Simulation for control strategies of hybrid wind/ hydrogen systems for smart grid applications in Kampala and Tororo-Uganda

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ABSTRACT

The production of electrolytic hydrogen using electricity generated from a non-polluting source is one of the strategies to promote access to sustainable energy in Africa. One of such system is the wind energy conversion system (WECs). This paper presents results of a system consisting of a wind turbine of 200 kW, an Electrolyzer, and a 3.5kW peak electric load connected to an electric grid required to produce 4-5kg of hydrogen per day. The electric grid is taken as large enough to serve as a back-up supply. Mathematical equations are derived for the interconnecting components of the system and programmed in MATLAB to simulate the operation and control strategies of the system. The model has been tested using wind speeds for Kampala City and Tororo Town in Uganda. This results show that it's feasible to produce 4-5 kg of hydrogen from a non-polluting source. The smart grid monitors the hydrogen flow within storage and optimizes the flow of power from the wind generator and the electric grid to meet the hydrogen and load demand for the day. The paper demonstrates that such an integrated system has the potential to support remote investments in the production of electrolytic hydrogen from a non-polluting source for stationary and transportation activities.

Keywords: control strategies; hybrid wind/hydrogen system; Matlab simulation, smart grid.

1. Introduction

In order to secure the energy supplies in countries which are fully dependent and also net importers of fossil fuels, renewable energy sources are identified as alternatives in the reduction of greenhouse gas (GHG) emissions (Zhou & Francois 2009)**.** These GHGs are brought about by emissions from mostly utility generation plants and millions of transport vehicles, this then requires to limit greenhouse gas emissions using renewable energy (Carton & Olabi 2015). For the latter, Hydrogen gas (H_2) is regarded as a promising energy carrier from renewable energy sources (Korpås & Greiner 2008). Thus, emission free renewable energy sources such as wind energy (WE), can be used to provide the required H_2 as an alternative to the fossil fuels. Since WE is intermittent in nature due to the variability in wind speed, hydrogen cannot be produced as required on demand. Hence energy storage facilities –in this case the electric grid, can be integrated with the wind turbine to store excess of electricity generated when the hydrogen demand has been met for use in no wind or/ low cut in speed; in addition to supplying the electric load. The connection of intermittent renewable energy to the electricity networks calls for new methods of managing and operating them (Carr et al. 2012). This requires robust strategies for operating the Electrolyzer to prevent too frequent start-ups and shut-downs and, at the same time, having the Electrolyzer connected directly to the grid. In addition, this then requires implementation of efficient control strategies to regulate the flow of electricity from the wind turbine to the grid at wind power peaks when the hydrogen demand has been met and from the grid to the Electrolyzer at low wind speeds to produce hydrogen.

Many control strategy studies have been made on the production of electrolytic hydrogen. In (Korpås & Greiner 2008), (Elbaset 2011) and (Greiner et al. 2007) the results indicate clear benefits of using the grid as a backup for production of hydrogen at times of low wind speeds. (Beccali et al. 2013), provides suggestions in planning, development and sizing of wind hydrogen power systems in considerations of local and regional resources, demands constraints and opportunities for such a system. This paper considers the idea of producing hydrogen for each hour to achieve the daily hydrogen load. But since wind has stochastic tendencies that can affect both power quality and planning of power systems, then energy storage systems are required in controlling wind power output and providing the required ancillary services to the power systems(Diaz-Gonzalez et al. 2012)Control strategies are required for a scenario where a wind hydrogen system is connected onto a grid and where excess wind energy is sent to the electric load and grid. The smart grid applications of such a system involving supervisory control strategies that combine all the equipment models are investigated.

1.1 Nomenclature

$P_{wind}(t)$	Power generated by wind turbine	Vci	cut in speed of the turbine
$P_{ely}(t)$	Electrolyser power	Vco	cut-out speed of the turbine
$P_{grid}(t)$	Grid power	Vr	Rated speed
P_r	Rated power of the turbine	$\dot{m}_{h,load}$	H_2 load
Eff_{AD}	Efficiency of AC/DC converter	$\dot{m}_{h,ely}$	the flow rate of H_2 from electrolyser
C_P	efficiency of the wind turbine	$m_h(t)$	mass of stored H_2
ρ	Air density	$\dot{m}_{h,def}(t)$	amount of H_2 not supplied
SPC_C	specific power consumption of the compressor	$\dot{m}_{h,fill}(t)$	the flow rate of H_2 to the storage
SPC_e	specific power consumption of the Electrolyzer	$M_{H2,max}$	Daily hydrogen storage capacity
d_{H2}	average hourly H_2 demand	A	Swept area

1.2 Methodology

This paper considers the idea of producing hydrogen for each hour to achieve the daily hydrogen load of 4-5kg. This required to set up control models for the hybrid wind hydrogen system. The researchers were able to identify major inputs and outputs of the hybrid system, identifying the various control strategies required to achieve the flow of energy from the various components. This means that the electrolyser and compressor are selected depending on the capacity to produce the required daily hydrogen load. The set up system is then simulated using Matlab software, first using hypothetical inputs of wind speeds and electrical loads and then validated using input data for the two towns in Uganda that include Kampala and Tororo to find out if it meets the required objectives. The input data for the validation area was got from RETScreen software for the wind speeds and then expounded using Weibull probability density function to obtain the 24 values using as this function is used in energy assessments since it conforms well to the observed long-term distribution of mean wind speeds for a range of sites.

2. System layout and interconnection

The system configuration is shown in Figure 1. Electrical current will flow from the wind turbine generators to the electrolyser, the load and grid at wind power peaks and from the grid to the electrolyser and the load at low wind speeds. The wind energy that is produced in excess of the electrolyser and load demand is sent to the grid. At low wind speeds or low cut in speeds the energy will flow from the grid to the electrolyser and load. The dimensioning of the grid connected system is based on a constant average hourly H_2 demand. The rationale for this is that transport and stationary activities run with fairly constant running patterns every day year around (Greiner et al. 2007)

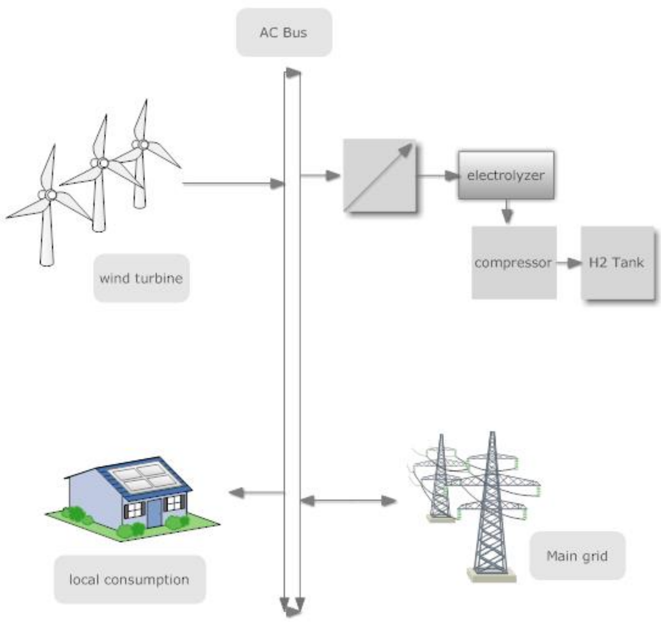

Figure 1: Layout of the system

3. System component models and specifications

3.1 The Wind Turbine model

In the wind turbine model, the average hourly wind speeds are evaluated and converted to wind turbine power. When the speed is between the cut in and rated speed of the wind turbine, the power generated by the wind turbine is given by (Nelson et al. 2006) as in equation 1. A Utility grade turbine with a size of 200kW is considered with a cut-in speed of 3.8 m/s and the cut-out speed of 25 m/s. The wind turbine will not generate useful power if the wind speed is below the cut-in speed. Mathematically, the power generated by the wind turbine is given as in equation 1.

$$P_{wind}(t) = \frac{1}{2}\rho A(Vt)^3 C_P Eff_{AD},$$

$$P_{wind}(t) = V < Vci\ ,$$
$$P_{wind}(t) = \frac{1}{2}\rho A(Vt)^3 C_p Eff_{AD},\ Vci < V < Vr\ ,$$
$$P_{wind}(t) = P_r\ ,\quad Vr < V < Vco\ ,$$
$$P_{wind}(t) = P_r,\quad V > Vco, \qquad (1)$$

Where P_r is the rated power, V_{ci}, V_{co} and V_r are the cut in, cut-out and rated speed of the wind turbine. Therefore the following parameters are constants; Cp = 0.59, A = 490.87 m^2, Eff_{AD} = 0.98 and ρ = 1.225 kg/m^2

3.2 The Electrolyser, Compressor and Hydrogen Storage

According to (Green et al. 2011) adding hydrogen electrolyser to energy system changes the capacity mix in generation by adding the viable capacity of these stations. The model used for the electrolyser and compressor is the combined electrolyser/compressor (Korpås & Greiner 2008). The relation between the Electrolyzer power and the mass flow rate of hydrogen, $\dot{m}_{h,ely}$ (kg/h) is given by equation (2);

$$P_{ely}(t) = SPC_e \dot{m}_{h,ely}(t) \qquad (2)$$

Where SPC_e (kWh/kg) is the specific power consumption of the Electrolyzer, taking into account rectifier losses, power required for water splitting, H_2 compression and auxiliary power (Korpås & Greiner 2008). The electrolyzer operation is limited by the restriction in equation (3).

$$P_{ely}^{min} \leq P_{ely}(t) \leq P_{ely}^{max}(t)\ or P_{ely}(t) = 0 \quad (3)$$

Where P_{ely}^{max} is the Electrolyzer capacity or rated capacity and P_{ely}^{min} is the power consumption at minimum H_2 production. The restriction in equation. (3) States that the Electrolyser is either be operated at $P_{ely}(t) \geq P_{ely}^{min}$ or switched off. Recently, depending on electrolyser manufacturer, these units have a minimum operating point ranging from 10% to 50% of nominal power (Elbaset 2011)

The H_2 storage balance is as in equation (4).

$$m_h(t) = m_h(t-1) + (\dot{m}_{h,ely}(t) - \dot{m}_{h,fill}(t))\Delta t (4)$$

Where m_h (kg) is the mass of stored H_2 and $\dot{m}_{h,fill}$ (kg/h) is the flow rate of H_2 to the storage. The amount of H_2 that can be stored and extracted is limited by the minimum and maximum allowable storage levels as in equation (5):

$$m_{ely}^{min} \leq m_h(t) \leq m_h^{max}(t) \qquad (5)$$

If there is not enough stored H_2 to cover the storage at time step t, there will be a deficit of H_2 represented by equation (6):

$$\dot{m}_{h,def}(t) = \dot{m}_{h,load}(t) - \dot{m}_{h,fill}(t) \quad (6)$$

Where $\dot{m}_{h,load}$ is the H_2 load and $\dot{m}_{h,def}$ is the amount of H_2 not supplied at that particular hour. In this assessment the minimum amount of hydrogen per day is 4 kg and the maximum required hydrogen per day is 5 kg. Therefore, SPC_{ely} (kWh/kg) is taken as a summation of the individual power consumptions of the electrolyser and compressor. The minimum electrolyser power is found by equation (8).

$$P_{ely,min} = SPC_e x d_{H2} (7)$$

Where $P_{ely,\ min}$ (kW) is the minimum electrolyser power, SPCe (kWh/kg) is the specific power consumption of the electrolyser and dH_2 (kg/h) is the average hourly H_2 demand. The same approach for the electrolyser is used when dimensioning the compressor as in equation (9) (Greiner et al. 2007).

$$P_{C,min} = SPC_C x\, d_{H2} \quad (8)$$

Where $P_{c,min}$ (kW) is the minimum electrolyser power, SPCC (kWh/kg) is the specific power consumption of the electrolyser and dH_2 (kg/h) is the average hourly H_2 demand.

The maximum daily Hydrogen demand is 5.0 kg/day. Considering a 24 hour day at the site this makes an hourly demand of hydrogen of 0.208 kg/hr.

According to (Levene et al. 2006), 39.40 kwh/kg is required to produce 1 kg of H_2 at 25 ^{O}C. Therefore efficiencies of electrolysis systems can be calculated dividing the energy per kg used in the system into 39.40 kwh/kg of H_2.Thus the energy required for the electrolyser is calculated as 8.20 kW. For the compressors the specific power consumption is 2.2 kwh/kg of H_2. Thus the energy required for each of the compressor is 0.46 kW. The power converter is dimensioned to deliver the maximum amount of power required by the actual electrolyser and compressor when in 100% operation as in equation (9) (Greiner et al. 2007)

$$P_{PC,min} = \frac{P_{ELY}+P_C}{\eta_{PC}} \quad (9)$$

This implies that the maximum amount of power required can be (8.20+ 0.46) = 8.66kW, and the minimum is taken as 30% of the maximum power, or 0.2598kW, this is for the both the required maximum and minimum required mass of hydrogen per day.

3.3 The hydrogen tank

Since the amount of hydrogen being produced per hour is known, the net hydrogen generation is found by subtracting the hydrogen load from the hydrogen produced (Geer et al. 2005). The net hydrogen produced is the change in the hydrogen storage. Here storage is assumed to be lossless. The system is to be operating in constant power mode. This makes the hydrogen produced to always be equal to the hydrogen load and therefore the net hydrogen production is always zero.

4. The control strategy for the system

The operational control strategies are based on the routes of energy flow per hour within the system, the objectives of the control strategy are to;

1. Maximize the utilization of available wind energy;
2. Minimising the amount of H_2 not produced to meet the daily limit and;
3. Overcome the inconvenience of the continuous start/stop of the electrolyser by ensuring the operation of the electrolyser at its nominal power or minimum required power over long periods of time by maintaining power supply from the grid to meet the nominal requirement of the electrolyser, while maintaining the constant power to the load demand.

Objective 1 is handled by adjusting the electrolyser power in periods of high wind power output so that excess power can be sent to the load and the grid. The daily energy that reaches the load and the grid varies according to the wind speed and limited by restriction in equation (10)

$$P_{ely}^{min} \leq P_{ely}(t) \leq P_{ely}^{max}(t) \quad or\ P_{ely}(t) = 0 \ (10)$$

Objective 2 is handled by adjusting H_2 production supply security limit m_h^{lim}, for the stored H_2 in order to maximise the amount of H_2 produced up to the required limit. However, in practice the power export may be limited by voltage quality or voltage stability (Linh 2009). Thus it varies with the power flow situation. However, the modelling framework is not limited to constant power export limit (Korpås & Greiner 2008). According *to* (Korpås 2004), it is shown how P_{ely}^{req} and P_{wg}^{lim} are determined where steady state voltage rise is the limiting factor for the quantity of wind power that can be transferred to the main grid.

The hydrogen storage capacity is minimized by the maximum hydrogen production during the day and is set by equation (11);

$$M_{H2,max} = 24\frac{P_{ely,max}}{SPC_{ely}} \quad (11)$$

It should be noted that the system operates for 24 hours in a day however it should be designed to work for 20 hours where 4 hours are used for maintenance.

Objective 3 is handled by adjusting operation of the electrolyser as follows;

1. If the excess power is greater than the power required for the load, the rest of the power is directed to the electrical grid;
2. If the hydrogen supply security is reached, all the power from the wind turbine is directed to the load and any remaining to the electric grid;
3. If the electrolyser is not covered by the wind turbine production, the power needed to cover the electrolyser demand and the load is supplied by the grid as P_{grid}.

A MATLAB program was developed to simulate the wind energy-hydrogen and grid system and to test the proposed control strategy to find out if it meets the required objectives. This program has been tested using hypothetical inputs of wind speeds and electrical loads and then validated using two towns in Uganda that include Kampala (0.3 ^{0}N , 32.6 E, elevation 1,140m) and Tororo (0.7 ^{0}N , 34.2 E, elevation 1,171m). The assessment in the hypothetical area included balancing of the energy for over 12 months in a year and the power utilisation of the integrated system components given. Simulated input wind speed data for the hypothetical area is shown in Figure 3 for the 24 hours for selected months of the year.

In order to validate the model, two selected areas in Uganda were identified these include Kampala city and Tororo Town. The reason for this selection was that both areas are grid connected and have a well-developed transport system, and in the future there are hopes that hydrogen vehicles will be used in such areas. These wind speeds were got using RETScreen software version 4.1, the average data for wind speeds for each month and other parameters for Kampala and Tororo were obtained as seen in Table 1

Wind speed distribution for Kampala City and Tororo Town are calculated in RETScreen as a Weibull probability density function. The 24 values representing each hour of the day of the month are calculated. This distribution is used in wind energy assessments, as it conforms well to the observed long-term distribution of mean wind speeds for a range of sites. The Weibull probability density function expresses the probability p (x) to have a wind speed x during the year.

Figure 2 shows a flow chart of the control strategy:

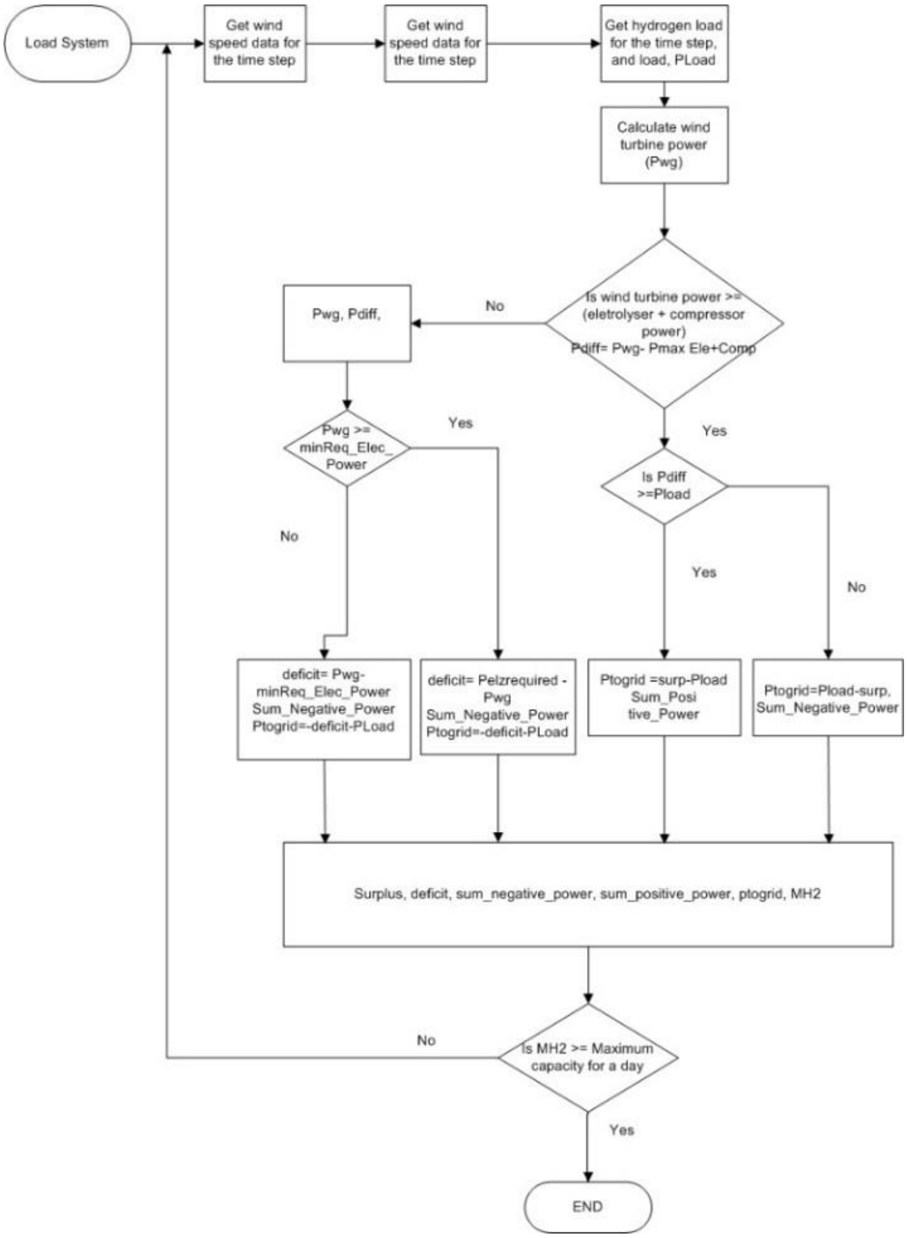

Figure 2: Summary of the operational control strategies

Table 1: wind speeds for Kampala and Tororo as seen in Retscreen.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Kampala	3.8	4.0	4.1	4.1	4.0	4.0	3.9	3.7	4.0	3.9	3.7	3.5
Tororo	3.2	3.3	3.1	3.1	3.3	3.4	3.4	3.4	3.3	3.1	3.1	3.0

Source: *NASA (Retscreen version 4.1)*

5. Simulation results and discussion

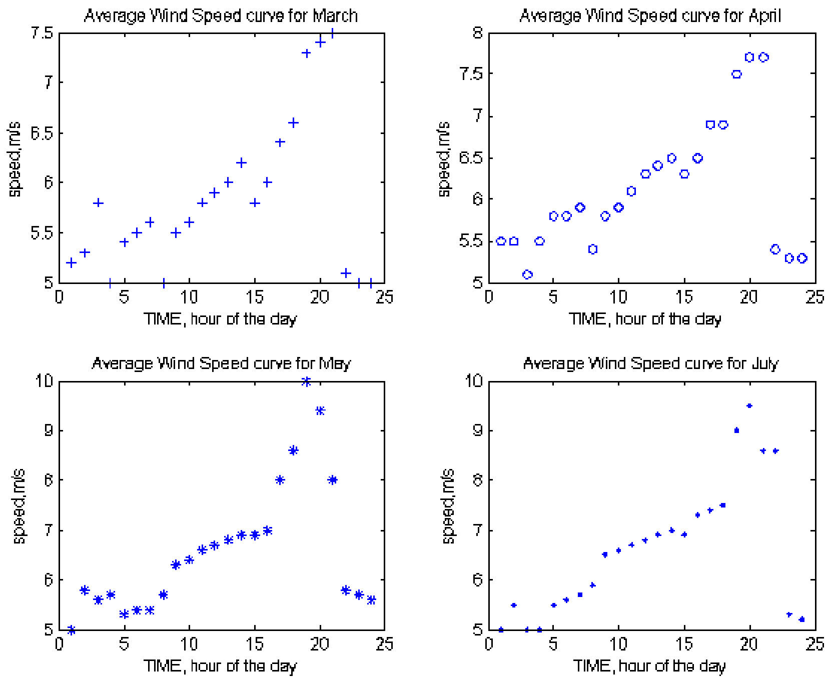

Figure 3: Hypothetical hourly wind speeds for March, April, May, July and August

The wind power generated for the site is given in Figure 4.

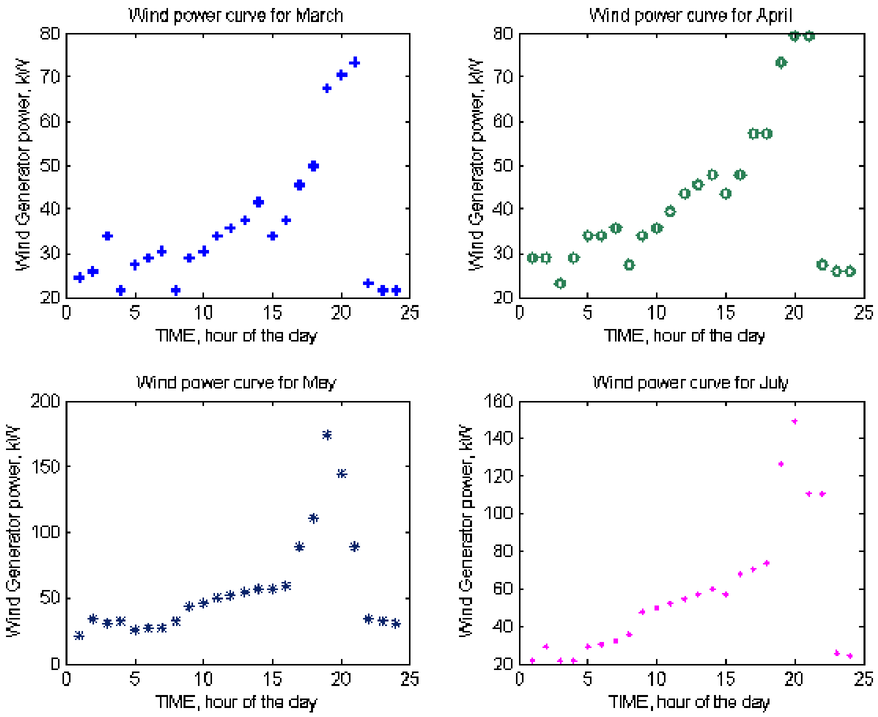

Figure 4: The wind power curve from the hypothetical wind speeds for March, April, May, July and August

The characteristics of the wind generator are that the generated power does not exceed the designed turbine power which is 200kW as can be seen in May. Table 2 shows the annual energy produced by the wind-driven generators, energy demand, electrolyser energy, amount of hydrogen production, and surplus and deficit energy for the hypothetical site and for Kampala city and Tororo Town. Negative sign means deficiency and positive is surplus.

For the hypothetical site, the total energy produced by wind generators on an average day of a month is equal 1068.59kWh. The amount of energy supplied to the electrolyser on an average day of a month is 204.81 kWh, and the average load energy required is 52.25 kWh. Therefore the average daily hydrogen load as can be seen with the various months of the year is between 4 and 5 kg. This brings a total hydrogen load of 4.92 kg, which is between 4 and 5kg as required by constraints of the study.

The average monthly energy surplus to the electrical grid is equal to 814.27kwh and the average energy taken from the grid is equal to 2.39 kWh. This shows that the system is sustainable since the deficit is almost 0% thus production of electrolytic hydrogen with a non-polluting source is possible. Here the energy surplus is 40% and the deficit energy is 0%. This implies that energy can be sold to the grid at a time when there is surplus energy –a typical smart grid scenario.

The Figure 5 shows the wind power generated, electric load demand, and electrolysis plant load and grid power on hourly basis. There is surplus in March, July, and part of August which shows that the system is self-reliant. This indicates that electrolytic hydrogen can be got using a clean source of energy.

Table 2 shows the results for the simulation of the model using Kampala city and Tororo town data, indicating the wind energy produced, the electrolyzer energy use, the load energy use and hydrogen produced. The same figure like that in figure 5 can be generated out of that information from the Weibull distribution.

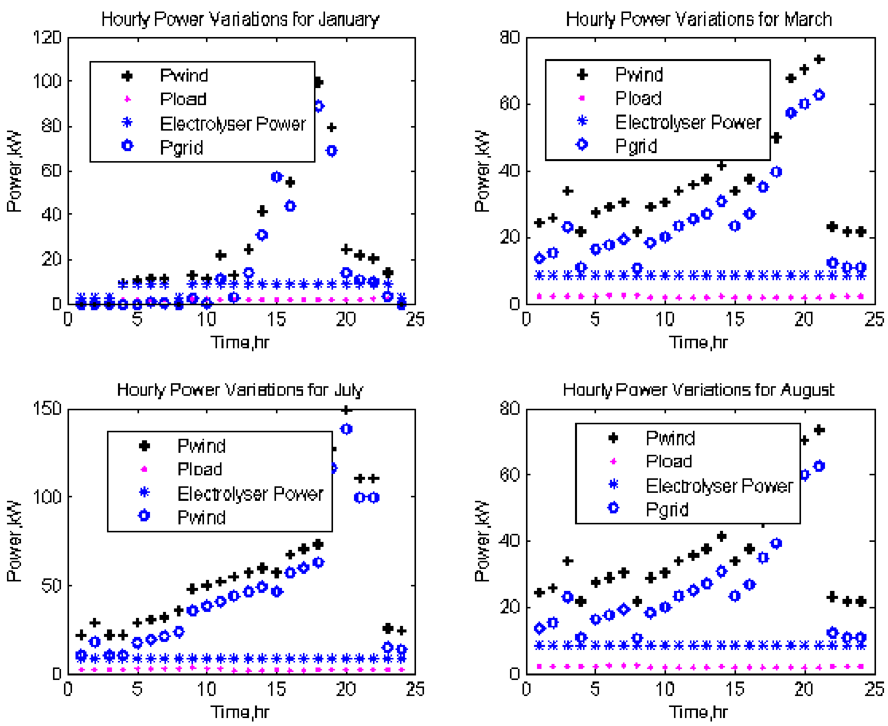

Figure 5: Hourly variations in power for January, March, July and August based on hypothetical data.

Table 2: The Energy flow for each average day of the month in a typical year for a hypothetical site

Annual Power parameters/ site	Wind Energy, kWh	Electrolyzer energy demand, kWh	Load Energy, kWh	Hydrogen Production, kg	Energy to /from Grid	
					Surplus, kWh	Deficit, kWh,
Hypothetical	12823.178	2457.708	627.030	59.031	9771.297	-28.697
Kampala	9279.73	2491.20	627.03	59.89	8126.00	-1957.25
Tororo	7702.68	2491.20	627.03	59.89	6683.29	-2094.68

6.0 Conclusion

The supervisory control strategy for a wind hydrogen system connected to an electric grid showed feasibility. The system model has been validated using wind speeds for Kampala City and Tororo Town in Uganda as in Table 1 and Kampala with surplus energy sent to the grid than Tororo is best place to have such a model operational as in Table 2. Technically, therefore, a good wind resource is a critical factor to the success of a commercial wind energy project.

The smart grid application of the model is feasible in many aspects; the model monitors and manages in real time the amount of hydrogen in storage and then coordinates with the wind generator and the electric grid to act accordingly to meet the hydrogen demand of the day. At the same time, the model can monitor the needs of the electric loads to supply power in real time at the time of use, these loads must not exceed the power exported to the grid.

The results obtained herein, confirmed that with such dimensioned components, it's possible to produce 4-5kg of hydrogen in an area with wind speeds above 4m/s measured at a height of 10 m from a non-polluting source and also that such an integrated system has the potential to support remote investments in the production of electrolytic hydrogen.

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