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Energy Capacity and Economic Viability Assessment of the Renewable Hydrogen Energy Storage as a Balancing Mechanism in addressing the Electric System Integration Issues Inherent with Variable Renewable Energy Resources

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Abstract

Energy requirements continue increasing as the industrialisation spreads and the standards of living rise. Most of the world's power consumption is still generated from fossil fuels combustion which despite of its advanced development has only a maximum efficiency of about 50%, generates almost 35% of the greenhouse emissions, as well as becoming expensive and insecure with the recent instability of oil prices. Renewable energy sources such as wind, solar, micro-hydro, wave, geo-thermal, and biomass are potential solutions for clean energy problem, but still challenges exist. Britain's target to reduce carbon emissions by 32% by 2020 through producing up to 34% of electricity and 15% of all energy from renewables cannot be met unless the contribution of such intermittent energy sources becomes more effective. Storing energy harnessed from renewables using energy storage technologies allows integration of such intermittent weather dependent energy sources while balancing the grid. Hydrogen Energy storage technology is proposed here to enable the UK to utilise its vast, but intermittent renewable energy resources with increased reliance. The objective within this study is to evaluate this process which represents genuine energy carbon neutrality. Energy capacity and economic viability assessment of an existing wind/hydrogen energy system operating in conjunction with the grid is provided here as a case study.

1 Introduction

The unhealthy trinity facing mankind can be summarized in:

- Environment – global warming, pollution.
- Energy – continuous rise in demand while days of cheap and abundantly available energy are over.
- Economy – affected directly by high energy costs and the environmental damage.

Renewable energy will not only contribute to future climate goals and securing energy independence, but can turn a serious energy supply problem into an opportunity for Europe in the form of commercial benefits, technology research, exports and employment. Renewables, depending upon national policies, are set to increase in total worldwide production capacity from 5% to 18%, with coal and oil likely to lose market share, while fossil fuels' contribution to primary energy growth is projected to fall from 83% to 64% [1]. However, the addition of such unpredictable power sources to the grid can undermine the balance. The adaptation of energy storage will allow higher renewable penetration into the grid without affecting the system stability and without having to cease the renewable energy production and pay penalties. However, storage technologies are faced with different controversies like high initial cost rates, additional transformation losses and environmental impacts largely depending on the correlation between the technologies used and the site selected [2].

The adaptation of traditional electrochemical battery energy storage technique with renewables into the grid will not achieve the previously mentioned purposes as they are not particularly durable and do not survive repeated deep discharge cycles without significantly impacting their operational life span. This paper is proposing Renewable hydrogen energy storage technique as a balancing mechanism while integrating variable renewables into the power grid. The paper will examine the added value of Hydrogen Energy storage technology in terms of energy capacity and economic viability to define the break-even point where such technology is viable.

2 Grid Balancing

The admission of renewable power inputs to the grid provides genuinely green energy at the points of entry, but it creates a huge operational problem in managing the central generators to cover any transient variations in the renewable power input and consumer demand. The need to cover such variations in order to balance the grid will lead to increased operation of large fossil (coal and gas) plant at part load, keeping plant idling just in case the renewable input dies away sooner than forecast, this is known as “spinning reserve” which is expensive and carbon intensive. In this “spinning” mode of operation fossil plants are operating at lower efficiency and generating relatively high CO2 outputs per kWh generated. On the other hand, to maintain grid balancing, remarkable renewable energy production cannot be absorbed by the network due to the mismatch between the electricity production and the corresponding load demand. The outcome of this incapability is significant financial loss of the wind parks owners, hindering further exploitation of the local renewable potential. In early April in Scotland, strong winds and heavy rain made the Scottish grid network not able to absorb all the energy being generated and had to constrain wind power off the system paying very high prices to compensate wind generators for their lost income. Approximately £890,000 was paid over few hours to six wind farms, these costs being ultimately destined to pass on to the consumer.

3 Hydrogen Energy Storage

Hydrogen is an important source of clean energy that has three times much energy as for the same quantity of oil [3, 4]. When hydrogen is used as a source of energy, it gives off only water and heat as by-products with no carbon emissions. Hydrogen can be used as an energy carrier, stored and delivered to where it is needed. Hydrogen-based energy systems have the potential to become a major energy source in future, however a new infrastructure will be needed for the technology to take hold. Only hydrogen has the capacity to work at a utility scale in proportion to the need. Hydrogen is a complementary supplement to smart grid operation considering storage and stabilization. Utilising hydrogen energy storage will allow an added stabilizing capability that will support the grid, reduce the need for spinning reserve, avoids load shedding and grid collapse, and provide peak demand support.

Hydrogen is seen by many industry leaders as an energy vector that has the potential to provide essential energy stores required to facilitate the wide spread connection of renewable energy inputs from sources such as wind, solar, wave and tide [5]. During excess renewable production, instead of dumping it and paying penalties, water is split through an electrolyser to produce hydrogen fuel using cheap electricity, to be used later to produce energy during peak demand. What we are proposing here is renewable hydrogen storage mechanism that will help driving the low carbon economy, allow energy security, eradicate constraint payments to wind farms for reducing their output when it exceeds demand, as well as allowing more distributed generation and storage thus reducing the transmission & distribution charges. The unique advantage of hydrogen as a form of energy storage is that it can deliver a fuel for making power or heat or for fuelling a car, while absorbing intermittent power inputs from renewable sources. This inherent flexibility is the overarching reason to integrate hydrogen generation by electrolysis and storage within the UK energy system. Using hydrogen in transport, a modified combustion engine, a fuel cell, a boiler or a power plant releases no CO2, but releases just the water from which it was created, so there is no carbon penalty and it improves the air quality. Hydrogen production through electrolysis is an independent energy storage mechanism from the fuel cell technology which is utilised for releasing the stored energy on demand; this allows strategic energy storage reserves to be sited in a more flexible manor than the traditional electrochemical energy storage technologies. Studies conducted previously indicate there is market potential for wind- hydrogen energy systems, particularly in remote areas and areas where there is weak electrical infrastructure. It has also been shown to have market potential for vehicle fuelling stations in both urban and remote rural areas [5]. In remote areas, hydrogen produced locally from renewable energy is considered to compete with traditional fossil fuels (petrol and diesel) sooner than in more densely populated urban areas [6-8].

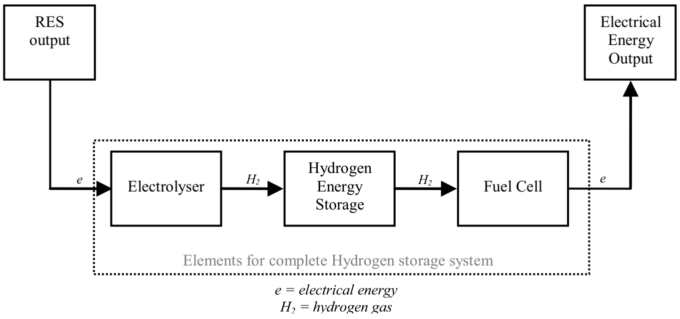

Figure 1: Basic elements of a hydrogen energy system

4 Hydrogen Energy Storage System Efficiency

All electrical Energy Storage Systems (ESS) have varying degrees of inefficiency since part of the energy supplied into it cannot later be discharged due to system efficiency losses. Typical efficiency factors range from 45% to 80% depending on technology and storage application, and is the main weakness of all existing electrical storage technologies [9].

The energy conversion process in *turnaround efficiency* of hydrogen powered electric power plants (energy generation to storage back to energy generation) is similar to pumped storage hydro-electric power plants. The electrolyser is used to convert electrical energy from an energy source (typically renewable) into Hydrogen for storage in the Hydrogen storage system. The Hydrogen storage can take a number of forms (pressurised gas, Metal Hydride, liquid Dewar tank). A hydrogen energy conversion system then recovers the stored chemical energy in the hydrogen and converts it back into electrical energy for use. The hydrogen energy conversion system commonly cited for use in such energy systems is a fuel cell. A fuel cell is commonly cited for use as its conversion efficiency is a lot higher than combustion engine technology [10]. Typical average electrical conversion efficiencies recorded for the fuel cells used in two projects, the PURE Project energy system and the Hydrogen Office, range between 40% - 50% compared with a maximum of 37% for a small combustion engine [11]. Although the efficiency of electrolysis is high, the overall *turnaround efficiency* is lower. However, the output heat from the electrolysers and fuel cells can be used for process heating, thus increasing this efficiency. Furthermore, capturing and storing excess renewable energy, that could have otherwise been wasted, increases the economical efficiency.

Energy storage efficiency can be viewed in a number of ways. The most common method of measuring energy storage system efficiency is by comparing the input energy used to fill the energy storage with the recoverable output energy. However, it is also important to consider the economic efficiency of an ESS. Hydrogen as a potential energy storage mechanism has the ability not only to store electrical energy for re-use like conventional energy storage systems, but also can offer to sell both hydrogen and oxygen gases as commodities. Hydrogen energy storage systems have three possible revenue streams while conventional energy storage systems have only one possible revenue stream for energy. Typically conventional network connected energy storage systems allow for energy to be stored and realised in the form of only electrical energy while Hydrogen has the additional ability to provide opportunity to generate revenue from the two additional outputs. These are the sale of hydrogen gas and Oxygen gas as well as the potential to release electrical energy. It is these additional revenue streams that give the potential for hydrogen ESS to offer greater financial efficiency. This 3:1 increase in revenue options also opens up potential for possible downstream applications. Literature shows potential for a great deal of flexibility for hydrogen usage where conventional energy storage systems do-not, for example fertiliser production, electrical generation and high and low grade heat applications [12]. Thus, the economic viability of Hydrogen ESS is considered in this paper and is applied to examine the Hydrogen office ESS as a case study. On the other hand, it is also important to identify the energy capacity of the Renewable Hydrogen ESS, i.e. the renewable resources ability in meeting a given load profile and the amount of energy that can be exported to the electrical grid and the total amount of annual energy that is expected to be captured for a given renewable-hydrogen energy system location. A model that examines the performance of such an energy system has been developed for that purpose in this study. This model has then been applied to assess the Hydrogen office energy system as a case study.

5 Economic Viability of Hydrogen ESS

On assessing the economics of hydrogen as an energy storage vector, the costs of energy storage have been considered using a levelised cost approach similar to that used for energy generation [13]. Thus, the Levelised Storage Cost (LSC) for an ESS can be expressed as shown in equation (1). Note that the input energy cost (EC_t) applied to the energy storage can be considered as the levelised cost of generation. The levelised cost (or total annualised cost) of energy generation (LGC) is given by the Net Present Value (NPV) of electrical generation divided by the NPV of the energy generation station.

$$LSC = \frac{\sum_{t=1}^{n} \frac{ISC_t + SOM_t + EC_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{EO_t}{(1+r)^t}} \qquad (1)$$

Where:
ISC_t = Invested Storage Capital in year (t)
SOM_t = Storage Operation and Maintenance costs in year (t)
EC_t = input energy cost (t)
r = Annual discount rate (typically 10%) [10]
EO_t = Value of released energy in year (t)

Energy storage developed around Hydrogen technology will have additional revenue potential as previously discussed, realised in the sale of both hydrogen and oxygen gasses as a commodity. Equation 1 can therefore be expanded upon to include $H2_t$ and $O2_t$, where the $H2_t$ and $O2_t$ are the realisable value of both hydrogen and oxygen in year (t). Therefore the levelised cost of Hydrogen ESS can be expressed as shown in equation 2.

$$LSC = \frac{\sum_{t=1}^{n} \frac{ISC_t + SOM_t + EC_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{EO_t + H2_t + O2_t}{(1+r)^t}} \qquad (2)$$

Several configurations can be considered for hydrogen storage systems economic evaluation. Analysis should evaluate scenarios for producing hydrogen and oxygen gases utilising surplus or ‘constrained’ renewable energy as previously discussed. To conclude the most economic scenario, the analysis should assume different scenarios for operating a hydrogen energy storage system:

1. No FC - (no energy sale), 100% 02 & H2 gas sold
2. 100% energy sale (FC), 100% 02 sold, no h2 sale
3. 50% O2 & H2 gas sold, 50% H2 sold as Energy through a FC
4. No FC - (no energy sale), No 02 Sold, 100% H2 sold
5. 100% Energy sold (FC), no O2 nor H2 sold

6 Developing a Simulation Model

In order to enable the assessment of a Renewable Hydrogen energy system’ performance in a variety of renewable conditions, component sizes and load demands, a simulation model needs to be developed. Although a number of software packages are available for creating simulations to investigate different aspects of the energy system performance [14], a model has been developed here to examine the “Hydrogen office” renewable H2 energy system’ performance due to the nature of its components and its configuration.

The proposed parametric model takes a number of input variables and calculates the desired output variables. The input variables are the wind turbine rotor power (kW) or the its hourly energy (kWh), the fuel cell efficiency (%), the initial storage energy level (kWh), the load energy requirements (kWh), the maximum storage input rate for the electrolyser (kWh) and the maximum energy storage in the vessels (kWh), all shown in table 1. The output variables that are required in order to gain a good indication of the energy system' performance are the annual wind turbine output (kWh), storage capacity (kWh) and the energy available for export to the grid (kWh). This information identifies the energy system' renewable resources and its storage abilities in meeting a given load profile, highlights the amount of energy that can be exported to the electrical grid and the total amount of annual energy that is expected to be captured in the project location. The model initially starts by calculating the hourly output values then uses this to generate the required time series simulation data necessary to assess the annual performance of the energy system.

P_R	Wind turbine rotor power / hourly energy (kW) / (kWh)
FC_{eff}:	Fuel Cell Efficiency (%)
EL_{eff}	Initial storage energy level (kWh)
$\boldsymbol{E_L}$	Load Energy Requirements (kWh)
$P_{S\,\max}$	Electrolyser' Maximum storage input rate (kWh)
$E_{S\,\max}$	Vessels' Maximum energy storage (kWh)

Table 1: Model Input Variables

The first step in simulating the energy system is to obtain the hourly time series for wind speed data. As this data has not been freely available, a method that simulates statistically representative time series wind speed patterns has been used. A Monte-Carlo Simulation [15] has been deployed here to simulate the variable nature of the renewable energy input to the energy system. The simulation time base is fixed at hourly intervals for a total of 8760 hours to simulate the variability of renewable wind speed resource over a year. Monte Carlo simulation is applied to good effect in this case as it generates statistically representative data for wind speed values. Statistically representative time series wind speed data has been derived by using the average wind speed value $\bar{v}$ and the statistical 'shape', or k value, for the wind speed variation. This simulated wind speed data then forms the input power source for the hybrid energy system. Equation 3 shows the Probability Density Function (PDF), which has been used to calculate statistically representative wind speed, after modulation to incorporate annual seasonal variation:

$$v = 1 + S_{var} \cos\left(t_{hr}\left(\frac{360}{8760}\right)\left(\frac{\pi}{180}\right)\right) exp\left\{\left(-\left(\frac{\bar{v}}{C}\right)^{k}\right)\right\} \tag{3}$$

Where:
v: hourly wind speed
S_{var}: percentage of seasonal variation
t_{hr}: hour during year
$\bar{v}$: mean average site wind speed
C: Dimensionless scale factor
K: Dimensionless shape factor

The wind speed v is then converted into electrical power using equation 4:

$$P_R = \left(\frac{1}{2} C_p \rho A v^3\right) \tag{4}$$

Where:
P_R: Wind turbine rotor power (kW)
C_P: Rotor power coefficient
ρ: Air density (kgm3)
A: Wind turbine rotor swept area (m2)
v: Wind speed (m/s)

The simulated wind turbine hourly energy output is then passed to the energy storage system simulation model given by equations 5 to 8:

$$E_{\text{bal}} = E_{\text{T}} - E_{\text{L}} \tag{5}$$

$$E_{\text{S}} = E_{\text{bal}}.\ El_{\text{eff}} \tag{6}$$

$$E_{\text{GD}} = E_{\text{bal}} - P_{\text{Smax}} \tag{7}$$

$$E_{\text{S}} = E_{\text{S-1}} FC_{\text{eff}} + E_{\text{bal}} \tag{8}$$

Where:
E_T: Wind Turbine hourly energy output
P_{Smax}: Maximum storage energy absorbable
E_{bal}: Systems Energy Balance
EL_{eff}: Electrolysis efficiency
FC_{eff}: Fuel Cell efficiency
E_s: Energy held in storage
E_{GD}: Energy Exported to grid
E_L: Energy Supplied to load

To assess the energy storage system' performance through seasonal variation, a time series simulation over a minimum time period of a year is then considered. This also enables the storage level to be assessed for its ability to maintain the load demands. If the hydrogen energy storage system level falls below 0 kWh during the simulation then this indicates insufficient primary input energy, energy storage or electrolyser capacity. It may also indicate that the load demand is too big to be supplied by the energy system.

7 Case Study (The Hydrogen Office)

To understand, improve access to, and demonstrate how a renewable-hydrogen energy system technology can provide safe and reliable power, a number of installations have been implemented worldwide. Many of these have been based around small-scale wind turbines of only a few tens of kilowatts with exceptions to this in recent years are the Hydrogen Mini Grid System (HMGS) in Rotherham Yorkshire, the Utsira (Norway) energy system, and the Hydrogen Office in Methil Docks Business Park in Scotland shown in figure 2, which has been chosen to be the case study for this paper. Within the Hydrogen Office, a groundbreaking autonomous wind/hydrogen energy storage system has been installed to demonstrate the potential of storing surplus renewable energy as hydrogen for a range of on-demand applications that require reliable, quiet, and very clean energy sources. The main components installed in the system are a 750kW wind turbine providing the renewable energy input to the system, energy storage achieved by using a 5Nm3/h electrolyser and 136Nm3 storage vessel at 12 bar where surplus renewable energy is stored for times when renewable energy may not be available, i.e. insufficient renewable energy supply [16]. Stored Hydrogen is utilised in a 10kW Proton Exchange Membrane (PEM) fuel cell to provide electrical energy on demand in a UPS mode for the office building electrical loads and can be utilised in other applications for which renewable energy may not be directly suitable (i.e. transport or uninterruptible power supply).

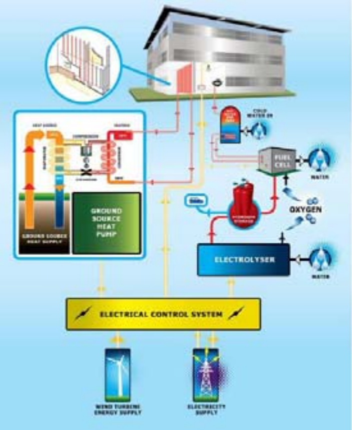

Figure 2: The Hydrogen Office Energy System

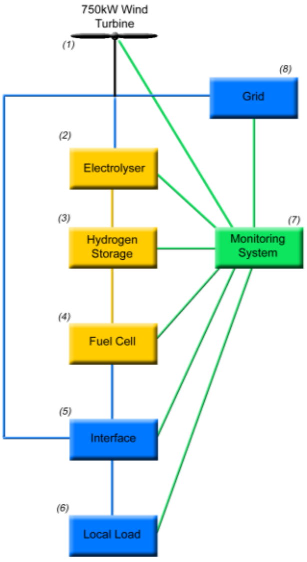

Figure 3: The Hydrogen Office Simplified System Overview

1. 750kW grid connected double wound synchronous induction wind turbine
2. 5Nm3/h 12 bar alkaline electrolyser (31 kWh)
3. 136Nm3 hydrogen storage (450 kWh)
4. 10kW PEM fuel cell
5. Power factor correcting inverter interface
6. Hydrogen Office electrical load
7. Automatic control & monitoring system
8. Import/Export Grid connection

7.1 The Building Efficiency and the Economic Viability of the Hydrogen office ESS

The Hydrogen Office has been built to the following high energy efficiency specification in order to minimise its energy demand:

- Increased insulation and efficient glazing to minimise heat loss and unwanted heat gain
- Natural ventilation to remove the need for air conditioning
- A layout that maximises natural daylight to minimise the need for artificial lighting
- Efficient lighting and control systems
- A ground source heat pump, to recover the waste heat from the fuel cell and the electrolysis unit, in order to be used in providing most of the heating and hot water needs for the building

To investigate the most economic scenario for operating the hydrogen office energy storage system, the analysis considered the 5 previously proposed scenarios in section 5. Using the previously developed formula in that section, the levelised cost per unit output for each scenario has been calculated using the given below hydrogen capital costs data for the Hydrogen office as provided by the Pure Energy Centre [17]:

Electrolysis 2500 €/kW
Pressurised Storage 77 €/kWh (HHV)
Fuel Cell 4000 €/kW

Results:
Levelised cost for H2 ESS Scenario 1 = 0.2064 €/kWh
Levelised cost for H2 ESS Scenario 2 = 0.3237 €/kWh
Levelised cost for H2 ESS Scenario 3 = 0.5199 €/kWh
Levelised cost for H2 ESS Scenario 4 = 0.9082 €/kWh
Levelised cost for H2 ESS Scenario 5 = 1.9535 €/kWh

Results obtained show that the most economic scenario i.e. the lowest output unit cost can be realised in scenario 1, while the highest unit output cost can be seen in scenario 5.

7.2 Simulation Results

In the simulation of the Hydrogen office ESS, the Department of Energy and Climate Change (DECC) national weather database has been used to find an annual average site wind speed of 7.3m/s at the hub height of 45m. This 7.3m/s defines the mean wind speed, $\bar{v}$ in equation 3. "k" has been selected as 3 due to the costal location of the wind turbine and the value used for air density is 1.225kgm3. On using these values in the given simulation model, a simulated annual output of approximately 1.8GWh is obtained when corrected for turbine generation losses and the effect of turbulence at the site. Notice that the H2 office fuel cell efficiency used in the model is 40%, the system initial storage energy level used is zero kWh and the load energy requirement used is 10 kWh. It can be seen from the summary of the annual energy flow, given by table 2, that 95% of the energy produced by the on-site wind turbine will be exported onto the electrical grid.

E_{GD} (energy sent to grid)	1’749’737 kWh
E_S (energy stored)	9’167 kWh
E_T (Production total)	1’841’570 kWh

Table 2: Annual Production Summary

The simulation output results of the wind speed data for 8760 hours, or one year, are shown in figure 4. This simulation has been verified by using these values in obtaining the annual simulated wind speed distribution, i.e. the % of happening of each speed throughout the year, and comparing this to the statistical ideal distribution as shown in figure 5.

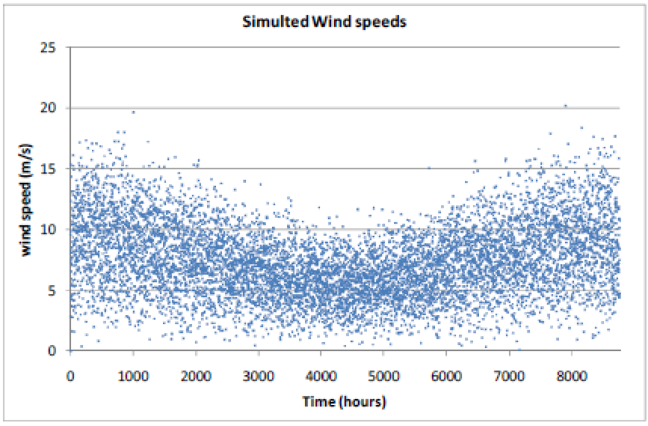

Figure 4: Simulated Wind Speeds

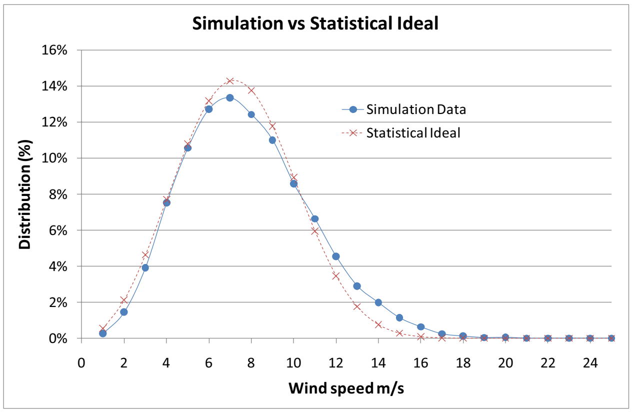

Figure 5: Deviation from ideal

The worst-case load demand within the hydrogen office is assumed here to be 10kWh continuous demand. The electrolysis system, fuel cell and hydrogen storage tank sizes have been simulated in accordance with the values given in figure 3. Using these values, the performance of the energy storage system has been analysed to identify if this hydrogen energy storage system would ever run out of stored energy. The simulation results can be seen in figure 6.

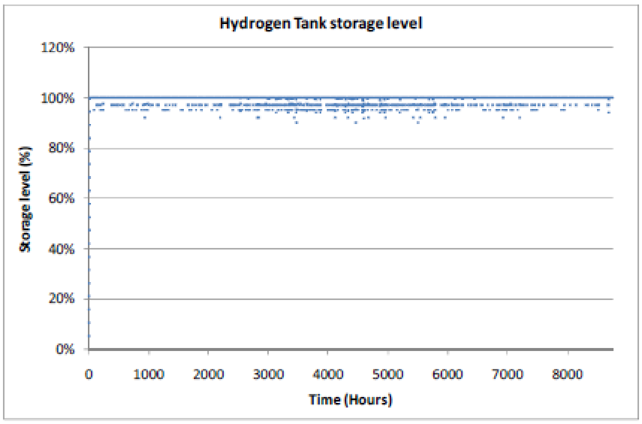

Figure 6: Energy Storage level

The effect of increasing the load demand on storage has also been simulated as shown in figure 7.

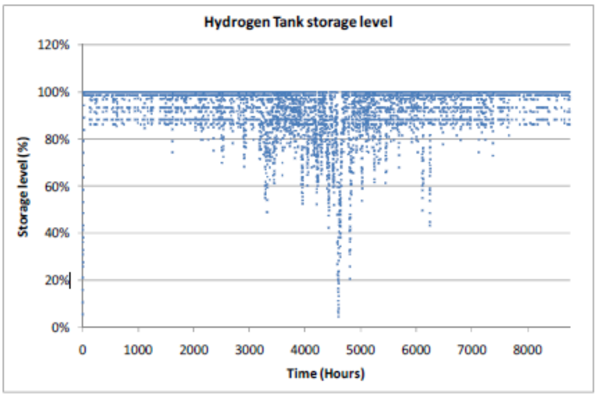

Figure 7: Effect of Increased Demand on Storage

Additional simulation has then been done to identify the potential for future expansion of demand supplied via the hydrogen energy storage system in the Hydrogen office. After repeated simulations it was found that only a future upgrading of just the existing fuel cell system will allow the continuous supply of a maximum demand of 28.5kW, given that the hydrogen production and storage capacities stay the same.

8 Conclusion

The cost effect of introducing Hydrogen energy storage technologies to enable the projected increase of renewables onto electrical power grids has been examined. Hydrogen has the greatest potential and financial benefit to enable the projected increase in renewable generation onto the electrical network as it allows surplus renewable energy alternative economic pathways to be utilised. This is due to hydrogen energy storage systems ability to utilise hydrogen directly as an energy carrier and take advantage of its inherent flexibility of end use. i.e. H2 is not only limited for electrical energy production but can be sold for other purposes. It has been shown that hydrogen energy storage mechanism has the most economic potential when oxygen is sold as well.

A simulation model has also been developed to demonstrate the hourly operation data of a Renewable H2 energy system for a year. The simulation results for the Hydrogen Office system have shown that the energy system will be able to meet the worst case demand that can be placed on the installed infrastructure at the project site. Further simulation has also shown that the existing energy storage system and wind turbine have the potential to support up to 29kW of continuous demand with just an upgrade of the fuel cell component. The simulation results have also shown that 95% of the energy produced by the on-site wind turbine will be exported onto the electrical grid.

References

[1] BP Energy Outlook 2030

[2] Denholm P, Kulcinski GL. “Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems”, *Energy Conversion Manage,* 2004; 45(13–14):2153–72.

[3] The Open University. “The potential of fuel cells to reduce energy demands and pollution from the UK transport sector”, http://oro.open.ac.uk/198461/1/pdf76.pdf.

[4] Stanford University. “Hydrogen FQA sustainability”, http://www.formal.standford.edu/jmc/progress/hydrogen.html.

[5] International Energy Agency, “IEA Agreement on the Production and Utilization of Hydrogen”, Task 18; subtask B, Final Report (2007).

[6] R.Gazey, S.K.Salman, D.D.Aklil-D’Halluin. “A field application experience of integrating hydrogen technology with wind power in a remote island location”, *Elsevier Power Sources Journal*, POWERD-05-01096, February (2006).

[7] Peter Forsberga, Magnus Karlström. “On optimal investment strategies for a hydrogen refuelling station”, *International Journal of Hydrogen Energy*, 32 (2007) 647 – 660, (2006).

[8] Daniel Aklil D’Halluin, Elizabeth Johnson, Ross Gazey, Et al. “Remote Communities & Islands - An Economical Case For Hydrogen Technologies”, *UNIDO* (2008).

[9] Dr. Timothy E. Lipman, Mr. Ryan Ramos, Professor Daniel M. Kammen. “An assessment of battery and hydrogen energy storage systems integrated with wind energy resources in California”, University of California, Berkeley, September 2005.

[10] Dr. D.Ali, Dr, D.Aklil. “Modelling a Proton Exchange Membrane (PEM) Fuel Cell System as a hybrid Power Supply for standalone applications”, 2011 Asia-Pacific Power and Energy Engineering Conference, *APPEEC 2011 – Proceedings*, database: Compendex APPEEC.

[11] T.Wallner, H.Lohse-Busch, N.Shidore. “Operating strategy for a hydrogen engine for improved drive-cycle efficiency and emissions behaviour”, *International Journal of Hydrogen Energy*, September 2008.

[12] J.C. Ganley. “Solid State and Electrolytic Ammonia Production”, Howard University, Department of Chemical Engineering.

[13] Mott MacDonald. “UK Electricity Generation Costs Update”, Department of Energy & Climate Change, June 2010.

[14] S.K. Salman, D.Aklil, R.Gazey. “Development Of A Modelling Tool For A Hybrid Renewable And Hydrogen Energy System”, *UPEC Proceedings (2005)*.

[15] Daniela E. Popescu, Corneliu Popescu, Gianina Gabor. University of Oradea, Str. Armatei Romane nr.5, Oradea, România. “Monte Carlo Simulation using Excel for Predicting Reliability of a Geothermal Plant”, *International Geothermal Conference, Reykjavík, Sept. 2003*.

[16] http://www.hydrogenoffice.com/building/index.asp.

[17] Dr.D.Aklil. “Market analysis data”, internal documentation, Pure Energy Centre, 2010.