Evaluation of hydrogen office wind/hydrogen demonstration system using operational data and simulation tools.

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EVALUATION OF HYDROGEN OFFICE WIND/HYDROGEN DEMONSTRATION SYSTEM USING SIMULATION TOOLS

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ABSTRACT

The first minister for Scotland, Alex Salmond, opened the Hydrogen Office officially in January 2011. Within the Hydrogen Office, a groundbreaking autonomous wind/hydrogen energy storage system has been installed. The main components installed in the system are a wind turbine (750 kW), pressurised alkaline electrolyser (5.3 Nm^3/h), hydrogen gas storage (136 Nm^3 @ 12 bar), and a modular PEM fuel cell (10 kW). The system gives up to two weeks of autonomy for the hydrogen office based on present energy consumption. Since operations started in July 2010, a sizeable quantity of operational experience has been gathered. One of the objectives within this study is to evaluate the operation of the Hydrogen Office system. Using simulation tools developed hourly operation data of the system are simulated for a year. A brief discussion on the design and operation of a wind/hydrogen energy system operating in conjunction with the electrical distribution and transmission system (the 'grid') is provided.

INTRODUCTION

Figure 1: Hydrogen office opening with First Minister Alex Salmond, Derek Mitchell of Hydrogen Office Ltd, Adrian Gillespie of Scottish Enterprise and Dr Daniel Aklil of Pure Energy Centre [1]

Hydrogen is seen by many as a means to store surplus renewable energy from sources such as wind, solar, wave and tide [2]. 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 [3]. 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 [3-5].

Over the last ten years, many wind hydrogen concepts and system designs have been investigated [6-8], and a number of installations have been implemented. Many have been based around small-scale wind turbines of only a few tens of kilowatts. 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. All these systems utilise commercially available alkaline electrolysers with rated hydrogen production capacities in the range of 0.2 to 10Nm^3/h and operating pressures in the range of 7 to 20 bar. An important exception to this is the PURE Project (3.5Nm^3/h, 55bar prototype). In comparison, the Hydrogen Office utilises a 5Nm^3/h, 12 bar commercial electrolyser.

The rationale for the Hydrogen Office is to demonstrate how a renewable-hydrogen energy system can provide safe and reliable power to a commercial building within Scotland and improve access to, and understanding of, the technology. After several years of concept development, system design and project planning undertaken by several partners [9], the decision to build the Hydrogen Office was taken. The installation of the hydrogen energy system was realised by the Pure Energy® Centre [10], whilst the buildings were developed by Alshera developments [11]. The main objective of this paper is to provide an evaluation of the performance of the Hydrogen Office system using modelling tools.

SYSTEM DESCRIPTION

The Hydrogen Office forms the centrepiece of the new Methil Docks Business Park, which has been developed as part of a large investment to support the regeneration of the Levenmouth area. The project demonstrates and promotes 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. In the background of figure 1 the hydrogen storage solution and wind turbine at the Hydrogen Office is shown. The 750kW wind turbine provides the renewable energy input to the system. Surplus renewable energy is then stored for times where renewable energy may not be available, i.e. insufficient renewable energy supply or peak demand. Energy storage is achieved using a $5Nm^3/h$ electrolyser and $136Nm^3$ storage vessel at 12 bar. A 10kW Proton Exchange Membrane (PEM) fuel cell is utilised to provide electrical energy on demand in a UPS mode for the office building electrical loads. It is planned that stored Hydrogen will be utilised for other applications for which renewable energy may not be directly suitable (i.e. transport or uninterruptible power supply). Represented in Figure 2 is a simplified overview of the hydrogen office system.

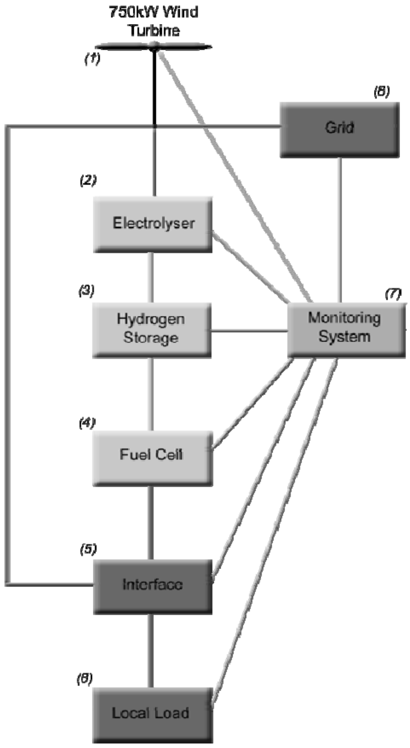

Figure 2: simplified system overview

1. 750kW grid connected double wound synchronous induction wind turbine
2. $5Nm^3/h$ 12 bar alkaline electrolyser
3. $136Nm^3$ hydrogen storage
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

REVIEW OF MODELING TOOLS

A number of simulation models have been developed for simulating hybrid power systems in recent times. Researchers have developed numerous analytical models with varying sophistication and general use for wind/diesel and hybrid power systems. In general, these models can be classified into two broad categories: Logistical and Dynamic models [12].

Logistical models are used primarily for long-term performance predictions and component sizing. Logistic models can generally be divided into three main categories.

- **Time series:** This model type requires long-term time series input of variables such as load profile and wind speed.

- **Probabilistic:** This type of model generally requires long-term monthly or seasonal load and resource data. The analytical model is then based on the use of statistical modelling techniques.

- **Combined time series and probabilistic:** This technique employs a combined time series and probabilistic approach to simulating an energy system. Time series data is utilised to account for the resource and load variations over intervals usually extend from 10 minutes to 3 hour intervals. Shorter term fluctuations are then simulated using statistical techniques.

Dynamic models are generally applied to energy systems that incorporate little or no energy storage. They are used primarily for component design and assessment of system stability and determination of power quality. The energy system under consideration within this project has been developed with considerable energy storage in the form of Hydrogen. As such the dynamic modelling techniques are not considered here. Figure 3 highlights available modelling techniques and categorises the available software into their methodological approach.

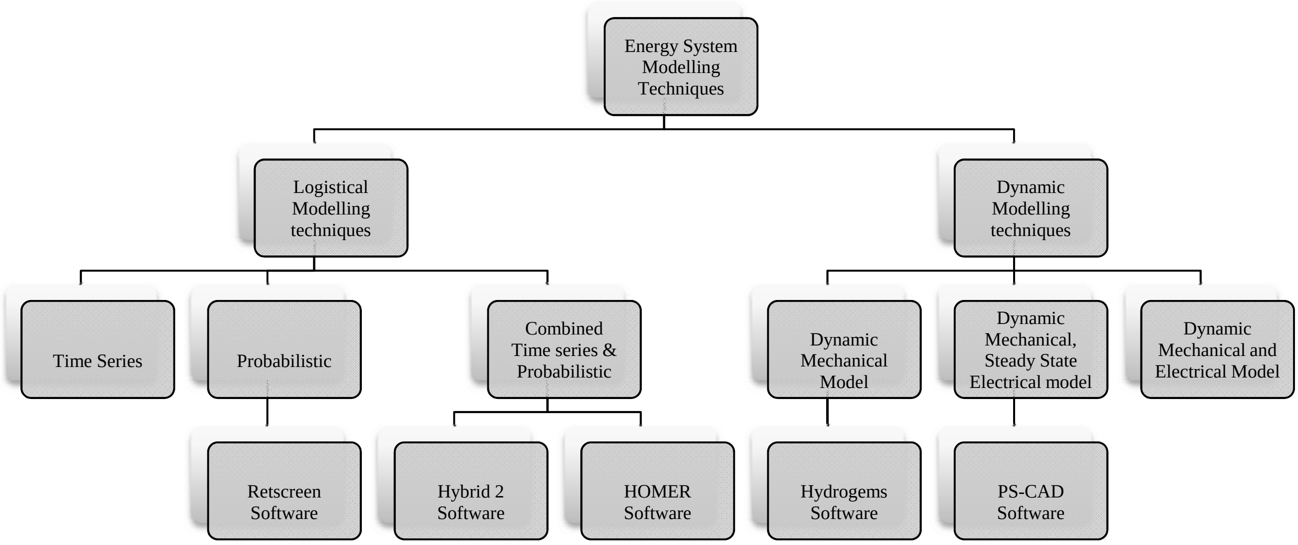

Figure 3: Summary of simulation tools considered

DEVELOPING SIMULATION TOOL

The aim of the simulation tool was to enable the assessment of the energy systems performance in a variety of wind conditions, component sizes and load demands. The results of this simulation make it possible to ascertain if the components considered for use will meet the energy requirements of the load. As describe previously a number of software packages are available for creating simulations to investigate different aspects of the energy system performance. However due to the configuration and nature of the system components within the hydrogen office system a model has been developed to examine the system performance.

When developing the simulation it was first required to produce a model of the energy system under development. The parametric model takes a number of input variables and calculates the desired output variables as shown in Figure 4. The output variables that are required to gain a good indication of the energy systems' performance are the annual wind turbine output, storage capacity and energy delivered to the grid. This information helps in identifying the renewable resources ability to meet a given load profile. It also 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 initial model only calculates single hourly output values that are independent of time. In order to simulate the annual performance the model has to calculate the required outputs for each hourly interval. This generates the required time series simulation data necessary to assess the annual performance of the energy system. The first step in simulating the energy system is to obtain hourly time series wind speed data. However, time series data was not freely available and a method to simulate statistically representative time series wind speed patterns was used. It is possible to derive statistically representative time series wind speed data by using the average wind speed value $\bar{v}$ and the statistical 'shape', or k value for the wind speed variation. The simulated wind speed data then forms the input power source for the hybrid energy system. Equation 1 shows the Probability Density Function (PDF) used to calculate statistically representative wind speed. The PDF has been modulated to incorporate annual seasonal variation as shown:

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

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 2:

$$P_R = \left(\frac{1}{2}C_P \rho A v^3\right) \quad (2)$$

Where:

- P_R Wind turbine rotor power (kW)
- C_P Rotor power coefficient
- ρ Air density (kgm^3)
- A Wind turbine rotor swept area (m^2)
- v Wind speed (m/s)

A time series simulation over a minimum time period of a year is required to assess the energy storage systems' performance through seasonal variation. The time series output 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 0kWh during the simulation this indicates there is insufficient primary input energy, energy storage or electrolyser capacity. It may also indicate that the load demands are too great to be supplied by the energy system.

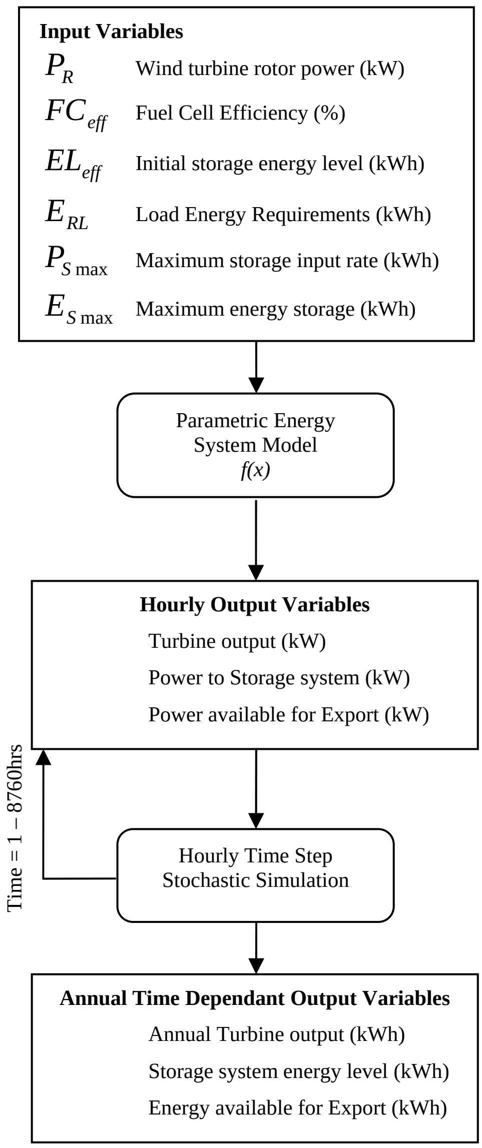

Figure 4: Simulation process

The first step is to simulate the variation in the primary energy source input. This generates statistically representative input wind speed data from the available site data described. A Monte-Carlo Simulation has been developed 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 more commonly used for the simulation of reliability and failure rates. However, the technique can also be applied to good effect in this case to generate statistically representative data for wind speed values.

The simulated wind turbine output is passed to the energy storage system simulation represented by the simplified schematic in figure 5 below:

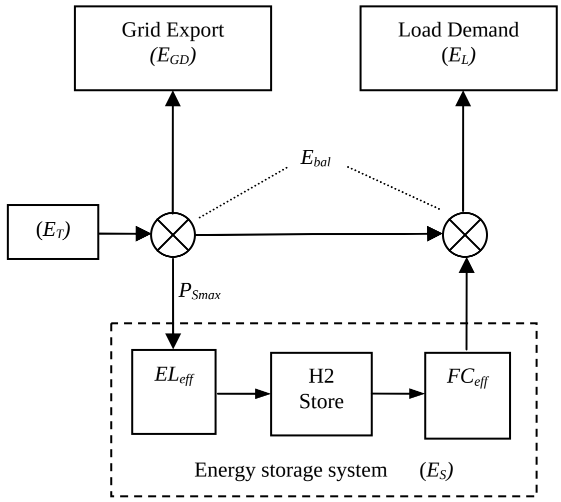

Figure 5: block diagram of energy storage model

The calculations performed in the energy storage simulation shown in figure 5 are shown by equations 3 to 5

$$E_{bal} = E_T - E_L \quad (3)$$

$$E_s = E_{bal}.El_{eff} \quad (4)$$

$$E_{GD} = E_{bal} - P_{Smax} \quad (5)$$

$$E_s = E_{s-1}FC_{eff} + E_{bal} \quad (6)$$

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

RESULTS

Annual average wind speeds are available from publicly available national wind speed databases.

Using the Department of Energy and Climate Change (DECC) national weather database an annual average site wind speed of 7.3m/s was found at the hub height of 45m. The value of 7.3m/s was then used as the input value for mean wind speed, $\bar{v}$, in the simulation. The value used for k has been selected as 3 due to the costal location of the wind turbine and the value used for air density is 1.225kgm^3.

This produced a simulated annual output of approximately 1.8GWh when corrected for turbine generation losses and the effect of turbulence at the site. A summary of the annual energy flow expected can be seen in table 1.

Table 1: annual production summary

Annual simulation totals summary		
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

Shown in figure 6 are the simulation output results of wind speed data for 8760 hours, or one year. Figure 7 summarises the variance between the statistical ideal and the annual simulated wind speeds calculated during the system simulation.

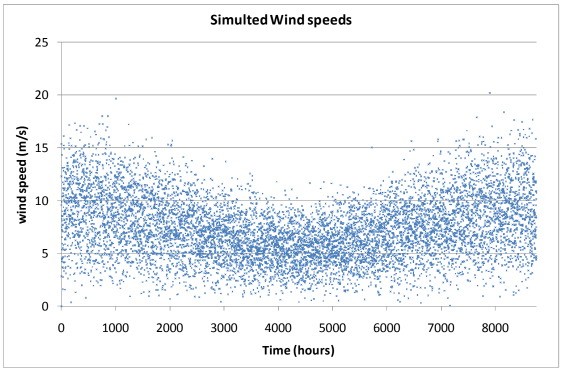

Figure 6: simulated wind speeds

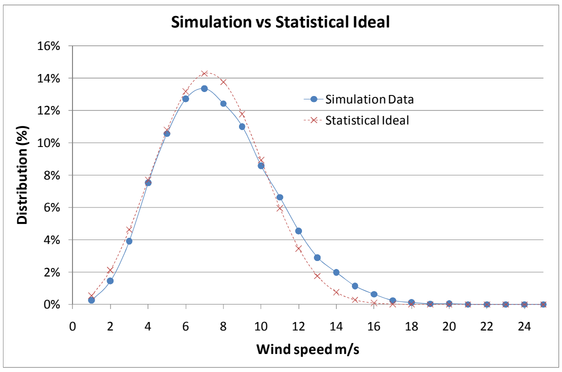

Figure 7: Deviation from ideal

The worst-case load demands for the offices within hydrogen office are assumed as a 10kW continuous demand. The electrolysis system, fuel cell and hydrogen storage tank sizes have been simulated in accordance with the values given in figure 2.

Using these values, the performance of the energy storage system can be analysed to identify if the hydrogen energy storage system would ever run out of stored energy. The simulation result can be seen in figure 8.

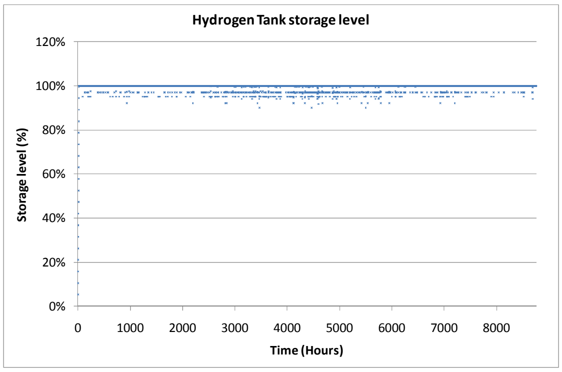

Figure 8: energy storage level

EFFECT OF INCREASING LOAD

The effect of increasing the load demand for electrical energy has also been simulated and is shown in figure 9. Additional simulation has been done to identify the potential for future expansion of demand supplied via the hydrogen energy storage system. After repeated simulations, the maximum demand that could continuously be supplied was found to be 28kW. Any expansion would only require an upgrade of the existing fuel cell system. The simulation assumes hydrogen production and storage capacities stay the same.

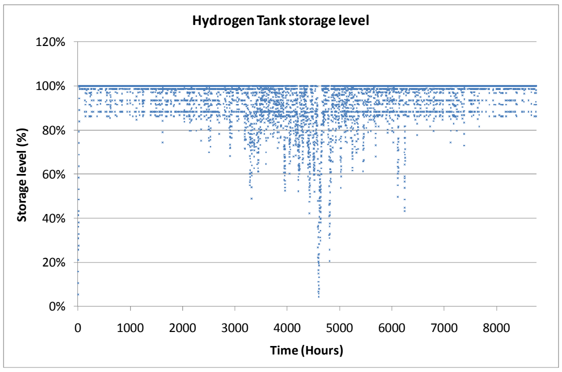

Figure 9: effect of increased demand on storage

CONCLUSION

Using the simulation tools developed hourly operation data of the system have been demonstraighted for a year. The simulation results of the Hydrogen Office system have shown that the energy system will be able to provide for the worst case demands 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 also has the potential to support up to 29kW of continuous demand with an upgrade to only 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.

FURTHER WORK

It is hoped to expand upon the work presented within this paper to detail the operational parameters of the electrolysis, fuel cell and storage components. This would include thermal and pressure responses to a renewable energy input.

ACKNOWLEDGEMENT

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