W = \frac{n \cdot R \cdot T}{n-1} \cdot \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n \cdot R \cdot T}{n-1} \cdot \left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right]. \tag{5}$$

The flow of hydrogen, α (moles/s), was calculated using Eq. (6). The term η_c covers the mechanical and the motor drive efficiency. P_c (W) is the compressor rated power.

$$\alpha = \frac{\eta_c \cdot P_c}{W}. \tag{6}$$

3.2.4. Storage

The buffer is filled with hydrogen directly from the electrolyser. For energy efficiency, the compressor starts to fill either the low or the high pressure tanks when the pressure inside the buffer reaches the pressure of the electrolyser outlet. Describing the state variables (P,V,T) for tanks and buffer is done with van der Waals equation, here Eq. (7). Compared with the ideal gas law, the van der Waals state equation takes into account that the molecules interact with each other, which result in more accurate estimates. In this study, the electrolyser outlet pressure is 80 bars, while the maximum pressures for the tanks the low and high pressures are 450 bars and 850 bars.

$$\left[P + a \cdot \left(\frac{N}{V}\right)^2\right] \cdot (V - N \cdot b) = N \cdot R \cdot T. \tag{7}$$

3.2.5. Hydrogen dispenser

The role of the dispensing unit is to securely fill the FCEV’s tank with hydrogen from the cascade storage. Unlike most gases hydrogen's temperature rises if the gas expands due to the fact that the Joules-Thomson coefficient value for hydrogen turns negative for a temperature higher than -68°C. Therefore the hydrogen expanding in the FCEV's tank will increase the tank's temperature. For safety reasons the surface temperature of the tank should remain below 85°C which result in an operating limit for the dispenser. According to the international standard for hydrogen vehicle fueling, SAE TIR J2601 [18], enforcing a minimum fueling time limits the temperature rise in the FCEV's tank. The standard is a result of a measurement campaign. It specifies a number of tables for different dispenser types depending on the target pressure and on the pre-cooling temperature, as shown in Table 1. Each table specifies the minimum fueling time according to the ambient temperature and the pressure in the car tank at arrival.

Table 1. SAE TIR J2601 dispenser types [19]

Dispenser type	**Target pressure (bar)**	**Min. pre-cooling temperature (°C)**
A70	700	-40
A35	350	-40
B70	700	-20
B35	350	-20
C35	350	0
D35	350	Ambient

A lookup table method was implemented for the simulation model to determine the flow rate for the refill of each car. The dispenser type considered is B, refilling at 700 bar with hydrogen pre-cooled at -20°C. An example of the calculation of the refilling minimum time is given in Table 2.

Input: 330 bar

Input: 26°C

Type B-70 1-7 Kg	**Actual Fuelling Times (min)**										
	Initial Tank Pressure, P_0 (bar)										
Ambient Temperature, T_{amb} (°C)	20	50	100	150	200	300	400	500	600	700	>700
>50	-	-	-	No	fuelling	-	-	-	-	-	-
50	41	39	36	33	30	24	18	13	7	1	-
45	29	28	25	23	21	17	13	9	5	1	-
40	21	20	19	17	16	13	10	7	4	1	-
35	16	16	14	13	12	10	7	5	3	1	-
30	13	12	11	10	10	8	6	4	2	-	-
25	11	10	9	9	8	6	5	3	1	-	-
20	9	8	8	7	6	5	4	2	1	-	-
10	5	5	4	4	2	1	1	2	1	-	-
0	5	5	4	3	2	1	1	1	0	-	-
-10	5	5	4	3	2	1	1	1	0	-	-
-20	5	5	4	3	2	1	1	1	-	-	-
-30	5	5	4	4	3	2	1	0	-	-	-
-40	5	5	4	4	3	2	1	0	-	-	-
<-40	-	-	-	No	fuelling	-	-	-	-	-	-

Table 2. Example of the lookup table method used to identify the minimum fueling time for a dispenser of Type B

Pre-cooling of the hydrogen is needed to compensate for the temperature increase suffered when expanding in the FCEV's tank. Empirical data reported in reference [20] indicate an energy of 0.18 kWh/kg H_2 required to chill the gas from 15°C to -20°C and 0.33 kWh/kg H_2 to reach -40°C.

3.2.6. Hydrogen demand

The hydrogen demand at the fueling station is set by the FCEV cars, more specifically on the arrival rate and the initial state of the on-board tank range. Stochastic modelling is applied to find the dispensed hydrogen over a period of time. The time interval between two consecutive car arrivals is given by the exponential distribution function from Eq. (8), where γ is the car arrival rate. The time of the first arrival is chosen from a random uniform distribution between 06:00 and 08:00.

$$P_x(k) = \gamma \cdot e^{-\gamma k}. \tag{8}$$

The total number of cars arriving at the fueling station each day was modelled using the Poisson probability distribution function from Eq. (9), where λ is the average number of vehicles arriving. The initial state of the on-board tank at the time of arriving at the fueling station was determined using the statistics collected by the UK Department for Transport [21]. The probability distribution function of the daily driving distance is given in Fig. 6 of the Appendix.

$$P_x(k) = \frac{\lambda^k \cdot e^{-\lambda}}{k!} \ . \tag{9}$$

3.3. Economic model

An economic module was developed around the technical module. The goal was to compare the influence of the technical and economic parameters on the final cost of the hydrogen. There are two costs streams: electricity costs, annualised capital costs, and operation and maintenance costs, as depicted in Fig. 1. The first stream, electricity costs, is calculated by the economic model by multiplying the instant power consumption with the electricity rate relevant at the consumption time. The electricity rates vary according to the generation type: grid or renewables. The power consumption is measured at the connection point of the refuelling station to the distribution board. The second cost stream is constituted of the annualized capital cost, and the operation and maintenance costs, which provides the cost of owning the refueler station per year. The final price of the hydrogen at the pump is dependent on the demand supplied by the refueler stations.

The cost of hydrogen delivered to the consumer is calculated using Eq. (10) from reference [5].

$$U = \frac{C_c + C_e}{Y}, \tag{10}$$

where U is the unit cost of H_2, Y is the annual hydrogen production from the dispensing station, C_e is the annual cost of electricity consumed by the electrolyser and the balance-of-plant system and C_c is the annualized capital cost including the annual operation and maintenance.

The parameter C_c, introduced Eq. (11), includes the annualized capital cost of the electrolyser stacks, balance-of-plant system, the annual cost of operation and maintenance, and the insurance and propriety taxes.

$$C_c = (e + s + c) \cdot (CRF + op + m + i + t)\,, \tag{11}$$

where *e* is the capital cost of the electrolyser stack including power supply, system control and gas drier, *s* is the capital cost of the storage, *c* is the capital cost of the compressor, *op* is the annual expenses of operating the station, *m* is the annual expenses incurred in maintenance of the station, *i* is the annual insurance, conveyed as a percentage of the capital cost and *t* is the annual propriety taxes.

The Capital Recovery Factor (CRF) converts a present value, in this work it is the refuelers station capital cost, into a stream of equal annual payments over a specified time, at a specified discount rate.

$$CRF = \frac{d}{1-(1+d)^{-N}}\,, \tag{12}$$

where *d* is the discount rate and *N* is the expected number of years of return on investment.

In order to be a financially viable investment, the refueler stations must raise revenue that will exceed the interest rate on the borrowing which is used to finance the station. The discount rate is equal to the internal rate of return on investment *r*, corrected by inflation *i*, as can be seen in Eq.(13). For UK investors in low-carbon technologies, such as onshore wind and biomass, *r* takes values between 6.6% and 11.6% [22]. A value of *r* equal to 8% was considered for this report.

$$d = r + inf \cdot (1 + r), \tag{13}$$

where *r* is the after-tax real rate of return on investment and *inf* is the annual rate of inflation.

The cost on the electric energy consumed by the station can be expressed as in Eq. (14). It is determined by the operation of the electrolyser stack, compressor, cooling equipment and the efficiency of the rectifier.

$$C_e = \eta_{AC/DC} \sum_t P_t \cdot c_t\,, \tag{14}$$

where $\eta_{AC/DC}$ is the efficiency of the rectifying equipment which supplies the electrolyser stacks, *t* is time index, P_t is power consumption of the refueler station at time *t* and c_t is the electricity rate at time *t.*

4. CASE STUDY: ISLAND HYDROGEN

4.1. Simulation assumptions

In this case study the simulation models the system trialled in the UK Island Hydrogen project [23]. The components and their key parameter are listed in Table 3. The wind turbine detailed specifications are listed in Table 5 of the Annex. A wind speed dataset [24], measured in the Sheffield area where the trial is located, was used to calculate the power output of the wind turbine. The dataset covers a period of one year. The probability density function of the wind measurements dataset is given in Fig. 7 of the Appendix.

The cost of the wind turbine is not introduced in our calculation in order to take into consideration that the turbine and the refueler can be owned by different parties. The refueler operator pays the Feed-in-Tariff for the electricity supplied from the turbine. In the UK the Feed-in-Tariffs with Contract for Difference [25] differ according to the generation technology. In the latest tender, the prices for onshore wind energy was £82.5/MWh, price which was considered in the simulation.

Table 3: Components of the Island Hydrogen trial

Onshore wind turbine	*225 kW*	Compressor	*20 kW*
Rectifier efficiency	*94%*	Low pressure tank (max. 450 bar)	*160 kg* H_2
Electrolyser stacks	*270 kW*	High pressure tank (max. 850 bar)	*54 kg* H_2
Buffer (max. 80 bar)	*30 kg* H_2	FCEVs Hyundai ix35	*100 kW*

A self-pressurising PEM electrolyser which outputs hydrogen up to 80 bar was considered. When supplied with electricity from grid, the refueler station can be classified as a medium industrial consumer (with annual consumption between 500 – 20,000 MWh). The average price of electrical energy paid by medium industrial consumers in the UK for the July-December 2014 period was £96.1/MWh [26].

The vehicles considered are passengers FCEVs with a 100 kW maximum power fuel cell. The vehicle cost was not included in the simulation. In the last years the price of FCEVs continued to drop to values similar with all-electric EVs and internal combustion cars [27]. The price of petrol[3] equivalent to one kilogram of H_2 was derived from comparing the energy consumption of the same car type with fuel cell and internal combustion engine, as can be seen in Table 6 of the Appendix.

4.2. Results

Two types of analyses were carried out for the case study; performance and operational analysis. The first analysis evaluates the performance of different technologies and operating modes of the refuelling station. Although the electrolyser in the pilot project is based on PEM technology, alkaline technology was also assessed as it is a widely used solution for water electrolysis. The operating modes considered for the refueler are; operate on grid electricity, wind turbine generated electricity, or combined. The performance indicator is the unit cost of hydrogen. This embeds both the technical system efficiency and the economic data.

The operational analysis investigated the capacity of the refueler under different operating modes. The capacity is measured in the number of cars that refill at the station. The number of cars unserved is also examined. In the case of the refueler being supplied by the electricity from the wind turbine, the energy which is not captured by the refueler is calculated.

[3] The retail petrol price considered in this study was £1.15/l, as recorded in the UK on April 2015

4.3. *Performance analysis*

For the next section of the results we have focused on the performance aspects of the hydrogen refueler. The unit cost of hydrogen for different return on investment periods are plotted in Fig. 2. The hydrogen cost components are highlighted: capital and O&M with orange colour, while electricity cost is depicted in blue. The alkaline and PEM electrolysis technologies were compared. Three scenarios have been investigated; refueler station supplied: by grid electricity, by wind turbine generated electricity only, and by both grid and wind turbine electricity. As a benchmark the cost equivalent of petrol is depicted with grey colour. In the simulation, with the duration of one year, the input λ of Eq. (9), the average number of vehicles arriving daily, is 25.

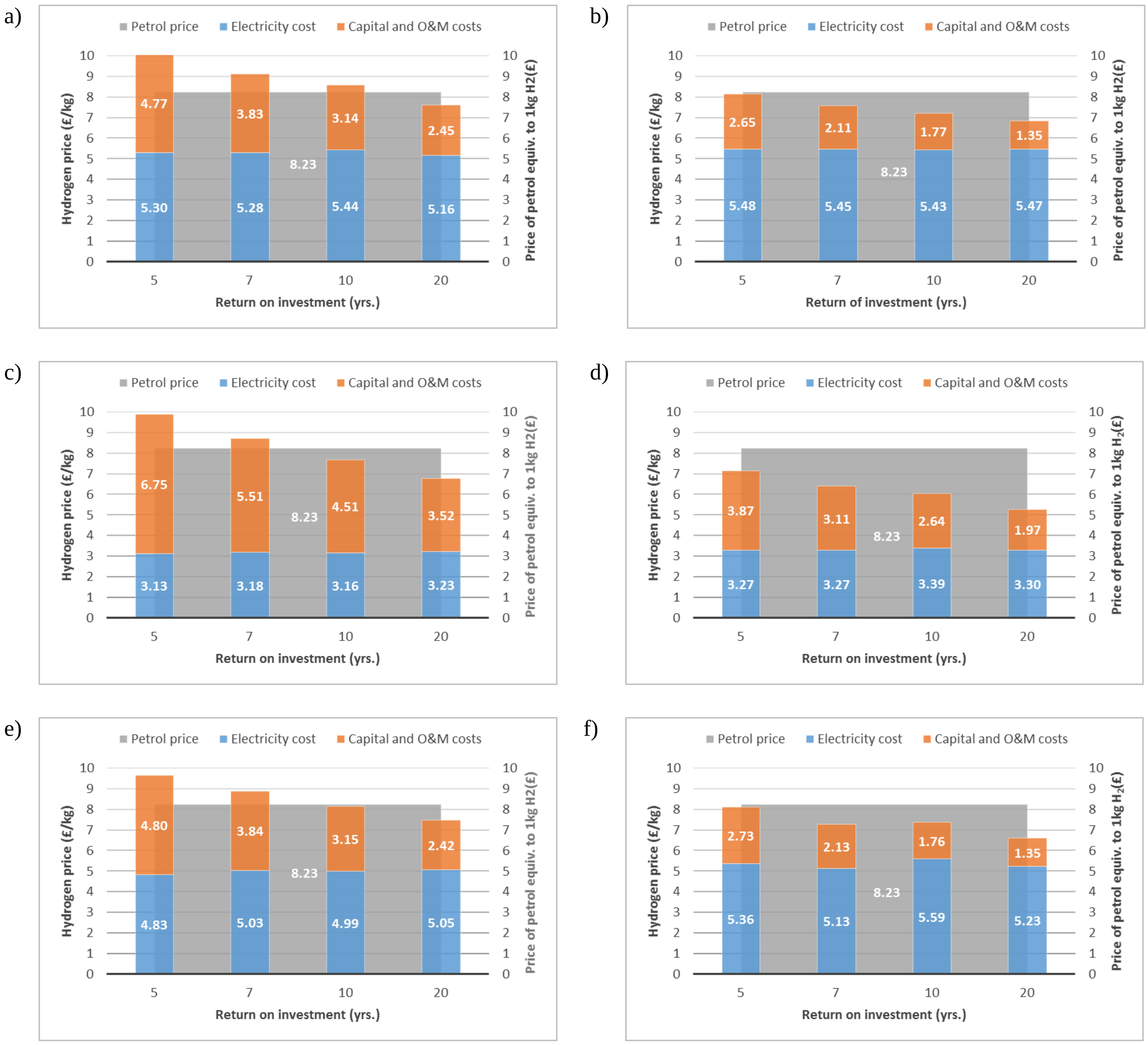

Fig. 2: Cost of hydrogen for: (a) PEM tech. operating with grid electricity, (b) Alk. tech. operating with grid electricity, (c) PEM tech. operating with renew. electricity, (d) Alk. tech. operating with renew. electricity, (e) PEM tech. operating with grid & renew. electricity, (f) Alk. tech. operating with grid & renew. electricity.

The results from Fig. 2 indicate hydrogen to be a good cost alternative to the carbon intensive fuels. When comparing the results of the two technologies, PEM and alkaline, it can be observed that the alkaline technology offers a lower price for hydrogen because the capital cost of alkaline electrolysers is half of the PEM electrolysers. However, the PEM is a relatively new technology compared with alkaline, and therefore its cost is expected to decrease in the future. PEM technology returns a slightly better energy efficiency, than alkaline, per unit of hydrogen produced. This can be observed by comparing the electricity cost component of hydrogen for the two types of technologies.

Comparing Fig. 3 a), c) and e), it can be seen that the hydrogen unit cost is similar. However, the share of the hydrogen cost components differ. The capital share of the cost of hydrogen is smaller for the scenarios where the refueler is supplied by grid electricity because the hydrogen is produced in larger quantities than in the wind scenario. The electricity share of the hydrogen cost is the smallest in the scenario where the refueler is supplied by wind turbine generated electricity because the electricity rate for onshore wind is less than the rate for the grid.

In Fig. 3 a comparison is made between the hydrogen unit cost without subsidies and the hydrogen unit cost considering a subsidy for the capital cost of the refueler. The latter scenario is relevant for many refueler that were built using governments' research and development grants. It can be observed in Fig. 3 that when the capital cost is alleviated, the hydrogen cost is comprised of the electricity cost component, with the largest share, and the operation and maintenance costs. The capital subsidy levelled the differences between the hydrogen unit costs for the two technologies: PEM and alkaline. Furthermore, by alleviating the capital cost, the subsidy also promotes operating the refueler just on energy from the renewable as it cheaper than grid electricity. However, further work should be done here given that the intermittency of the renewable resources can induce to a low utilisation of the refueler which capital has been subsidised.

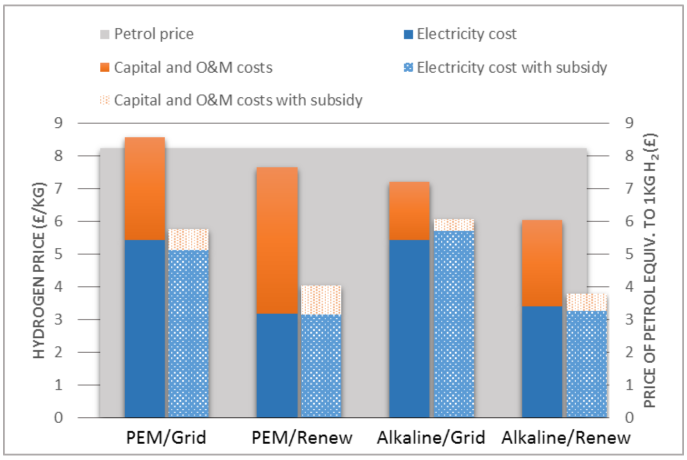

Fig. 3: Hydrogen cost for ROI=10 considering a subsidy for the refueler capital costs

4.4. Operational analysis

For the next section of the results we have focused on the operational aspects of the hydrogen refueler. The outputs of a simulation of the refueler, over the time span of one year, are the electrolyser stacks utilisation and the average number of vehicles unserved daily, are plotted in Fig. 4. The vehicles unserved are the vehicles that cannot refill because of hydrogen shortage. To investigate the capacity of the refueler, the average number of cars arriving daily at the refueler, λ, was varied from 10 to 60 cars.

It can be observed that in the scenario where the refueler is supplied just on the electricity generated by the wind turbine, in Fig. 4 a), there are cars unserved even for λ=10. The reason is that for a number of days within the year there is a shortage of wind resource, which increases the annual average of cars unserved. In the same scenario, the utilisation of the electrolyser saturates close to 50% when λ=25, as it is limited by the amount of energy produced by the wind turbine. In the scenario where the refueler is supplied by grid electricity, in Fig. 4 b), the shortage in hydrogen appears a higher λ compared with the previous scenario. Also the utilisation of the electrolyser reaches 100%.

It can be concluded that to make the best use of the refueler capacity is to have a grid connection that will provide electricity in the periods of wind resource shortage. However, the results don't show any impacts of the high utilisation such as degradation of stacks and equipment lifetime resulting from continuous operation of the refueler.

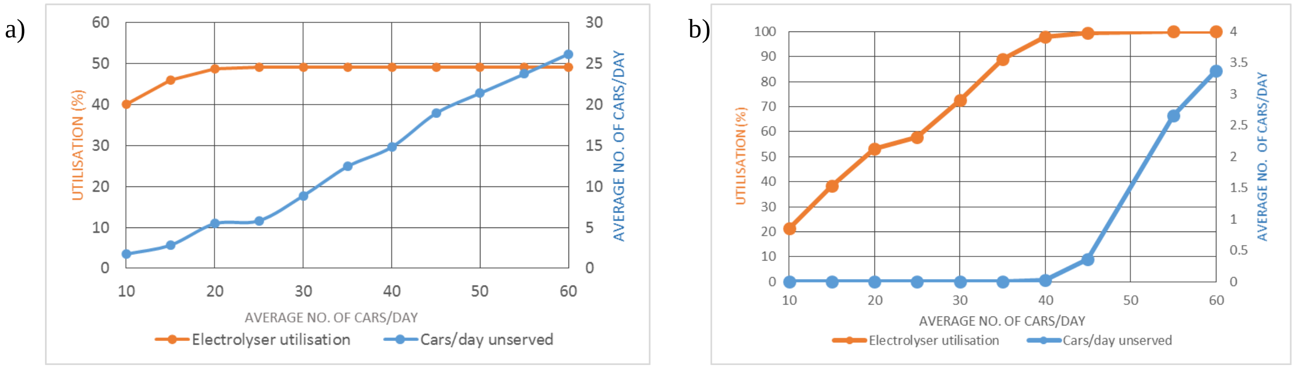

Fig. 4: Utilisation for PEM Electrolyser and the no. of cars served by the refueler supplied with: (a) grid electricity, (b) renewable electricity

The energy from the wind turbine which is not captured by the refueler over the time span of one year is shown in Fig. 5. For λ=10, even though there are cars unserved, there are also approx. 150MWh of renewable energy which are not captured. This is caused by the intermittency of the wind resource. Long periods of high wind speed are sufficient to supply the hydrogen demand and charge the refueler storage to the maximum pressure, forcing the electrolyser to shut off. If more cars are considered, the hydrogen demand captures all the energy produced. However, with the increase in arrivals, the number of cars unserved has also increased.

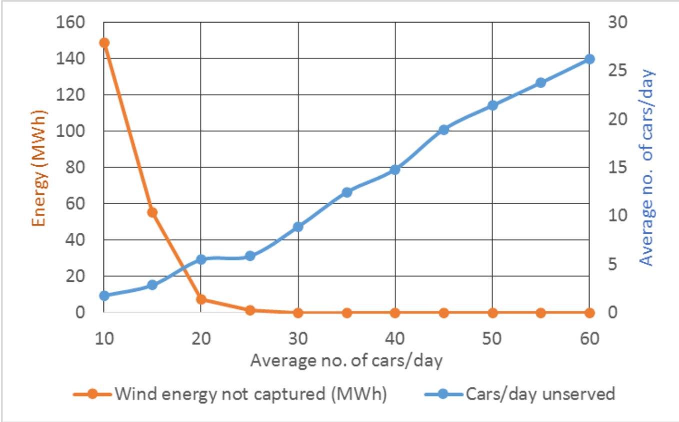

Fig. 5: Wind turbine generated energy which is not captured by the hydrogen refueler

5. CONCLUSIONS AND FUTURE WORK

This work has presented a technical-economic analysis of a hydrogen refilling station. The tool, developed in Matlab®, models an integrated energy system which combines hydrogen refuelling with on-site hydrogen production through water electrolysis, renewable energy supply and hydrogen vehicles demand. An economic model is also embedded in the tool, model which will output the unit cost of hydrogen. A case study investigated a refilling station based on a pilot project located in the UK.

A comparison between PEM and alkaline technology showed that the capital cost component of the hydrogen unit cost is smaller for alkaline technology. However, the PEM technology is more efficient, thus the electricity cost component of the hydrogen unit is smaller for PEM. Another comparison between operating modes of the refilling station showed that even though the hydrogen unit cost is similar if the same technology is used, the share of the capital and electricity cost is different. The capital cost is the main component if the refilling station operates only on electricity generated by the wind turbine, while the electricity cost is the main component if the refilling station operates only on grid electricity. A combined wind and grid connected station is preferred in order to benefit from the lower price of wind energy and the high utilisation offered by the grid connection, which will see that a higher number of customers are served.

The analysis showed that hydrogen represents a good fuel alternative to the carbon intensive fuels. If the expected return on investment period is over 10 years for PEM electrolysers and 5 for alkaline electrolysers the hydrogen unit cost is below that of petrol. We also show that subsidies on capital costs levels the hydrogen unit cost between the PEM and alkaline technologies, with both of them cheaper than the equivalent price of petrol. Subsidies also encourage the use of electricity generated by wind turbine.

This effect of subsidies can be seen as a proxy for partially funded pilot projects. This can provide some policy level insight whereby pilot project funding can be used to offset capital costs and thus create better commercial grounding for driving a business forward.

The intermittency of the wind resource means that not all the energy from the wind turbine is captured by the refueler. Increasing the size of the hydrogen storage could offer a solution. However, the impact on the cost that the increase in hydrogen storage will have be studied further.

The degradation of the electrolyser stacks should be modelled in a future work to study the economic impact as there is a trade-off between capital cost component recovery and utilisation of the refueller. Another aspect that has not been explicitly modelled is demand created by the take-up of FCEV’s. It would be a good step forward to model the dynamic adoption of FCEV’s by consumers and integrate this with the refueler model so that a more realistic short-medium term scenario is represented which includes the demand side.

Acknowledgements

The authors would like thank their partners in the Island Hydrogen project (funded by Innovate UK - project no 101292) for helpful discussions and suggestions for this work.

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Appendix

Table 4. Parameters description and values

Parameter	Description	Value	Unit of measurement
R	Ideal gas constant	8.3144	J/(mol·K)
F	Faraday's constant	26.801	A·h/mol
z	Electrons transferred per ion for H_2	2	-
η_c	Compressor mechanical and the motor drive efficiency	0.8 [6]	-
n	Polytropic exponent for H_2	1.609	-
a	Constant of the van der Waal's eq. (7) for H_2	0.0247 [28]	$J \cdot m^3/mol^2$
b	Constant of the van der Waal's eq. (7) for H_2	$2.65 \cdot 10^{-5}$ [28]	m^3/mol
N	Number of moles	-	mol
V_{Buffer}	Volume buffer	9.26	m^3
V_L	Volume low pressure tank	11.59	m^3
V_H	Volume low pressure tank	2.6 [6]	m^3
U_0	Reversible cell voltage	1.229	V
η_F	Faraday efficiency	-	-
A_{alk}	Alkaline cell area	0.25	m^2
A_{PEM}	PEM cell area	0.025	m^2
a_1	Empirical parameters Eq. (2)	0.995 [28]	-
a_2	Empirical parameters Eq. (2)	-9.5788	m^2/A
a_3	Empirical parameters Eq. (2)	-0.0555	$m^2/(A°C)$
a_4	Empirical parameters Eq. (2)	0	-
a_5	Empirical parameters Eq. (2)	1502.7083	m^4/A
a_6	Empirical parameters Eq. (2)	-70.8005	$m^4/(A°C)$
a_7	Empirical parameters Eq. (2)	0	-
r_1	Parameter for ohmic resistance of electrolyte	7.331e-5	$\Omega\ m^2$
r_2	Parameter for ohmic resistance of electrolyte	-1.107e-7	$\Omega\ m^2/°C$
r_3	Parameter for ohmic resistance of electrolyte	0	-
s_1	Parameters for overvoltage on electrodes	1.586e-1	V
s_2	Parameters for overvoltage on electrodes	1.378e-3	V/°C

s_3	Parameters for overvoltage on electrodes	-1.606e-5	V/°C^2
t_1	Parameters for overvoltage on electrodes	1.599e-2	m^2/A
t_2	Parameters for overvoltage on electrodes	-1.302	m^2/(A°C)
t_3	Parameters for overvoltage on electrodes	4.213e2	m^2/(A° C^2)
$i_{0,an}$	Exchange current density at anode	1e-6	A/cm^2
$i_{0,cat}$	Exchange current density at cathode	0.287	A/cm^2
P_{H2}	Anode partial pressure	13.1	bars
P_{O2}	Cathode partial pressure	2.068	bars
α_{H2}	Anode transfer coefficient	2 [16]	-
α_{H2}	Cathode transfer coefficient	0.5	-
T, T_{CELL}	Temperature of the cell	353	°K
T_{an}, T_{cat}	Constant temperature of the	353	°K
δ_m	Membrane thickness	0.0178	cm
C_{H+}	Concentration of H_2 ions in the membrane	1200	mol/m^3
D_{H+}	Diffusivity of H_2 ions in the membrane	1.28e-10	m^2/s
γ	Arrival rate of cars	-	-
λ	Average number of cars arriving at the station	-	-
e	Capital cost of the electrolyser stack including power supply, system control, gas drier — Alk. [29]	750	£/kW
	PEM [29]	1500	
s	Capital cost of the storage	133	£/kg
c	Capital cost of the compressor	333	£/kW
m	Annual expenses incurred in maintenance of the hydrogen station	2	% capital cost
i	Annual insurance	1.5	% capital cost
t	Annual propriety taxes	0.5	% capital cost
d	Discount rate	-	%
N	Return of investment	-	years
r	After-tax rate of inflation	8	%
inf	Inflation	1	%

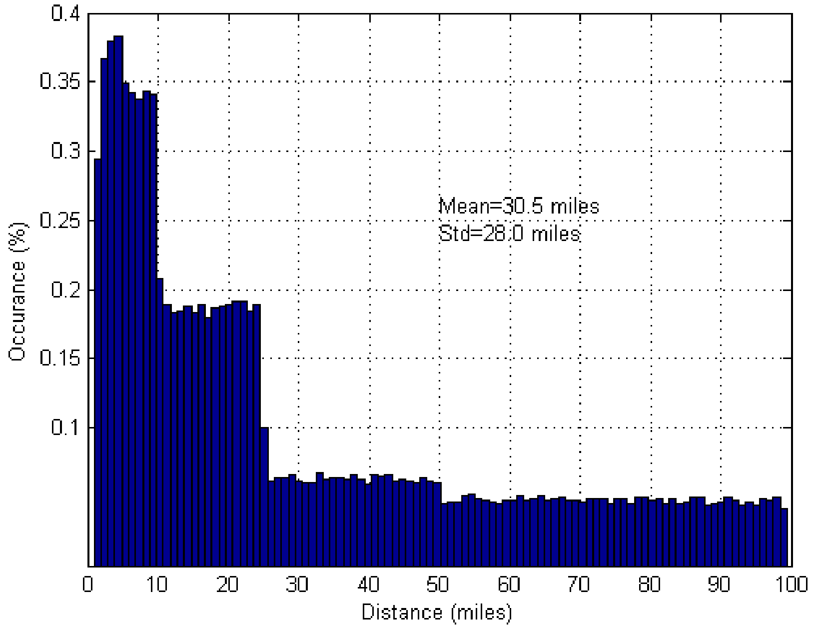

Fig. 6: Daily driving distance in the UK

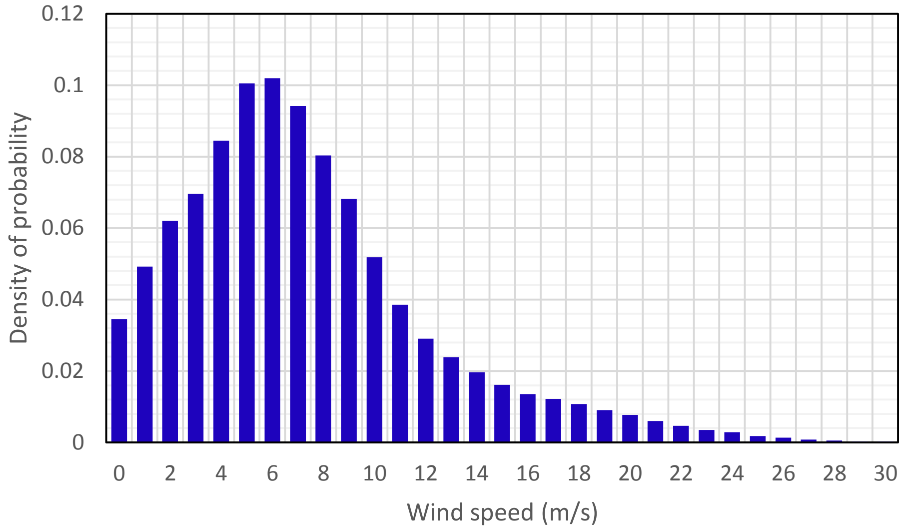

Fig. 7: Probability density function of the wind speed measured in Sheffield, UK area in 2014

Table 5: Parameters of the Vestas V29 wind turbine at the Island Hydrogen site [30]

Make/Model	Rated power	Cut in speed (m/s)	Rated speed (m/s)	Cut out speed (m/s)
Vestas V29	225 kW	3.5	14	25

Table 6. Performance specification for an FCEV and a car with internal combustion engine

Make/Model	Fuel type	Power (kW)	Consumption (combined)
Hyundai ix35	Petrol	99	6.8 l/100 km
Hyundai ix35 FCEV	Hydrogen	100	0.95 kg H_2/100 km