

Life Cycle Energy and Greenhouse Gas Emission Assessment of a Wind Turbine Installed in Northeast of Iran

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Abstract: At the present, Iran's policy-makers are interested in renewable energy development thus in the recent years, the use of renewable energies, especially wind energy for electricity generation has been highly invested. Although wind technology produces no emissions during operation nevertheless there is some environmental impact associated with the wind energy development during the entire life cycle of the plant; from manufacturing and production of the parts to decommissioning of the wind farm. Therefore evaluation of the life cycle energy and greenhouse gas emission of the wind turbine account as an important factor in promoting this type of renewable. This paper concentrates on total life cycle energy consumption assessment and energy payback time of a typical onshore Vestas V47-660KW wind turbine installed in Binaloud wind farm in the northeast of Iran. The life cycle energy consumption of the wind turbine from manufacturing of the components to decommissioning and recycling of the parts were considered. The total energy consumption by the turbine over its life cycle was evaluated as 3233 GJ. For evaluation of energy payback time, 4 different plant operation scenarios are considered. Results indicated that under worst case; where both 2% turbine annual degradation and 30% grid curtailment is considered, the wind farm can retain the life cycle energy consumption within less than 14 months of the designed 20 year operation period. The outcome of this study could be used as a reliable data to promote more sustainable policies in order to support wind energy and generate wind farms similar to Binaloud in another part of the country.

Keywords: Renewable Energy, Wind Turbine, Energy Payback Time, Life Cycle Energy

1. Introduction

Iran is a developing country with a population of more than 76 million [1], an area of 1,648,195 km² and is experiencing a rapid power demand growth. Consequent upon the implementation of economic evolution and targeted subsidies, especially in the energy sector, the demand for renewable energies, particularly wind energy, have recorded a substantial increase. On the other hand, Iran offers feed-in tariff and investment credits to support renewable energies development [2] and thus, it is believed that in the future, renewable energies particularly wind power will play an important role in Iran's renewable energy package. Currently, about 0.17% of Iran's electricity demand is supported by

wind energy [3]. Figure 1 illustrates wind atlas of Iran based on measured wind speeds on 137 wind stations at an altitude of 80m in different parts of the country. This was prepared by the Iran Renewable Energy Organization (SUNA) in 2014 and is available for 40, 60 and 80 m heights [4]. Recent wind potential studies have shown that 26 regions throughout the country are suitable for the construction of wind farm. This includes more than 45 suitable sites with the nominal capacity of the site in a region of approximately 6.5 GW. This level of energy is considered to be of medium level among different countries. However, some locations in Iran are prone to strong winds desirable for the production of electricity [3, 5].

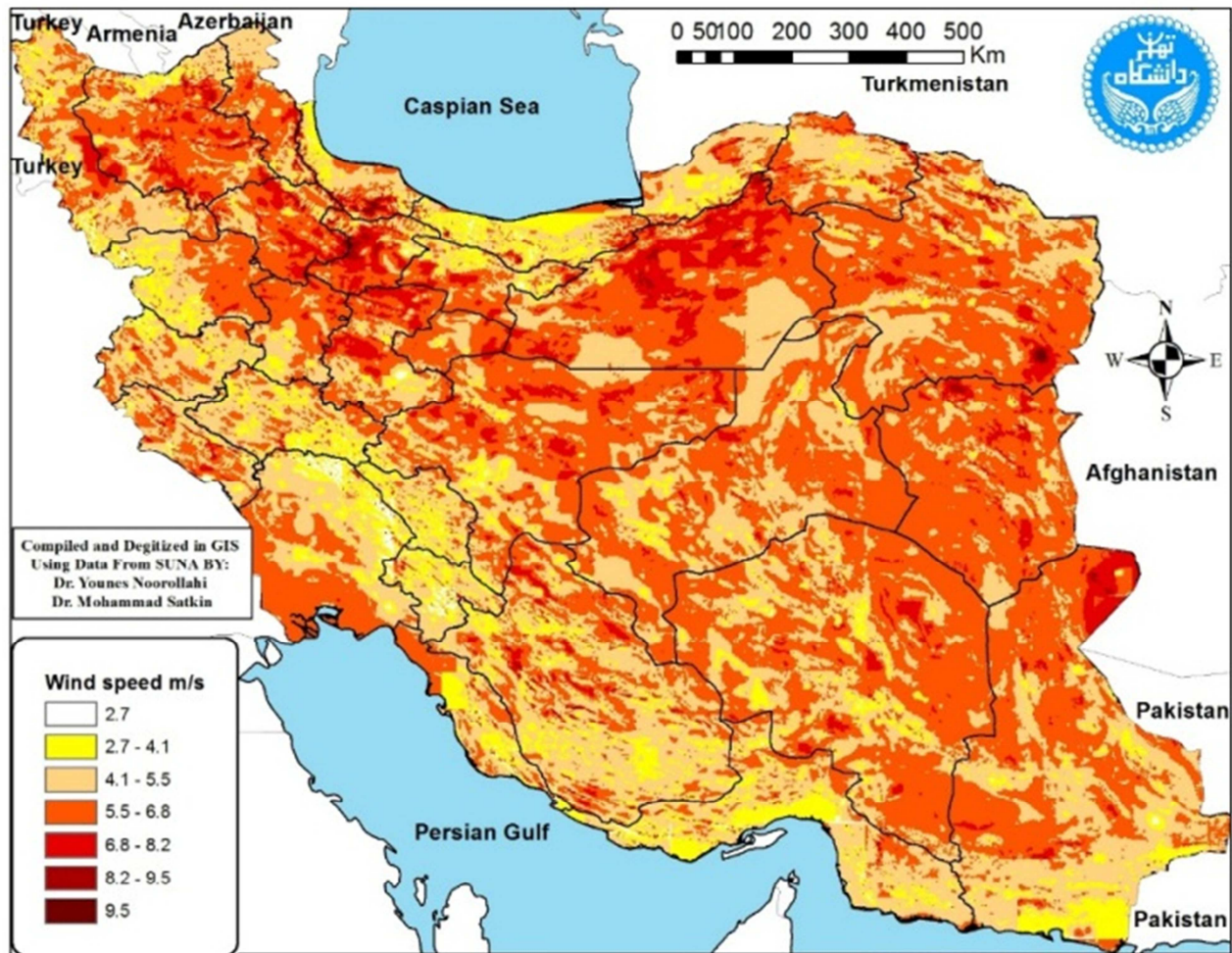


Figure 1. Iran's wind speed map at 80m height [4].

Iran is one of the major countries in the Middle East having large-scale wind power installations, totaling 153.07 MW from 184 wind turbines, installed at the end of 2015. The country currently has three major wind farms: Manjilin in Gilan Province, Kahak in Ghazvin Province and the Binaloud wind farm in Khorasan Province with an installed capacity of 65.8, 25 and 28.38 MW, respectively at the end of 2015 [2]. Further studies are currently being carried out for the utilization of wind resources in Qazvin and some other southern provinces [6]. A total of 161 wind stations with overall capacity studies revealed that Iran has a potential for wind power development of about 15 GW [7, 8]. Among the different types of wind turbines, the horizontal axis three blade wind energy converters are the most commercially common [9]. The majority of wind farms in Iran are currently utilizing the 660 kW Vestas type of wind turbines [2].

This study assessed the life cycle energy consumption and energy payback of a typical wind turbine, Vestas class V47-660 kW. This type of wind turbine is currently being used in the inland wind farms of Iran. This study is based on a life cycle analysis (LCA) model of a Vestas wind turbine where total energy consumption during production, manufacture, use, disposal, and recycling of the system is taken into

consideration. This study included the total energy consumption for the entire lifecycle of the system and evaluated the energy payback time of the system during 20 years of the power production process. To determine energy payback time, the efficiency of the wind turbine was determined and used to assess system degradation and power production rate of the turbine during the 20-year working period. Different system degradation scenarios have been taken into consideration. For each case; total system operating time, total system power production and total energy payback time were calculated.

2. Goal and Scope Definition

The main objective of this study is to evaluate the relevant parameters associated with total life cycle energy consumption and energy payback time of a typical Vestas V47-660KW wind turbine in Binaloud wind farm, northeast of Iran, between the cities of Mashhad and Neyshabour, in the north of Khorasan Province. This is an inland wind farm, already in operation and operating data were sourced from the Iranian energy balance sheet in 2011 and data were provided for the Binaloud site. The Binaloud wind farm has a

total of forty-three (43) V47-660-kW wind turbines with a total capacity of 28.38 MW. Based on the evaluation of wind energy potential as a power generation source for electricity production in Binaloud, all the wind turbines installed are V47-660 kW [3, 6].

In this regard, a few number of studies have been conducted in Iran and other countries. Mathieu *et al.* [10], used a methodology to evaluate the economic impacts of wind energy projects with an application to the Canadian setting. This methodology is based on modified input-output techniques using the national/provincial economic Input-Output tables and multiplier coefficients by use of investment profile for a generic 100 MW wind energy project, based on publicly available financial data. Subsequently, a case study was performed to assess the economic impact of both the construction and operations phases of a generic 100 MW wind farm project in the province of New Brunswick, Canada. They concluded that, including direct, indirect and induced jobs, the construction phase could create a total of 225 person-years of labor, while the operations and maintenance phase could create a total of 17 person-years of labor annually.

For this study, all the inventory data required for assessment of the V47-660KW wind turbine, during its manufacturing stage were extracted from the turbine manufacturer's data manual in Denmark and available literature on Vestas wind turbines.

3. Methodology

3.1. LCA Assessment

In this study, the life cycle energy consumption of wind turbines from the manufacture of the components up to the decommissioning stage was considered. Figure 2 shows the diagram of the wind turbine life cycle. The dash lines in the model illustrate the system boundary of the wind turbine, thus the energy associated with the life cycle of transformers or other additional components such as voltage boost station as well as grid losses in transformers and in the distribution grid was ignored.

The type and quantity of materials required for each system vary depending on size (kW rating), design features and site conditions.

For the manufacturing stage, all the materials required for the manufacturing of different system components were taken into consideration. As shown in Figure 3, the study included all materials and energy used for manufacturing and fabricating different turbine components, tower and foundation.

The manufacturing phase includes upstream processes such as mining, refining, processing, and construction of the main components of the wind turbine.

3.2. Service Life

The service life of a wind turbine refers to their expected lifetime or the acceptable period of use in service. The longer life time of a turbine, the greater opportunity to generate

energy to offset the life cycle energy requirements and potentially improve the energy yield [12].

In this study, the lifetime of wind turbines was assumed to be 20 years which is commonly found in the specification of various systems [13].

4. The LCA Model Used in Wind Farms

4.1. Wind Turbine Manufacturing

Table 1 shows the physical, and mechanical characteristics of the Vestas V47-660 kW wind turbine as well as the different components associated with the manufacturing of turbine, tower, and foundation. These data were extracted from the Vestas turbine manufacturer's catalog and other relevant literature performed on the LCA of this type of wind turbine [14-16]. As shown, the base (foundation) of the structure constructed with reinforced concrete carried the most weight of materials, consuming about 80% of the total weight of wind turbine systems.

Different amounts and sources of energy were used for manufacturing, fabrication, and production of different turbine components. The sources and amount of energies could be different in different countries, depending mainly on the source of energy and the type of manufacturing technique being used in that country. The turbines used in this study were manufactured in Denmark, thus the type and amount of energy consumed during the manufacturing of each component of the turbine are based on Danish materials manufacturing conditions. Table 2 shows the source and amount of energy consumption (in MJ) for the production and manufacturing of different materials used in manufacturing different components of the vestas wind turbine [15].

Table 1. Characteristics and materials used for one wind turbine system.

Characteristics of wind turbine system	
Turbine system	Vestas (V-47)
Power capacity (kW)	660
Rotor diameter (m)	47
Tower height (m)	40.7
Cut-in wind speed (m/s)	4
Wind speed for Rated Power (m/s)	15
Cut-out wind speed (m/s)	25
Rotor weight (incl. hub) (kg)	7200
Nacelle weight (kg)	20100
Tower weight (kg)	28900
Base weight (kg)	182000
Total weight (kg)	238200
Material requirement for V-47 wind turbine	(unit: kg)
steel	44257.56
aluminum	684.83
copper	613.37
plastic	1298.19
glass	1250.55
sand	357.3
reinforced iron (rebar)	4984.34
concrete	185123.08
Oil products	11.91
other products	434.72

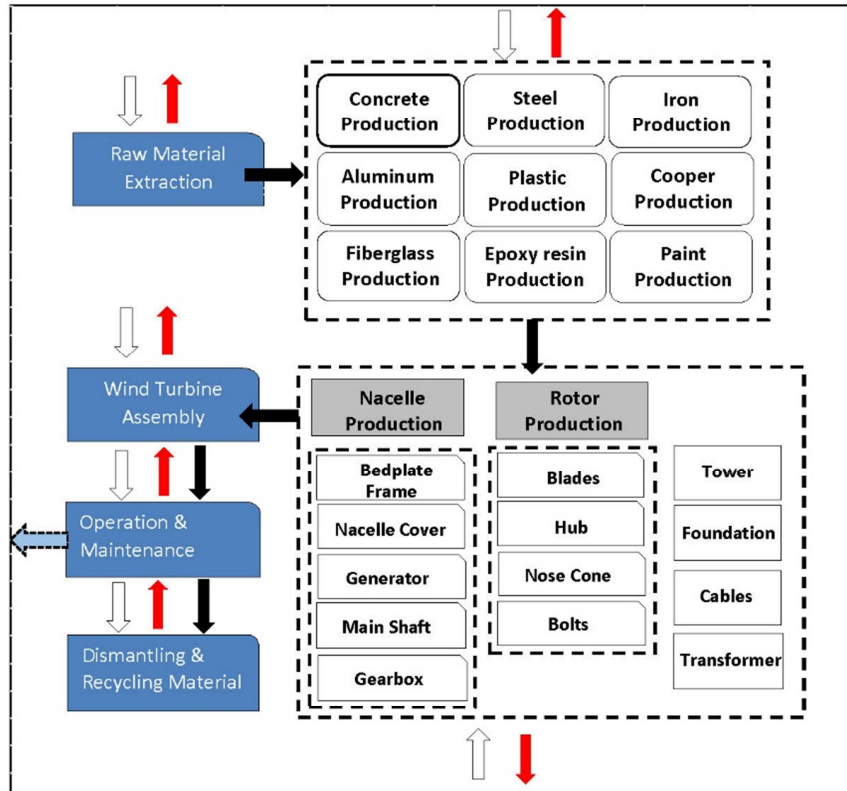


Figure 2. Life cycle analysis methodology model for typical wind turbine.

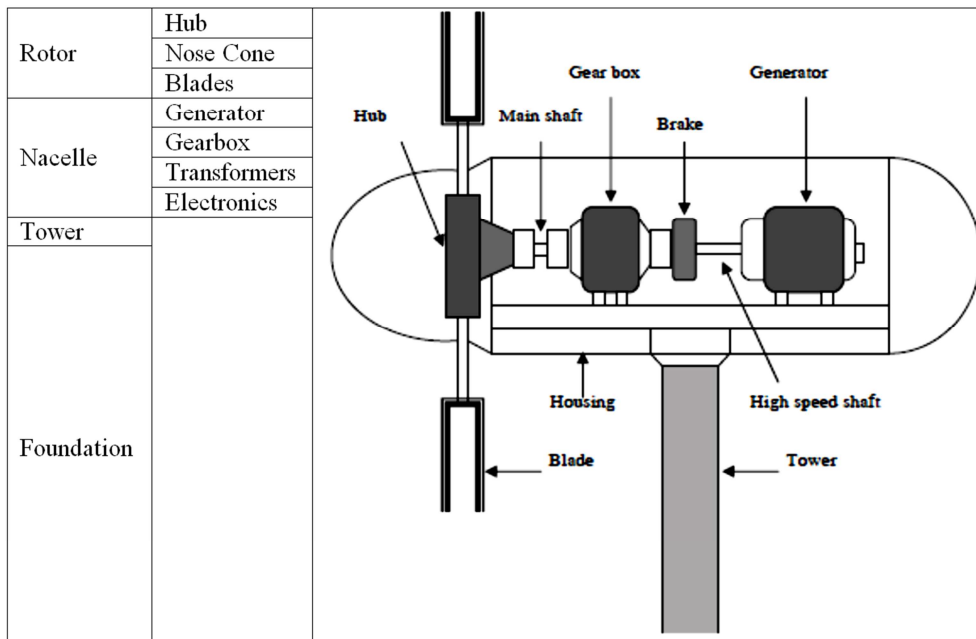


Figure 3. Main components of the wind turbine [11].

These data were used to calculate the total energy consumption for the manufacturing and fabrication of wind turbine components. Table 3 shows the energy is consumed during the manufacture of different elements within the Vestas wind turbine. These data were calculated by combining data associated with total energy consumption for the production of each material type and amount of materials used for manufacturing of wind turbine components, using data extracted from Tables 1 and 2.

The foundation was manufactured from reinforced concrete. In this study, it was assumed that the same amount of energy used for manufacturing sand (i.e. aggregate) was considered for the manufacture of concrete (i.e. cement).

Also, glass and polyester are used in the manufacture of fiberglass for the blades. However, due to lack of sufficient data, for the blades, only the energy consumed during the manufacture of glass and polyester was taken into consideration and the energy used in the manufacture of fiberglass (from glass and polyester) was ignored.

4.2. Transportation to Site

The turbine components are manufactured in Denmark and are only being assembled onsite in Iran. Thus in this study, the energy consumed for transportation of turbine components to the site was ignored.

4.3. Operation and Maintenance

Energy input is required for turbine operation, such as starting the machine, brake system, yaw and rotor pitch control.

For system maintenance, complete oil change of the gearbox and the cooling system, as well as regular lubrication of the gears and other mechanical parts of the system were considered.

Thus, the energy consumption of the turbine during 20 years of operation and maintenance of the system as 1% of the total power generated by the turbine [3] was assumed. Table 3 shows the total energy consumption for operation and maintenance of a turbine.

Table 2. Total primary energy consumption in MJ for production of specific materials per kg [15].

Material	Coke (MJ/kg)	Coal (MJ/kg)	Oil (MJ/kg)	Natural gas (MJ/kg)	Total (MJ/kg)
Steel	1.6	14.1-20.7	4.9-8.2	0.1	20.7-30.6
Aluminium	0	23.1-31.5	8-11.4	1.4-2.9	32.5-45.8
Copper	3	45.1	13.6	16.5	78.2
Plastic (polyester and epoxy)	0	30.8	9.8	5.1	45.7
PVC	0	19	12.6	6.6	38.2
Rubber	0	19.8	20.5	0	40.3
Reinforced iron (rebars)	7.4	10.6	18.2	0.1	36.3
Concrete	0	3.45	0.23	0	3.68
Lead	0	20.3	9	6.3	35.6
Zinc	0	61.3	9.3	2.4	73
Float glass	0	1	0.8	7.5	9.3
Packing glass	0	2	0.8	5.3	8.1
Insulation, Rock-wool (/m)	168	84	81	3	336
Insulation, Glass wool (/m)	0	121	6	102	229

4.4. Dismantling and Transportation

In this work, the energy required during disassembly and transportation of the wind turbine, either for recycling or disposal, was assumed as 0.2 MJ/kg of all material components [15]. This correlates with the previous works performed on the LCA of the wind turbine. Table 3 shows the energy consumption of the wind turbine components at the disassembly and transportation stage.

For wind turbines, a large fraction of the materials is recycled, while a smaller fraction is disposed of. Plastic materials, PVC, and rubber are burned at waste power plants where the metals (aluminum, mild steel, copper), glass fiber parts and reinforced concrete components become fully recycled.

4.5. Disposal and Recycling

During the decommissioning stage, energy input is required for dismantling and disposal of materials. Based on a previous study on the LCA of wind turbines, it was assumed that energy consumption for the dismantling and disposal stage requires 2.5% of the total energy consumed by the wind turbine during its manufacturing stage [15]. Table 3 shows the energy consumption of wind turbine components at the disposal and dismantling stage.

Based on the computation shown in Table 3, total energy consumed by a Vestas V47-660KW wind turbine for the Binaloud wind farm site, is 3233.6 GJ. The energy consumption for the life cycle of the Binaloud wind farm comprised of 43 Vestas V47-660KW is 139044.8 GJ.

Table 3. Energy consumption related to; material production, transportation to site, Operation and maintenance, dismantling, disposal and recycling of Vestas V47-660 kW wind turbine.

	Material production (GJ)	Transportation to site	Operation and maintenance (GJ)	Material Dismantling and transportation (GJ)	Material Disposal and recycling (GJ)
Steel	1135.21			8.85	28.38
Aluminum	26.81			0.14	0.67
Copper	47.97			0.12	1.20
Plastic	59.33			0.26	1.48
Glass	11.63	-	987.84	0.25	0.29
Sand	1.31			0.07	0.03
Reinforced iron (requires)	180.93			1.00	4.52
Concrete	681.25			37.02	17.03
Total	2144.44			47.71	53.61

Total energy consumption by the turbine over its life cycle= 3233.6 GJ

5. Energy Payback Time

One of the most important aspects of evaluating the life cycle of wind turbines is its energy payback time. This shows the relation between the turbine's energy consumption for manufacturing, operation, transport, dismantling, disposal and the expected average energy production.

For the Binaloud site, based on the available site operating data, the annual operating hours and total annual energy generation for a turbine wind turbine are 6878 h and 1.372 GWh, respectively. This is based on the assumption that there is no system degradation or grid curtailment within the operating system [17].

This study analyzed four different scenarios regarding the performance of the wind turbine over 20 years of operation time.

1. The turbine generating power over a 20-year operation with no annual degradation or grid curtailment.
2. The turbine generates power with annual 2% degradation reduction over a 20-year operation period, ignoring grid curtailment.
3. The turbine generates power over a 20-year period with grid curtailments.
4. The turbine generates power, having both annual 2% degradation reduction over a 20-year operation period and grid curtailments.

Grid curtailment occurs when a wind turbine is required to reduce its generation output or shut down due to relevant issues such as lack of grid availability, planning conditions or turbine overloading. Generally, the main reason for grid curtailment is the congestion of the transmission grid and insufficient transmission capacity. For Binaloud site, the grid curtailment value was taken as 30%, as a worst-case scenario.

For plant degradation, a 2% reduction value was considered. This agrees with previous literature [18, 19, 20]. However, no additional maintenance or energy requirements

have been considered due to regular interruption of operation. Table 4 shows the power generated by the system during 20 years of operation time, considering the discussed operational scenarios [18, 19, 20].

6. Net Energy Analysis

In net energy analysis (NEA), total energy produced by the system (E_p) is compared with the total energy consumed by it throughout its lifecycle, from its manufacturing to disposal stage (E_c). The ratio between the annual energy produced and consumed by the system during its life cycle is often termed as the Energy Payback Ratio (EPR). Thus;

$$EPR = \frac{E_p}{E_c}$$

In this study, Table 4 shows the energy produced (E_p) by the turbine over its 20-year production lifetime which is 27440 MWh and assumes no degradation or curtailments.

Total energy consumption (E_c) by the turbine over its life cycle, shown in Table 3, is 2246.03 GJ (=0.62 GWh).

Entire energy consumption (Table 3) and total energy production (Table 4) with typical Vestas V47-660KW turbine, the total energy payback time for different scenarios was calculated. Results (Table 5) shows that under ideal but the less realistic situation (Scenario 1), where there is no system degradation or grid curtailments, the energy payback time for this type of turbine is 7.8 months. For the more realistic situation, when either 2% annual degradation (Scenario 2) or 30% grid curtailment (Scenario 3) is imposed on the wind farm, the total energy consumption within the life cycle of the turbine would pay back within 9.5 and 11.16 months of its operating time. For the more pessimistic scenario (Scenario 4), where both 2% annual turbine degradation and 30% grid curtailment is considered together, the energy payback time of the turbine is 13.44 months.

Table 4. Average annual energy production over for 20 year operation time for system with/without degradation.

Average annual energy production – Vestas V47-660 kW turbine		
year	Senario 1 (No degradation) (MW)	Senario 2 (2% degradation) (MW)
1	1372	1372
2	1372	1345
3	1372	1318

Average annual energy production – Vestas V47-660 kW turbine		
year	Senario 1 (No degradation) (MW)	Senario 2 (2% degradation) (MW)
4	1372	1291
5	1372	1265
6	1372	1240
7	1372	1215
8	1372	1191
9	1372	1167
10	1372	1144
11	1372	1121
12	1372	1099
13	1372	1077
14	1372	1055
15	1372	1034
16	1372	1013
17	1372	993
18	1372	973
19	1372	954
20	1372	935
All energy production (MWh/20 year)	27440	22802
Annual energy production (MWh/ year)	1372	1140
New operation hour (hr/year)	2078	1727

Table 5. Results for different operating scenarios.

	Different Scenarios				
	Units	(Scenario 1) Ideal	(Scenario 2) 2% degradation	(Scenario 3) 30% curtailment	(Scenario 4) 2% degradation + 30% curtailment
Total Cumulative energy	(GWh)	0.9	0.9	0.9	0.9
Annual energy generated	(GWh/year)	1.37	1.14	0.96	0.8
Energy payback	(year)	0.65	0.79	0.93	1.12
Operation hour	(hr/year)	2078	1727	1455	1209

7. Conclusion

The aim of this study was to assess the energy life cycle and energy payback time of a typical onshore Vestas V47-660 kW wind turbine, currently being used in the Binaloud and Manjil wind farms in Iran.

This study was based on a Life Cycle Analysis model developed in Denmark for the LCA assessment of similar types of materials for the Vestas type wind turbine.

The total energy consumption of the wind turbine was determined over the life cycle of the system, from production and manufacturing of the parts to their maintenance and decommissioning stages. Results indicated that each turbine consumes a total of 3233.6 GJ energy during its lifespan.

For the energy payback time, four different wind farm operational scenarios were investigated. The results indicated that under the worst case situation where both turbine annual degradation and grid curtailment is considered, the wind farm can retain the total life cycle energy consumption within less than 14 months of the designed 20 year operation period.

The most important parameters calculated in this LCA are the energy payback time and the total CO₂ emission within the life cycle of the system.

This is especially important for countries like Iran facing rapid growth in energy demand and CO₂ emissions, yet forced to make a reduction in fossil fuel usage and greenhouse gas emissions. It is therefore very important to invest in an alternative source of energy and renewable

technologies, in order to achieve a more sustainable development.

Four different scenarios are analyzed and in more realistic situation, when either 2% annual degradation (Scenario 2) or 30% grid curtailment (Scenario 3) is imposed on the wind farm, the total energy consumption within the life cycle of a turbine would pay back within 9.5 and 11.16 months of its operating time.

It is believed that results from this study could be used as a reliable data to promote more sustainable policies, in order to support wind energy and generate wind farms similar to the Binaloud and Manjil in the country.

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