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Life Cycle Assessment of Wind Turbine in Turkey

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Abstract—**This article aims to assess a life cycle analysis of a wind turbine in Turkey regarding production, transport, construction, operation, and disposal processes in terms of energy and environment. In this context, a 2-MW three-bladed horizontal axis wind turbine has been selected. Two different scenarios have been studied in this paper, which comprises wind turbines using Al-Conductor cable and wind turbines using Cu-Conductor cable. Although the cost of Al-Conductor cables is lower, their joule losses are higher. The life cycle assessment of a wind turbine includes production, transportation, construction, operation and disposal, and the energy has been generated in its operation time which is selected as 20 years. Iron, cast iron, steel, copper, aluminum, and oil have been sent to a recycling facility and the composite material has been sent for incineration at the end of its life. The energy payback period has been calculated as 10 months in both scenarios and the embodied energy is 2858.2 MWh and 2830.3 MWh for a wind turbine using Al-Conductor cable and a wind turbine using Cu-Conductor cable during its lifetime, respectively. Air emission and wastewater generation have been calculated to assess environmental impacts (global warming, acidification, eutrophication, etc.) whose consequence provides an evaluation of the life cycle assessment of a wind turbine. For example, global warming is 14.44 g eq./kWh and 15.24 g CO_2 eq./kWh for a wind turbine using Al-Conductor cable and a wind turbine using Cu-Conductor cable, respectively. As a result, the life cycle analysis of the wind turbines has been evaluated and compared regarding two different scenarios according to the definition of ISO 14040 standard throughout its life from production to disposal.**

Index Terms—**Al-Conductor Cable, Cu-Conductor Cable, Life Cycle Assessment, Wind Turbine**

I. Introduction

ONE OF the branches of renewable energy is wind energy has worked the kinetic energy of wind turns into electrical energy by wind turbines. The wind has been used for various purposes such as milling, pumping water, sailing since ancient times. [1] Due to an increase in CO_2 emission and water consumption and the decrease in fossil fuels, the wind has been one of the energy sources with high growth recently [2]. Wind, solar, biomass, ocean, geothermal, hydropower energies are among renewable energies and are therefore called clean energy and green [3].

The purpose of the paper is to examine the life cycle assessment of a wind turbine according to its energy indexes and environmental impacts. In this context, energy consumption, energy payback time, energy intensity, and CO_2 intensity have been assessed in detail. During its life cycle, the wind turbine has five stages including production, transportation, construction, operation, and disposal. Two types of cables have been used in the electrical infrastructure of wind farms; thus, the results have been evaluated in two scenarios for wind turbines using Al-Conductor and Cu-Conductor cables which aim connection of turbines with each other. On the other hand, Cu-Conductor cables are used inside of the turbines.

A. Life Cycle Assessment

The issue of better understanding and reducing the environmental impacts caused by the production and consumption of products have gained importance in recent years. Therefore, one of the enhanced techniques has been life cycle assessment which aimed that assess environmental impacts and improve the environmental performance of a product throughout its lifetime. In this study, it has been maintained the approaches for life cycle assessment that have been presented in ISO 14040 series standards which have four phases which are goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation [4]. And this association according to phases has been shown in Fig. 1.

B. Environmental Impacts

Environmental impacts have been evaluated as a result of the life cycle assessment, such as global warming, acidification, eutrophication, human toxicity, freshwater aquatic eco-toxicity and photochemical oxidation. Environmental impacts have been determined based on characterization factor and amounts of chemicals. Each chemical has different characterization factor according to environmental impact. Global warming, which is caused by CO_2, NO_2, CH_4 and CFCs, has a global effect. Global warming gives rise to poles to melt, seasons to change, lose to soil moisture and forests to disappear.

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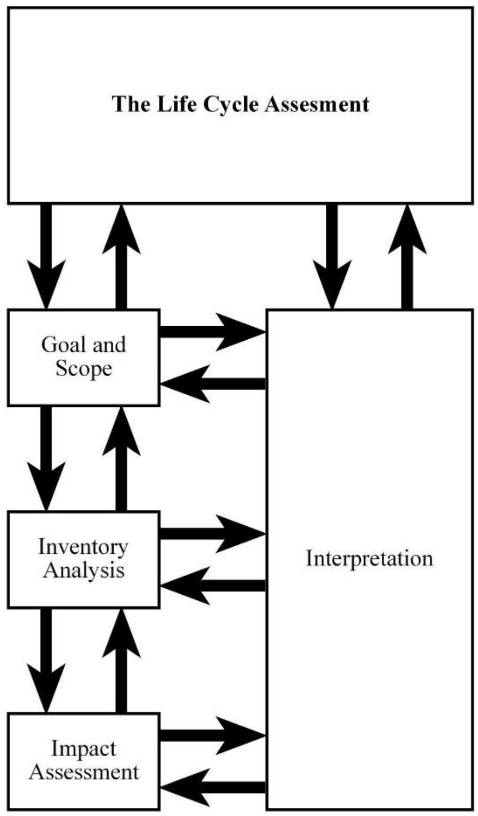

Fig. 1. The Life Cycle Assessment [4]

Acidification has both regional and local effects, commonly caused by SO_x, NO_x, HCL, HF, and NH_4. Acidification leads to corrosion of building, the body of water acidification, vegetation, and soil effects. Eutrophication, is caused by nutrients which are PO_4, NO, NO_2, nitrates, and NH_4, has local effects. Human toxicity stems from chemicals released into the soil, water, and air, increasing the effects of morbidity and mortality at global, regional, and local scales. Aquatic ecotoxicity stems from toxic chemicals at the local scale, which induces decreasing biodiversity in the waterbody. Photochemical oxidation is caused by non-methane hydrocarbon, which leads to smog and vegetation damage [5].

C. Wind Turbine

Wind turbines may be classified on the basis of their rotational axis into horizontal and vertical wind turbines. Nowadays, horizontal axis wind turbines are used more for commercial purposes due to higher efficiency and high power density. On the other hand, the vertical axis wind turbines may be divided into two major types which are the Savonius and the Darrieus. In vertical axis wind turbines design, generator and gearbox are located on the ground, which means that they do not need any tower causing low efficiency due to low wind speed. Vertical axis wind turbines do not need yaw systems since they do not follow the wind direction [6], [7].

In this paper, energy and environmental examinations have been conducted for horizontal axis wind turbines, including life cycle analysis has been evaluated. Thus, components of the horizontal axis wind turbine were examined to analyze the life cycle assessment. The components of the wind turbine are basically divided into four parts which are foundation, tower, rotor, and nacelle [8].

1) Foundation

The most important role of foundation in wind turbines is to provide stability by fixing the wind turbines to the ground. The broadest foundation classifications are slabs foundations and pile foundations [9], [10].

2) Tower

The tower, which is generally made of steel with a tubular form, enables that carry rotor and nacelle. Large static loads due to changing wind power are captivated by the tower. The tower comprises one of the significant components in terms of the cost of the wind turbine [9], [10].

3) Rotor

The rotor can mainly be assessed under two headings: blades and hub. The geometry of blades has been designed by examining aerodynamics; in this context, it resembles the airplane wings which means its cross-section is asymmetric. In order to minimize the loads and fatigue, lightweight materials are chosen, in these circumstances, the blades generally are made of synthetics reinforced with carbon fibers and fiberglass, and epoxy resin. Nowadays, three-bladed horizontal axis wind turbines, which provide the highest efficiency, are preferred. The hub provides that the blades are fixed to the rotor shaft, and it is generally made of cast iron due to its complex structure. The enormously significant function of the hub is that the energy coming from blades transmitted to the generator [9], [10].

4) Nacelle

The nacelle comprises wind turbine machinery which are the main shaft, main bearing, main gear, couplings, mechanical brake, hydraulics systems, generator, machine support frame, nacelle enclosure, and yaw system. Rotational energy coming from the hub is directed to the gearbox or the generator by the main shaft which also hands over the loads to the fixed system nacelle. Main gear, which transports energy among the rotor and the generator, provides that increase speed. Brakes in wind turbines can be categorized into two groups: aerodynamic brake systems and mechanical systems. The aim of the generator is that the mechanical energy is converted to electrical energy. The yaw system provides that the rotor adjusts the right position according to the wind direction [9], [10].

D. Wind Energy in Turkey

In 2019, 8 percent of electricity produced in Turkey provided by wind energy. The estimated wind power installation potential is 48 GW in Turkey, where has suitable areas in the Aegean and Mediterranean region [11]. 1.30% of the area of Turkey has high wind energy potential [12]. The data obtained from the Turkish Wind Energy Association about the cumulative installations of wind energy in Turkey have been shown in Fig. 2.

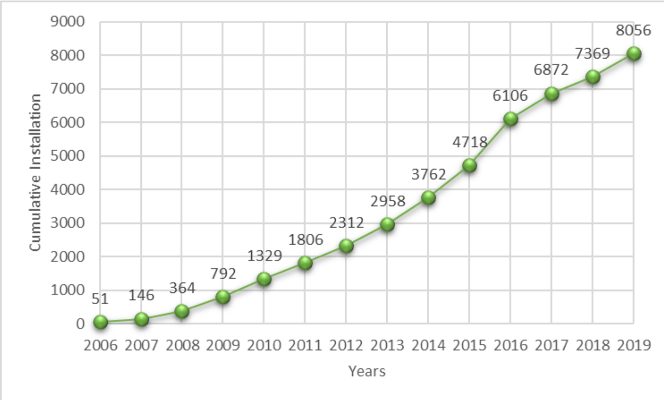

Fig. 2. Cumulative Installation of wind energy in Turkey [13]

II. Stages

The ISO 14040 series standards have defined Life Cycle Assessment (LCA), giving the requirements for its execution. The definition of the ISO 14040 series standards has been used in the determination of environmental impacts of the wind turbine during its entire lifetime. The wind turbine Gamesa G8X model with 2 MW has been investigated in this study in order to calculate the energy consumption and environmental impacts of the wind turbine and its components [8]. Gamesa G8X-2.0 MW wind turbine is a three-bladed horizontal design, active yaw system, upwind and pitch regulated [14]. To start with, necessary materials for the production of the wind turbine have been sorted according to their weights and then their energy requirement has been found to calculate the energy requirement of production of the wind turbine and its components. These materials of the wind turbine are transported and constructed afterward. The operation time of the wind turbine is estimated as 20 years [8]. After complete its life, components of the wind turbine have been sent to proper disposal facilities. As a result, the life cycle assessment of the wind turbine is conducted in five different stages which are production, transportation, construction, operation, and disposal. Fig. 3 represents the stages of a wind turbine life cycle.

TABLE I.
WEIGHT OF WIND TURBINE MATERIALS [8]

Material	Value	Unit
Resin	13	t
Fibre Glass	9	t
Cast Iron	14	t
Iron	44	t
Steel	180	t
Silica	0.3	t
Copper	4	t
Concrete	270	m^3

A. *Production of Wind Turbine*

The wind turbine consists of foundation, tower, rotor, and nacelle. Concrete, steel and iron have been used for foundation which comprises of ferrule and footing. The tower is made of steel and 67 m tall. The nacelle is made of iron, steel, silica, copper, fiber glass and resin. Nacelle includes a bed frame, main shaft, transformer, generator, gearbox, and nacelle cover. Rotor is made of resin, fiber glass and cast iron. Rotor includes three blades, blade hub and nose-cone. The length of a blades is 39 m [8]. The necessary materials and their weights have been given in Table I.

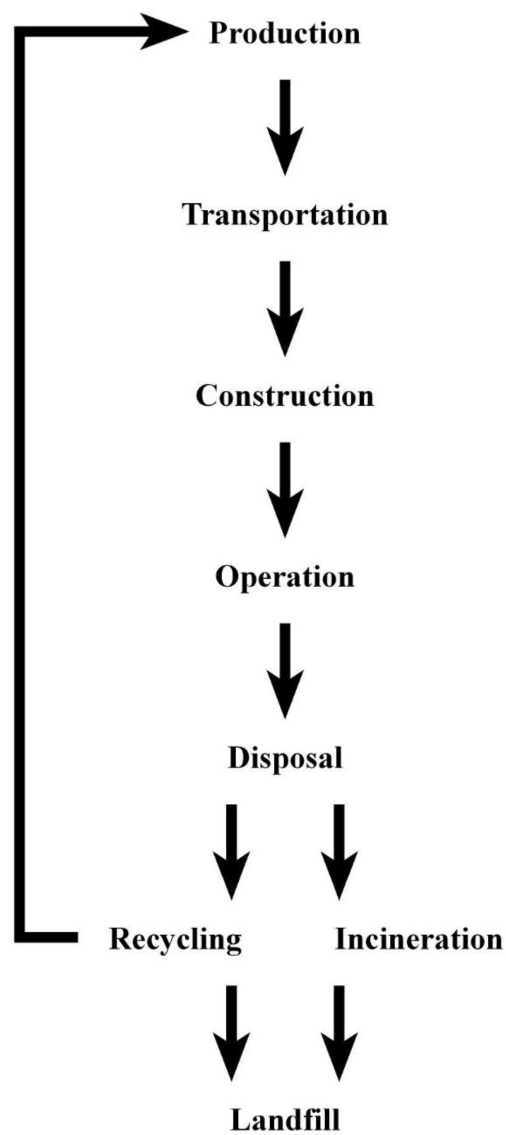

Fig. 3. Summary Life Cycle of a Wind Turbine

Furthermore, cabling has been one of the most significant components of the production of wind turbine. Converting wind energy into electrical energy is made by wind turbines which need an electrical supply system used medium voltage generally. All turbines are connected to the main transformer by cables which transmit the energy. Cables play an important role in terms of their cross-sections and lengths that varies with distance and wind farm structure [15]. XLPE cable has used both internal and connection cabling. XLPE cable in the wind turbine may be divided into two types of cables that Al-

Conductor and Cu-Conductor cable. Al-Conductor cable is made of aluminum and copper; however, Cu-Conductor cable is only made of copper, and both have a triple formation [16]. 50 mm^2 cross section Cu-Conductor cables have been used in internal cabling. In contrast to internal cabling, both Al-Conductor cable and Cu-Conductor cables have been used in connection cabling. It is assumed that 95 mm^2,120 mm^2 and 185 mm^2 cross-section Al-Conductor cables have been used in the connection. In the past, Cu-Conductor cables were used in wind farms. Al-Conductor cables have been used in recent years in Turkey instead of Cu-Conductor cables. Al-Conductor cables have high unit length resistance, notwithstanding it costs less compared with Cu-Conductor cables. Despite the high joule losses, Al-Conductor cables are selected in Turkey because of the cost. The optimization of the position of the cables has not been implemented in Turkey. After the location of wind turbines is determined, the road is determined for construction equipment according to the slope and wind turbine location. Therefore, cables have laid parallel to the road. However, the length of the cables can be shortened owing to optimization. The location of the wind farm has not been determined specifically in this study. Because of this reason, the calculation has been made according to 1 km of cable length.

B. *Transportation of Wind Turbine*

Transportation is one of the most vital stakeholders in life cycle assessment of wind turbines. A specific wind farm has been not specified in this study. However, average distances have been determined from Europe to Turkey via trucks. It is assumed that the tower and foundation have been manufactured in Turkey. The distances from tower and foundation manufacturers to the wind farm are 500 km and 150 km via trucks, respectively. The rotor and nacelle have been transported from Europe to the wind farm, whose distances have been measured as 3500 km and 4000 km, respectively [17].

C. *Construction of Wind Turbine*

Construction equipment, which is necessary for both construction and deconstruction, cause energy consumption and emissions. In this context, crane, forklift and excavation digger have been used both construction and deconstruction. Working hours that seemed appropriate have been decided for construction equipment. The crane has worked for 2 days, the forklift and excavation digger have worked for 1 day and the same working hours have been accepted meanwhile in deconstruction. The fuel consumption of hourly crane, forklift, and excavation digger is 620.1 L, 64 L, and 44.1 L, respectively [18].

D. *Operation of Wind Turbine*

It is predicted that the wind turbine has been 20 years in operation. The wind turbine should be maintained during its operation period. In this context, the 300.8 ton lubricant in the gearbox and the cooling systems of the wind turbine should be changed [19]. The generator, which is made of steel, copper, and silica, should be changed in the operation stage [8].

E. *Disposal of Wind Turbine*

After the wind turbine has completed its life, the components will be sent to appropriate disposal facilities. Iron, cast iron, steel, copper, aluminum and lubricant have sent to recycling facilities. The issue of composite materials has been a controversial subject within the field of disposal methods. In contrast to other materials, composite materials have been sent to the incineration facility in this study [20], [21]. Moreover, it has been taken into account the transportation calculation from the wind farm to disposal facilities.

III. RESULTS

The result part has defined and demonstrated key parameters, which are energy payback time, energy intensity, CO_2 intensity, and environmental impacts. There are two different scenarios currently being adapted in research into life cycle assessment. One is the wind turbine using Al-Conductor cable for connection and the other one is the wind turbine using Cu-Conductor. The reason why it is made two scenarios is two different types of cables used in wind farms. Therefore, it has been calculated in two different scenarios, mentioned and compared their results in detail.

A. *Capacity Factor, Lifetime and Electricity Generation*

Capacity factor varying between 10 and 50% has presented the actual energy production of the wind turbine. However, the capacity factor relevant to modern wind turbines is ranged from 20 to 35%. Reasons for changing the capacity factor can be location, size of the wind turbine, wind reliability, and wind availability. On the other hand, lifetime of a wind turbine can be varied between 20 and 30 years. For many years, the tower and foundation can last, but the generator, gearbox and blades may constitute a problem, so they should be changed relevantly [22].

It is assumed that the 2 MW wind turbine has been used for a duration of 20 years, having a capacity factor of 20%. The assumptions of the present study demonstrate that the annual electricity generation of the wind turbine is 3504 MWh.

B. *Embodied Energy*

One of the energy indexes that may be significant to take into consideration is embodied energy, which may variate according to materials in the production stage, the weight or type of materials, and the choice of the wind turbine, as well as affect the life cycle analysis from wind turbine manufacturing to its disposal stage [22].

Embodied energy has been calculated for five different stages in both scenarios. The total embodied energy of both scenarios has been shown in Table II.

C. *Energy Payback Time, Energy Intensity and CO_2 Intensity*

The term "Energy payback time" refers to a quantitative parameter that recovers initial investment [23]. Eq. (1) below illustrates the calculation of energy payback time [18]:

$$Energy\ Payback\ Time = \frac{Embodied\ Energy}{Generated\ Energy} \tag{1}$$

According to this formula, energy payback time has been calculated for each scenario, and the results have been given in Table II.

Two other indexes are energy intensity and CO_2 intensity, which have a significant role in the life cycle assessment of the wind turbine [24]. The results obtained from both scenarios have been compared in Table II.

TABLE II
ENERGY INDEXES

Wind Turbine	Embodied Energy (MWh)	Energy Payback Time (months)	Energy Intensity (MWh/MWh)	CO_2 Intensity (kg CO_2/kWh)
Wind Turbine using Al-Conductor Cable	2858.2	10	0.0408	0.016
Wind Turbine using Cu-Conductor Cable	2830.3	10	0.0404	0.017

A comparison of the two embodied energy results reveals that there is no strict difference between Al-Conductor and Cu-Conductor wind turbines. The reason why the high result in the embodied energy of the wind turbine using Al-Conductor cable is energy consumption in both production and disposal stages. Comparing the two results of energy payback time, it can be seen that these two results are the same in both scenarios. No important difference has been found between both wind turbines in terms of energy and CO_2 intensity. These parameters have played such a significant role in the life cycle assessment of wind turbines that they have compared them with other results obtained from the literature, and it has been shown in Table III.

TABLE III
LITERATURE COMPARISON

Wind Turbine	Lifetime (years)	Onshore/Offshore	Power (MW)	Energy Payback Time (years)	Energy Intensity (MWh/MWh)	CO_2 Intensity (gCO_2/kWh)
Wind Turbine using Al-Conductor	20	Onshore	2	0.82	0.041	15.92
Wind Turbine using Cu-Conductor	20	Onshore	2	0.81	0.040	16.71
France [24]	20	Onshore	3	1.03	0.051	11.77
France [24]	40	Onshore	3	0.81	0.04	8.87
Italy [25]	20	Onshore	0.66	-	-	14.8*
Vestas V110 [26]	20	Onshore	2	0.67	-	7.2*
Vestas V112 [27]	20	Onshore	3	0.67	-	7*
Siemens Wind Power [28]	-	Onshore	2.3	0.52	-	6*
Siemens Wind Power [28]	-	Onshore	3.2	0.43	-	5*
Siemens Wind Power [28]	-	Offshore	4	0.93	-	10.9*
Siemens Wind Power [28]	-	Offshore	6	0.83	-	7.8*

*given in terms of gCO_2-eq/kW

It can be seen from the data in Table III that the lifetime of the wind turbine generally evaluates as 20 years. It is apparent from this table that all wind turbines except one have less than a year of energy payback time. It has been reported similar results for energy intensity. However, it has been listed various results for CO_2 intensity due to different acceptance.

D. Air Emission and Wastewater Generation

Air emissions and wastewater generation have been calculated in order to conclude a better understanding of the life cycle assessment of the wind turbine and predict the environmental impacts of the wind turbine. It is assumed that wastewater has been generated during the production of the materials. Table III illustrates some of the main parameters of the wastewater generated by wind turbine production. Unlike wastewater generation, all stages have resulted in air emissions. Air pollutants may be classified two categories which are primary air pollutants and secondary air pollutants. Primary air pollutants have been released directly to the atmosphere from a source, that pollutants are NO_x, CO, SO_x, PM and Hydrocarbons. Primary pollutants cause diseases that have a great risk for human health such as cardiovascular disease, cancer, chronic obstructive pulmonary disease and asthma [29]. Apart from hydrocarbons, all primary air pollutants have been listed in Table IV.

TABLE IV
WASTEWATER GENERATION

Pollutant	Wind Turbine using Al-Conductor	Wind Turbine using Cu-Conductor	Unit
Chemical Oxygen Demand (COD)	0.047	0.047	g/kWh
Suspended Solid	0.005	0.005	g/kWh
Total Organic Carbon (TOC)	0.004	0.004	g/kWh
Biochemical Oxygen Demand (BOD_5)	0.002	0.002	g/kWh

TABLE V
AIR EMISSION

Pollutant	Wind Turbine using Al-Conductor	Wind Turbine using Cu-Conductor	Unit
SO_2	0.01	0.01	gSO_2/kWh
NO_x	0.04	0.04	gNO_x/kWh
CO	0.02	0.01	gCO/kWh
$PM_{2.5}$	0.002	0.002	$gPM_{2.5}$/kWh

E. Life Cycle Assessment

Wastewater and air emissions give rise to environmental impacts, and the resulting substances have been calculated by characterization factors. Environmental impacts are listed in Table V as a result of the entire life cycle of the wind turbine.

TABLE VI
LIFE CYCLE ASSESSMENT

Environmental Impact	Wind Turbine using Al-Conductor	Wind Turbine using Cu-Conductor	Unit
Global Warming (GWP100)	14.44	15.24	g CO_2 eq./kWh
Eutrophication (EP)	5.39	5.39	mg PO_4- eq./kWh
Acidification (AP)	14.43	14.43	mg SO_2 eq./kWh
Human Toxicity (HT)	699.86	700.02	mg 1,4-dichlorobenzene eq./kWh
Freshwater Aquatic Eco toxicity (FWAE)	86.30	85.03	mg 1,4-dichlorobenzene eq./kWh
Photochemical Oxidation (POCP)	1.17	1.02	mg ethylene eq./kWh

It is seen obviously that both scenarios are quite similar in terms of environmental impacts. However, it is necessary to express which scenario causes more environmental impacts. Wind turbines using Al-Conductor cable have a greater effect on global warming, eutrophication, human toxicity; although, wind turbines using Cu-Conductor cable have a higher effect on photochemical oxidation and freshwater aquatic eco-toxicity. And both scenarios have the same acidification effect on the environment. As shown in Fig. 4 and 5 that transportation, construction, and operation stages have the same rate in both cases, and production and disposal stages present a difference in these two situations because of cables.

F. Disposal and Total Energy Consumption

On the other hand, the share of disposal in the energy consumption has a great importance. 27.0% of the total energy consumption has been spent on a wind turbine using Cu-Conductor cable and 26.6% of the total energy consumption has been spent on a wind turbine using Al-Conductor cable. This situation indicates that disposal is a significant indicator in energy consumption due to its higher than one-quarter portion.

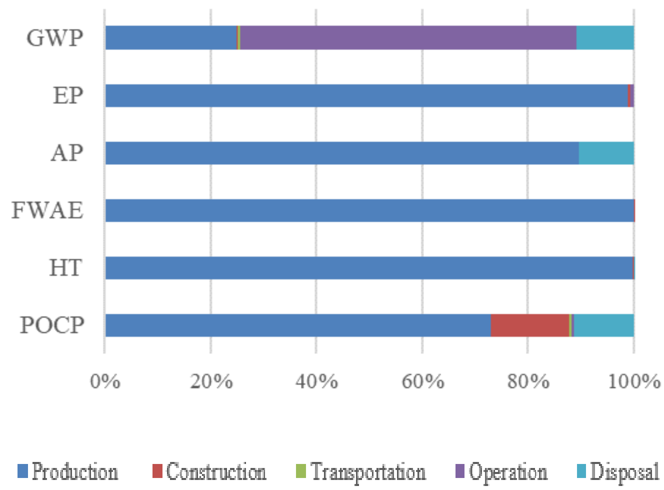

Fig. 4. Wind Turbine with Al-Conductor Cable

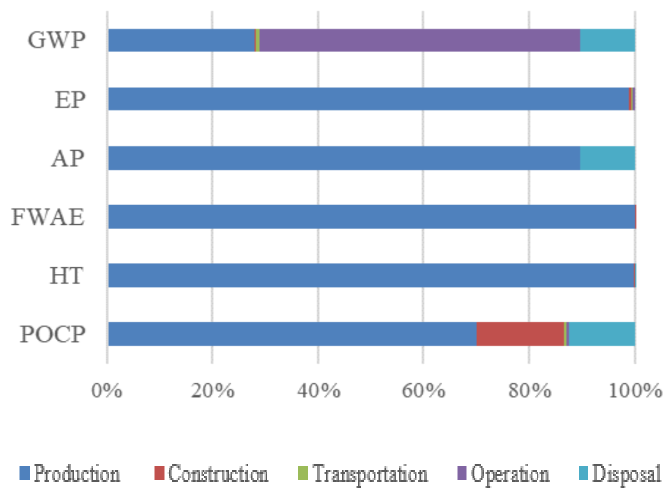

Fig. 5. Wind Turbine with Cu-Conductor Cable

IV. DISCUSSIONS

This paper has set out to determine the life cycle assessment of a wind turbine in Turkey, consisting of a comparison between wind turbine using Al-Conductor and wind turbine using Cu-Conductor. This paper has shown the energy indexes and environmental impacts of a wind turbine, and the results have been given based on comparative analysis. Considering the comparison of the energy payback times of the scenarios, the wind turbine using the Al-Conductor cable is longer than the wind turbine using the Cu-Conductor cable; as a result, the wind turbine using the Cu-Conductor cable provides shortening the energy payback time. Al-Conductor cable is more widely used nowadays because of its cost. Although a wind turbine using an Al-Conductor cable is higher in embodied energy, its impact on global warming is less. The data given in this article for Al-Conductor cable is of great importance for many countries. The calculations could change according to the geography of the wind farm, the location of wind turbines and cabling and the design of cabling; therefore, it cannot be generalized.

V. Conclusion

Further research in the disposal method of the blades would be useful to clarify the subject. In this study, it was determined that the blades are sent to the incineration facility since their recycling efficiency is low. On the other hand, the foundation has been left in the wind farm after the wind turbine completes its lifetime, and this situation should be evaluated in further research. In this study, cables were sent to a recycling facility, but cable sales are another option for this situation. Further research has needed to be done to establish whether sales of cable or recycling of cable is more efficient.

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BIOGRAPHIES

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