Optimal operation of a hydrogen refuelling station combined with wind power in the electricity market

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Abstract

An optimisation routine has been developed to analyse the performance of hydrogen refuelling stations combined with wind power operating in electricity markets. This optimisation routine includes the minimum turn down ratio of the electrolyser in its formulation resulting in a mixed integer nonlinear programming optimisation. The optimisation routine has been used to analyse the performance of a hydrogen refuelling station located at the advanced manufacturing park in Rotherham, UK. The performance of the optimisation routine for various scenarios of hydrogen demand and wind power has been assessed. This includes the effect of operating the electrolyser to reduce wind curtailment in a grid constrained scenario. It is found that the optimisation routine is capable of increasing profits when operating in the market, but this is dependent on various factors such as the level of hydrogen demand and wind power.

Key Words: hydrogen refuelling station; hydrogen vehicle; electricity market; optimisation; electrolyser

1. Introduction

With increasing concerns over energy security and anthropogenic climate change [1], new methods of generating and utilising energy must be developed. Hydrogen has the potential to aid in increasing the use of renewables and reducing greenhouse gas emissions by acting as an energy carrier and storage medium [2]. Increasing the use of alternative fuels in the transportation sector is vital to reduce greenhouse gas emissions, with hydrogen fuel cell electric vehicle (HFCEV) and battery electric vehicles (BEV) both having the potential to achieve this [3]. HFCEVs are increasingly becoming commercially available. In order to support the deployment of hydrogen vehicles, it is important to develop a refuelling network, and to assess the performance and operation of refuelling stations. BEVs are at a more advanced stage in their deployment, and the benefits of using BEVs for demand management has been investigated by a number of researchers. Druitt and Früh investigated the use of BEVs to provide demand management to the UK system assuming high wind penetration, finding that this method could aid in integrating wind power as well as allowing vehicle owners to derive revenue from operating in the electricity market [4]. Boait et al investigate the use of BEVs as part of a domestic demand side response method in the UK [5] whilst Sortomme and El-Sharkawi determine the performance of different charging algorithms for BEVs operating in an electricity market [6]. To take part in demand side management and balancing actions, BEVs must be somehow attached to the electricity network. This makes them dependent on suitable infrastructure, limits the times at which they can take part in balancing and market operation, and is dependent on the local network to which they are connected allowing power flows at appropriate times. Hydrogen energy storage can be used as a means of helping to integrate renewables on to the electricity network, with both round trip storage [7] and demand from HFCEVs [8] having the ability to increase renewable penetration on constrained networks. Hydrogen can aid in implementation of smart energy networks by providing an energy storage and distribution vector [9].

HFCEVs are likely to be refuelled in a manner similar to conventional vehicles. The shorter refuelling time for HFCEVs compared to battery electric vehicles means that hydrogen refuelling infrastructure is likely to consist of hydrogen refuelling stations, where drivers of HFCEV's can refuel in a similar manner to conventional vehicles. In the UK, development of a hydrogen refuelling infrastructure is being investigated [10]. One possible method of providing hydrogen to forecourt refuellers could be on-site electrolysers with hydrogen storage facilities. These electrolysers will have the ability to generate hydrogen independently of refuelling demand, which could help facilitate their operation in electricity markets.

A number of different aspects relating to hydrogen refuelling stations have previously been investigated. Those studies focussing on operation of the station without considering hydrogen generation have investigated hydrogen storage tank sizing, configuration and control strategies [11] minimizing energy use due to compression through cascaded storage tanks [12,13] and minimzing refuelling time [14]. Oi and Sakaki [15] looked at the optimal sizing of electrolysers in hydrogen refuelling stations operating off-peak, but did not investigate the electrolyser operation. Dagdougui et al [16] determine the optimal performance of a network of hydrogen refuelling stations powered by renewable electricity based on population density and renewable supply. The ability of electrolysers to replace spinning reserve in a high wind penetration UK scenario was investigated by Kiaee et al [17], but they did not investigate factors such as hydrogen demand and control strategies. Other investigations have provided feasibility studies of renewable hydrogen stations [18, 19] including residential refuelling stations [20], determined the impact of environmental conditions on refuelling station operation [21], and analysed the optimal performance conditions for renewably power refuelling stations [22].

A small number of electrolytic hydrogen refuelling stations are now operational in various countries. For example, Kiaee et al [23] report on a hydrogen refuelling station located in Norway. The hydrogen is produced by a pressurised alkaline electrolyser and various scenarios are investigated including being powered by renewable energy. Whilst detailed performance is characterised, operational detail such as investigating the electrolyser scheduling and vehicles refuelled is not reported.

As stated previously, a major advantage of electrolytic hydrogen refuelling stations is that they can separate refuelling demand from electrolyser operation. By doing this they can aid in integrating renewable electricity, and can take advantage of operating in the electricity market. Korpas et al [24] investigate using hydrogen storage in an electricity market, including a hydrogen demand from a single bus in their simulation. The paper demonstrates the ability of hydrogen storage to increase profits in market operation, but focusses primarily on round trip storage. When considering the minimum electrolyser power, they do not include it fully in the optimisation routine, which could lead to sub-optimal results. In [25] Korpas et al consider a similar system operation with a grid constrained electricity import/export capacity, but do not consider market operation. Xiao et al [26] report on the performance of a hydrogen filling station operating in the electricity market, finding that the cost of hydrogen can be reduced by this method, but they do not consider the possibility of operating in a constrained grid, or the operational constraints of the electrolyser such as a minimum power input.

In this paper an analysis of a hydrogen refuelling station based at the advanced manufacturing park (AMP) in Rotherham, UK is presented. The effect of operation in the electricity market is determined, as well as the number of cars which the station can refuel and how this affects operation in the electricity market. The minimum operating power of the electrolyser is modelled by including an on-off variable in the optimisation, resulting in a mixed integer non-linear programming optimisation problem. This allows the performance of different electrolyser technologies to be compared. The ability of the refuelling station to operate with wind power in a grid constrained scenario, and the effect of this on performance is also investigated.

2. Description of refuelling station and parameters

2.1 Refuelling station at the advanced manufacturing park, Rotherham.

The Island Hydrogen project [27] aims to deploy and investigate the performance of hydrogen refuelling stations in the UK. As part of this, a hydrogen refuelling station has been developed by ITM power at the AMP in Rotherham. The site was already the location for a 225 kW wind turbine. The refuelling station, wind turbine and an office building are all connected to the local electricity network via the same substation as represented in Figure 1. The network is sometimes constrained so that the electrolyser is not always able to operate at 100% power.

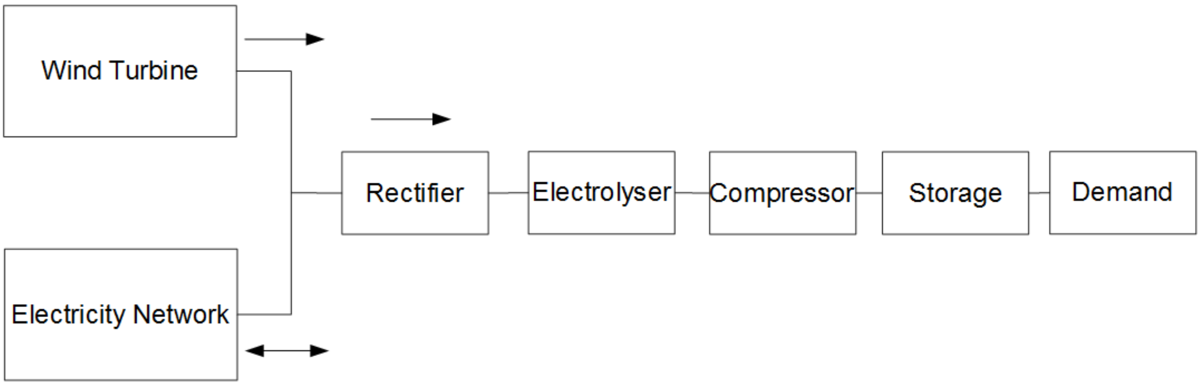

Figure 1: Schematic of the hydrogen refuelling station and grid connection

The electrolyser is a recently installed PEM type electrolyser with a power rating of 270 kW. The electrolyser consumes 52 kWh/kg hydrogen produced, equivalent to 76% electrolyser efficiency based on hydrogen HHV. After production, the hydrogen is compressed before it is stored at a maximum pressure of 350 bar. The combined compressor and dispenser unit consumes 10.2 kWh/kg of hydrogen with a peak power consumption of 45 kW. This gives a total efficiency of 63%, with a peak power of 315kW. When operating, it is assumed that the electrolyser and combined compressor and dispenser unit vary their power together. The hydrogen storage is capable of storing 220 kg of hydrogen in pressurised cylinders. The electrolyser used at the Rotherham site is capable of operating between 0-100 percent of its full power output, but when used for extended periods of 6 hours or more, its minimum load is 12.5 percent of max load.

2.2. Refuelling station model overview

A model of the refuelling station at the AMP has been developed using Matlab. The model is used to simulate operation of the station with the goal of optimising the performance in the electricity market. The model uses half hourly time steps to simulate the performance, and includes the refuelling station components described in section 2.1 and Figure 1. The time series of wind power, hydrogen demand and electricity market pricing used as inputs to the simulation are described in sections 2.3-2.5, whilst the optimisation procedure and scenarios investigated are described in section 3.

2.3 Wind power time series

Time series for the wind power output are taken from the UK generic distribution system networks at the centre for Sustainable Electricity Distribution (SEDG) [28]. The time series is in half hourly periods over the course of one year and ranges from 1 for full output to 0 for no output. The time series can then be scaled by the wind turbine size.

2.4 Hydrogen demand

The time series for the hydrogen demand is derived from a modified Chevron^{TM} profile in the H2A analysis [29, 30]. The demand profile takes into account hourly, daily and seasonal variations [8]. The time series are combined to create a half hourly time series representing the variation in refuelling demand. The time series is scaled to a maximum demand. This maximum demand is altered to give a certain number of vehicles refuelled per day. An average tank size of 5.6 kg of hydrogen is used, based on a mid-sized hydrogen fuel cell vehicle with a range of 350 miles [31]. The peak hydrogen demand for a given number of average vehicle refills per day can then be determined by the ratio of the hydrogen demand time series multiplied by the tank size to the number of time periods in a day (48) multiplied by the time series average.

2.5 Electricity market description

Data from the UK power exchange (UKPX) is used as a basis for variable electricity pricing in a market system [32]. Historic pricing data is available from UKPX and is used as an input to the simulation. This approach is used in in the Nordic system [24], and to compare different storage methods for wind energy [33]. Under current market arrangements, the price paid for electricity is constant, however with the rise of smart metering time-dependent electricity pricing is increasingly possible [34]. As well as determining the performance of the station in time-dependent pricing regimes, the method described could indicate the ability of the station to provide balancing services to the network, assuming that high pricing coincides with periods of high demand.

3 The optimisation procedure

The optimisation procedure is carried out using Matlab. The system is modelled to include the components shown in Fig 1. The wind turbine is represented by its power capacity in combination with a time-series as described in section 2.3 to give the wind power output. The grid connection is represented by a constraint in the optimisation which limits the power which can be exchanged, as described in more detail in this section. The electrolyser and compressor operation are represented by their power capacity and modelled as described in section 2.1. The hydrogen storage size of 220 kg is represented by a constraint in the optimisation as described in more detail in this section, whilst the hydrogen demand is represented by a time series as described in section 2.4. The equations used to model the station and simulate its performance are fully described in equations (1) – (11). The optimisation procedure minimises the cost of operating the refuelling station over a set time-frame with an on-line methodology as described below

The objective function (OF) given in equation (1) attempts to minimize/maximize the price paid for electricity bought/sold, whilst minimizing the amount of hydrogen demand not met, where $C_{e,i}$ is the cost of electricity in time period i, PT_i is the power transferred to the grid in time period i, C_h is the penalty cost of not meeting the hydrogen demand, $H_{Dem,i}$ is the hydrogen demand in time period i and $H_{Del,i}$ is the hydrogen delivered in time period i. C_h is chosen so that hydrogen demand is always met if there is sufficient hydrogen in the storage. Positive PT_i means that power is being exported to the grid whilst negative PT_i means power is being imported from the grid. The OF is optimised over np half hour time periods, where np can be decided by the user, and in this case is chosen to be 48 representing a full day of half hour periods. All of the hydrogen demand being met could be formulated as a constraint in the optimisation problem, but the optimisation would then not converge if this condition could not be achieved. Including the hydrogen demand in the OF allows the effect of increasing hydrogen demand to be investigated, as not meeting the entire demand may be acceptable in some circumstances, for example if it were possible to import hydrogen. The optimisation routine is carried out at half hour time steps over 30 days, meaning the optimisation procedure is carried out 1440 times. At each time step j, the optimisation procedure schedules the optimum electrolyser operation for the next 48 time steps (i). The routine then retains the values of the decision variables for the current time step, and moves on to the next time step j, with updated information on the hydrogen level in the store. This can be described as on-line operation [24].

$$OF = \sum_{i=j}^{np+j} C_{e,i} \times PT_i - C_h \times \left(H_{Dem,i} - H_{Del,i}\right) \tag{1}$$

Linear constraint:

$$SL_1 = SL_{np} \tag{2}$$

Nonlinear constraints:

$$SL_{i+1} = SL_i + 0.5n_e \times n_c \times EL_i \times ELon_i/HHV - H_{Del,i} \tag{3}$$

$$PT_i = WP_i - (EL_i \times ELon_i) \tag{4}$$

The decision variable are $PT_i, H_{Del,i}, SL_i, EL_i, ELon_i, WP_i$. EL_{on} is defined as an integer value.

The decision variable bounds are:

$$-PT_{max} < PT_i < PT_{max} \tag{5}$$

$$0 < H_{Del,i} < H_{Dem,i} \tag{6}$$

$$0 < SL_i < SL_{max} \tag{7}$$

$$EL_{min} < EL_i < EL_{max} \tag{8}$$

$$0 < ELon_i < 1 \tag{9}$$

$$0 < WP_i < WP_{max\,i} \tag{10}$$

The optimisation is performed subject to the constraints given in equations (2) to (4) where SL_i is the storage level in period i, n_e is the electrolyser efficiency, n_c is the compressor efficiency, EL_i is the electrolyser power in period i, $ELon_i$ is an integer variable which can be 0 or 1 which determines if the electrolyser is operating or not, HHV is the higher heating value of hydrogen (39.41 kWh/kg) and WP_i is the wind power output in period i. These are split into linear and non-linear constraints. Equation (2) requires that the storage level at the beginning of the optimisation period is equal to the storage level at the end. Without this requirement, the store would tend to empty, as importing energy to produce hydrogen consumes energy which increases the value of the OF. Equation (3) ensures the hydrogen storage level in each time step is dependent on the level in the previous time step, the hydrogen produced by the electrolyser in the previous time step, and the hydrogen used to refuel vehicles in the previous time step. As the optimisation is over half hour time periods, a factor of 0.5 must be in included in equation (3) when converting electrolyser power to hydrogen generated, as the HHV of hydrogen is given in kWh/kg. Equation (4) determines the power transferred to the grid is equal to the wind power produced minus the electrolyser power in each time step. The bounds on each decision variable are given in equations (5) to (10). The nonlinear constraints given in equations (3) and (4) actually consist of np constraints each, one for each optimisation period i. The same applies for each decision variable.

$H_{Dem,i}$ and $WP_{max,i}$ are determined for each period i prior to each optimisation by multiplying the hydrogen demand maximum and wind power capacity by the hydrogen demand and wind power time series respectively for the period $i = j$ to $i = np + j$. $C_{e,i}$ for periods j to $np + j$ is selected from the electricity market price time series. Including the wind power output as a decision variable, WP_i, with its maximum determined by the wind turbine size and power series allows for wind power curtailment to be modelled. The OF given in equation (1) maximises the power transfer to the grid PT_i, so maximising wind power WP_i, but in scenarios where the grid connection is constrained below the maximum wind power output, some wind power may need to be curtailed.

Inclusion of a minimum electrolyser power below which the electrolyser much be switched off results in the optimisation becoming non-linear, as seen from equation (3). The decision variable $ELon$ can only take the integer values of 0 or 1, meaning the problem becomes a mixed integer non-linear programming (MINLP) optimisation problem. This is an increase in complexity compared to the linear optimisation problems investigated in [24, 26]. To solve the problem a suitable MINLP solver must be used. The optimisation suite OPTi-Tool box [35], integrates a number of optimisation procedures in to the MATLAB environment. In this analysis, the Solving Constraint Integer Programs (SCIP) procedure is used [36]. SCIP solves MINLP problems to a global optimum. The SCIP procedure generally solves quickly to a global optimum, but on occasion it fails to converge to a solution. This is then caught in the time series loop and a gradient based MINLIP solver BONMIN is used [37]. BONMIN is capable of converging to a solution when SCIP is not, but takes longer than SCIP to converge.

In order to assess the performance of the market optimisation procedure against non-market optimisation, an analysis with the OF given in equation (11) is also carried out for each scenario. This OF maximises wind energy production whilst minimising hydrogen demand not delivered, but does not consider the market price of electricity. The price paid for electricity bought and sold is then calculated after the optimisation using the market price.

$$OF = \sum_{i=j}^{np+j} C_w \times WP_i - C_h \times \left(H_{Dem,i} - H_{Del,i}\right) \tag{11}$$

$C_w$is a cost function chosen to maximise wind energy production in the optimisation procedure. The storage level is initially set to be half the maximum capacity, i.e. 110 kg. A number of scenarios are investigated to determine the performance of the electrolyser.

3.1 Number of cars refilled

The analysis is carried out at six different hydrogen demand levels. These represent 5, 10, 15, 20, 25 and 30 cars being refilled per day. The daily hydrogen demand is shown in Table 1.

Table 1: Daily hydrogen demand variation with vehicles refuelled per day.

No of Cars	Daily Hydrogen Demand (kg)
5	28
10	56
15	84
20	112
25	140
30	168

3.2 Wind turbine size increased above constraint

The grid connection at the AMP where the wind turbine and refuelling station are located has a maximum power transfer of 500 KVA. Under normal operation the demand from the office building on site requires that the electrolyser must limit its power intake to 50% of capacity between 7am and 7pm. This case is not considered here, but left to future work, but does indicate the constrained nature of the local grid. In this paper two scenarios are considered. Firstly the case that the wind turbine is of size 225 kW, and secondly that the wind turbine is increased to 815 kW. In the first case this is the original sizing, but there is no need to operate the electrolyser to support the wind turbine. In the second case, the wind turbine maximum output is equal to the grid constraint, plus the electrolyser and compressor power at maximum consumption. The hydrogen station should then operate to minimise curtailment of wind power, whilst also minimizing costs in the market environment

3.3 Electrolyser turn down ratio

Two different values for electrolyser turn down ratio are considered. These are full range from 0-100% reflecting the capability of the electrolyser at the AMP, and a minimum turn down of 30%, which represents the current performance of alkaline electrolysers [38].

All combinations of the above scenarios are investigated to determine the performance of the hydrogen refuelling station at the AMP. In order to compare the ability of the optimisation to reduce the cost of electricity, an analysis is carried out for each scenario where the optimisation only attempts to minimise hydrogen not delivered whilst maximising wind power production, by using the OF given in equation 11 rather than equation 1.

The simulations are all carried out over a one month time period, with the month chosen being August. This month is chosen as the wind power time series in this month has a capacity factor of 0.316, roughly equivalent to a typical UK wind power capacity factor.

4 Results

Tables 2 to 5 show the net profit made from operating the refuelling station and wind turbine in combination. The values are only for the net profit/cost of operating in the electricity market, and do not include any potential value for hydrogen sold. As a comparison, the market profit from selling electricity from the wind turbine independently would be £1988 for the 225 kW turbine and £7549 for the 815 kW turbine, whilst the cost of electricity bought for the generation of hydrogen is £1841 for 5 cars per day in the non-market optimisation. The decreasing values for profit as the number of cars per day being refuelled increases is due to the increasing electricity demand meaning more electricity is bought. When comparing the analysis for different scenarios it is important to note that differing amounts of hydrogen can be left in the store at the end of the analysis period. This means the electrolyser may have been operating at different amounts for the different scenarios, affecting the profit figure as more electricity would have been brought. The figures are then adjusted by calculating the average cost of electricity bought to match the final hydrogen storage level with the initial storage level. This figure is shown in the adjusted profit column in Tables 2 to 5. It can be seen from Table 2 to 5 that the optimisation procedure can increase the profit from operating in the electricity market. The optimisation routine did not always converge to an optimal solution for the case of an 815 kW wind turbine, 5 cars per day refuelled and 30-100% range electrolyser. For this reason, the first row of results in table 5 is left blank. For all other scenarios, the optimisation routine always converged to optimal solutions.

Table 2: Comparison of profit from trading in electricity market for electrolyser with 0-100% range in output, 225 kW turbine

	Raw profit (£)		Hydrogen left in store (kg)		Adjusted profit (£)		
Cars/day	Non market optimisation	Market optimisation	Non market optimisation	Market optimisation	Non market optimisation	Market optimisation	Difference
5	242.92	315.52	6.54	117	-8.43	332.59	341.02
10	-2060.28	-1685.72	3.45	142	-2319.08	-1606.92	712.16
15	-4735.85	-3636.44	167	63.8	-4597.79	-3748.58	849.21
20	-6731.85	-6063.87	190	25.8	-6538.30	-6268.39	269.90
25	-6998.55	-6998.55	3.47	3.47	-7257.35	-7257.35	0
30	-6998.55	-6998.55	1.93	1.93	-7261.10	-7261.10	0

Table 3: Comparison of profit from trading in electricity market for electrolyser with 30-100% range in output, 225 kW turbine

	Raw profit (£)		Hydrogen left in store (kg)		Adjusted profit (£)		
Cars/day	Non market optimisation	Market optimisation	Non market optimisation	Market optimisation	Non market optimisation	Market optimisation	Difference
5	-297.89	314.40	209	118	-56.29	332.94	389.24
10	-1887.29	-1683.33	1.23	141	-2151.54	-1607.10	544.44
15	-4596.21	-3637.43	135	64	-4534.86	-3748.48	786.38
20	-6740.82	-6068.84	188	27	-6550.30	-6270.00	280.3
25	-6998.55	-6998.55	3.47	3.47	-7257.35	-7257.35	0
30	-6998.55	-6998.55	1.93	1.93	-7261.10	-7261.10	0

Table 4: Comparison of profit from trading in electricity market for electrolyser with 0-100% range in output, 815 kW Turbine

	Raw profit (£)		Hydrogen left in store (kg)		Adjusted profit (£)		
Cars/day	Non market optimisation	Market optimisation	Non market optimisation	Market optimisation	Non market optimisation	Market optimisation	Difference
5	5521.61	5623.97	8.41	108	5274.82	5619.77	344.96
10	3356.87	3785.96	3.98	92.4	3099.30	3743.11	643.81
15	1119.32	1724.17	1.30	80.8	855.24	1653.17	797.93
20	-701.62	-615.16	3.88	40.5	-959.43	-784.01	175.42

25	-1533.92	-1533.92	162	3.47	-1408.78	-1792.72	-383.94
30	-1533.92	-1533.92	116	1.93	-1518.78	-1796.48	-277.70

Table 5: Comparison of profit from trading in electricity market for electrolyser with 30-100% range in output, 815 kW Turbine

	Raw profit (£)		Hydrogen left in store (kg)		Adjusted profit (£)		
Cars/day	Non market optimisation	Market optimisation	Non market optimisation	Market optimisation	Non market optimisation	Market optimisation	Difference
5	-	-	-	-	-	-	-
10	3506.50	3784.38	20.3	88.8	3288.67	3732.96	444.30
15	1325.07	1705.11	2.45	86.1	1063.79	1647.04	583.25
20	-789.12	-623.10	3.88	30.7	-1046.92	-815.86	231.06
25	-1533.92	-1533.92	3.47	3.47	-1792.72	-1792.72	0
30	-1533.92	-1533.92	1.93	1.93	-1796.48	-1796.48	0

When looking at the raw profit, the market optimisation increases profit for cases up to 20 cars refuelled per day, but does not affect the profit for the cases of 25 and 30 cars refuelled per day. This is because the electrolyser is always operational at these higher hydrogen demands, as can be seen in Figure 2, so it cannot adjust its operation to try to take advantage of price imbalance. Beyond a certain point, the hydrogen demand is so great it cannot always be met despite the electrolyser operating at 100 % utilisation. This can be seen from Figure 2 where the hydrogen demand can always be met for 5 to 20 cars refuelled per day, but the demand not met increases above 20% of the total demand when refuelling 30 cars per day.

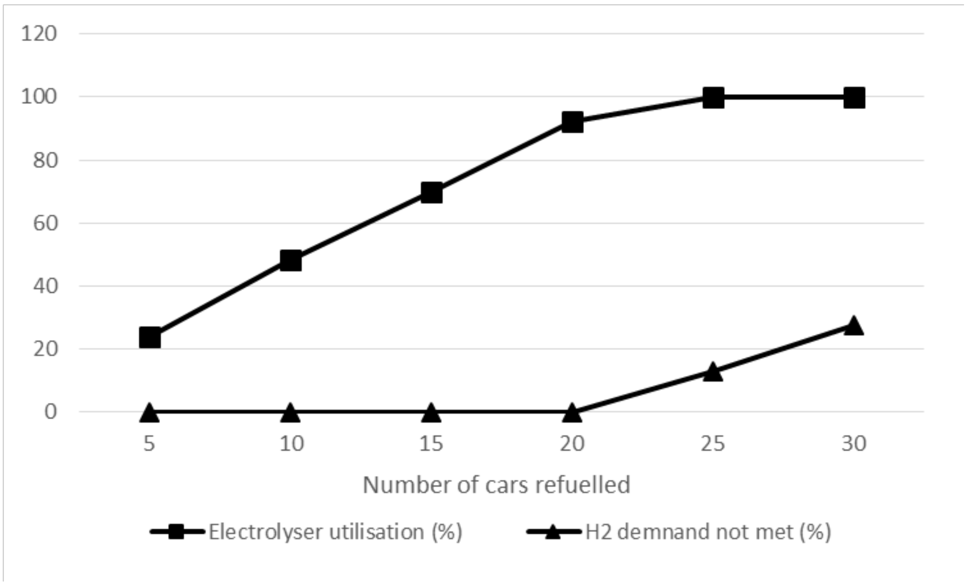

Fig 2: Percentage electrolyser utilisation and hydrogen demand not met with varying vehicles refuelled per day

Figure 3 shows the power transfer for the first 10 days of the analysis period for the case of a 225 kW electrolyser with 15 cars refuelled per day, demonstrating the difference in power transfer with the grid between the market optimisation and non-market optimisation.

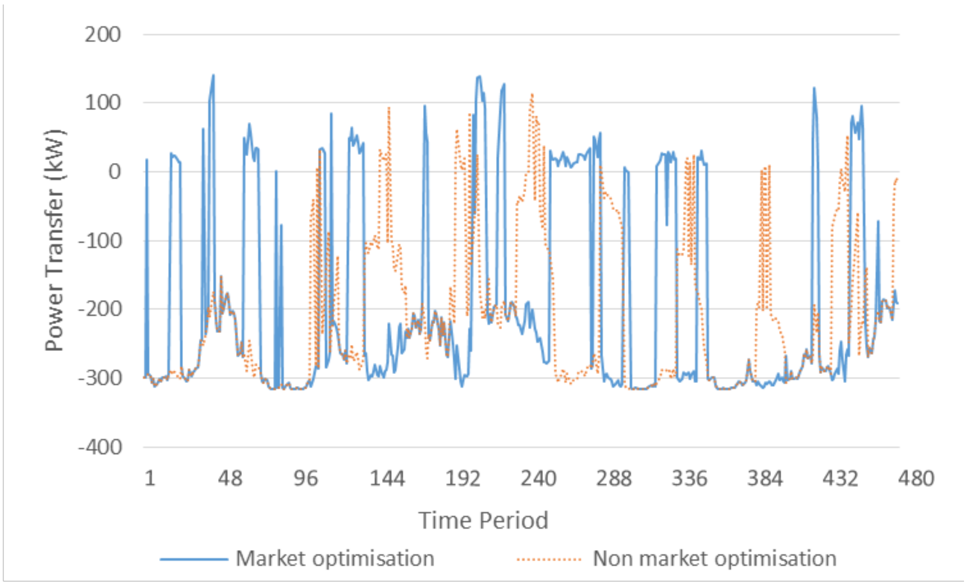

Fig 3: Power transfer for market optimisation compared with non-market optimisation, 225 kW hydrogen demand and 15 cars refuelled per day with a 0-100% range electrolyser

At first increasing hydrogen demand increases the profit difference, as the electrolyser operates more to meet the hydrogen demand, providing more opportunity to operate during low electricity price periods. As the demand increases though, the electrolyser operates more frequently, and low price periods are already occupied to meet hydrogen demand, meaning the effectiveness reduces. This can be seen in Figure 4 comparing the electrolyser power operation for 15 and 20 cars per day for the first 10 days of the optimisation period. When meeting demand for 20 cars, the electrolyser's capacity factor is much higher, meaning it has less opportunity to shift its operation to low cost periods.

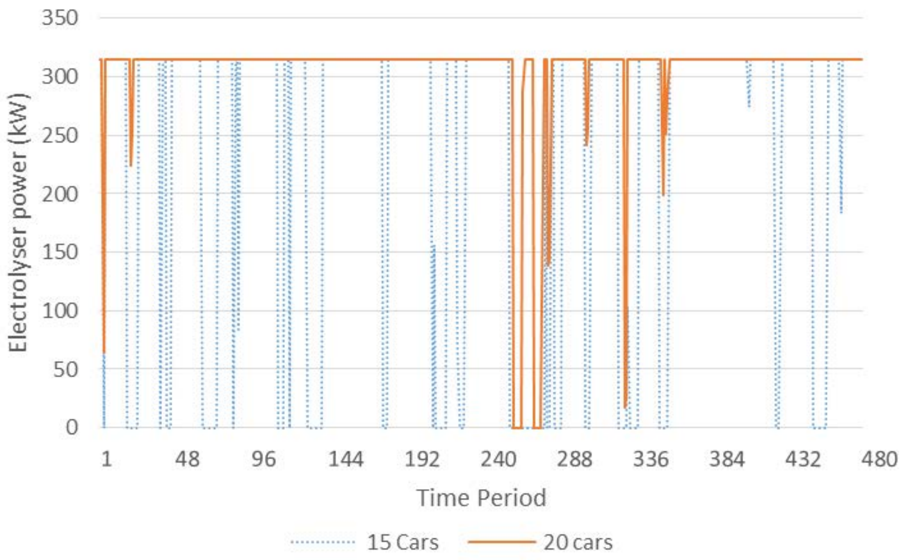

Fig 4: Comparison of electrolyser power for 15 cars refuelled per day and 20 cars refuelled per day, 0-100% range, 225kW wind turbine

It can be seen from comparing tables 2 and 3 with tables 4 and 5 that increasing the wind turbine size from 225 kW to 815 kW also reduces the ability of the market optimisation to increase profits. In this case the electrolyser operates to reduce wind curtailment, restricting its ability to take advantage of electricity cost differences. This can be seen from figure 5, which compares the electrolyser operation in combination with a 225 kW wind turbine and an 815 kW wind turbine. With the 815 kW turbine, when the electrolyser operates to reduce curtailment this may be at times of high electricity price when otherwise the electrolyser would not have operated, or would have operated at a lower power level.

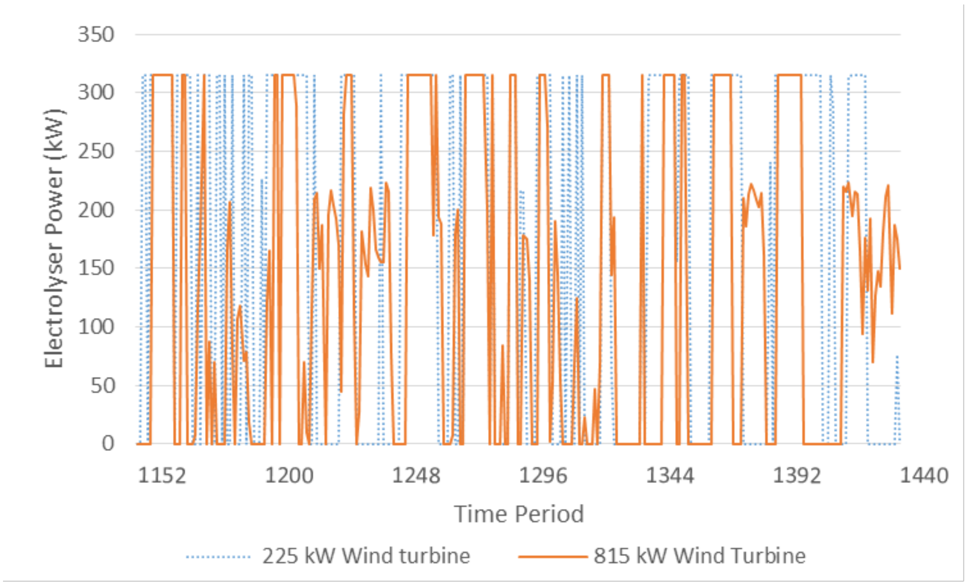

Fig 5: Change in electrolyser power in combination with 225 kW wind turbine and 815 kW wind turbine. 0-100% range, 10 cars per day refuelling.

It can be seen by comparing table 2 with table 3 and table 4 with table 5 that changing the range of the electrolyser from 0-100% to 30-100% results in a small reduction in both the raw and adjusted profit when using the market optimisation routine. The effect is larger with the 815 kW wind turbine. Figure 6 compares the electrolyser power for the case of 0-100% range electrolyser and 30-100% range electrolyser for the last 6 days of the analysis period. A number of differences in electrolyser operation can be seen.

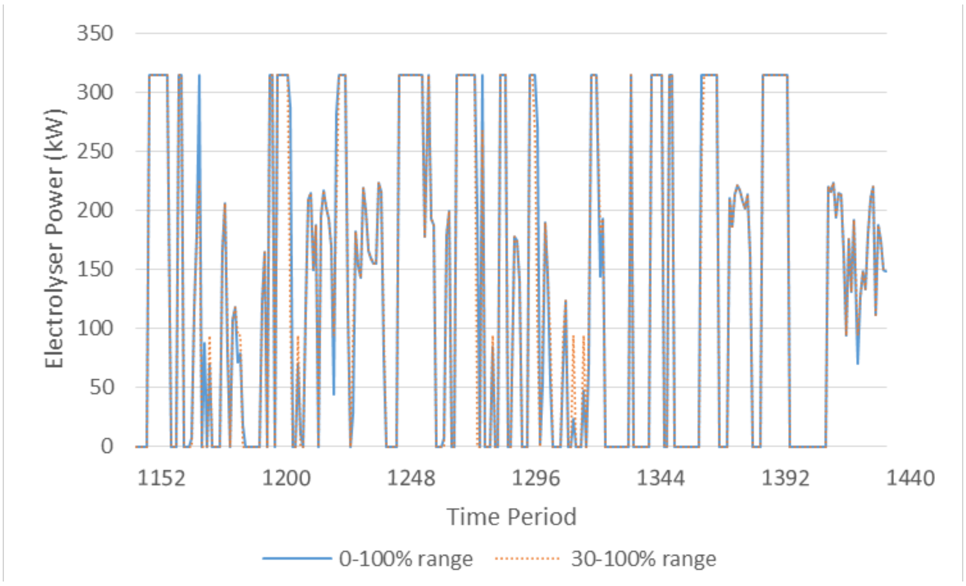

Fig 6: Change in electrolyser power for 0-100% range electrolyser and 30-100% range electrolyser. 815 kW Wind turbine, 10 cars per day

The evolution of the hydrogen storage level over the analysis period is shown in figure 7. It can be seen that the storage does not use the full range available to it. This is due to the constraint given in equation (2), which forces the optimisation procedure to ensure the hydrogen demand at the end of each optimisation period is scheduled to be the same as at the beginning. It is important to note that the storage level can still vary over time. For example, starting at the first time period, the optimisation schedules the optimal electrolyser operation for time periods 1 to 48, ensuring that for this schedule the storage level in time period 48 is equal to that in time period one. The optimisation routine then stores the decision variable for time period one, updates the storage level for time period 2, and carries out the next optimisation for time periods 2 to 49, and so on. New information is added at each time step, so that when the optimisation routine reaches time period 48 as the start time, the storage level (and other decision variables) will not match those which were originally scheduled in time period 1. This allows the storage to vary over the optimisation period, and in some high hydrogen demand scenarios empties completely, but the constraint in equation 2 may restrict the ability of the store to take advantage of long periods of low electricity prices by filling the store, or high prices by emptying the store. One way of avoiding this may be to optimise over a longer time period, but this quickly increases the size of the optimisation problem, leading to longer solving times and more risk of the optimisation not converging. Equation (2) could be reformulated as part of the OF to aid this, but this is left to future work.

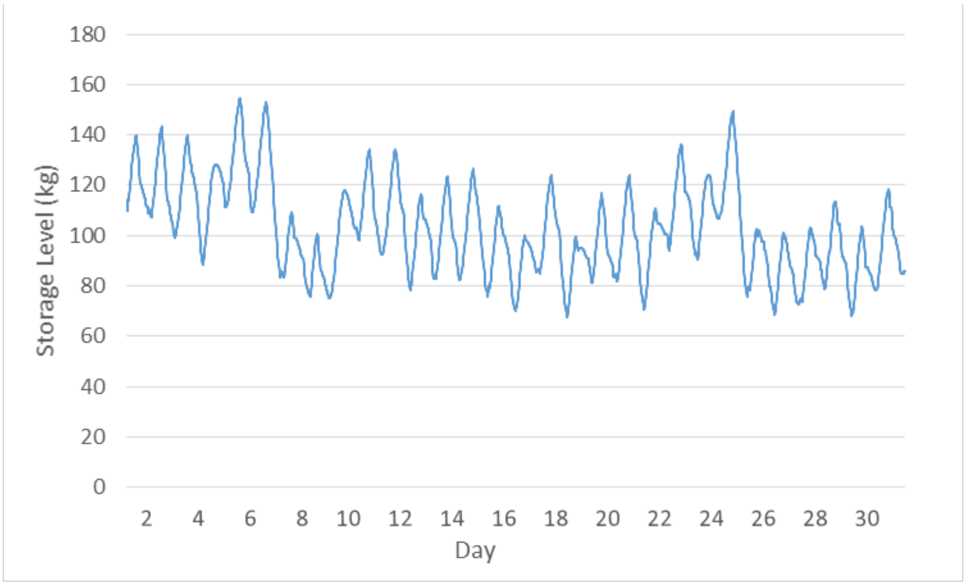

Fig 7: Evolution of storage level over on month, 225 kW wind turbine, 15 cars per day hydrogen demand.

When the wind turbine is increased to a size of 815 kW, with a grid constraint of 500 kW and combined electrolyser and compressor power of 315 kW, it should always be possible to operate the electrolyser to eliminate wind curtailment except from when the storage level is too high or full. The 815 kW wind turbine is capable of producing 185 MWh of wind over the analysis period. With the grid constraint but without electrolyser operation, 17.7 MWh of this production would have to be curtailed. In most cases, all of this wind curtailment can be avoided by operating the electrolyser at times when the full wind turbine output cannot be accepted by the grid. In some low hydrogen demand cases, up to 1 MWh of wind power is still curtailed, due to the storage being too full to allow the electrolyser to operate.

5 Discussion

In this investigation, it is assumed that wind power output, electricity price and hydrogen demand are perfectly predicted over each 48 time period, 24 hour optimisation. Xiao et al [19] compared perfect forecasting of these parameter with various levels of uncertainty from 10 to 50 % over a 168 hour (1 week) optimisation period. They found that whilst increasing the uncertainty did decrease the benefit of operating in the market, in all cases the performance of the market optimiation is significantly better than without market optimisation.

The optimisation procedure determines electrolyser power, wind power output and hydrogen demand met for each half hour time period. In the market optimisation, the optimal electrolyser power for each time period is dependent on the electricity price variation. In most cases, all hydrogen demand can be met, and no wind power needs be curtailed, leading to only on globally optimal solution. In high hydrogen demand cases, even with the electrolyser operating at 100% capacity, some hydrogen demand cannot be met. In this case, the optimisation procedure must decide in which time steps of the optimisation the hydrogen demand should not be met. Given the cost in the optimisation of not meeting hydrogen demand is the same for all time steps, this can lead to more than one globally optimal solution. This can lead to some differences in the results. In table 4, whilst the raw profit for the 25 cars per day and 30 cars per day is equal as expected, there are different amounts of hydrogen left in the store, leading to the adjusted profit appearing to show the non-market optimisation performing better. This is due the non-market optimisation tending to schedule hydrogen demand in the first time step, whilst the market optimisation schedules hydrogen demand not met in later time steps. In each case, the optimisation will converge to the same value of global optimum, but as only the values for the first time period in the optimisation are retained, different overall results will be found. In this case, less of the hydrogen demand is met overall in the non-market optimisation than in the market optimisation. It may be that it is always better to schedule unwanted outcomes (wind curtailed, hydrogen demand not met) late on in each individual optimisation, as the optimisation procedure progresses, the new information from the time series may result in these unwanted outcomes not taking place.

Whilst producing hydrogen from renewable resources is an important factor in reducing associated GHG emissions [3], the situation examined in this paper of an electrolyser and wind turbine being situated at the same location may not be typical of future refuelling stations. The methodology developed can be utilised for optimising joint operation of electrolyser and renewable generation where the two are situated remotely from each other, as long as a renewable grid constraint is not considered. The methodology could also be applied to generation of hydrogen which is remote from demand, assuming the hydrogen could then be transported to demand centres, allowing further investigation of its use to reduce renewable curtailment. The hydrogen demand would then be replaced by one representing transportation to demand centres, or potentially from a local vehicle fleet.

6 Conclusions

An optimisation procedure to determine optimal performance of a hydrogen refuelling station in an electricity market has been developed. The optimisation procedure includes the turn down ratio of the electrolyser in its formulation resulting in a MINLP optimisation. The optimisation procedure has been used to investigate the potential performance of a typical on-site electrolyser based hydrogen refuelling station located at the AMP at Rotherham, UK. The analysis has demonstrated the advantage of the optimisation procedure when operating in an electricity market, but shown that this is dependent on a number of factors such as the level of hydrogen demand. When a wind turbine with its output limited by a constrained grid is included, the electrolyser can be operated to limit curtailment of the wind turbine, with a small effect on the electricity market performance.

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