MODELLING OF WIND FARM GREEN HYDROGEN PRODUCTION FOR FUTURE CITIES AND ZERO EMISSION TRANSPORT FLEETS

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ABSTRACT

The cost-benefit of producing green hydrogen from wind turbines by use of electrolysers is quantified by numeric modelling in order to establish the investment case for wind farm owners under various market conditions and project configurations. The modelling accounts for the possibility of green hydrogen export to an external market as well as the possibility of wind farm owners such as large utility companies, local government or other entities employing green hydrogen transport fuel within their internal vehicle fleets and produced from their own wind turbines. This can establish a virtuous circle whereby economy of scale offsets and justifies hydrogen infrastructure capital expenditure. The role of green hydrogen is considered in the context of future cities along with possible support mechanisms to allow consumers to benefit from convenient green hydrogen motoring with fast, high range vehicles having low refueling time, zero carbon dioxide emission and avoiding unhealthy pollutants which are lowering the quality of life within present day cities from Glasgow to Beijing.

Keywords: green hydrogen, wind energy, electrolyser utilisation, investment case, numeric modelling, future cities, sustainable zero emission transport

Introduction

A numeric simulation model has been developed for assessing and quantifying the case for exporting green hydrogen produced by splitting water with electrolyser technology installed at wind farms.

Green hydrogen technology application offers a holistic solution to many problems relevant to future cities projects and indeed for rural and other communities. Green hydrogen vehicles offer zero emission transport, eliminating pollution and carbon dioxide emissions. By incorporating green hydrogen vehicles into transport policy, dependence on fossil fuel imports can be reduced, thus providing energy security and enabling continuity of operations in times of fossil fuel supply interruption or oil price spike shocks.

Green hydrogen fuel can be produced and sold locally, offering economic opportunities to owners of residential or commercial solar roofing, wind turbines, and other renewable energy generators. Instead of exporting local wealth to distant fossil fuel producers economic advantage is provided to local communities, reinforcing economic stability. Improved employment has numerous positive effects within communities and helps avoid crime, state dependence and alienation, reinforcing pride and quality of life within neighbourhoods and helping to avoid societal divisions caused by a brain drain or lack of opportunity.

Apart from indirect benefits there are many direct benefits of green hydrogen transport including improved air quality and health of local residents within future cities. All these benefits are relevant globally, from Glasgow to Beijing.

Present day hydrogen fuel cell electric vehicles tend to be much more consumer friendly (400 mile range, 3 minute refueling time, reasonably similar to petrol/diesel vehicles) than battery electric counterparts. Hydrogen vehicles are sometimes criticised for having lower efficiency than battery electric vehicles but efficiency quantifies what you get out compared with what you put in. In the case of green hydrogen the renewable energy input costs nothing and will never run out, so efficiency is less important. Efficiency is much more relevant to cases where the input fuel is costly and is running out, as for battery electric vehicles being charged from non-renewable electricity supplies.

Moreover, green hydrogen fuel can be cheaper per mile than diesel fuel which is good for the consumer. However, this advantage is tempered by high capital expenditure costs for early adopters meaning that there is a case for subsidising early adoption of green hydrogen technology.

Therefore one futuristic vision of our cities and other communities involves the rapid adoption of green hydrogen transport.

And where market conditions permit, green hydrogen export can offer renewable energy generators increased revenue over electricity export. In particular where renewable energy is being wastefully dumped then green hydrogen offers the possibility to capture and export excess renewable energy from the electrical network into transportation or other uses, thus avoiding wasteful dumping of energy.

Green hydrogen is a form of energy storage which offers flexibility to a future sustainable smart grid.

Green hydrogen export offers an alternative to simple electricity export for wind farm owners equipped with an electrolyser, thus enabling a profitable trading response to low electricity export prices. Wind farm owners trading electrical energy on a future grid having high wind energy penetration and without any energy storage will leave themselves open to risk of low market prices at times when their generating asset is most productive (ie when it is windy and there may be a glut of wind generation on the grid).

In order to supply green hydrogen to their local communities and new markets renewable energy generators and owners will be interested to quantify the green hydrogen yield and calculate Internal Rate of Return (IRR) for specific investment cases.

In order to serve the above vision, knowledge of wind farm operation and wind farm curtailment has been applied within a time stepping computer simulation model for quantifying the green hydrogen electrolysis yield, calculating curtailment energy capture and investment parameters such as IRR for wind farm owners, investors or policy makers.

Simulation Model Description - H2WindSim

The H2WindSim model is a numeric model designed, developed, maintained and owned by Green Hydrogen Consulting Ltd in order to process large quantities of wind farm historic data, as well as user controlled model parameter variation.

Historic data input can be either synthetically generated data or standard wind farm historic SCADA (Supervisory Control and Data Acquisition) system records. Processing one year of typical 10-minute interval SCADA data for wind farm output and matching curtailment data can be executed conveniently on a typical PC. If required the model could be adapted to run in parallel to make use of distributed computing resource on a network of computers.

The initial H2WindSim model version assumes that the wind farm electricity export price is constant as for a constant Power Purchase Agreement (PPA). If required the model can be readily adapted to run with synthetic or historic electricity market trading data with changing electricity export price.

The model allows variation of numerous parameters including normalised historic wind farm power profile/capacity factor, normalised historic wind farm curtailment profile/curtailment impact percentage, electrolyser efficiency/output profile, electrolyser installed capacity (MW), wind farm installed capacity (MW), wind farm electricity export price (£/MWh), green hydrogen market price (£/kg), electrolyser investment lifetime (years), investment hurdle/discount rate (%) and electrolyser price (£/MW).

For each interval within the simulation year the model calculates the power available to the electrolyser and the corresponding hydrogen yield. The wind farm curtailment levels are also checked to establish whether there is the opportunity to capture wind farm curtailment energy which would otherwise be dumped. The electrolyser electricity price is calculated for each interval. If there is no curtailment during an interval, or if there is curtailment but the wind output is at too low a level for the curtailment export limit to have any impact, then the usual market electricity price is applied. In case the electrolyser can be powered partially or wholly by curtailment energy then the electrolyser electricity price for the interval is adjusted accordingly with zero cost being ascribed to the use of curtailment energy which would otherwise be dumped.

Finally the Internal Rate of Return (IRR) calculation is performed in order to estimate the investment case for installing an electrolyser on a wind farm for purposes of green hydrogen export sales. The IRR calculation includes calculation of Capital Expenditure based on electrolyser cost and other costs such as storage tanks. Operating costs such as electricity costs and maintenance costs are included. Discounted and undiscounted Net Present Value (NPV) are also calculated, making use of the investment hurdle discount rate as appropriate.

The following Figures 1, 2 and 3 may be viewed side by side since they all relate to the same one week time period randomly selected from one year model data for a particular simulation parameter set.

Figure 1 shows a one week sample of simulation data including the power used by a 0.375 MW electrolyser (upper trace, in red, right hand ordinate axis) as well as the power generated by a 30 MW wind farm (dark blue) and the curtailment export limit (green).

Figure 2 shows a corresponding data sample with the upper trace (in green, right hand ordinate axis) depicting the green hydrogen yield in kg per 10-minute interval. The lower traces in yellow and blue show curtailment and wind power expressed as a fraction of wind farm capacity (ie curtailment MW divided by wind farm capacity and wind farm output power divided by wind farm capacity).

It is noted that in this context curtailment MW is defined as wind farm capacity minus curtailment export limit. This is the notional curtailment power dumped in case the wind farm is producing maximum power. However, the wind farm often produces less than maximum power. The simulation model compares available wind power with curtailment export limit in order to establish how much free energy is available to the electrolyser.

Figure 3 shows the corresponding week of simulation data for the green hydrogen electricity cost (black, right hand ordinate axis) per 10-minute sampling interval against electrolyser power (red, left hand ordinate axis). The electricity cost for running the electrolyser frequently falls to zero even when the electrolyser is producing hydrogen at maximum power. This indicates that curtailment energy is being captured.

The electricity cost of electrolysis also falls to zero when the electrolyser has no power but under these circumstances (ie under extremely low wind conditions) no hydrogen will be produced.

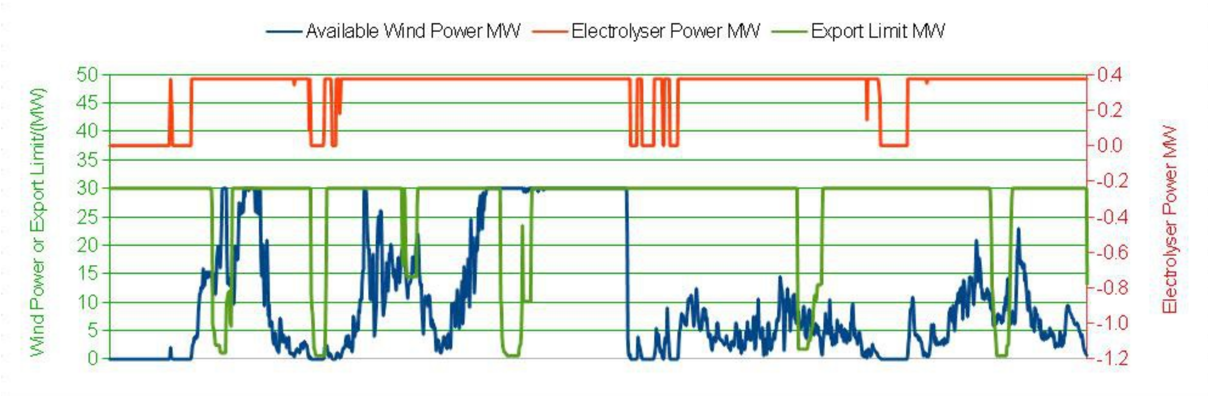

Figure 1 - One week sample of electrolyser power (red, right hand ordinate axis) at a 30 MW wind farm with curtailment. In this case electrolyser capacity is 0.375 MW. Where the curtailment export limit (green, left axis) falls below available wind power (blue, left axis) excess wind power is available to the electrolyser for free, otherwise dumped through

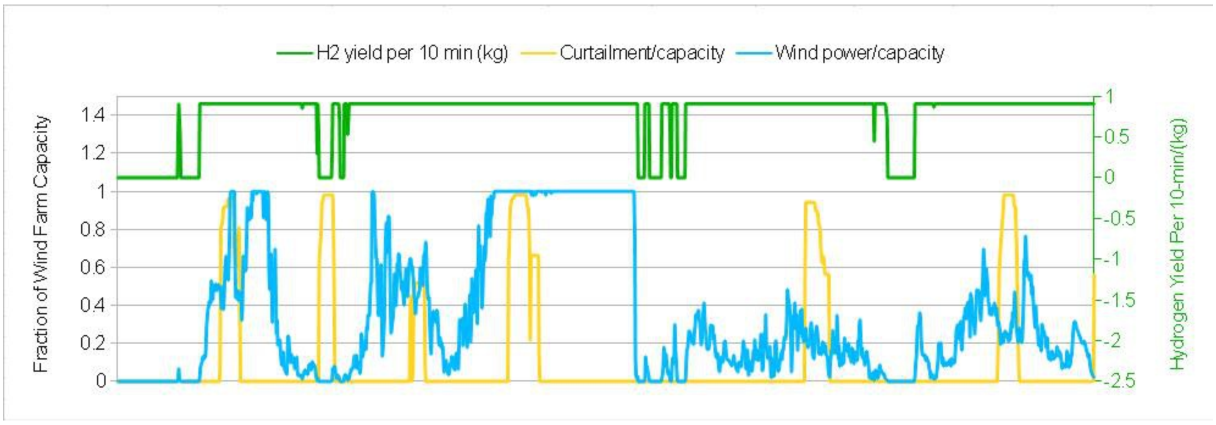

Figure 2 - Simulation profiles showing green hydrogen yield (right hand ordinate axis) above curtailment and available wind power expressed as a fraction of wind farm capacity.

Figure 3 - Corresponding profile comparing electrolyser power(red trace, left hand ordinate axis) and the electricity cost(black, right hand axis). Electricity cost is reduced, even to zero, when curtailment energy is utilised by the electrolyser instead of being dumped.

Initial Wind Farm Electrolyser Modelling

Initial modelling has simulated one year for each of 30618 investment parameter cases using 10-minute data. Eight parameters were each ascribed a small set of values and all possible parameter combinations were generated. Table 1 exhibits the parameter combinations and numeric values studied.

Parameter	Parameter Values Included	Cases
Electrolyser Installed Capacity (MW)	0.375, 0.75, 1.5	3
Wind Farm Installed Capacity (MW)	0.375, 0.75, 1.5, 7.5, 30, 150	6
Electricity Export/PPA Price (£/MWh)	50, 75, 100	3
Curtailment Regime (%)	0, 5, 10, 15, 20, 25, 30	7
Green Hydrogen Price (£/kg)	6, 8, 10	3
Electrolyser Investment Lifetime (yrs)	6, 8, 10	3
Investment Hurdle Discount Rate (%)	8, 10, 12	3
Electrolyser Price (£/MW)	1000000, 1250000, 1500000	3

Some model parameters were kept constant for the initial study but could be varied if required:

- Wind Farm Capacity Factor was held at 30%, typical of UK onshore wind farms.
- Hydrogen storage cost was fixed at £250/kg.
- Hydrogen storage capacity was modelled at a fixed fraction 2% of annual production.
- Annual maintenance costs were modelled at a fixed fraction 2% of capex costs.

For the purposes of this study some model assumptions were made which could be altered if required:

- Income from pure oxygen sales was not modelled.
- Water supply costs were considered negligible, not modelled.
- Planning costs were considered to be included in the electrolyser price.
- The cost of compressor systems was not included.
- Electrolyser and related balance of plant is assumed to be available for operation at all times.

The above parameters and assumptions, and/or associated results, should not be taken as investment advice but are presented as an illustration of H2WindSim modelling which could be undertaken by wind farm owners as part of a wider project to investigate cost-benefit feasibility.

Results and Discussion

Analysis of the simulation results emphasises some principles when designing a matching wind farm and electrolyser green hydrogen system. Firstly, although curtailment of wind farms is common, and offers an opportunity to capture free energy which is otherwise dumped and wasted, this generally occurs for a minor part of the year. Therefore, assuming the electrolyser is utilised as much as possible according to the available wind energy, most of the energy used by the electrolyser will not be curtailment energy. Consequently, this energy will be wind energy which can no longer be exported and sold from the wind farm. This means that the electricity cost per kg of green hydrogen will be higher in case of higher wind farm energy export price (the “displaced export price”).

Figure 4 illustrates the increasing electricity cost per kg of hydrogen with the wind farm electricity export price. The scatter plot contains markers for all parameter sets described above and shows that much more attractive investment cases (higher IRR) can be obtained when the displaced export price is at £50/MWh versus £100/MWh.

Figure 4 also shows that certain project parameters lend themselves to potentially lucrative investment cases. However, there are also many scenarios which indicate inadequate return for investors. The message is that excellent green hydrogen investments are possible but the investor needs to carefully study the model sensitivities for their particular project as well as any assumptions made.

It is noted that £100/MWh could be the typical revenue obtained from a present day UK onshore wind farm including ROCs (Renewable Obligation Certificates) and LECs (Levy Exemption Certificates) combined at around £45/MWh. Therefore a price of approximately £50 could reflect the wind farm electricity export price without ROCs and LECs. Therefore, if a UK onshore wind farm owner were permitted to retain ROCs and LECs for electrical energy used for the electrolyser this would be a significant support to the green hydrogen business case whilst remaining faithful to the principle of ROCs for renewable energy generation. Suitable metering could be installed at the electrolyser connection (within the wind farm/renewable generator electrical network) in order to record the amount of renewable energy used by the electrolyser.

The recently proposed alternative UK market mechanism of Contracts for Difference (CFD) would benefit from some additional incentive for green hydrogen production since a fixed strike price for wind farm export may not contain any ROC component for retention and sale by the wind farm owner.

It is important to note that green hydrogen should be produced at the renewable energy generator and that the electrolyser must not import electricity from the grid for producing hydrogen since this could be a non-renewable electricity supply resulting in “brown” hydrogen. Green hydrogen has a unique selling point over non-green hydrogen since transport users can be sure that their transport fuel produces zero emissions. As such green hydrogen should command a premium price at the point of sale for vehicle fleets and other users who aim to reduce their fossil fuel dependence, carbon dioxide emission and other pollution.

Figure 5 illustrates the relationship between electrolyser utilisation and the ratio between wind farm installed capacity and co-located electrolyser capacity. A large wind farm capacity in relation to electrolyser capacity will produce power output to cover the maximum electrolyser demand even at relatively low wind speeds and much more frequently than could be supplied by a wind farm of smaller installed capacity. This implies much higher electrolyser utilisation which is important for the financial model because the electrolyser capital cost is typically high and can only be justified with sufficient hydrogen yield (ie sufficient electrolyser utilisation).

Figure 1 also illustrates high electrolyser utilisation by showing power used (in red) by a 0.375 MW capacity electrolyser in response to wind power from a 30 MW capacity wind farm. Even under low wind conditions very low wind farm power (relative to the 30 MW wind farm potential) is sufficient to take electrolyser power to maximum capacity. The electrolyser remains at maximum green hydrogen output for most of the week despite the fact that wind farm output is low for most of the week shown.

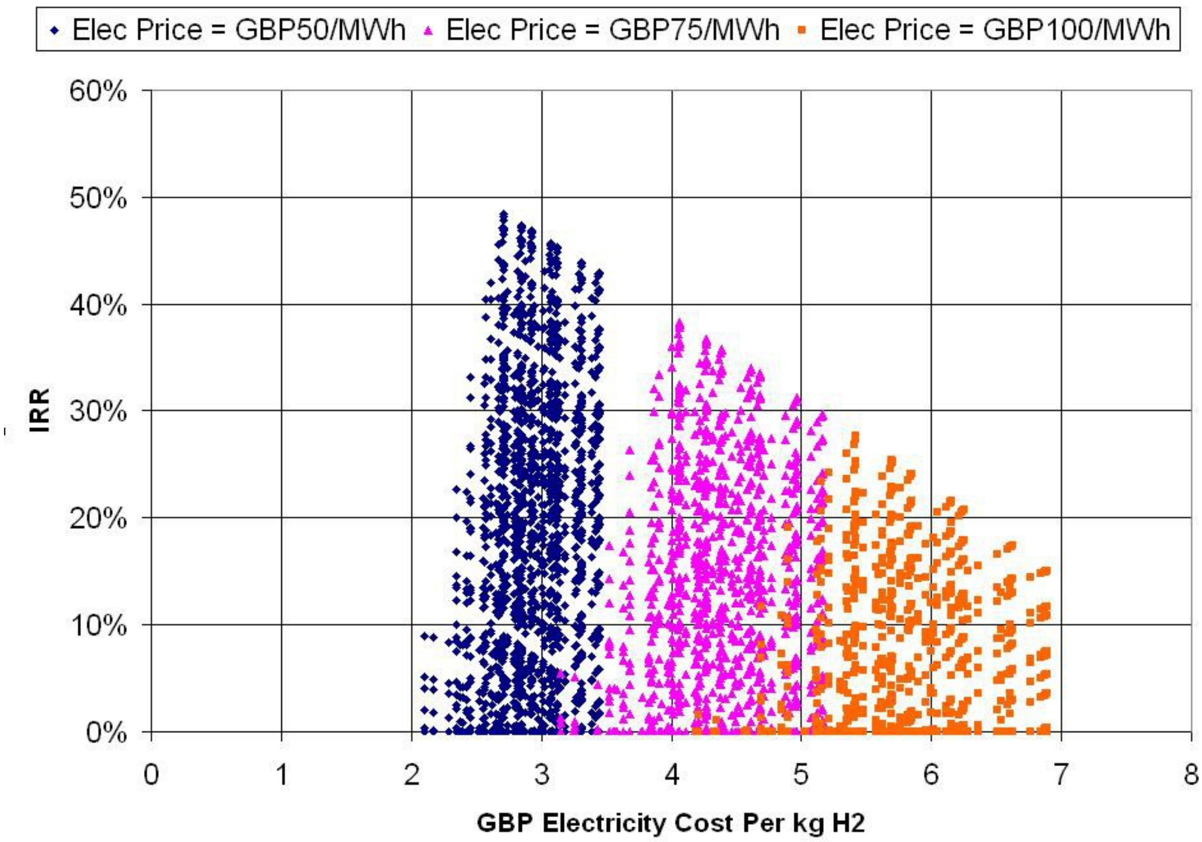

Figure 4 - Scatter plot showing IRR versus Electricity Cost per kg of green hydrogen for all scenarios. Wind farm PPA/electricity export price is critical as indicated by the key.

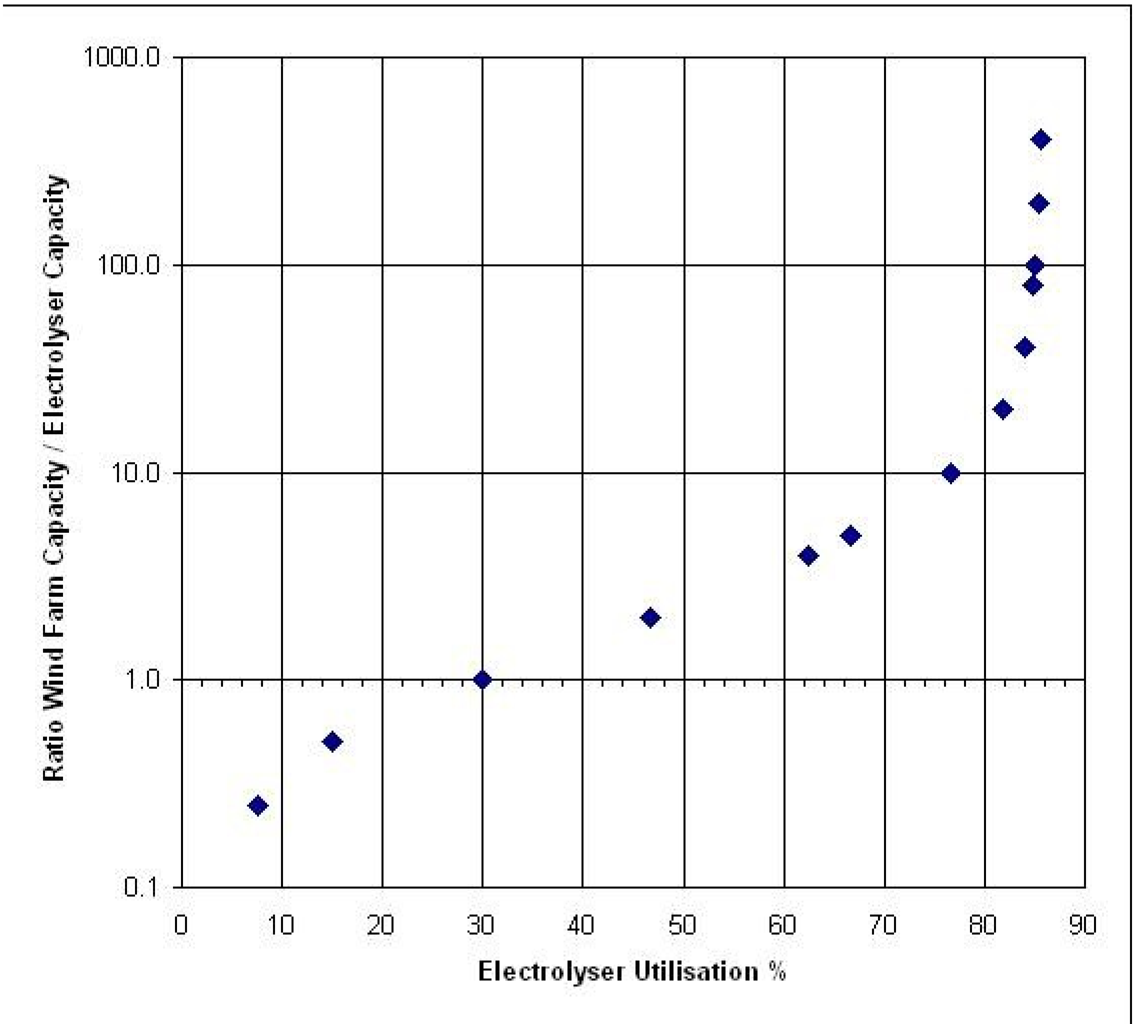

Figure 5 - By installing the electrolyser at a wind farm of installed capacity many times greater than the electrolyser capacity it is possible to increase the electrolyser utilisation.

Green Hydrogen Policy Options

Energy storage methods including green hydrogen offer many advantages for managing variable renewable energy on a future smart grid, offering energy security, sustainability and reduced carbon dioxide emissions as well as reducing the emission of pollutants which are causing respiratory and other health problems in present day cities from Glasgow to Beijing.

Green hydrogen offers the sector export of energy from electricity and into transport. Although this may be achieved more efficiently by use of battery electric vehicles in some cases it is noted that present day hydrogen fuel cell vehicles have superior driving range (eg 400 miles) and much quicker refueling times (eg 3 minutes), thus offering an acceptable motoring option to the consumer which is similar to the existing experience but without dependence on fossil fuel.

Government often claims to be technology neutral but in the present day UK local and national governments are encouraging the take up of battery electric vehicles and installing fast charging points. Conversely, the recent Green Bus Fund 4 offering grants to bus companies in England and Wales for introducing “the latest green technology” specifically prohibits bids for buses using hydrogen [1], despite the fact that hydrogen buses have been extensively demonstrated across the world and are carrying fare paying passengers in London. Hydrogen vehicles are not offered a level playing field despite their great potential and the UK has very little hydrogen refueling infrastructure while everyone has access to electric charging from the mains electricity infrastructure.

Zero emission transport fleets of sufficient scale and annual mileage can benefit from low cost zero emission green hydrogen fuel generated from local wind farms. However, the capital costs of the hydrogen vehicles need to be covered. The vicious circle due to lack of hydrogen refueling infrastructure remains. Taking an example from Germany the UK and/or Scottish governments could invest in the roll out of green hydrogen infrastructure in order to help enable a level playing field.

To further demonstrate technology neutrality and commitment to carbon emission reduction targets both national and local government vehicle procurement (except specialist vehicles) could be undertaken on a 50% battery electric and 50% green hydrogen basis on the grounds that these are the only two zero emission transport options (provided the battery electric vehicles are charged directly from renewable energy sources rather than increasing the requirement for fossil fuel electricity generation).

Government could also require or incentivise large private vehicle fleets to employ green hydrogen vehicles where practicable. An obvious candidate is the electricity utility company, many of which have thousands of regular cars within their fleet whilst simultaneously operating renewable energy generators such as wind farms. Such companies could be compelled or encouraged to spend some of their profits on investment into green hydrogen vehicles operating within their own fleets and associated refueling infrastructure. Once established this hydrogen fleet refueling infrastructure can be shared with other fleets and opened to the general public to further enable a level playing field and a green hydrogen choice for the consumer.

Where green hydrogen and other forms of energy storage are considered beneficial then it would be advantageous if market mechanisms (eg the proposed CFD mechanism within the UK) included some incentive to encourage deployment of green hydrogen and other forms of energy storage.

One possible incentive for deployment of energy storage including green hydrogen electrolysers on wind farms would be to ensure that compensation/reimbursement is provided to wind farm owners or other renewable energy generators instructed to curtail output but that energy storage methods such as green hydrogen electrolysers are positively encouraged to capture this waste energy and sell it to market at a later time. If a generator is called upon to limit output for the benefit of wider grid stability and a price is agreed for this service then the generator can be paid accordingly irrespective of where the energy is dumped to. Presently wind farms are being instructed to deliberately become less efficient and to dump energy which would normally be harvested from a free renewable source.

Encouraging wind farm owners to install energy storage methods for capturing this energy will add to future grid stability and enable more renewable energy to be accommodated on a smarter more sustainable grid, thus reducing emissions and avoiding fossil fuel dependence. Additional energy security advantages will accrue by stimulating a distributed energy storage resource co-located with variable renewable generators and tackling the problem at source instead of concentrating energy storage resource within a handful of targets which could be taken out by mechanical failures or hostile acts. A distributed energy storage system offers smart grid resilience and system robustness. By encouraging the re-sale of captured curtailment energy all renewable energy generators, large or small, can be incentivised to participate in electrically co-located energy storage within the grid connection point of their wind farm or other renewable generator.

Finally it would be possible to introduce a support mechanism for lowering the cost of green hydrogen for users of this fuel. The UK Hydrogen Fuel Cell Association (UKHFCA) has suggested [2] a hydrogen fuel supply offset at a rate of £2.88/kg and points out that this measure would stimulate demand for hydrogen which would naturally stimulate supply and the development of infrastructure for production and distribution.

It should be noted that the particular benefits of green hydrogen (as opposed to brown/grey hydrogen from fossil fuel/industrial by-products) can be targeted by policies specific to green hydrogen from local renewable energy over and above other forms of hydrogen.

The H2WindSim model allows for the insertion of green hydrogen fuel supply subsidy by altering the green hydrogen sale price. Figure 6 shows the histograms of IRR distribution of all parameter sets studied for three different cases of hydrogen export price. The differences in hydrogen export price could represent different fuel price subsidies (ie £2 or £4 per kg subsidy on a £6 market price feeding back to the green hydrogen supplier in this study). This demonstrates one example showing how the H2WindSim model can be used by policy makers to study the impact of policies on the business case for green hydrogen suppliers.

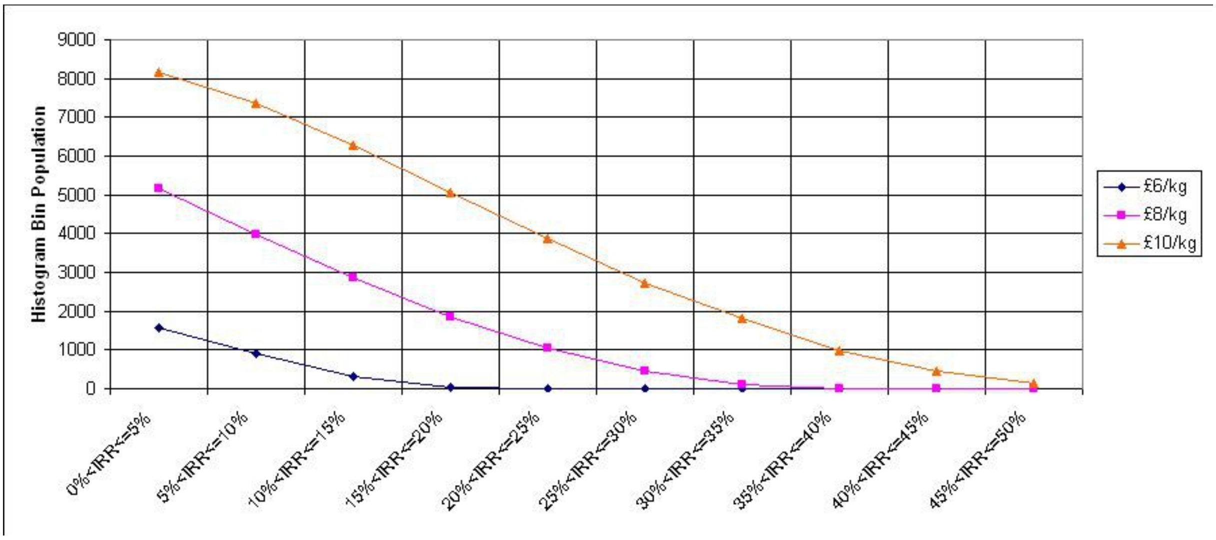

Figure 6 - Histograms showing distribution of IRR results modelled for the three separate cases of hydrogen export price.

Conclusion

Green hydrogen investment cases depend on very many parameters. A simulation tool has been produced for estimating the business case for installing electrolyser technology on wind farms and exporting green hydrogen. The tool allows wind farm owners, investors and policy makers to use historic wind farm power output and curtailment data in order to estimate and calculate beneficial green hydrogen investment cases with high IRR.

Modelling shows that it is important to take into account the relative installed capacity of the wind farm and electrolyser. Electrolysers installed at larger wind farms can obtain very much higher utilisation. This is beneficial to the investment case.

Curtailment energy can be captured but needs to be calculated on a case by case basis.

Green hydrogen contributes solutions to many problems including energy security, sustainability, pollution and clean transport in future cities and beyond, carbon dioxide emissions, economic dependence on imports. However, green hydrogen vehicles are not presently given a level playing field due to lack of infrastructure implying that the consumer is denied the green hydrogen choice.

Considering the benefits of green hydrogen there would be a number of possible mechanisms by which government could assist, stimulate or incentivise hydrogen from renewable energy:

- encapsulate incentives preferably within the current Energy Market Reform, or else in additional schemes, in order to encourage renewable energy generators to include energy storage of all types electrically co-located with their variable generators, and specifically dealing with green hydrogen incentives for the purpose of exporting local renewable energy in the form of transport fuel;
- require government and/or large private fleet procurement to employ hydrogen vehicles and install corresponding green hydrogen infrastructure, possibly shared between multiple fleets and open to the public;
- introduce a green hydrogen fuel subsidy in order to stimulate demand which would have a positive impact on green hydrogen fuel producers and early adopters of green hydrogen technology. Stimulating demand will stimulate supply.

ACKNOWLEDGEMENT

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