Using Wind Energy and Fuel Cells to Construct an Autonomous Energy System

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Abstract: This research presents an assessment of using wind energy in addition to fuel cells instead of diesel generators in autonomous power system. A small community in Sinai (Abu Geida) is electrified for a period of 8 hours per day, in the context of which an autonomous power system based on a 48 kW diesel generator is installed. Simulation results based on wind energy plus fuel cells system has been developed for Abu Geida autonomous power system. The simulation and optimization of the case study have been performed by using the HOMER software tool.
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Key words: Wind Energy, Fuel Cells, Autonomous Energy System

1. Introduction

Autonomous power systems are used by many communities around the world that have no access to grid electricity. But whereas most of these autonomous systems are still based on fossil fuel power production, the use of renewable energy within these systems is growing as a consequence of rising fuel prices and environmental concerns. The integration of wind energy system based on a long-term seasonal storage of hydrogen is considered as a promising solution to overcome the limitations associated with the intermittency of renewable sources.

2. Wind Energy

Wind energy has been used for many centuries. First use of this kind of energy was to propel sailboats, 5,500 years ago [1]. In antiquity wind energy was converted to mechanical power in order to be used in irrigation and windmills.

In the last decades another conversion was pointed out: wind energy to electricity conversion. This idea appeared on the background issues relating to green energies [2].

Renewable energy sources such as photovoltaic cells, wind turbines and fuel cells have been found to be promising energy sources toward building a sustainable and environment friendly energy economy in the next decade [3].

The environment pollution and rapid depletion of fossil fuel resources on a world-wide is another motive to find veritable alternative energy resources [4].

A drawback, common to wind options, is its unpredictable nature and dependence on weather climatic changes and the variations of wind energy may not match with the time distribution of demand. In spite of this drawback, the wind electricity market is a fast growing one. The worldwide installed wind power capacity was about 120 Giga-watt at the end of 2008. It has grown with about 27 percent comparing to the end of 2007. Already today wind provides more than 1.5 % of the global electricity consumption and the wind industry employs half a million people [5].

The power that can be produced by a wind turbine is given by the following equation [6]:

$$P = \frac{1}{2} \rho A C_p v_w^3 \qquad (1)$$

where:
ρ is the air density (kg/m^3)
A is the rotor swept area (m^2)
C_p is the aerodynamic efficiency factor. It is a function of the rotor blades design and angle as well as the relative speed of the rotor and wind (known as the tip speed ratio)
v_w is the effective wind speed (m/s)

3. Hydrogen Energy Technology

3.1 Hydrogen Production (Water Electrolysis)

Hydrogen can be produced from water or steam electrolysis using simple technology. There are two types of water electrolyzers today, the ones with an alkaline electrolyte and the ones with a polymer electrolyte membrane (PEM) [7]. The conventional electrolytic methods are known as alkaline water electrolysis, which has been mature technology for decades and its efficiencies are around 70–80% HHV (higher heating value) [8]. The alkaline electrolyzers usually operate at a process temperature of 70–80 °C [9]. Pressurized alkaline electrolyzers, however, operate at a somewhat elevated temperature; 90–130°C. The process temperature of PEM electrolyzers is usually 70–80 °C. The net reaction for producing hydrogen and oxygen by water electrolysis is given by:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad (2)$$

3.2 Hydrogen Storage

Hydrogen can be stored as compressed gas, as cryogenic liquid, in solids (metal hydrides, carbon materials) and in liquid hydrogen carriers (methanol, ammonia). In the real applications, it is focused on large-scale stationary storage systems, which makes compressed gas storage most relevant. Compression of hydrogen is normally obtained by the use of piston compressors or centrifugal compressors. Several stages of compression are required because of the low density of hydrogen [10]. The theoretical work for isothermal compression of ideal gas from pressure p_1 to p_2 is given by:

$$W_{1,2} = p_1 V_1 \ln\left(p_2 / p_1 \right) \qquad (3)$$

where V_1 is the volume of the gas at pressure p_1. Because of the logarithmic relationship, the electricity consumption of the compressor is highest in the low-pressure range. It is therefore interesting to consider high-pressure electrolyzers that can reduce or even eliminate the electricity consumption related to hydrogen compression. Conventional methods of above-ground hydrogen storage range from small high-pressure gas cylinders (>200 bar) to large low-pressure 12-16 bar spherical gas containers. For large-scale storage of hydrogen, underground storage is expected to be two orders of magnitude cheaper [11]. However, this option requires hydrogen storage in for example salt caverns or depleted natural gas reservoirs, which limits the potential usage.

3.3 Hydrogen Re-Electrification (Fuel Cells)

Hydrogen can be combined with oxygen without combustion in an electrochemical reaction (reverse electrolysis) and produce direct-current electricity [12]. The device where such a reaction takes place is called a fuel cell. Depending on the type of the electrolyte used, there are several types of fuel cells:

- Alkaline fuel cells (A-FC)
- Polymer electrolyte membrane or proton exchange membrane fuel cells (PEM-FC)
- Phosphoric acid fuel cells (PA-FC)
- Molten carbonate fuel cells (MC-FC)
- Solid oxide fuel cells (SO-FC)

Of these fuel-cell technologies, most attention is being given to the proton exchange membrane (PEM), which uses a fluorocarbon ion exchange with a polymeric membrane of the Nafion type as the electrolyte. PEMs have the advantage of fast start-up, high power density and ruggedness [13]. PEM cells operate at between 50 and 80 °C, and can vary their output to meet shifting power demands of a load. Other researchers favor alternative technologies such as alkaline fuel cells, which are used on the Space Shuttle, though these are receiving much less interest for motor vehicles [14].

4. Sample System Study (Abu Geida, Ras Sedr, Egypt)

Ras Sedr (29° 25′ 57.5″ N, 32° 47′ 25.5″ E) is situated along the western coast of the Sinai Peninsula, about 60 km south of the city of Suez and 18 km south of the town of El Sedr.

In the area of Ras Sedr there is a small community (Abu Geida) of thirty four houses. Abu Geida is inhabited all year round and it is estimated that approximately 202 people live in this community, which do not have access to the main electricity grid. This community has been electrified by South Sinai governorate for a period of 8 hours per day, in the context of which an autonomous power system based on a diesel generator has been developed. In more detail, the nominal capacity of the diesel generator is 48 kW.

The profile of electricity demand in Abu Geida for a day is presented in Figure (1) with daily variation of 5% and hourly variation of 5%. The annual average of the electric load for this community is in the region of 193 kWh/day, the annual peak of the load is 29.9 kW and the total annual electricity consumption in Abu Geida is in the order of 70 MWh.

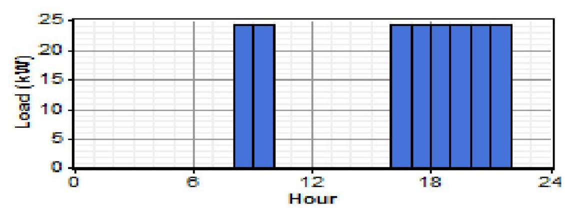

Figure (1): Electric load profile for a day

4.1 Results And Discussion For The System Of Abu Geida

4.1.1 Abu Geida Diesel-Based Power System

A basic scheme of the configuration of the existing diesel autonomous power system is presented in Figure (2). The main power component of this system is diesel generating set. To simulate this system and perform a techno-economic analysis individual costs (capital cost, replacement cost, operation and maintenance cost) have to be identified for each component.

The capital costs for diesel generators range between 200 and 500 €/kW, depending on the size of the generator. Since a relatively small generator is used in this system, a cost of 400 €/kW is used in the 48–kW diesel engine generator set operating in Abu

Geida (including the diesel tank), resulting in a total capital cost of 19,200 €. Moreover, a diesel fuel price of 0.8 €/L is used in the calculations. As can be seen from Table (2), the project lifetime used in the techno-economic analysis is 15 years.

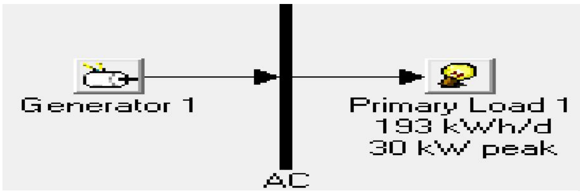

Figure (2): Basic configuration of the diesel power system simulated by HOMER

Table (1): HOMER input part 1 of the diesel power system

AC Generator	Size	48.00 kW
	Capital	19,200 €
	Replacement	17,900 €
	O&M	0.07 €/hr
	Lifetime	15,000 hrs
	Min. load ratio	30%
	Heat recovery ratio	0%
	Fuel used	Diesel
	Fuel curve intercept	0.08 L/hr/kW
	Fuel curve slope	0.25 L/hr/kW
Generator control	Check load following	Yes
	Check cycle charging	No
Fuel (Diesel)	Price	0.8 €/L
	Lower heating value	35.42 MJ/L
	Density	820 kg/m^3
	Carbon content	88.0%
	Sulfur content	0.33%

Table (2): HOMER input part 2 of the diesel power system

Economics	Project lifetime	15 yr
	Capacity shortage penalty	0 €/kWh
	System fixed capital cost	1000 €
	System fixed O&M cost	1000 €/yr
Emissions	Carbon dioxide penalty	8 €/t
	Carbon monoxide penalty	8 €/t
	Unburned hydrocarbons penalty	8 €/t
	Particulate matter penalty	8 €/t
	Sulfur dioxide penalty	8 €/t
	Nitrogen oxides penalty	8 €/t
Constraints	Maximum annual capacity shortage	5%

The analysis conducted showed that the system produces annually 70,445 kWh, which cover the electric demand of the community. These results are summarized in Table (3).

As can be seen from Tables (4) & (5), the autonomous power system of Abu Geida produces 75,903 kg/yr of CO_2 emissions, and it consumes 28,824 L/yr of diesel fuel. The diesel generator operates approximately 2920 h/yr. The average monthly energy production of the autonomous power system of Abu Geida is given in Figure (3).

The simulation results revealed that the cost of energy produced by the system of Abu Geida is extremely high (0.405 €/kWh), the total net present cost of the existing system is estimated at 427,876 € and the operating cost is estimated at 27,178 €/yr. Therefore, the introduction of wind-hydrogen energy technologies in this autonomous power system might also be an economically viable solution and it is worthwhile to investigate such an alternative solution. The distribution of system costs (in terms of net present and annualized costs) is presented in Tables (6) & (7).

As can be seen from these tables, the major cost factor for such a system is attributed to the operation of the diesel generator, therefore diesel fuel consumption accounts for approximately 81% of total annualized costs.

Table (3): Electrical energy production and demand

Annual electricity production	
Diesel generator	70,445 kWh (100%)
Renewable fraction	0 (0%)
Total production	70,445 kWh
Annual electric load served	
AC primary load served	70,445 kWh
Total load served	70,445 kWh
Other	
Excess electricity	0 (0%)
Unmet electric load	0 (0%)
Capacity shortage	0 (0%)

Table (4): Generator 1

Quantity	Value
Hours of operation	2,920 hr/yr
Number of starts	730 starts/yr
Operational life	5.14 yr
Fixed generation cost	4.42 €/hr
Marginal generation cost	0.205 €/kWh
Electrical production	70,445 kWh/yr
Mean electrical output	24.1 kW
Min. electrical output	17.9 kW
Max. electrical output	29.9 kW
Fuel consumption	28,824 L/yr
Specific fuel consumption	0.409 L/kWh
Fuel energy input	283,629 kWh/yr
Mean electrical efficiency	24.8%

Table (5): Emissions of the diesel-based power system

Pollutant	Emissions (kg/yr)
Carbon dioxide	75,903
Carbon monoxide	187
Unburned hydrocarbons	20.8
Particulate matter	14.1
Sulfur dioxide	152
Nitrogen oxides	1,672

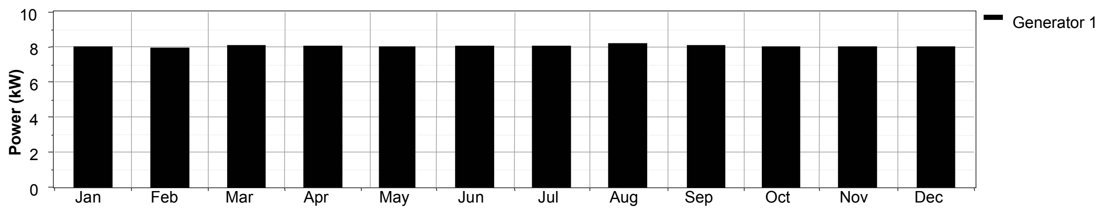

Figure (3): Monthly Average Electric Production

Table (6): Distribution of net present costs for the diesel-based system

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generator 1	19,200	35,800	3,066	345,888	-1,432	402,522
Other	1,000	0	24,354	0	0	25,354
System	20,200	35,800	27,420	345,888	-1,432	427,876

Table (7): Distribution of annualized costs for the diesel-based system

Component	Capital (€/yr)	Replacement (€/yr)	O&M (€/yr)	Fuel (€/yr)	Salvage (€/yr)	Total (€/yr)
Generator 1	1,280	2,387	204	23,059	-95	26,835
Other	67	0	1,624	0	0	1,690
System	1,347	2,387	1,828	23,059	-95	28,525

4.1.2 Abu Geida Wind-Hydrogen Power System

The renewable energy source (wind energy), will supply power to serve the electric demand, while excess electricity produced by this source will be used to produce hydrogen through water electrolysis that will drive a PEM fuel cell, which will provide power to the system at periods when the natural resource is not available.

The HOMER tool is used to optimize the sizes of different energy equipment (including wind turbines, water electrolyzers, hydrogen storage tanks, fuel cells), evaluating technical feasibility of the overall system and minimizing total net present cost and the cost of energy produced by the autonomous power system.

After some preliminary runs with HOMER it was decided that the most suitable numbers of the wind turbines to be considered were 1, 2, 3, and 4 units of 25 kW.

The capital costs for wind turbines range between 900 €/kW for large wind generators and 4000 €/kW for small wind turbines (in the 1–5 kW range). For the wind turbines simulated in Abu Geida a capital cost of 2000 €/kW will be used in the analysis, resulting in a total capital cost of the order of 50,000 € for each wind turbine. Operation and maintenance costs for wind turbines constitute 2% of the total capital cost per year. The lifetime of the wind turbine is 15 years.

The capital cost of PEM fuel cells used in the optimization process is 3000 €/kW and lifetime is set to 15,000 operating hours. Sizes considered for the PEM fuel cell are 14, 15 and 16 kW.

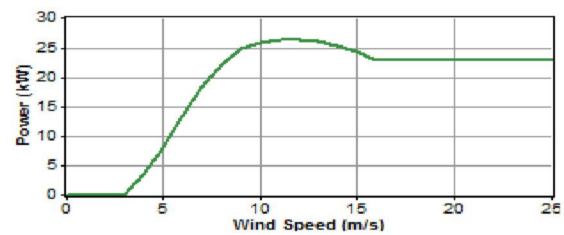

Figure (4): Power curve of the wind turbine

Water electrolyzers have found to comprise a major cost factor in a complete hydrogen-based autonomous power system. In this case a cost of 8150 € per N m^3/h of hydrogen produced (1630 €/kW) was used in the calculations. The high cost of commercial electrolysis units is attributed to the lack of mass production from all manufacturers. Three sizes for electrolysis units have been considered in the analysis: 0.8, 1 and 1.2 N m^3/h of hydrogen produced (4, 5 and 6 kW). The lifetime of the electrolyzers is 20 years.

The optimization of the wind-hydrogen autonomous power system, presented schematically in Figure (6) revealed that the optimum system configuration comprises 3 wind turbines with a capacity of 25 kW, a 15–kW PEM fuel cell, an electrolyzer with a nominal capacity of 5 kW and a hydrogen storage tank capable of storing 8 kg of compressed gas.

As expected the renewable energy fraction of energy produced from this system is 100% and therefore diesel fuel consumption and carbon emissions are now eliminated.

The proposed wind-hydrogen autonomous power system operates 100% with renewable energy and produces 452,277 kWh annually. The majority of Abu Geida's wind-hydrogen power is produced by the wind turbines (approximately 99%), while the fuel cell contributes 1% of total power production. The fuel cell operates approximately 1245 hr/yr, consuming 304 kg/yr of hydrogen. According to these figures the estimated lifetime of the PEM fuel cell is estimated at around 12 years and the average electrical output of the unit is 4.07 kW. The envisaged system nevertheless produces a significant amount of excess electricity, which is estimated at 81%. Therefore, we can easily conclude that the envisaged wind-hydrogen power system has a potential of serving higher loads in the community of Abu Geida, especially if we introduce deferrable loads in the system. The operational parameters of the optimum wind-hydrogen power system with respect to power production and demand are presented in Table (12).

4.1.3 Abu Geida Wind-Hydrogen Power System Techno-Economic Analysis

The simulation and techno-economic analysis of the wind-hydrogen power system using current costs of hydrogen technologies revealed that the cost of energy produced equals 0.287 €/kWh, which is 29% lower compared to the cost of energy produced by the original diesel-based power system of Abu Geida. Moreover, the total net present cost of the wind-hydrogen power system of Abu Geida equals 295,733 €, which is 31% lower compared to the total net present cost of the existing diesel-based power system. The operating cost is estimated at 5,880 €/yr. The distribution of costs that were estimated using current costs of hydrogen technologies is summarized in Tables (13) & (14).

The tables show that the most significant total annualized cost factor comes from the wind turbines, which accounts for 66% of the total cost of Abu Geida's wind-hydrogen autonomous power system, followed by fuel cell, which contribute approximately 25% of total annualized costs. The electrolyzer and hydrogen storage tank are relatively small due to lack of seasonal storage for hydrogen and therefore they are considered as minor cost factors for this system.

5 Conclusions

The comparison between using wind energy plus fuel cells, and using diesel generators in autonomous energy system, shows the advantages and disadvantages of each of them.

5.1 Using wind energy and fuel cells in autonomous energy system

➢ **Advantages:**

a) The cost of energy produced is low
b) It accomplishes security of power supply to the loads
c) It does not produce emissions approximately
d) It produces less noise

➢ **Disadvantages:**

a) The capital cost is high
b) The technology is not fully developed
c) The public awareness for this technology is low

5.2 Using diesel generators in autonomous energy system

➢ **Advantages:**

a) The capital cost is low
b) The technology is fully developed
c) The public awareness for this technology is high

➢ **Disadvantages:**

a) The cost of energy produced is high
b) It does not ensure security of power supply to the loads
c) In produces more emissions
d) It produces more noise

Table (8): HOMER input part 1 of the wind-hydrogen power system

AC Wind Turbine	Size	25.00 kW
	Capital	50,000 €
	Replacement	50,000 €
	O&M	1000 €/yr
	Quantities to consider	0, 1, 2, 3, 4
	Lifetime	15 yr
	Hub height	25 m
Generator control	Check load following	Yes
	Check cycle charging	No
Fuel Cell	Size	16.00 kW
	Capital	48,000 €
	Replacement	48,000 €
	O&M	0.991 €/hr
	Sizes to consider	0, 14, 15, 16 kW
	Lifetime	15,000 hrs
	Min. load ratio	1%
	Heat recovery ratio	0%
	Fuel used	Stored hydrogen
	Fuel curve intercept	0 L/hr/kW
	Fuel curve slope	0.06 L/hr/kW
AC Electrolyzer	Size	6 kW
	Capital	9,780 €
	Replacement	9,780 €
	O&M	196 €/yr
	Sizes to consider	0, 4, 5, 6 kW
	Lifetime	20 yr
	Efficiency	85%
	Min. load ratio	0%
Hydrogen Tank	Size	8 kg
	Capital	3,384 €
	Replacement	3,384 €
	O&M	17 €/yr
	Sizes to consider	0, 7, 8, 9 kg
	Lifetime	20 yr
	Initial tank level	10%
	Constrain year-end tank level	No

Table (9): HOMER input part 2 of the wind-hydrogen power system

Economics	Project lifetime		15 yr
	Capacity shortage penalty		0 €/kWh
	System fixed capital cost		1000 €
	System fixed O&M cost		1000 €/yr
Emissions	Carbon dioxide penalty		8 €/t
	Carbon monoxide penalty		8 €/t
	Unburned hydrocarbons penalty		8 €/t
	Particulate matter penalty		8 €/t
	Sulfur dioxide penalty		8 €/t
	Nitrogen oxides penalty		8 €/t
Constraints	Maximum annual capacity shortage		5%
	Operating reserve as percentage of	hourly load	10%
		peak load	0%
		wind power output	50%

Table (10): Wind resource

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Speed (m/s)	5.6	5.8	7.2	7.7	8.0	9.2	8.5	8.6	8.4	7.8	5.8	5.6

Table (11): Advanced parameters

Weibull k	3.06
Autocorrelation factor	0.846
Diurnal pattern strength	0.098
Hour of peak wind speed	13
Scaled annual average	7.36 m/s
Anemometer height	24.5 m
Altitude above sea level	6 m
Wind spead profile	Logarithmic
Surface roughness length	0.03 m

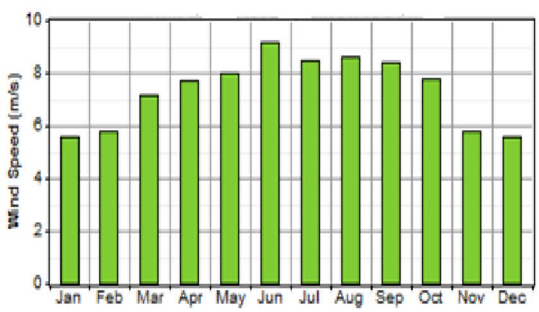

Figure (5): Wind resource

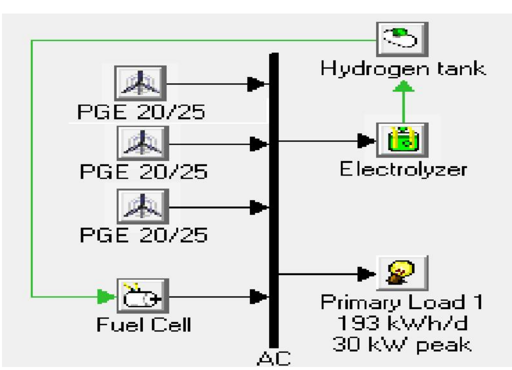

Figure (6): Optimum configuration of the wind-hydrogen power system

Table (12): Electrical energy production and demand

Annual electricity production	
Wind turbines	447,212 kWh (99%)
Fuel cell	5,064 kWh (1%)
Renewable fraction	1.0 (100%)
Total production	452,277 kWh
Annual electric load served	
AC primary load served	68,767 kWh (83%)
Electrolyzer load	14,380 kWh (17%)
Total load served	83,146 kWh (100%)
Other	
Excess electricity	369,130 kWh (81.6%)
Unmet electric load	1,678 kWh (2.4%)
Capacity shortage	3,475 kWh (4.9%)

Table (13): Distribution of net present costs for the wind-hydrogen system

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Wind Turbines	150,000	0	45,000	0	0	195,000
Fuel Cell	45,000	45,000	17,350	0	-33,975	73,375
Electrolyzer	8,150	0	2,450	0	-2,038	8,562
Hydrogen Tank	3,384	0	255	0	-846	2,793
Other	1,000	0	15,002	0	0	16,002
System	207,534	45,000	80,057	0	-36,859	295,733

Table (14): Distribution of annualized costs for the wind-hydrogen system

Component	Capital (€/yr)	Replacement (€/yr)	O&M (€/yr)	Fuel (€/yr)	Salvage (€/yr)	Total (€/yr)
Wind Turbines	10,000	0	3,000	0	0	13,000
Fuel Cell	3,000	3,000	1,157	0	-2,265	4,892
Electrolyzer	543	0	163	0	-136	571
Hydrogen Tank	226	0	17	0	-56	186
Other	67	0	1,000	0	0	1,067
System	13,836	3,000	5,337	0	-2,457	19,716

Table (15): AC Wind Turbine

Variable	Value
Total rated capacity	75.0 kW
Mean output	51.1 kW
Capacity factor	68.1 %
Total production	447,212 kWh/yr
Minimum output	0.00 kW
Maximum output	79.2 kW
Wind penetration	635 %
Hours of operation	8,467 hr/yr
Levelized cost	0.0291 €/kWh

Table (16): Fuel Cell

Quantity	Value
Hours of operation	1,245 hr/yr
Number of starts	495 starts/yr
Operational life	12.0 yr
Capacity factor	3.85%
Electrical production	5,064 kWh/yr
Mean electrical output	4.07 kW
Min. electrical output	0.15 kW
Max. electrical output	15.0 kW
Hydrogen consumption	304 kg/yr
Specific fuel consumption	0.06 kg/kWh
Fuel energy input	10,129 kWh/yr
Mean electrical efficiency	1,245 hr/yr

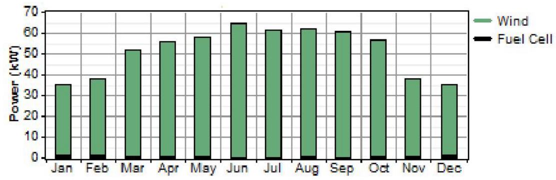

Figure (7): Monthly average electric production

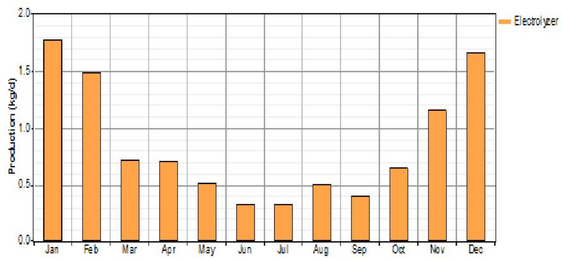

Figure (8): Monthly average hydrogen production

Table (17): Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	-2.94
Carbon monoxide	1.87
Unburned hydrocarbons	0.207
Particulate matter	0.141
Sulfur dioxide	0
Nitrogen oxides	16.7

Table (18): Hydrogen Tank

Variable	Value
Hydrogen production	310 kg/yr
Hydrogen consumption	304 kg/yr
Hydrogen tank autonomy	33.2 hours

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