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Modeling and Control of a Wind Farm and Electrolyzer System Connected to an Electrical Gird

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A. Elbaset and O. Abdalla

Abstract**—**This paper presents modeling and control analysis of a combined Wind-H2 system connected to an electrical grid and supplying a local electric load. The system consists of a wind farm for electricity generation and an electrolyzer to produce hydrogen for a filling station. A computer program has been developed in MATLAB for simulating the operation and control of the integrated system. Energy balances and hydrogen flow balances are calculated for each time step based on a system model and the specified control strategy. The input of this program are hourly wind speed, characteristics of wind turbine generators, hourly load demand, maximum grid capacity, rated power of electrolyzer, and minimum operating power of electrolyzer. The hydrogen produced will be supplied to a filling station where local vehicles can be filled. Hydrogen production is evaluated and the number of cars served per year is estimated.

Keywords**—** Electrolyzer, Hydrogen production, Renewable energy, Wind turbine.

1. Introduction

In recent years, there has been an increasing interest in system analysis of integrated renewable/Hydrogen systems. Hydrogen production from wind energy is more challenging than from solar since the power fluctuations are faster and more irregular.

Prototype wind- hydrogen (Wind-H_2) plant has been constructed at the ENEA Casaccia Research Centre in Italy. It is a part of an EC-funded project [1], [2]. The plant consists of a wind turbine (5.2 kW), a storage battery (330 Ah), an electrolyzer (2.25 kW) and a connection to the power grid to supply electric energy to auxiliary equipment. The operation of the plant was satisfactory with no major stability problems or general operational problems for the electrolyzer [3]. A similar wind-hydrogen plant has been constructed at the University of Applied Sciences in Stralsund, Germany. This larger plant comprises a 100 kW windmill, a 20 kW alkaline electrolyzer and a 200 Nm^3 pressure tank [4]. Several attractive projects were initiated during the nineties of the last century. These include the German-Saudi HYSOLAR Program, the Neunburg vorm Wald solar hydrogen demonstration project and the Phoebus-Jülich demonstration plant project [3], [5].

In Japan, electrical power demand and use of electric vehicles have increased. This leads to the development of a new supply strategy both in the short-term and long-term. Wind energy is one of the most interesting alternative renewable energy sources. Wind farms interconnected with electrical grids are installed to provide clean energy to modern societies.

Extensive progress in the field of renewable hydrogen energy has been achieved in Japan [6]-[8]. The Japanese initiative, WE-NET (World Energy Network) [7], was started in 1993. The main objective are: (i) to introduce and activate a world-wide network for the development of globally available renewable resources of energy such as water, solar, wind, etc. (ii) transportation of the reusable energy to places where it is needed, and (iii) utilization of energy in various applications. The network contributes in solving worldwide problems in energy and environmental fields through the production of clean usable energy, thus reducing the impact of greenhouse gases [7].

This paper focuses on modeling, control and simulation of a Wind-H_2 plant. A wind farm provides electric energy to an electrolyzer and a local load. Hydrogen produced from water is used as a fuel for vehicles. The system is connected to the power grid for exchanging electricity. A model of the Wind-H_2 system is developed to perform simulation studies using MATLAB. Section II presents a brief description of the system components. Section III describes the energy flow control strategy and computer model. Section IV describes a case study and presents simulation results. Section V summarizes the main conclusions.

2. Energy System Description

The Wind-H_2 system to be evaluated is shown in Fig. 1. It consists of a wind power plant, an electrolysis plant, an electrical grid and a local electrical load. The Wind–H_2 system is connected to a power grid via a transmission line with limited capacity and can exchange power at any time with the grid. H_2 production is supplied to a filling station where local vehicles can be served.

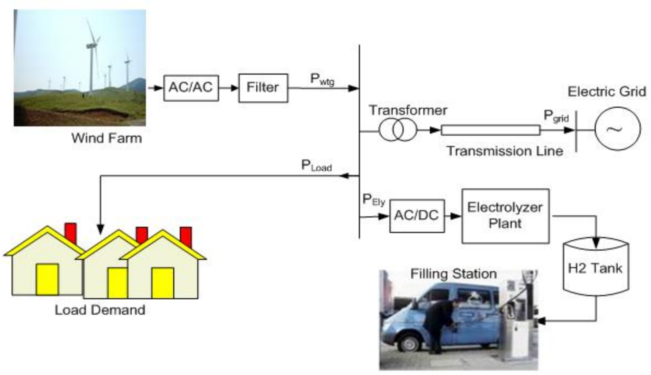

Fig. 1 Wind-H_2 System connected to electrical grid

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The hydrogen is produced by the electrolyzer when the electricity supplied by the wind power plant is higher than load demand or if the hydrogen storage drops below a specified supply security limit. Excess wind power is exported to the grid.

3. Modeling and Control Strategy

3.1 Modeling Energy Flow Control Strategy

The system energy balance is checked at each time interval of the simulation time. The wind speed data is fed to the computer control program to calculate the amount of energy that can be generated by the wind farm generators. The amount of wind-generated electricity is compared with the load demand to determine the amount of energy flows to the electrolysis plant and the electric grid. The objectives of the control strategy are to:

1. Maximize the utilization of available wind energy.
2. Minimize the amount of H_2 not supplied.
3. Overcome the inconvenience of the continuous start/stop of the electrolyzer by ensuring the limited operation of the electrolyzer at its nominal power or minimum required power over long periods of time, whilst maintaining constant power supply to the load demand.

The first aim is handled by adjusting the electrolyzer power periodically with high and low wind power output. The daily energy that reaches the electrolyzer varies according to the wind farm or electric gird in the case of low wind speed. For each time interval, it is possible to find the required electrolyzer operation power P_{Ely}^{Req}. Electrolyzer operation power is limited by the following restrictions:

$$P_{Ely}^{min} \leq P_{Ely}^{Req}(t) \leq P_{Ely}^{max} \quad (1)$$

Where; P_{Ely}^{max} , P_{Ely}^{min} are the rated power of electrolyzer and minimum power consumption at minimum H_2 production. With present technology, electrolyzers have a minimum operating point ranging from 10% to 50% of nominal power depending on the manufacturer.

The second aim is handled by adjusting H_2 supply security limit, V_H^{lim}, for the stored H_2 in order to minimize the amount of H_2 not supplied. If the hydrogen storage drops below a specified supply security limit, V_H^{lim} the electrolyzer is operated at full H_2 production by drawing power from the external grid. This ensures that the H_2 storage will not be empty during longer periods with low wind speed. The relation between volumetric hydrogen production rate, Nm^3/hr and electrolyzer power is given by the following equation:

$$\dot{V}_{H2}(t) = P_{Ely}(t)/\eta_e \quad (2)$$

η_e is the specific power consumption of the electrolyzer, including rectifier losses, power required for water splitting and consumption of power for hydrogen compression, kWh/Nm^3.

The hydrogen storage balance is expressed as

$$V_{H2}(t+1) = V_{H2}(t) + P_{Ely}(t)/\eta_e.\Delta t - \dot{V}_{H2l}(t).\Delta t \quad (3)$$

Where;

$\dot{V}_{H2l}(t)$: The hydrogen load, Nm^3/hr.

The amount of H_2 that can be stored and extracted is limited by the minimum and maximum allowable storage levels and is given by the following Equation:-

$$V_{H2}^{min} \leq \dot{V}_{H2l}(t) \leq V_{H2}^{max} \quad (4)$$

Where;

V_{H2}^{max} is the maximum storage capacity, Nm^3,

V_{H2}^{min} is the minimum storage capacity, Nm^3.

The hydrogen storage capacity is minimized by maximum hydrogen production during the day and is setting by:

$$V_{H2}^{max} = 24\frac{P_{Ely}^{max}}{\eta_e} \quad (5)$$

The third aim is handled by adjusting operation of the electrolyzer as follows:

1. If the excess power is greater than the power required by the electrolyzer, the rest of the power is directed to electrical grid.
2. If the excess power is lower than the power required for the electrolyzer, the rest of the power needed to operate the electrolyzer is supplied by electrical grid.
3. If there is no power excess from the wind turbine, or supply security limit reached all the energy needed to operate the electrolyzer is supplied by electrical grid.
4. If the load demand is not covered by the wind turbine production, the rest of the power needed to cover the load demand is supplied by the grid.

3.2 Computer Control Algorithm

A computer program has been written in MATLAB to simulate operation and control of the interconnecting wind-farm generators, electrolyzer, and electrical grid. The time interval size for updating information in the computer program is chosen to be one hour. Energy balances and hydrogen flow balances are calculated for each time step based on the system model equations and the specified control strategy.

The input data of the proposed program are:

1. Hourly wind speed, m/s: The hourly wind speed for the selected site is the first data required for operation of the Wind-H_2 system.
2. Characteristics of WTG's.
3. Hourly load demand in kW: It is assumed here that the load demand varies monthly. This means that each month has daily load curve different from other months. Therefore, there are twelve daily load curves through the year. Fig. 2 shows the hourly load demand.
4. Maximum grid capacity in kW.
5. Rated Power of Electrolyzer in kW.
6. Minimum operating power of electrolyzer, P_{Ely}^{min} in kW.

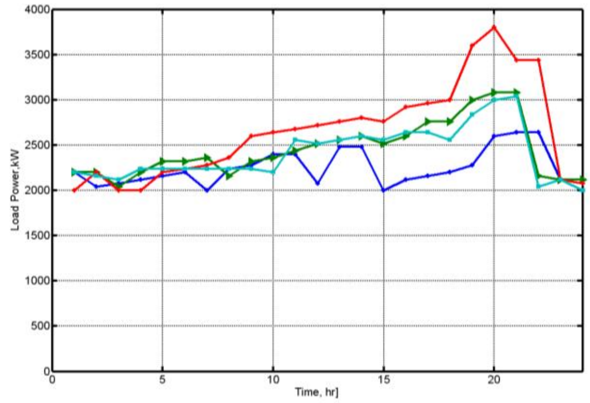

Fig. 2 Average Daily Load curve for January, April, July and October

The following steps show the control strategy in the computer model.

Calculate $P_{wtg}(t)$ according to Equation (2) and compute:

$P_{diff}(t) = P_{wtg}(t) - P_{Load}(t);$

if $P_{diff}(t) > 0$

if $P_{diff}(t) \geq P_{Ely}^{max}$

$P_{Ely}^{Req}(t) = P_{Ely}^{max}$;

$P_{grid}(t) = P_{diff}(t) - P_{Ely}^{Req}(t)$

if $\dot{V}_{H2}(t) < V_{H2}^{max}$

$$\dot{V}_{H2}(t) = \frac{P_{Ely}^{Req}(t)}{\eta_e}$$

$$V_{H2}(t+1) = V_{H2}(t) + \frac{P_{Ely}^{Req}(t)}{\eta_e} * \Delta t - \dot{V}_{H2l}(t) * \Delta t$$

Else

$\dot{V}_{H2}(t) = 0;$

$$V_{H2}(t+1) = V_{H2}(t) + \frac{P_{Ely}^{Req}(t)}{\eta_e} * \Delta t - \dot{V}_{H2l}(t) * \Delta t$$

$P_{grid}(t) = P_{diff}(t)$

end

else

$P_{grid}(t) = 0;$

$P_{Ely}^{Req}(t) = P_{diff}(t);$

if $P_{Ely}^{Req}(t) < P_{Ely}^{min}$

$P_{Ely}^{Req}(t) = P_{Ely}^{min}$;

$P_{grid}(t) = P_{diff}(t) - P_{Ely}^{min}$;

else

$P_{Ely}^{Req}(t) = P_{diff}(t);$

$P_{grid}(t) = 0;$

end

if $\dot{V}_{H2}(t) < V_{H2}^{max}$

$$\dot{V}_{H2}(t) = \frac{P_{Ely}^{Req}(t)}{\eta_e}$$

$$V_{H2}(t+1) = V_{H2}(t) + \frac{P_{Ely}^{Req}(t)}{\eta_e} * \Delta t - \dot{V}_{H2l}(t) * \Delta t$$

else

$\dot{V}_{H2}(t) = 0;$

$$V_{H2}(t+1) = V_{H2}(t) + \frac{P_{Ely}^{Req}(t)}{\eta_e} * \Delta t - \dot{V}_{H2l}(t) * \Delta t$$

$P_{grid}(t) = P_{diff}(t)$

end

end

else

% Deficit Power will be supplied from grid to load demand and Electrolyzer

$\mathrm{deficit}(t) = P_{diff}(t) - P_{Ely}^{Req}(t)$

if $\dot{V}_{H2}(t) < V_{H2}^{max}$

$P_{Ely}^{Req}(t) = -P_{Ely}^{max}$;

$$\dot{V}_{H2}(t) = \frac{P_{Ely}^{Req}(t)}{\eta_e}$$

$$V_{H2}(t+1) = V_{H2}(t) + \frac{P_{Ely}^{Req}(t)}{\eta_e} * \Delta t - \dot{V}_{H2l}(t) * \Delta t$$

else

$P_{Ely}^{Req}(t) = 0$

$$\dot{V}_{H2}(t) = \frac{P_{Ely}^{Req}(t)}{\eta_e}$$

$$V_{H2}(t+1) = V_{H2}(t) + \frac{P_{Ely}^{Req}(t)}{\eta_e} * \Delta t - \dot{V}_{H2l}(t) * \Delta t$$

end

end

4. System Simulation Results

4.1 Application Example

An application example is selected to study the operation and control of the integrated Wind-H2 system. The simulated system consists of a wind farm containing ten turbines of 1750 kW each, a 2000 kW electrolyzer. The parameters of the application example are listed in the Appendix. Calculations are performed by using the power curve of a typical wind turbine. The local grid voltage is 11 kV.

5.1 Simulation results

A computer program has been developed to simulate the energy system and to test the proposed control strategy. The output of the computer program is the power, energy supplied to electrolysis plant and energy delivered to or from the electrical grid. The studies include the balance of the energy over 12 months and the power of the integrated system in addition to each component. The hydrogen produced, stored and consumed is obtained. Table I shows energy produced by the wind-driven generators, energy demand, electrolysis energy, amount of hydrogen production, and surplus and deficit energy for each month. Negative sign means deficiency and positive is surplus. The energy produced by the wind generators is used to supply the load demand during every hour of the year and to produce hydrogen via the electrolysis plant. From this table it can be seen that, the total energy produced by wind generators in a typical year is equal to 62294 MWh, while the total energy required to electrical load demand equals 20971 MWh. On the other hand, the amount of energy supplied to the electrolyzer in a typical year is equal to 13909 MWh. Therefore, the annual hydrogen production is 1939907 Nm^3, which equal to 174358 kg. The number of cars which can be served is approximately 872 cars per year. This number of cars is determined by considering a car requires approximately 200 kg of hydrogen per year. This is based on the assumption that a car travels about 19,200 km per year, and that a vehicle will travel 96 km per kg of hydrogen [9]. In April, for example, the maximum amount of H_2 produced equals about 188355 Nm^3.

The annual energy surplus to the electrical grid is equal to 37986.45 MWh and the annual energy taken from the electrical grid is equal to 10572.54 MWh. The energy sold annually to the electrical grid will be the difference between surplus and deficit and is equal to 27413.9 MWh. Form the results listed in Table I, it can be seen that the operation and control of the Wind-H_2 system provides a good matching between wind energy system, load demand and hydrogen production. Fig. 3 shows the annual energy balance of the system. Fig. 4 shows the percentage of energy required for load demand, electrolysis plant and surplus, deficit energy with respect to energy produced from wind farm generators. From the figure it can be seen that the energy surplus is 61% and deficit energy is 17 % so the energy sold to the grid is 44% of energy produced from wind and the energy required to supply the load and electrolysis plant is 46 % of the energy produced from wind. The energy required for electrolysis plant consists of energy required for electrolyzer its purification and compression at 250 bar, along with auxiliary consumption. But besides these consumptions, we must also take into account the losses associated with adapting the electricity: self-consumption and losses due to the Joule effect in the various components.

Table II shows the monthly energy consumption and losses of each component in the electrolysis plant.

Fig. 5 shows the annual energy consumption of each of the components in the system. From this figure it can be seen that the electrolyzer requires over 63% of the energy required to the electrolysis plant and the energy required for purification and compression at 250 bar is 12% of the energy required to the electrolysis plant. Finally energy required for air compressor is 3% of the energy required to the electrolysis plant. Also, the imperfect performances of the wiring, inverter, transformer and controller are 2%, 1%, 7%, and 12% respectively.

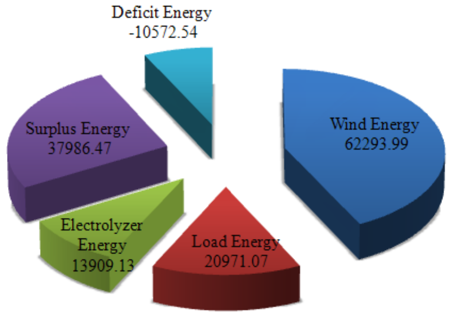

Fig. 3 Anaual Energy balance of the system

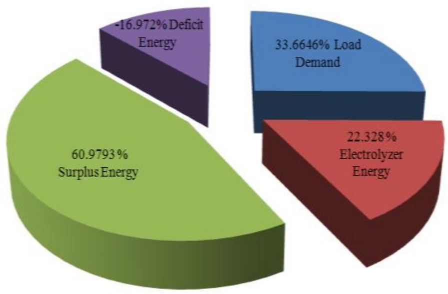

Fig. 4 Percentage of energy required

Table I
Energy flow Each Month

Month	Wind Energy, MWh	Load Energy, MWh	Electrolyzer energy demand, MWh	Hydrogen Production Nm^3	Energy to/from Gird	
					Surplus MWh	Deficit MWh
January	5301.29	1576.19	1112.08	155102.3	3230.25	-617.22
February	6788.55	1590.79	1079.26	150524.33	4195.98	-77.46
March	6534.99	1640.07	997.9	139176.59	3990.67	-93.63
April	6916.36	1722.8	1350.5	188354.75	4952.14	-1109.07
May	2265.23	1865.15	1345.03	187590.89	1138.19	-2083.13
June	6564.85	1900.43	938.64	130912.56	3826.42	-100.63
July	5681.41	1872.45	1320.08	184112.27	3701.4	-1212.52
August	5642.57	1805.53	1327.62	185162.51	3798.13	-1288.69
September	5232.33	1703.33	1030.17	143678.35	3084.25	-585.42
October	2767.13	1694.21	1089.03	151886.53	1172.26	-1188.36
November	3714.33	1701.51	1154.47	161013.74	1927.81	-1069.44
December	4884.95	1898.61	1164.35	162392.15	2968.97	-1146.97
Yearly Energy	62293.99	20971.07	13909.13	1939906.97	37986.47	-10572.54

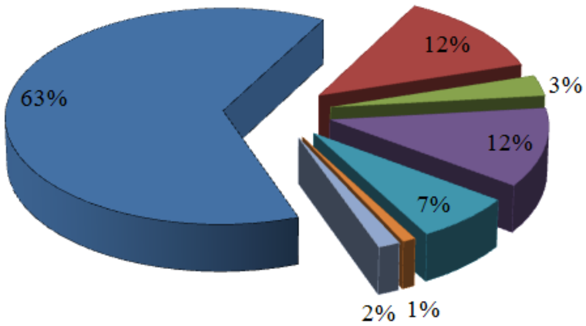

Fig. 5 Percentage of energy consumed by each component in the system

The following figures presented to check the proposed control strategy described in Section III. We have included aspects such as the electrolyzer's range of working power, the power fluctuations of the wind generators as a result of wind speed.

Figs. 6 and 7 show wind power generated, load demand, electrolysis plant load, and grid power on an hourly basis during January and April, respectively. The system imports power from the grid mainly during low wind speed or when the minimum hydrogen production is reached. Subsequently, the system exports power when the generated power from wind is greater than the load power and electrolysis plant power.

Fig. 8 shows daily Hydrogen production during January, April, July and October. Fig. 9 shows hydrogen produced from electrolysis plant for every month.

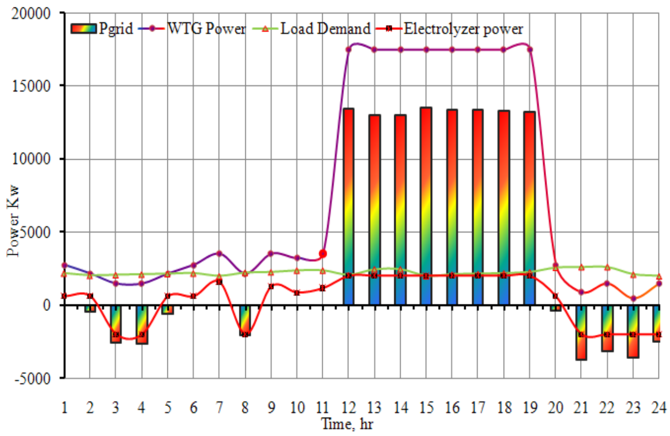

Fig. 6 Hourly variations in wind power, local load, electrolyzer power, and gird power in January

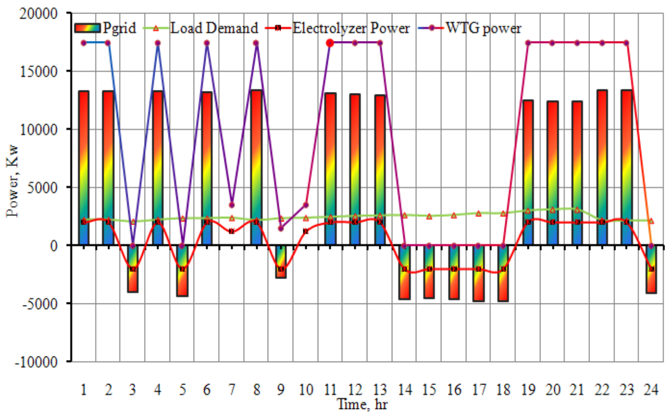

Fig. 7 Hourly variations in wind power, local load, electrolyzer power, and gird power for April

Table II
Monthly energy consumption and losses, in MWh

Month	Electrolyzer Energy	Purific.+ Compr.250 bar	Air compressor	Controller	Transformer Loss	Inverter loss	Wiring loss
January	704.72	137.51	34.38	130.63	77.35	10.31	17.19
February	683.92	133.45	33.36	126.78	75.06	10.01	16.68
March	632.36	123.39	30.85	117.22	69.41	9.25	15.42
April	855.8	166.99	41.75	158.64	93.93	12.52	20.87
May	852.33	166.31	41.58	157.99	93.55	12.47	20.79
June	594.81	116.06	29.02	110.26	65.28	8.7	14.51
July	836.53	163.23	40.81	155.06	91.81	12.24	20.4
August	841.3	164.16	41.04	155.95	92.34	12.31	20.52
September	652.81	127.38	31.84	121.01	71.65	9.55	15.92
October	690.11	134.66	33.66	127.92	75.74	10.1	16.83
November	731.58	142.75	35.69	135.61	80.3	10.71	17.84
December	737.84	143.97	35.99	136.77	80.98	10.8	18
Yearly Energy	8814.11	1719.86	429.97	1633.84	967.4	128.97	214.97

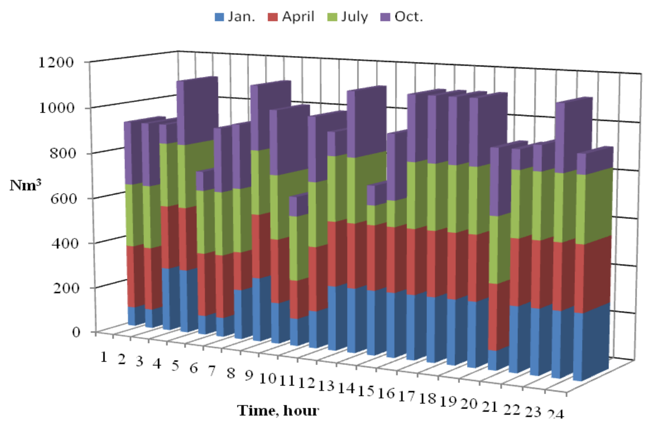

Fig. 8 Daily Hydrogen production during January, April, July and October

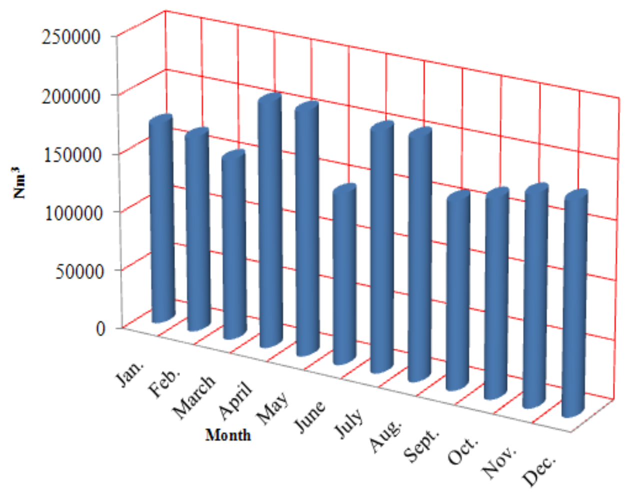

Fig. 9 Hydrogen production for each month.

6.CONCLUSIONS

The simulation results have shown the possibility of successful operation of a hybrid renewable energy system comprising wind-driven electrical generators connected to a power grid and supplying a local load and a hydrogen production plant. The hydrogen can be employed as a clean fuel for vehicles. A control strategy has been developed to coordinate the operation of the system components in an integrated and most useful manner. The proposed control strategy can be easily adapted and applied to similar renewable energy systems which contain multiple components working together. A computer program has been developed using MATLAB for simulating the operation and control of the wind farm and electrolyzer system. The program can readily be used to calculate the purchased/sold energy to/from the electrical grid, quantities of hydrogen production and the number of cars that can be filled from the available hydrogen.

The information presented in the paper can help designers to perform necessary preliminary studies before investing and connecting Wind-H_2 system to the electrical grid.

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APPENDIX: Parameter values for the case study

Average load, $\bar{P}_{Load}$ kW	2481.11
Maximum load, P_{Load}^{max}, kW	4000
Minimum load, P_{Load}^{min}, , kW	2000
Average yearly energy demand, MWh	20971.07
Characteristics of the WTG's Plant	
Rated power, $P_{wtg,max}$	1750 kW
Model	Vestas, V66-1.75
No. of WTG's needed	10
Nominal Power	1750 kW
Rated wind speed, m/sec	16
Cut-in wind speed, m/sec.	4
Cut-off wind speed, m/sec	25
Rotor diameter, m	66
Hub height, m	60
Average wind speed, $\bar{V}$, m/s	11.94
Characteristics of the Electrolyzer Plant [10]	
Model	Norsk Atmospheric
Electrolyzer Rated Power, P_{Ely}^{max}, kW	2000
Minimum Electrolyzer Power, P_{Ely}^{min}, kW	600
Hydrogen Production Rate , Nm^3	300 Minimum
	485 maximum
Hydrogen product pressure	2.068 kPa
SPC of Electrolyzer, kWh/Nm^3 H_2	4.8
SPC of Purific.+ Compr., kWh/Nm^3 H_2	0.8
SPC of Air compressor, kWh/Nm^3 H_2	0.2
SPC of Controller, kWh/Nm^3 H_2	0.76
SPC of Transformer, kWh/Nm^3 H_2	0.45
SPC of Inverter, kWh/Nm^3 H_2	0.06
SPC of Wiring, kWh/Nm^3 H_2	0.1
Characteristic of Electrical Gird	
Grid capacity, P_g^{max}, kVA	14000.00
Nominal Voltage	11 kV