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Optimal Hydrogen Storage and Demand on Electricity Distribution Networks with Excess Wind Power

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Abstract. The use of excess wind energy to generate hydrogen for use as a transport fuel is investigated using Optimal Power Flow (OPF) including a hydrogen demand, and a technoeconomic analysis carried out. Using this method to generate hydrogen increases the utilisation of wind energy and allows for a hydrogen demand to be supplied at or near to the point of use. An OPF routine is developed in order to optimise the amount of wind energy utilised, as well as minimising the amount of hydrogen demand not met. The cost at which the hydrogen is produced was found to be dependent on the operating methodology, component investment costs, and level of hydrogen demand.

Key words

Optimal Power Flow, Wind power, Energy storage, Hydrogen economy, Modelling and simulation.

1. Introduction

Hydrogen has the potential to play a major role as a part of our future energy system as, along with it being energy dense by weight and possible to produce from a number of sources, it can be used as a store of intermittent renewable energy and as an energy carrier for vehicle fuel [1]. Renewable energy from variable sources such as wind is expected to make an increasing contribution to UK and worldwide energy supplies in the near future [2]. Connection of an increasing amount of intermittent renewable energy to electricity networks requires new methods by which to manage and operate these networks [3]. The problems associated with connecting distributed generation to electricity distribution networks serves to limit the amount of generation it is possible to connect, and can result in underutilisation of viable renewable energy resources. Energy storage has advantages as a potential solution to this problem, in that it can shift the time of use of the energy generated by intermittent

renewable energy sources such as wind power. The use of hydrogen for energy storage not only allows for the time of use to be shifted, but for the energy stored to be used for purposes other than supplying electricity demand, i.e. in a hydrogen economy.

The literature on hydrogen futures, contain a number of visions ranging from decentralized systems based on renewables through to centralized systems based on nuclear and carbon capture [4]. Centralized and decentralized hydrogen storage options may both be viable in a future hydrogen economy [5]. The transition to a hydrogen economy, if it occurs, will involve a large amount of investment and effort. It is likely hydrogen will first be used in niche applications. One of these could be as energy balancing, which will drive technological innovations and will allow renewable generators to sell hydrogen for hydrogen economy uses.

Previous work on integrating renewable energy onto electricity networks has focussed on aspects such as curtailment of wind power or adjustment of network parameters [6], whilst work concerning energy storage, or hydrogen generation has not taken the network into account, or used a constant export/import limit [7]. In this paper the operation of hydrogen storage and demand for use as a transport fuel is included in the objective function of an OPF in order to determine its effectiveness in aiding the integration of wind energy onto a distribution network along with the level and cost at which the hydrogen demand can be met. A number of scenarios are investigated to assess the optimal method of operating and utilising the hydrogen store. A technoeconomic analysis is then carried out to determine the cost at which the hydrogen can be produced.

2. Problem formulation

In order to determine the performance of the system an OPF routine is run on an electricity distribution network with wind farms attached at half hourly time steps over the course of 1 year. The time series of wind power output and electrical load are obtained from [8], whilst the creation of a hydrogen demand time-series is described in the following sections. The analysis is run both with and without hydrogen generation on the network in order to determine the extra energy from the wind which hydrogen generation and storage allows. The cost at which the hydrogen is produced is then determined.

A. Construction of hydrogen demand

First the vehicle fuel energy demand is calculated as a proportion of electricity demand. The values for the total final energy demand for electricity and road transport for Wales are taken from, "Total final energy consumption at regional and local authority level" [9]. These give the final energy demand for road transport in Wales (where the network assessed is located) from road transport as 23,056.7 GWh, and from electricity (including both domestic, and industrial and commercial demand) to be 17,567.1 GWh. This gives a ratio of final energy demands of 1.31:1.

Next the hydrogen car efficiency compared to gasoline car efficiency is determined. When converting to a hydrogen economy, it is assumed that the hydrogen vehicle fleet will be powered by hydrogen fuel cells. Hydrogen fuel cells are more efficient than the current internal combustion engine, so this must be taken into account when working out the energy demand from hydrogen fuel cell vehicles (HFCV). The values for the comparative energy efficiencies of hydrogen and conventional vehicles depend on the assumptions made regarding average efficiencies of the current conventional vehicle fleet, and a future fleet comprising fuel cell vehicles. The value used in this study for the average conventional vehicle efficiency is 32 mpg as this is the value given by the DfT [10] for the average fuel consumption of a UK car. The value used in this study for the equivalent efficiency of a HFCV is 58 mpg. This gives an improvement of 0.55 in fuel demand. These values are supported by Granovskii et al [11] who use a fuel consumption of a gasoline vehicle of 236.8 MJ per 100 km, with the fuel consumption of a HFCV of 129.5 MJ per 100 km, meaning HFCV's similarly need 0.55 times the energy of an internal combustion engine vehicle. Ahman et al [12], use values for the total power train efficiency of a hydrogen fuel cell power train of 34% compared to a conventional engine of 16%, meaning 0.47 time the energy is needed.

When considering centralised production, the losses in distribution to the consumer must be taken into account. The figures used in this analysis are based on the hydrogen being compressed to 7000 psi before being transported in gas trucks capable of holding 660 kg of hydrogen with an average round trip journey of each 80 km. Losses are then given as 1.4%, and only apply to the centralised scenario. The figures are taken from the US Department of Energy

H2A analyses [13], [14]. Spatial modelling of the networks studied would allow for more accurate values to be obtained for the delivery losses.

B. Time series shape

The time series used is based on a modified ChevronTM demand profile taken from the H2A analysis. The demand takes hourly, daily and seasonal variations into account and is taken from [15] and [16].

These profiles are combined to create a half hourly time series and scaled to give a peak demand of 1, which is reached at 4:30 PM on a Friday afternoon. A sample summer week is shown in Figure 1.



Fig. 1. Profile of a summer weeks hydrogen demand, Monday-Sunday

The correlation between peaks in the electricity load demand and the extra demand from the production of hydrogen is likely to be important in determining the ability of the network to cope with the extra demand. The hydrogen demand used here is not specific to the areas studied. An investigation of the effect of the correlation between the two demands would be beneficial in improving the accuracy of the modelling.

C. Hydrogen demand levels

The systems are studied with hydrogen demand levels 1-5, where 1 represents $1/5^{\text{th}}$ of the demand of the entire vehicle fleet considered being converted to HFCV's, 2 represents $2/5^{\text{ths}}$, 3 represents $3/5^{\text{ths}}$, 4 represents $4/5^{\text{ths}}$ and 5 represents $5/5^{\text{ths}}$, or the whole fleet, being converted to HFCV's.

Time series OPF using an objective function which attempts to maximise the amount of energy utilised whilst minimising the amount of vehicular hydrogen demand not supplied is run for a number of scenarios as detailed below.

D. Network Studied

The network studied is part of the South Wales electricity distribution network and was obtained from the Western Power Distribution Long Term Development Statement [20]. It is mainly a 66 kV network and is connected to a 132 kV network. The network supplies 51.9 MVA of load at a power factor of 0.93. The load is located on 11 kV feeders, connected to the 66 kV network through

OLTC's. The network is a mixture of meshed and radial design. A diagram of the network is shown in Figure 2.



Fig. 2. Diagram of Network: Based on a section of South Wales distribution network

Four wind farm sites are chosen to be at locations remote from the main grid connection point and are generally located at the ends of individual feeders in order to represent plausible locations for wind farms. Three different wind farm penetration levels are considered:

- *a)* The wind farms are sized such that at minimum load they have the maximum combined capacity with no power needing to be curtailed, representing a 'fit and forget' approach. This method reflects the current (passive) methodology of allocating generating capacity, but does not take constraints such as fault levels, substation reverse power flow and N-1 security constraints, whereby the system can withstand the loss of any single component, into account.
- b) The wind farms are sized such that, considered individually their maximum output can be accepted at maximum load on the network. This sizing gives wind farm capacities which are suitable for each individual node, but cause curtailment when considered together.
- c) Each wind farm bus has a capacity of 150% of that determined in b). This will increase the level of curtailment experienced, allowing a comparison of the effectiveness of energy storage at different capacity levels.

The capacity allocation is carried out by running an OPF routine with generators operating at unity power factor. Table I presents the wind farm capacity allocations [17].

Table I Wind farm capacity allocation scenarios							
Wind farm	Capacity (MW)						
bus							
	<i>a</i>)	<i>b</i>)	<i>c</i>)				
13	0	22.44	33.66				
18	31.94	36.40	54.6				
19	4.27	25.88	38.82				
20	7.09	17.51	26.27				
Total	43.3	102.2	153.3				

- E. Hydrogen demand allocation scenarios
 - a) Distributed demand, whereby the demand for hydrogen on the network is associated with the load at each bus, and is proportional to that load.
 - b) Centralised demand, whereby the whole of the demand is located at one node. in this case node thirteen as it is the optimal location for increasing energy delivered to the network [17]. The hydrogen is then assumed to be distributed by compressed gas trucks to the user, and a loss factor of 0.986 is used to represent losses in due to delivery.

F. Optimisation scenarios

- a) Active hydrogen demand, the priority is to maximise the amount of wind power on the network. The OPF uses an objective function to maximise the amount of wind accepted onto the network whilst minimising the amount of hydrogen demand not met.
- b) Passive hydrogen demand, the hydrogen demand acts as a dispatchable load on the network, which does not have to be met if network constraints don't allow it. In this case the hydrogen demand allows more wind power onto the network passively, through the additional load it creates.

The objective function used for these optimisation scenarios is defined as:

$$OF = -C_w \sum_{WF} P_{WF}(t) - C_s \sum_s (1-e) P_{el}(t) - C_h \sum_h (H_h^{dem} - H_h^{out})$$
(1)

Where C_w , C_s , and C_h are the nominal costs associated with wind power, storage and importing hydrogen. C_h is set high in order to minimise the amount of hydrogen demand which is not delivered.

For the active hydrogen demand scenario, C_w and C_s are of equal value, and the objective function works to maximise wind power onto the network whilst minimising the hydrogen demand not met.

For the passive demand scenario C_s is set greater then C_w but less than C_h , so that there is a large penalty for the electrolyser to operate. In this case it will not operate to increase wind power, but only to supply hydrogen demand. In this case *e* is set to 0.

The parameter e determines the priority given to minimizing wind curtailment and is analogous to the round trip efficiency. The value chosen can be decided by using a maximum generation, minimum load analysis and is chosen as 0.7 [17].

The constraints take into account the real and reactive power flows at each bus as well as the thermal, voltage, transformer and generator limits [17].

The OPF is run at each half our time-step over the course of one year in order to determine the extra energy which the hydrogen demand allows to be utilised from the wind power, compared to the network without hydrogen generation and storage.

G. Component cost scenarios

The investment costs used for the wind power, electrolyser, and hydrogen storage are defined for the five scenarios a), b), c), d) and e) in Table II. They are based on current and projected future costs available in the literature [18] - [22]

Table II Component cost scenarios						
Component	Cost Scenario					
	a)	b)	c)	d)	e)	
Wind Turbine (€/kW)	900	900	900	900	900	
Electrolyser (€/kW)	1820	910	455	182	91	
Hydrogen Storage (€/kg)	500	250	125	50	25	
Fuel Cell (€/kW)	2750	1375	687.5	275	137.5	

The levelised production costs are given by

$$LPC_{el} = \frac{IC_w}{el_{nostore}}$$

$$LPC_{H2} = \frac{IC_{H2} + C_{el_imp} * (el_{electrolyser} - el_{extra})}{E_{H2}}$$

where IC_w is the investment costs of the wind farms, IC_{H2} is the investment cost of the hydrogen production and storage systems, $el_{nostore}$ is the electricity accepted onto the network from the wind farms if no hydrogen storage is attached to the network, el_{extra} is the extra electricity from the wind farm that hydrogen generation allows to be utilised, C_{el_imp} is the price paid (0.1 €/kWh) for any net energy imported from the network to produce hydrogen, $el_{electrolyser}$ is the electricity used by the electrolyser to produce hydrogen and E_{H2} is the energy content of the hydrogen produced, based on the HHV of hydrogen.

3. Results

Figure 3 and 4 show the amount of extra energy accepted on to the network through the use of hydrogen generation and storage.



Fig. 3. Extra energy allowed onto network through use of hydrogen demand with wind farms sized using capacity allocation b).



Fig. 4. Extra energy allowed onto the network through use of hydrogen demand with wind farms sized using the capacity allocation c).

Figure 5 and 6 show the variation in LPC_{H2} for the different scenarios. The LPC of electricity is always 0.047 \in /kWh for capacity scenario b) and 0.057 \in /kWh, as these are equal to the price paid with no storage on the network. The effect of increasing the level of the hydrogen demand on the LPC_{H2} is determined by two factors; the amount of extra electricity needed to produce the hydrogen, and the effect the increased demand has on component costs through changes in component sizing.

4. Discussion

When using hydrogen storage to supply a hydrogen demand, the level of the hydrogen demand is important in determining the value of LPC_{H2} . In general with an active demand, the higher the hydrogen demand, the lower the value of LPC_{H2} . This is due to reduced storage costs, with low hydrogen demands resulting in a very high storage capacity. For passive demand, increased demand tends to result in an increased LPC_{H2} , this is due to a decreased proportion of the electricity used in generating the hydrogen being of zero cost, i.e. it would have been curtailed without storage. The equipment investment costs play an important role in determining the value of LPC_{H2} , and so the viability of this method of hydrogen production.



Fig. 5. LPC of hydrogen produced with varying hydrogen demand for, a) active distributed demand, b) active centralised demand, c) passive distributed demand, d) passive centralised demand. Wind farms sized using capacity allocation b).



Fig. 6. LPC of hydrogen produced with varying hydrogen demand for, a) active distributed demand, b) active centralised demand, c) passive distributed demand, d) passive centralised demand. Wind farms sized using the capacity allocation c).

5. Conclusion

The values for hydrogen production in this thesis range from 0.037 ϵ /kWh to over 1 ϵ /kWh. In comparison, the cost of hydrogen from reforming natural gas is given by Cherryman et al [1] as 0.0234 ϵ /kWh and the cost from wind electrolysis on it' own of 0.0594 ϵ /kWh. The costs are comparable for some scenarios, indicating that using excess wind energy to produce hydrogen may become economically viable, although this is dependent on a reduction in component costs. Adding value by the fact that this method allows increased carbon free energy to be utilised may increase its viability. Assumptions about the cost of electricity will also have an effect on the value of LPC_{H2} obtained. A relatively high price for electricity brought in is used in this thesis. A lower value may make this method of production even more competitive.

A single storage node generally results in a lower LPC_{H2} for all scenarios, due to decreased component sizes. The value of LPC_{H2} determined is for the hydrogen produced. Transportation costs to the point of use would have to be considered to compare the delivered values of LPC_{H2} . With distributed storage, the hydrogen is generated at or close to the point of use, eliminating or reducing transportation costs. This should be taken into account when comparing relative hydrogen costs, both between the different scenarios presented in this thesis, and those calculated for other production methods.

The electricity networks studied are able to supply the extra electricity demand from the distributed hydrogen generation the majority of the time, with only a small proportion of the hydrogen demand unable to be delivered.

The use of a hydrogen storage facility for the purposes of both supplying a hydrogen demand, and as an electricity store has not been considered. This may further reduce costs by decreasing the storage capacity needed, especially in the case of higher wind penetration scenarios with low hydrogen demand, where storage costs can dominate the LPC values.

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