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Comparison of renewables (onshore wind, offshore wind, conventional PV) for Bozcaada Island in Turkey

A.E. Şentürk
Hydraulics Laboratory, Civil Engineering Department, Middle East Technical University, Ankara, Turkey

E. Oğuz
Hydraulics Laboratory, Civil Engineering Department, Middle East Technical University, Ankara, Turkey
Center for Wind Energy Research (METUWIND), Middle East Technical University, Ankara, Turkey

D.D. Çiçek
Hydraulics Laboratory, Civil Engineering Department, Middle East Technical University, Ankara, Turkey

ABSTRACT: Renewable energy sources for the shift from fossil fuel have been considered as a solution to generate energy. In order to determine the optimal alternative for a specific region having more than one renewable energy sources prior to investment, Bozcaada Island is considered in this study. Two different renewable sources, wind and solar sources, are evaluated by life cycle assessment (LCA) methodology. For wind potential, operated onshore wind farm and proposed offshore wind farm are considered. A land based photovoltaic (PV) power plant are proposed to evaluate solar potential. "Cradle to grave" approach is applied for each case. The results of this study indicated that offshore wind farm is more advantageous than onshore wind farm in terms of environmental impacts apart from acidification potential (AP) whereas onshore wind technology is more beneficial than conventional photovoltaic (PV) system in terms of all selected impact categories.

1 INTRODUCTION

Global warming is one of the most alarming problems for the future of the world. A transition from fossil fuel to renewable sources in order to generate clean energy is strongly recommended by many researchers (Da Silva & Branco 2018, Keleş & Bilgen 2012, Larsen, 2014, Özkale et al. 2017) as a solution. However, there is limited research about the selection of the most appropriate renewable sources for a specific region (Oğuz & Şentürk 2019, Piesecka et al. 2019, Schmidt et al. 2017, Franzitta et al. 2016). For this purpose, Bozcaada Island is selected as the pilot area due to its potential for solar and wind energy sources. Three distinct configurations one of which is the actual case, land-based wind farm, and two proposed alternatives of offshore wind farm and conventional open ground photovoltaic power plant, are compared in terms of environmental impacts by means of life cycle assessment (LCA).

Brief descriptions of selected impact categories are summarized in the following. While phases for LCA application of energy generation systems are explained in Section 2.2, system boundaries related for all configurations are drawn in Section 2.3. Following this, source potentials and assumptions related with chosen configurations are mentioned for wind source and solar source in Section 3 and Section 4, respectively. In Section 5, results are compared and comments and future directions take place in Section 6.

1.1 *Acidification potential (AP)*

Acidification can be defined as the sedimentation of inorganic compounds such as nitrogen oxide (NO) and nitrogen dioxide (NO2) on the surface of the world (Üçtuğ, 2017) which are accepted to be the most significant air pollutants (Cindoruk, 2018). Acidification can alternatively be defined (Taşkın, 2018) as the creation and release of hydrogen ions by specific compounds (Şayan et al. 2010). Due to dissolved inorganic compounds in water, total dissolved inorganic carbon and the alkalinity of water are altered which leads to marine pollution. Atmospheric pollution due to the build-up of inorganic compounds causes acid rains (Kim & Chae, 2016).

1.2 *Eutrophication potential (EP)*

Eutrophication is a central issue concerning (Doğan-Sağlamtimur & Sağlamtimur, 2018) aquatic ecosystem quality (Frumin & Gildeeva, 2015) which is directly

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related to the excessive emission of nitrogen and phosphorus (Rabalais et al. 2009). The main symptom is observed that phytoplankton population grows due to extreme loading of nutrients (Yağcı, 2010).

1.3 *Cumulative energy demand (CED)*

Its description (Merta et al. 2017) is the primary energy requirement per the unit power production and it is calculated with primary energy demand values throughout this study.

1.4 *Energy pay-back time (EPBT)*

The ratio of total embedded energy to annual energy generation (Gkantou & Baniotopoulos, 2018) is defined as energy pay-back time.

1.5 *Global warming potential (GWP)*

It is a chosen metric to compare the capacity of heat retention in the atmosphere of each greenhouse gases (relative to CO2). In other words, it is the ratio of the warming caused by a substance which has similar mass to that of carbon dioxide (Demirel, 2014).

2 LIFE CYCLE ASSESSMENT (LCA)

Life cycle assessment is a method for evaluation of environmental impacts of a product, a system or a process (ISO, 2006a, b, Singh et al. 2013).

2.1 *Phases for LCA applied energy systems*

The methodology of life cycle assessment is applied by dividing the life cycle into four main phases: production, construction, operation and maintenance as well as decommissioning and recycling for energy production systems (Frischknecht et al. 2016).

2.1.1 *Production phase*

Extraction of raw materials consisting of manufacturing all parts such as transmission lines for the grid connection and infrastructure is included in this phase.

2.1.2 *Construction phase*

In the second step of LCA, all materials are required to be transported to the operation site. Construction phase also consists of assembly of all materials and testing procedure for the installation.

2.1.3 *Operation and maintenance phase*

The first stage of this phase is the generation of electricity. It contains periodic maintenance such as the cleaning of panels for PV plants, oil changes for wind plants and defect repairs like broken parts for all types of plants.

2.1.4 *Decommissioning and recycling or disposal phase*

Marked by the conclusion of electricity generation, the dismantling stage of parts takes place in plants. In this study, only transportation of disassembled parts is included while the recycling procedure is excluded.

2.2 *System boundaries*

General assumptions concerning all configurations and generalized system boundaries are listed as follows:

- All phases including production, construction, operation and maintenance as well as decommissioning and recycling or disposal are evaluated in a “cradle to grave” approach.
- Life cycle modeling is established with the aid of GaBi.
- Although production processes of primary raw materials such as cast iron and silica are considered in the study, their transportations are excluded from this study.
- During the assessment of the fourth phase, namely the decommissioning and recycling or disposal phase, only the transportation of parts for recycling is considered.
- During the assessment of the fourth phase, circular economy approach is applied for the scrap materials.
- The results are evaluated by means of CML2001-Jan 2016 method due to closeness of the selected region to Europe.
- The functional unit of LCA is selected as the unit power, MWh.
- The results are normalized in order to present them as a single emission type.
- The measure of greenhouse gas emissions is kg CO_2-eq./MWh.
- The measure of acidification potential is kg SO_2-eq./MWh.
- The unit of eutrophication potential is kg PO_4-eq./MWh.
- Energy payback time is measured in years.
- The unit of cumulative energy demand (CED) is MJ/MWh. Primary energy demand (PED) of GaBi database is the same concept of CED used in Ecoinvent database (Swart et al. 2015).
- Google Maps are used for the measurement of transportation distance.

3 WIND POTENTIAL AND ASSESSMENT

As mentioned in the introduction part, Bozcaada Island has wind potential (İncecik & Erdoğmuş, 1995) as a renewable source. Wind potential has been measured with the aid of one 250 kW turbine at the meteo-station (Türksoy, 1995, Dündar & Inan 1995) and its findings are that the average wind speed is 6,4 m/s at 10 m above ground level and the mean energy density is E= 324 W/m^2 for the island. In another study (Oğulata, 2003), average wind speed is measured as 6,2 m/s at 5 m and 8,4 m/s at 50 m, respectively. Thus, an onshore wind farm was established in 2000 and has been operated since. Offshore wind technology (Argin et al. 2019) can be regarded as an option to evaluate the wind potential of Bozcaada since offshore wind potential is two times higher than onshore wind potential for less than 30 m water depth in Turkey (Gaudiosi, 1994). In this study, the life cycle assessment of offshore wind farm on Bozcaada island is applied for the first time although other renewable systems for the island were considered in the literature (Güzel, 2012, Satir et al. 2018) in terms of environmental and economic characteristics. Hence, offshore wind farm is proposed as an alternative option based on the suggestion (Emeksiz & Demirci, 2019) that Bozcaada with 9,25 m/s mean average wind velocity at 100 m has the highest wind energy potential among all coastal regions in Turkey to evaluate the wind potential of the island and create a comparison to onshore counterparts in this study.

3.1 *Other assumptions for wind configurations*

In this section, general assumptions concerning the wind potential of the island are listed below:

- Useful life of wind turbines is assumed to be 20 years (Chipindula et al. 2018).
- Linear arrangement is assumed for offshore wind farm because the established counterparts have been arranged linearly.
- Production processes until the production of wind turbines themselves as one of the main parts for the wind farms are included for both the alternatives of onshore and offshore wind turbines. However, transportation of raw materials such as cast iron is excluded.

3.2 *Model structures of onshore and offshore wind farms*

An onshore wind farm was established and has been operated since 2000. Its installed capacity is 10.2 MW (Sahin, 2008). The farm is located on the west part of the island. The tower height as 44 m for the established farm is taken from the experts who have operated the farm. Underground wiring is 9 km up to the central transformer. The established onshore wind farm consists of 17 wind turbines, whereas 3 wind turbines are considered as the offshore counterparts in order to reach the approximately equal nominal power capacity as in the case of onshore technology. The onshore wind farm was installed with Enercon E-40 (600 kW) turbines (Hepbasli & Ozgener, 2004, TUREB, 2018) and the offshore wind farm is considered to be established with Vestas V-112 3 MW turbines.

In the case of the offshore wind farm, the tower height is accepted as 94 m since wind speed is (Satir et al. 2018) 9.1 m/s at 94 m height around the island. Lateral linear arrangement against the dominant wind direction is assumed for the three turbines. Distances of cabling between the turbines are calculated as 1120 m by means of five rotor diameters (Öksel et al. 2016) to minimize the effects of wake losses. A study suggested that there is no requirement of substation (Huang et al. 2017) for the offshore wind energy plants which has less than 30 MW nominal power. In addition, a substation on the sea is required when the distance of the plant is more than 10 km away from the coastal line even if the nominal power ranges between 30 MW and 120 MW (Huang et al. 2017). In other words, far shore design is needed for the distance that is at least 10 km (Güzel, 2012). Hence, the distance is accepted as 10 km for this study in order to avoid the necessity of the substation (Güzel, 2012, Huang et al. 2017).

High voltage alternating current and high voltage direct current power transmission are two alternative solutions for the transmission loss caused by the transmission cables. High voltage alternating current is the conventional solution for the system that has small or medium capacity (Olguin et al. 2014) and requires less than 100 km transmission line (Kirby et al. 2002). Thus, high voltage alternating current, similar to the other study on Bozcaada island (Köroğlu & Ülgen, 2018), is considered for this study.

3.3 *Life cycle inventory (LCI) for onshore and offshore wind farms*

In order to establish a wind farm either on land or on the sea, moving parts such as nacelle, rotors and cables, and fixed parts such as tower and base parts are required. However, foundations and roads are needed for onshore as a base, the basement for offshore system depends on water depth and its types can be regarded as monopile (Velarde & Bachynski, 2017), gravity-based or tripod (Kaldellis & Apostolou, 2017) suction caisson, multipod (tripod and jacket) (Oh et al. 2018) and floating (Oguz et al. 2018). For the water depth which is around 30 m in Bozcaada island (Satir et al. 2018) monopile is considered in the same way as in the research of (Oguz & Incecik, 2014).

Basic characteristics of turbines and material weights to manufacture them are listed in Table **1**. Enercon E-40 specifications are adopted from the previous studies (Lee et al. 2006, Oğuz & Şentürk, 2019) and the specifications of Vestas V112-3 MW model is found in the study (Tsai, 2013) apart from tower weight and tower height, respectively.

Table 1. Specifications of selected turbine models.

	Onshore	Offshore
	Enercon E-40*	Vestas V-112
Nominal power	0,6 kW	3 MW
Rotor diameter	43.70 m	112.00 m
Tower height	44 m	94 m
Rotor weight	8.27 t	49.18 t
Nacelle weight	19.77 t	92.63 t
Tower weight	29.91 t**	264.38 t ***
Base weight	220.00 t	700.00 t

* It is taken from the website (Enercon E-40/6.44-600,00 kW-Wind Turbine, n.d.)

** By means of linear interpolation, it is calculated for a - 44 m model (Lee, et al., 2006).

*** Tower weight is calculated in accordance with the determined tower height and by means of which is adopted from (Way & Van Zijl, 2015).

During the recalculations of tower weight for both systems, linear interpolation technique is applied for onshore system due to the lack of information related to geometric design or any other researches. However, the tower of offshore system is recalculated with the linear regression method by means of the data found in Way & Van Zijl (2015), which can be seen in Figure 1 as graph.

In the production phase, wind turbines for the onshore wind farm is produced in Germany. Thus, Deutch grid mix, as seen in Table 3, is used. Its nacelle comprises of steel and cast-iron materials. Metal roll forming (Ghenai, 2012) is applied for its production in GaBi. Glass fiber, epoxy resin, and cast iron are the materials utilized to manufacture its hub and blades. The manufacturing process of the tower is similar to the nacelle production. Concrete and steel are utilized as materials in the model of manufacturing foundations and roads. A similar procedure is applied for offshore wind turbine manufacturing. Due to the differences in production line, rotor blades are transported from Italy and nacelles are transported from Denmark in the case of the offshore farm. The location of offshore turbines is arranged laterally across the dominant wind direction. The 33 kV submarine cables (Öksel et al. 2016) are selected for the cables between the turbines of the offshore wind farm. The 132 kV cables (Tsai, 2013) are preferred for the transmission line to the coast. The weight of cables is taken as 29 t/km and 88 t/km for 33 kV submarine cable and 132 kV submarine cable (Birkeland, 2011), respectively. In the case of manufacturing of offshore wind farm parts, European grid mix is utilized to model the energy requirements of the related processes.

Due to the limitation of GaBi, excavator is considered to be assembled the parts together for both configurations. Procedures are similar except the extra motor ship usage for the assembly of offshore system parts throughout construction phase. In addition to this, Greek grid mix is used in the installation of onshore wind farm and offshore counterparts due to the lack of Turkish electricity mix in the software.

The third phase, namely operation and maintenance phase are initiated with the electricity generation from the farms in both cases. Electricity production of onshore wind farm is predicted to be 680 GWh throughout the life of the plant based on the average annual electricity production which is 34 GWh/year obtained from the interview with operating experts. The predicted annual electricity generation is calculated to be 14 GW/h for Vestas V112-3 MW from the research (Güzel, 2012).

The predicted annual energy production of this tower height, which is determined in accordance with the known (Satir et al. 2018) wind speed, 9.1m/s, at 94 m, is applicable as seen in Figure 2 and Table 2.

When the failure of the configurations is considered, spare parts are allocated initially for both systems as seen in Table 3. For the onshore wind farm, 1% of moving parts, namely cables, inverters, nacelle and rotor, is assumed to be broken and replaced. It is added to material flow in GaBi as spare parts. It can be seen in Table 3 that prediction of broken parts throughout useful life is increased to 15 % for generator and gearbox of offshore wind farm technology. Site maintenance is not required for the offshore case. It is also neglected for the

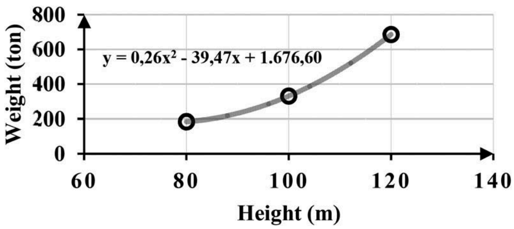

Figure 1. Weight vs height for V112-3MW turbine tower.

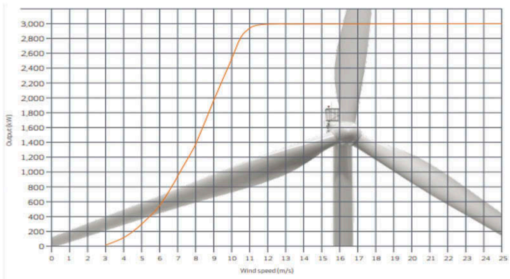

Figure 2. Power curve-Vestas V-112-3 MW-Offshore (Madariaga et al. 2012).

Table 2. Power curve-Vestas V112-3MW-Offshore (Madariaga et al. 2012).

Wind speed (m/s)	Annual Energy Production (MWh)
8.5	13.402
9	14.311
9.5	15.119
10.0	15.826

onshore system no maintenance requirement of access roads which has no traffic jam except maintenance of onshore wind farm.

Maintenance procedure consists of four different types:

- Visual controls are the first type of it. Although there is no material flow (Owens, 2019, Zeinali & Keysan) during the visual controls of both cases. It just should be noted that use of ferry is more necessary when it comes carrying parts of offshore wind farm.
- The requirement to maintain oil and lubricant is regarded as second type of maintenance procedure. The need to supplement oil and lubricant is more frequent for offshore wind farm than onshore wind farm due to the gearbox. According to experts who operates wind farms including Vestas models on the land in Turkey, Vestas V112- 3 MW is assumed to require 15.570 kg lubricant. Experts inform that requirement of oil supplemet depends on the quality and amount of oil. Hence, oil alteration of Vestas models lasts as a whole totally 6-7 years. As a result, oil and lubricant are amended three times completely during the useful life of Vestas models. However, there is no information about the lubricant requirement for Enercon models and turbines due to direct-drive mechanism they have (Owens, 2019, Zeinali & Keysan). The need of lubricants for an onshore wind farm throughout its useful life is assumed with the aid of the report (Razdan & Garrett, 2015) as 3.400 kg.
- The third type of maintenance is counted as mechanical maintenance since mechanic parts in the system should be controlled periodically. According to the research (Chan & Mo, 2017), these parts should be controlled twice a year. During these controls, broken parts should be amended. However, no extra material flow because of the initial allocation of spare parts is considered for both wind farms.
- Electrical maintenance is the last type for both configurations. The notion of its modelling is similar to mechanical ones. It can be seen in Table 3 that transportation distances are assumed as 300 km on the land both the processes of oiling and during the amendment of broken parts for onshore wind farm. In the case of offshore wind farm, 40 km and 200 km on the sea are assumed for repair and oiling procedure, respectively.

Table 3. LCA summary for different wind systems.

	Specifications	Onshore wind farm	Offshore wind farm
Phases	Mechanism	Direct-drive	Gearbox
	Nominal power	10.2 MW	9 MW
Production	Wind turbine	Germany	-
	Rotor blades	-	Italy
	Nacelle	-	Denmark
	Electricity mix	Deutch	European
Construction	Transportation up to/and installation	Extra motor ship usage required for offshore system.	
	Assembly	Excavator is used due to the lack of crane in the software.	
	Electricity grid mix	Greek	
Operation and maintenance	Transportation for periodic or sudden controls	Extra motor ship usage required for offshore system.	
	Amount of oil and lubricant	3400 kg	15570 kg due to gearbox
	Spare parts (allocated initially)	1 % for all moving parts	15 % for generator and gearbox
	Total transportation for the change of broken parts	300 km on the land	40 km on the sea
	Transportation for oiling	300 km on land	200 km on the sea
Decommissioning and disposal or recycling	Decommissioning	Extra motor ship usage required for offshore system	
	Transportation of scrap materials	Same distance is assumed for both systems.	

In the evaluation of decommissioning and disposal or recycling, scrap materials are transported to the same place to be recycled or for disposal as demonstrated in Table 3. Decomposition of offshore wind farm requires the utilization of motor ship although it is not necessary in the case of the onshore wind farm. It is indicated that the main production units such as nacelle and tower are decomposed into their materials as an onset of the fourth phase in order to classify. The ratio of classification into scrap materials and waste for disposal is also demonstrated in Table 4. According to Table 4, offshore wind farm has more variety of decomposed materials due to its more complex structure than onshore system. The end-of life treatment for concrete is landfill based on the suggestions of (Haapala & Prempreeda, 2014) and DTU International Energy Report (Andersen et al. 2014). Due to the difficulty of recycling of composite materials, rotor's end-of life treatment is considered as landfill similar to the International Energy Report of DTU. Open loop strategy, which means that recycled materials are not considered in the production phase, is applied for recycling.

3.4 *Life cycle impact assessment (LCIA) for onshore and offshore wind farms*

In this section, results based on the phases of each system are tabulated.

The total acidification ratio of the systems is approximately 1,5 for the wind farms. Table 5 shows that production phase causes the highest acidification in the case of the onshore wind farm while the construction phase of the offshore wind farm leads to the highest acidification potential. The reason why the highest acidification appears during the construction phase of the offshore system is excessive requirement of diesel utilized for the assembly and transportation.

Eutrophication potential is higher for the onshore wind farm than the offshore wind farm as indicated in Table 5. The main reason of it can be explained that concrete foundations of onshore system leaves in place.

As seen in Table 6, the offshore wind farm causes less greenhouse gas emissions than the onshore wind farm during the life of each configuration. While the most harmful phase is construction for the offshore wind farm, the production phase is the most harmful phase in the case of the onshore wind farm.

In terms of cumulative energy demand (CED), total energy requirement of the offshore wind farm

Table 4. End-of-life summary for both offshore and onshore wind farms.

	Materials Treated		Ratio		
	Material name	Mass (ton)	Recycling (%)	Landfill (%)	Decomposed Components
Offshore	Steel alloyed	2.343,7	90	10	Nacelle, tower, rotor, cables and monopile
	Aluminum	5,3	95	5	Nacelle and rotor
	Copper	293,8	95	5	Nacelle and cables
	Lead	220,0	90	10	
	Polyethylene	135,2	-	100	Internal and grid connection cables
	Polypropylene	77,1	-	100	
	Polyvinylchloride	5,3	-	100	Miscallenous
	Epoxy	8,2	-	100	
	Glass fiber	23,4	-	100	Rotor
Onshore	Iron	844,1	90	10	Nacelle and tower
	Composite	142,0	-	100	Rotor
	Aluminum	131,9	-	100	Electronic parts
	Concrete	3.740,0	95	5	Foundation

Table 5. Acidification and Eutrophication Potential.

Impact Categories	Acidification Potential (AP) [kg SO_2-eq.]		Eutrophication Potential (EP) [kg Phospate-eq.]	
Phases	Onw.	Offw.	Onw.	Offw.
Production	9107.4	492.0	966.3	47.0
Construction	666.5	13417.0	169.1	3248.7
O&M	12.7	1.9	1.3	0.5
DorR	723.1	1211.1	3287.8	250.9
Total	10509.7	15112.0	4424.5	3547.1

Table 6. Global Warming Potential [kg CO2-eq.].

Phases	Onshore W.F.	Offshore W.F
Production	4086925	189495
Construction	277250	4818827
O&M	4.211	295
DorR	2.867.824	1420491
Total	7236210	6429108

Table 7. Energy Demand Ratios Based on Phases [%].

Phases	Onshore W.F.	Offshore W.F
Production	90.236	5.620
Construction	5.570	84.808
O&M	0.262	0.005
DorR	3.931	9.567

and the total energy demand of the onshore wind farm are 81498922.9 MJ and 71374953.9 MJ, respectively. While the construction phase needs 69117297.9 MJ in the case of the offshore wind farm, 64406146.3 MJ is required for the production phase of the onshore wind farm.

It is observed from Table 7 that energy demand for operation of the maintenance phase increases with the number of turbines dramatically independent of the technology utilized gearbox or direct-drive mechanism.

4 SOLAR POTENTIAL AND ASSESSMENT

As mentioned in the introduction part, the solar potential of Bozcaada is one of the important renewable sources for the island (Kalinci, 2015). The island's solar energy potential per day and sunshine duration per day are 308.0 cal/cm^2 and 7,5 hours, respectively (Oğulata, 2003). For this purpose, the proposed land-based photovoltaic power plant is investigated in terms of different perspectives (Kalinci, 2015, Şentürk & Oğuz 2019). Life cycle of proposed land based photovoltaic power plant in Turkey is assessed for the first time in the study (Şentürk & Oğuz, 2019).

4.1 *Other assumptions for solar configuration*

In this section, necessary terms such as degradation rates, performance ratio are defined firstly. Following this, general assumptions concerning solar source are listed.

Degradation rate

Decrease in the solar panel efficiency due to environmental conditions is degradation. Dusting of solar panels and climatic conditions such as average temperature, humidity, temperature differences and ultraviolet (UV) irradiation are the main factors of the degradation phenomenon (Ascencio-Vasquez et al. 2019). Hence, there is a requirement of test to observe the decline of the efficiency of solar panel for different geographic region like in the study (Ozden et al. 2018) which degradation rate of multi-crystalline solar panel is determined as 0.7 % for Central Anatolia. However, it is dependent on geographical conditions and there is no data for the island. Thus, the overall system degradation ratio is assumed to be 0.6 % based on the research article (Jordan & Kurtz, 2013).

Performance ratio

For the photovoltaic technology, it is the ratio of actual electricity generation to the electricity production expected from the ideal case. Due to the need for actual production data, it depends on geographical conditions similar to degradation rates. However, in Turkey, actual electricity generation data from photovoltaic power plants is limited since the history of on-grid applications, started 2012, is relatively new for the photovoltaic technology (Karadogan et al. 2014). One of its important findings is that the estimation of electricity production of PVGIS database is less deviated from the actual electricity generation in Turkey than Metronom database (Karadogan et al. 2014). Hence, PVGIS database is taken into consideration for this study.

- Production processes until the production of silicon wafer itself are considered in the modeling of the first phase, while transportation of raw materials required to manufacture silica wafers is excluded from the study.
- Multi-crystalline cells are preferred for the plant.
- Useful life of conventional photovoltaic plant is assumed to be 30 years (Ito, 2011).
- Fixed-tilt mounting is assumed.
- Degradation ratio is accepted as 0.6 % as mentioned before.
- Performance ratio is accepted as 0.80 % for the conventional one.
- Useful life of inverters for PV plant is suggested as (Ito, 2011) 15 years. Therefore, change of inverters once throughout its life is applied in the modelling of the plant.

4.2 *Model structure of photovoltaic (PV) system*

Since solar configuration is hypothetical, nominal power capacity is accepted as 1.2 MW in order to make comparison easy because the established wind farm area of 20560 m^2 is utilized for the application of land-based PV plant. Site clearance is neglected in the selected area since there is no obstacle such as vegetation or slope for the application of land based farm. Optimum design parameters, provided by PVGIS database, which are 32° slope and 3° azimuth angles are accepted for the array of solar panels.

4.3 *Life cycle inventory (LCI) for photovoltaic (PV) system*

Due to the nominal capacity assumed, the number of total solar modules, each of which consists of 60 cells, are 4615 for the configurations. Mounting components are regarded as fences, support structures and cables for the conventional PV plant. In addition to this, low and medium voltage switchboards and inverters are required.

In the production phase, silicon wafers are produced in Taiwan by means of the Chinese electricity grid mix. They are transported 8689 nautical miles with an ocean-going ship. Open ground mounting structure for the conventional one is composed of aluminum and zinc coated steel.

Construction phase onsets with the transportation of the components. Solar panels are transported from Tekirdağ and transportation distance for three string inverters is totally 459 km (by 451 km truck and 8 km ferry).

During the operation and maintenance phase, spare inverters are changed once due to its limited life expectancy. Tap water is required for the cleaning of solar panels against dusting. 15 solar modules are assumed to be replaced in the conventional PV plant. Transportation for changing broken parts are considered by 371 km truck and by 10 km ferry. Cleaning of solar modules are required the transportation by 80 km truck. Total electricity generation throughout the PV plant is estimated to be 52.31 GWh with the aforementioned degradation rate.

In the last phase of the life cycle assessment, on-site deconstruction is applied to separate the scraps into recycling and disposal. Aluminum and copper, steel scraps coming from inverters, frames and cables are common scrap materials. These scrap materials are transferred by 300 km truck and by 8 km ferry transportation to the recycling area. Solar panels are transferred to Deutsche Solar AG Recycling Plant (Appleyard, 2009) by a cargo plane. Open loop recycling which means that there are no recycled materials turning to the production processes is applied apart from scrap solar panels.

4.4 *Life cycle impact assessment (LCIA) for photovoltaic (PV) system*

Impact assessment for solar configuration on Bozcaada island is evaluated by the LCA of open ground photovoltaic plant.

As seen in Figure 3, the highest energy which is 91.38 % of total energy demand is required for the production phase of PV plant whereas its operation and maintenance phase needs almost no energy.

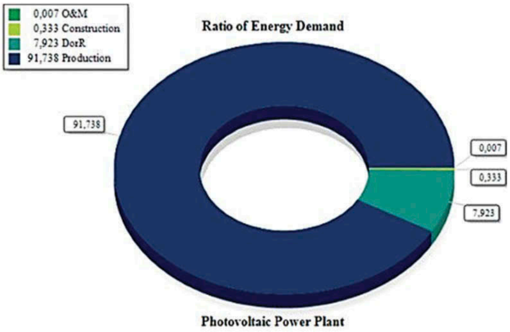

Figure 3. Ratio of energy demand of PV plant.

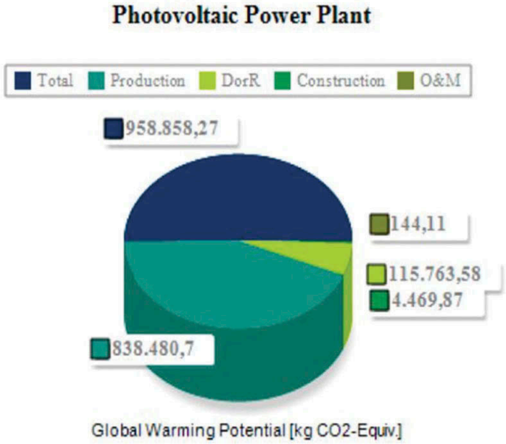

Figure 4. Global Warming Potential (GWP) of PV Plant.

In addition to this, Figure 4 indicates that greenhouse gas emissions during its operation is low for PV technology. The recycling procedure with current technology leads to high emission for photovoltaics although the highest ratio of global warming potential occurs in the production phase. Total GWP for the proposed PV plant throughout its life is 958858,27 kg CO2-eq.

5 RESULTS

The results based on functional unit of each system are tabulated in order to make comparison among all configurations. Selected impact categories for all configurations are tabulated in Table 8.

The offshore wind farm requires less energy to establish than does the onshore wind farm and land-based photovoltaic plant. In other words, it is the most advantageous system in terms of primary energy demand. As a result, its energy pay-back time

Table 8. Selected Impact Categories.

Specifications	Onshore Wind Farm	Offshore Wind Farm	Land-Based PV Plant
AP[kg SO_2-eq. /MWh.]	0.01545	0.01801	0.09816
EP[kg PO_4-eq. /MWh.]	0.00651	0.00422	0.00794
GWP[kg CO_2-eq. /MWh]	10.64	7.65	18.33
CED[MJ/MWh]	104.95	97.02	234.53
EPBT[year]	0.617	0.579	2.06
Total Production-[MWh]	680	840	52.31

is shorter than the other two alternatives related with energy demand.

In terms of environmental characteristics, it can be said that wind source is cleaner than solar source for Bozcaada since wind configurations cause less AP, EP and GWP than the land-based photovoltaic system. Although the offshore wind farm leads to more acidification than the onshore wind farm, it causes less eutrophication and global warming than its onshore counterpart.

6 DISCUSSION

In order to determine environmental characteristics, a road map can be derived with the aid of life cycle assessment of the proposed alternatives prior to investment.

As a suggestion related to the land-based photo-voltaic technology, the new methods should be investigated to diminish the impact of its production phase. The onset of grid-connection of photovoltaics on the world, when has been since the beginning of 1990s (Yudha et al. 2018), is taken into considerations, research on the recycling of solar panels should be accelerated in order to save the world from its contaminative effects.

As a result, offshore wind technology is recommended for the island in terms of environmental specifications by means of life cycle assessment. However, in order to determine the most feasible and sustainable alternatives, firstly, the number of systems examined should be increased. For instance, photovoltaics, floating photovoltaic plant can be considered as another alternative to assess the solar potential of the island or the wave potential of the island (Kalinci, 2015) should be evaluated. Secondly, economic aspects and risks of the options should be investigated with the aid of life cycle methodology to achieve the most feasible option for the island.

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