ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

LIFE CYCLE ASSESSMENT IN WIND TURBINES

M.Sc. THESIS

Buket KÜÇÜKKARACA

Energy Science and Technology Division

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JULY 2020

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Thesis Advisor: Dr. Lecturer Burak BARUTÇU

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

RÜZGAR TÜRBİNLERİNDE YAŞAM DÖNGÜSÜ ANALİZİ

YÜKSEK LİSANS TEZİ

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To my family,

FOREWORD

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ABBREVIATIONS

AC: Acidification Chemical
AP: Acidification Potential
BOD: Biological Oxygen Demand
BOF: Blast Oxygen Furnace
COD: Chemical Oxygen Demand
EAF: Electric Arc Furnace
EC: Eutrophication Chemical
EF: Emission Factor
EP: Eutrophication Potential
FWAE: Freshwater Aquatic Eco-Toxicity
GG: Greenhouse Gas
GHP: gross engine horsepower at governed engine rpm
GWP: Global Warming Potential
HAWT: Horizantal-Axis Wind Turbine
HCFC: Hydrochlorofluorocarbon
HT: Human Toxicity
IS: Impact Score
K: kg fuel used per brake hp/hour
KPL: weight of fuel in kg/L
LCA: Life Cycle Assessment
LMPH: liters used per machine hour
MAE: Marine Aquatic Eco-Toxicity
NMVOC: Non-methane volatile organic compound
ODC: Ozone Depletion Chemical
ODP: Ozone Depletion Potential
PAH: Polycyclic Aromatic Hydrocarbon
PCB: Polychlorinated Biphenyl
PM: Particulate Matter
POC: Smog Creation Chemical
POCP: Photochemical Oxidant Creation Potential
PV: Photovoltaics
SCN-: Thiocyanate
TOC: Total Organic Carbon
TSP: Total Suspended Particles
TSS: Total Suspended Solid
UV: Ultraviolet
VAWT: Vertical-Axis Wind Turbine
XLPE: Cross-linked polyethylene

SYMBOLS

Al: Aluminum
Amt_{AC}: the amount of acidification chemical released for any chemical
Amt_{EC}: the amount of eutrophication chemical released for any chemical
Amt_{GG}: the amount of greenhouse gas released for any chemical
Amt_{ODC}: the amount of ozone depleting chemical chemical released for any chemical
Amt_{POC}: the amount of smog forming chemical chemical released for any chemical
As: Arsenic
Cd: Cadmium
Cr: Chromium
Cu: Copper
EF_{AP}: equivalency factor for acidification potential
EF_{EP}: equivalency factor for eutrophication potential
EF_{GWP}: equivalency factor for global warming potential
EF_{ODP}: equivalency factor for ozone depletion potential
EF_{POCP}: equivalency factor for photochemical oxidant creation potential
eq: equivalent
Hg: Mercury
IS_{AP}: the amount of acidification for any chemical
IS_{EUTR}: the amount of eutrophication for any chemical
IS_{GW}: the amount of global warming for any chemical
IS_{OD}: the amount of ozone depletion for any chemical
IS_{POCP}: the amount of photochemical smog for any chemical
Ni: Nickel
Pb: Lead
PM_{10}: Particulate matter with 10 micrometers diameter
$PM_{2.5}$: Particulate matter with 2.5 micrometers diameter
Zn: Zinc

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LIFE CYCLE ASSESSMENT IN WIND TURBINES

SUMMARY

Today in the world, fossil fuels such as coal, natural gas, and oil, are the most widespread used source of energy. However, the use of renewable energy has been increasing over time. The driving factors of such an increase in the use of renewable energy sources are mainly the depletion of fossil fuels and environmental pollution. Renewable energy sources are not exhausted because they naturally replenish themselves and cause less environmental pollution than fossil fuels. However, renewable energy sources vary due to geography.

Wind is an environmentally friendly and inexhaustible source of energy. Wind turbines generate energy using wind power. These turbines can be built on land (onshore) and on the sea (offshore). Wind turbines built on land are easier to install and cost less. Additionally, there are two types of wind turbines which are horizontal and vertical axis wind turbines. The advantages of vertical axis wind turbines are that the generator is located at ground level and does not need a tower therefore they are less costly build and maintain. The disadvantages are low wind speed and low efficiency. Positions of horizontal axis wind turbines can be upwind or downwind. Due to high wind speed, horizontal axis wind turbines have higher efficiency.

Horizontal axis wind turbines have four elements which are foundation, tower, nacelle, and rotor. The foundation consists of concrete, steel, and iron, and is a part of the wind turbine used to fix it to the ground. The tower consists of steel and carries the nacelle and the rotor. The nacelle consists of a rotor shaft with bedding, gearbox, brakes and coupling, and a generator. Rotor converts kinetic energy of linear wind flow to rotational movement. In general, the blades are made from fibreglass and epoxy resin. The blade hub is located in the middle of the rotor and the blades are attached to this structure. The blade hub is made of cast iron and it provides the energy from the blades to be transmitted to the generator.

In this thesis, the life cycle assessment of horizontal axis onshore 2 MW wind turbines is made. Furthermore, energy consumption, emission, and wastewater generation during different stages of the wind turbines' life cycle and consequent environmental effects are investigated. These stages of the wind turbines are manufacturing, transportation, construction, operation, and disposal. Four different scenarios are studied for this thesis which are the use of cables with aluminum or copper conductors and whether there is transportation or not.

The rotor consists of a blade, hub, and nose cone which are made up of resin, fibreglass, and cast iron. The foundation consists of concrete, iron, and steel. The tower consists of three parts and is made of steel. Nacelle consists of bed frame, main shaft, transformer, generator, gearbox, and nacelle cover which consist of iron, steel, silicon, copper, resin, and fibreglass. Cables can be aluminum conductors or copper conductors. However, only copper cable is used inside the turbine with cross section of 50 mm^2. Since no specific wind farm is used, the estimation is made according to 1 km cables with a cross section of 95, 120, and 185 mm^2.

In transportation, since there is no specific wind farm, an estimation is calculated by using the average transportation data of various wind farms. However, while calculating, scenarios are created with and without transportation, because specific transportation data of each site is not clear and the use of different transportation methods such as trucks or ships creates a wide range of divergence.

Construction machines are required for the construction and deconstruction of the wind turbine at the end of its life. The use of cranes, forklift, and excavation digger is calculated.

It is predicted that the lubricant will be replenished and the generator will be replaced during the operation of the wind turbine. This operating time is assumed to be 20 years for the turbine used in this study.

In its disposal, it is aimed to send iron, cast iron, steel, copper, aluminum, and lubricant for recycling. Since the recycling of composite material has low efficiency, it is decided to send to incineration. This disposal process is carried out separately for both aluminum conductor and copper conductor cables. It is also taken into account that these materials are sent to recycling facilities after completion of their lifetime. Since there is no specific wind farm used for calculations, a distance of 100 km taken for disposal of each material.

Emissions and energy consumption are calculated for each scenario. In addition, wastewater generation during the production of the wind turbine is calculated. Environmental impacts from these emissions and wastewater are calculated for four different scenarios. Environmental impacts which are global warming, acidification, eutrophication, photochemical smoke, human toxicity, freshwater/marine toxicity, and terrestrial toxicity is evaluated in this life cycle according to the results of each stage. The effects of each process on how they contribute to the environmental impacts are evaluated under four different scenarios and displayed by graphs. Furthermore, these scenarios are compared with Vestas V100 wind turbines in terms of their contribution to environmental impacts. In addition to this comparison, the environmental impacts of the wind turbines used in this study are also assessed according to whether they are produced within Turkey or imported from Europe and transported to Turkey.

As a result, when these four scenarios are analyzed, there is a big difference between the scenarios with and without transportation in terms of energy payback period. Environmental impacts vary according to scenarios for each element. It is concluded that the environmental effects vary according to the materials used; aluminum cable or copper cable and different results are also obtained in terms of environmental impacts according to the inclusion or exclusion of the transportation stage.

In conclusion, if recycling is considered positive, more energy is required for the Cu-conductor wind turbine. However, if recycling is considered negative, Al-conductor wind turbine requires more energy. The effect of global warming is more in the copper conductor wind turbine.

For future studies, the disposal method for cables, blades, and foundation can be explored to handle better results in terms of environmental and economic aspects.

RÜZGAR TÜRBİNLERİNDE YAŞAM DÖNGÜSÜ ANALİZİ

ÖZET

Dünyada enerji kaynağı olarak ağırlıklı olarak fosil yakıtlar kullanılmaktadır. Fosil yakıtlara petrol, doğal gaz ve kömür örnek gösterilebilir . Ancak, zaman geçtikçe yenilenebilir enerji kaynaklarının kullanımı artmaktadır. Bunun başlıca sebepleri ise, fosil yakıtların tükenmesi ve çevre kirliliğidir. Yenilenebilir enerji kaynakları ise kendini yenilediğinden dolayı tükenmez ve çevreyi fosil yakıtlar kadar kirletmez. Ancak, yenilenebilir enerji kaynakları coğrafyaya göre değişkenlik gösterir. Yenilenebilir enerji kaynaklarına örnek ise güneş, rüzgar, biyokütle, dalga gösterilebilir.

BP'nin verilerine göre, dünyada birincil enerji tüketimi 2018 yılında %33,62 petrol, %27,21 kömür, %23,87 doğalgaz, %6,84 hidroelektrik, %4,41 nükleer ve %4,05 yenilenebilir enerjidir. Türkiye'de ise birincil enerji tüketimi 2018 yılında %31,63 petrol, %27,56 kömür, %26,49 doğalgaz, %8,77 hidroelektrik enerji ve %5,56 yenilenebilir enerjidir. Bu durumda, Türkiye'nin dünyaya oranla yenilenebilir enerjiden yararlanma oranı daha fazladır. Yenilenebilir enerji payı içerisinde ise dünyada %51 rüzgar enerjisi kullanılmakta olup Türkiye'de ise %53'tür.

Enerji sistemleri karşılaştırıldığında ömür bakımından rüzgar enerjisi 20-25 yıl gözükmektedir Diğer enerji sistemlerine göre daha az ömrü vardır. Örneğin hidroelektrik santralleri 70 yıl, nükleer santralleri 40 yıl, kömür ve güneş 30 yıl işletilebilir. Alan kullanımı bakımından incelendiğinde ise rüzgar enerjisi yaklaşık olarak 2 W/m^2' dir. Nükleer enerjide ise yaklaşık olarak 966 W/m^2'dir. Kapasite faktörü bakımından incelendiğinde ise rüzgar enerjisinin yaklaşık olarak %35, nükleer enerjinin %93, PV'nin %25 ve kömürün ise %54'dir.

Rüzgar çevre dostu ve tükenmeyen bir enerji kaynağıdır ve rüzgar türbinleri sayesinde elektrik üretilir. Rüzgar türbinleri karada ve deniz üstünde kurulabilir. Karada kurulan rüzgar türbinlerinin kurulumu daha kolay ve maliyeti deniz üstünde kurulan rüzgar türbinlerine kıyasla daha azdır. Diğer taraftan, yatay ve dikey eksenli rüzgar türbinleri olmak üzere iki tip rüzgar türbini vardır. Dikey eksenli rüzgar türbinlerinin avantajları, jeneratörün zemin seviyesinde bulunması ve kuleye ihtiyaç duyulmamasıdır. Dezavantajları ise düşük rüzgar hızı ve düşük verimdir. Yatay eksenli rüzgar türbinleri ise yüksek rüzgar hızından dolayı daha verimlidir. Dikey eksenli rüzgar türbinleri düşük rotor veriminden ötürü tercih edilmemektedir.

Yatay eksenli rüzgar türbinlerinde dört eleman vardır: temel, kule, makine bölümü ve rotordur. Temel; beton, çelik ve demirden oluşup kulenin sabit durması için bir elemandır. Kule ise genellikle çelikten oluşup makine bölümünü ve rotoru taşır. Makine bölümü ise hız mili, vites kutusu, kontrol ünitesi ve jeneratörden oluşur. Rotor ise rüzgar enerjisini kanatlar sayesinde mekanik enerjiye çevirir. Genel olarak kanatlar, fiberglas ve epoksi resinden yapılır. Gövde ise rotorun ortasında bulunup kanatlar bu yapıya tutunur. Gövde ise döküm demirden yapılır. Gövde kanatlardan gelen enerjinin jeneratöre iletilmesini sağlar. Bu çalışmada karada kurulan yatay eksenli rüzgar

türbinlerinin yaşam döngüsü analizi yapılmıştır. Bu yaşam döngüsünde çevresel etkiler değerlendirilmiştir.

İlk incelenen çevresel etki ise küresel ısınma potansiyelidir. Güneşten gelen ışınlar kısmen emilir ve doğrudan ısınmaya neden olur. Güneşten gelen dalganın diğer kısmı yansıtılır. Dünyanın yüzeyi bu ışınları atmosfere geri yansıtır, ancak bu dalgalar CO_2, metan ve CFC gibi sera gazları tarafından emilir. Bu dünyanın ısınmasına neden olur; dolayısıyla küresel ısınmaya neden olur. CO_2-eq ile tanımlanır. Asidifikasyon ise SO_2, NO_x, HCL, HF ve NH_4 gazlarının salınımı sebebiyle olur. Asidifikasyon korozyon oluşmasına, suların asitlenmesine, bitki örtüsüne ve toprağa zarar vermesine neden olur. Stratosferik Ozon Tabakası CFC, HCFC, halonlar ve CH_3Br gazlarından kaynaklanır. Ozon tabakasının incelmesi UV radyasyonunda artışa neden olur. Fotokimyasal duman, görüşün azalmasına, göz ve akciğer tahrişine, solunum yoluna ve bitki örtüsü ve materyallere zarar verir. Eko-toksisite potansiyeli bir ekosistemin üzerindeki zararlı etkileri özetlemeyi amaçlar. İnsan, karasal ve su olarak ayrı ayrı incelenir. Ötrofikasyonda ise PO_4, NO, NO_2, Nitratlar ve NH_4 kimyasalları sebep olur. Belirli bir su kütlesinde hava kirleticileri ve atık su nedeniyle besin zenginleşmesi gerçekleşir. Sonuç olarak, alg patlaması gerçekleşir. Bu nedenle, güneş ışığı su derinliklerine ulaşamaz ve canlılar fotosentez yapamaz ve oksijen azalır. Sonuç olarak, ekosistem yok olma tehlikesi ile karşılaşır.

Bu çalışmada, rüzgar türbini üretilirken, kullanılan parçaların transferi, inşaatı sırasında, ve rüzgar türbini çalışırken ve ömrünü tamamladıktan sonra bertarafı sırasında harcanan enerjiler ve bu süreçlerin çevresel etkileri incelenmiştir. Bu çalışmada 2 MW'lık bir rüzgar türbini incelenmiştir ve 4 farklı senaryo oluşturulmuştur. Alüminyum yada bakır iletkenli kablo kullanılması yada ulaşım olup olmaması durumları incelenmiştir.

Rotorda kanat, gövde ve burun konisinden oluşmaktadır. Kullanılan malzemeler resin, fiber glas ve döküm demirden oluşmaktadır. Temel ise beton, demir ve çelikten oluşmaktadır. Kule ise 3 parçadan oluşup çelikten yapılmıştır. Nacelle ise yatak, ana mil, transformatör, jeneratör, dişli kutusu ve nacelle kapağından oluşur. Kullanılan malzemeler ise demir, çelik, silisyum, bakır, resin ve fiber glastır. Kablolar alüminyum iletken yada bakır iletken şeklinde olabilir. Ancak türbin içinde yalnızca bakır kablo kullanılmaktadır. Belirli bir rüzgar tarlası kullanılmadığı için 1 km'lik 95, 120, 185 mm^2 kesitlik kablolara göre tahmin yapılmıştır.

Ulaşımda ise belli bir rüzgar tarlası olmadığı için belli rüzgar tarlalarının ortalama ulaşım verileri kullanılarak hesaplamalar yapılmıştır. Ancak hesap yapılırken ulaşımlı ve ulaşımsız olmak üzere senaryolar oluşturulmuştur çünkü her bir sahanın farklı ulaşım verileri bulunmaktadır. Tır yada gemi kullanımı büyük farklılıklar oluşturur.

Rüzgar türbinin inşaatı ve ömrünün sonunda sökülmesi için iş makinaları gerekmektedir. Vinç, yük kaldırma aracı ve kazı makinaları kullanılması durumları hesaplanmıştır.

Rüzgar türbininin işletimi sırasında bir jeneratör değişimi ve yağ değişimi yapıldığı öngörülmektedir. Bu işletim süresinin bu türbin için 20 yıl olduğu kabul edilmiştir.

Bertarafında ise demir, döküm demir, çelik, bakır, alüminyum ve yağ geri dönüşüme gönderilmesi hedeflenmiştir. Bu sayede kullanılan malzemelerde geri kazanım elde edilmiş olunacaktır. Kompozit malzemenin geri dönüşümünün verimliliği düşük olduğundan yakmaya gönderilmesi kararlaştırılmıştır. Bu bertaraf süreci hem alüminyum iletkenli hem de bakır iletkenli kablo için ayrı ayrı yapılmıştır. Ayrıca bu malzemelerin sökülmesinden sonra bertaraf tesislerine gönderilmesi de hesaba katılmıştır. Belirli bir rüzgar tarlası olmadığı için her bir malzeme için 100 km'lik bir uzaklık alınmıştır.

Her senaryo için çıkan emisyonlar ve enerji harcamaları hesaplanmıştır. Ayrıca, rüzgar türbininin üretilmesi sırasında çıkan atıksu da hesaplanmıştır. Bu çıkan emisyonlardan ve atıksulardan kaynaklı çevresel etkiler dört farklı senaryo için hesaplanmıştır. Çevresel etkilerin hangi süreç tarafından ne kadar etkilendiği dört farklı senaryo için grafik olarak gösterilmiştir.

Ayrıca dört farklı senaryo Vestas'ın V100 modeli ile çevresel etki bakımından karşılaştırılmıştır. Bu tez çalışmasında kullanılan rüzgâr türbininin çevresel etkileri imalatın Türkiye'de olup Türkiye'ye bu türbini kurma durumu ve Avrupa'dan Türkiye'ye ithali durumu incelenmiştir.

Bu dört senaryo incelendiğinde enerji geri ödeme süresinde ulaşımlı ve ulaşımsız senaryolarda büyük bir farklılık oluşmuştur. Çevresel etkiler ise her bir çevresel etki için senaryolara göre değişiklik gösterir. Alüminyum kablo yada bakır kablo kullanılması durumda nasıl çevresel farklılıkların olduğu bu tezin sonucundan çıkartılabilir. Ayrıca ulaşımın yarattığı çevresel farklılıklar da gösterilmiştir.

Sonuç olarak, geri dönüşüm pozitif olarak düşünülürse bakır iletken kablolu rüzgar türbini için daha fazla enerji gerekmektedir. Ancak, eğer geri dönüşüm negatif kabul edilirse alüminyum iletken kablolu rüzgar türbinlerinin enerji harcaması daha fazla olur. Küresel ısınmanın etkisi ise bakır iletkenli rüzgar türbininde daha fazladır. Gelecekteki çalışmalarda; kablolar, kanat ve temel için bertaraf yöntemleri üzerine araştırmalar yapılırsa çevresel ve ekonomik açıdan daha iyi sonuçlar elde edilebilir.

1. INTRODUCTION

The sustainability of energy is a key factor for both the survival of societies and the durability of their economies. Energy should be sustainable in order to meet the requirements of the societies. Most of the world's energy is supplied by fossil fuels which are coal, natural gas, and oil. Nonetheless, renewable energy, whose usage is being widely available, is started to gain importance [1]. The reason for this is that fossil fuels affect the environment adversely such as global warming, acidification, eutrophication. Additionally, fossil fuels will have availability and accessibility problems in the future. At the same time, unstable prices have an adverse effect on economies [2]. The energy requirement is necessary for residential, commercial, industrial, and transportational use. There are two types of energy sources which are non-renewable and renewable energy sources. Coal, natural gas, petroleum, and uranium are non-renewable energy sources. It is called non-renewable energy because energy sources are consumed in time. Biomass, hydropower, wind, geothermal and solar power are renewable energy sources which cannot be depleted over time [3]. The use of renewable energy provides cleaner energy which means their environmental pollution and their impact on human health are reduced in comparison to the other energy sources. Using renewable energy sources provides energy diversity and consequently increases their reliability. By using a domestic renewable energy source, dependency on fossil fuels and import costs are reduced. However, availability of the renewable energy sources strictly depends on geography and installation costs are very high. For years, the wind has had various utilizations such as the generation of electricity, pumping of water, and supply of power. Wind energy is handled from onshore wind turbines or offshore wind turbines. Wind energy has a big potential to meet the requirement of energy. The estimations of wind energy production changes between 20,000 TWh per year for only onshore wind turbines and 125,000 TWh per year for onshore and near onshore wind turbines [4].

1.1. Purpose of Thesis

The aim of this thesis is to determine the amount of environmental impact of wind turbine manufacturing, construction, transportation, operation, and disposal stages. In order to assess environmental impacts, air emissions and energy consumptions are calculated for each process. The wastewater production due to the manufacturing of wind turbine parts is also calculated in order to determine the environmental impact.

Four scenarios are created in order to compare different wind turbines. These scenarios are aluminum conductor cable with and without transportation, and copper conductor cable with and without transportation.

Energy consumption during the lifecycle of the wind turbine is calculated. This total energy consumption is divided to its yearly energy production in order to calculate energy payback time of the wind turbine. This energy payback time is calculated for each of the four scenarios.

Environmental impacts for these four scenarios are calculated. The environmental impacts which are used in this thesis are global warming, acidification, eutrophication, photochemical smoke, human toxicity, freshwater/marine toxicity, and terrestrial toxicity.

The first part of the study starts with a brief general information on energy including the disadvantages of fossil fuels and the advantages of renewable energy. Then it is followed by an explanation of the aim of the study and how it is structured.

The second part of the study examines the distribution of primary energy consumption in the world and in Turkey, and the distribution of the renewable energy in the world and in Turkey. The section is concluded by the literature review of the thesis.

The third part starts with an explanation of how wind energy is obtained and provides the different types of wind turbines used for this process as well as touching upon characteristics and the efficiency of each of the types. It is followed by concisely laying out the facts on the wind energy market both worldwide and in Turkey. Then, an examination on the parts of the wind turbine and its composition concludes the section.

The fourth part introduces the several environmental impacts that will be examined later on account of the contribution of wind turbine production to these environmental impacts. This section provides the definition of each environmental impact along with the chemicals that are causing them and shows the mechanism behind.

The fifth part includes the detailed account of parts of the wind turbine life cycle which are manufacturing, transportation, construction, operation, and disposal processes, including the energy consumption during these processes.

The sixth part includes total energy consumption and energy payback time. After adding the emission and wastewater amount data, the environmental impact is calculated. All of these calculations are performed for each of the four scenarios. These four scenarios are also compared with the Vestas V100 wind turbines. Furthermore, the aforementioned calculations are performed under the scenarios which the wind turbines are produced in Turkey and imported from European countries. The energy systems used throughout the globe are compared for their lifetime, land use, and capacity factors.

The seventh part gives a conclusion and recommendations about this thesis.

2. ENERGY

Energy is needed for the continuity of life and can be obtained from natural resources. Fossil fuels include coal, natural gas, oil and nuclear; solar, wind, biomass, hydraulic, geothermal, and wave are examples of renewable energy. Renewable energy continues to produce itself but depends on climate and region. At the same time, renewable energy produces less greenhouse gases and has less harmful effects on the environment. Fossil fuels are a widespread element of energy production; however, they cause environmental pollution. Typical pollutants from industries are flue gases, exhaust gases, SO_2, NO_x, hydrocarbons, and particulate matters that cause acidification. Additionally, heavy metals are released from these factories which can cause toxic effects on living organisms. Environmental pollutants can pollute water, air and soil and create problems for the future. Industrial activities are the biggest reason for environmental problems due to the use of fossil fuels in energy consumption, and their contribution to global warming is 49% [5].

2.1.The Distribution of Primary Energy Consumption in the World

In order to understand energy statistics, it is crucial to understand the terms of primary and secondary energy consumption. Primary energy consumption is the energy extracted or captured directly from natural resources. On the other hand, the secondary energy consumption is the usage of energy form which is converted from a primary or a different secondary energy source [6,7]

Fossil fuels take a large share in primary energy consumption in the world and it can be seen in the data provided below. Primary energy consumption of the world consists of 33.62% of oil, 27.21% of coal, 23.87% of natural gas, 6.84% of hydroelectric, 4.41% of nuclear, and 4.05% of renewables in 2018. The primary energy consumption is 13864.9 Mtoe in the world in 2018 [8]. Figure 2.1 shows the primary energy consumption of the world by fuels.

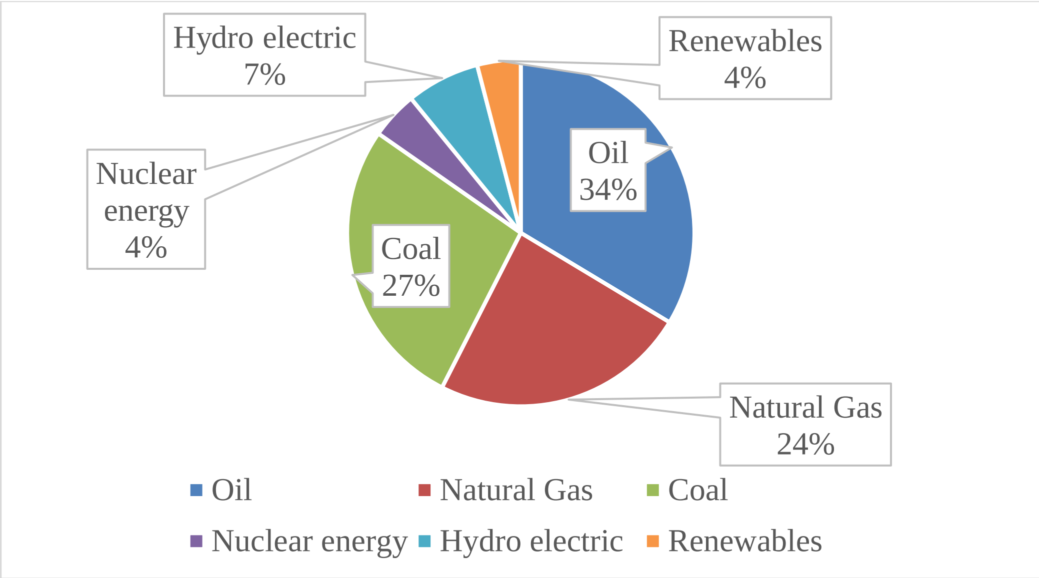

Figure 2.1: Primary energy consumption of world by fuels at 2018.

The use of renewable energy sources is also increasing. In the world, renewable energy generation consists of %51 of wind, %24 of solar, and %25 of other renewables which translates to 1270 TWh wind, 584.6 solar, and 625.8 others in 2018. Total renewable primary generation in the world is 2450.8 TWh [8]. Figure 2.2 shows the renewable energy generation in the world.

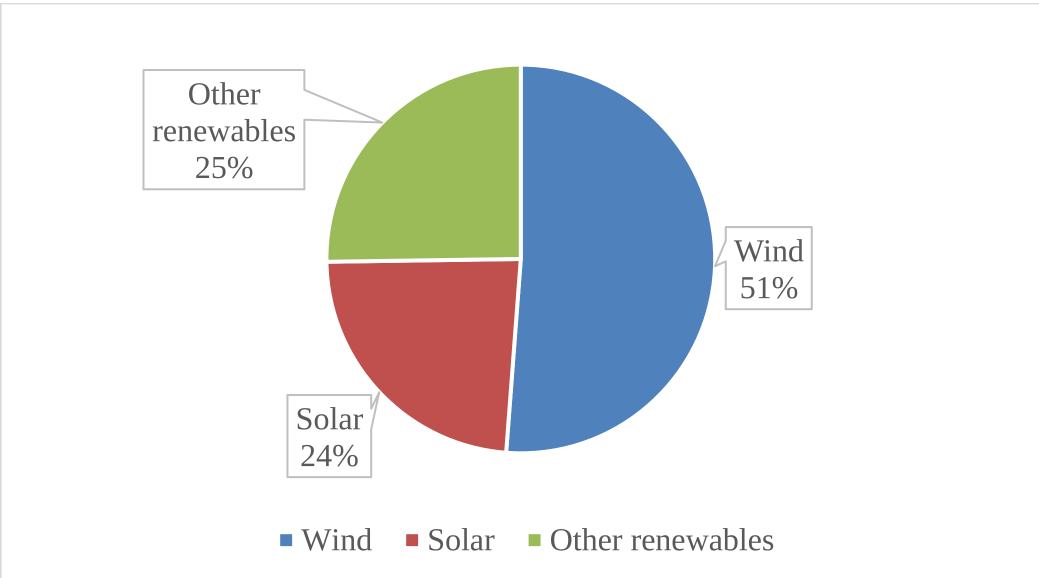

Figure 2.2: Renewable generation in the world.

2.2.The Distribution of Primary Energy Consumption in Turkey

According to BP data, the primary energy consumption of Turkey is 31.63% of oil, 27.56% of coal, 26.49% of natural gas, 8.77% of hydroelectric, and 5.56% of renewables in 2018. The primary energy consumption in 2018 is 153.5 Mtoe in Turkey [8]. Figure 2.3 shows the primary energy consumption in Turkey.

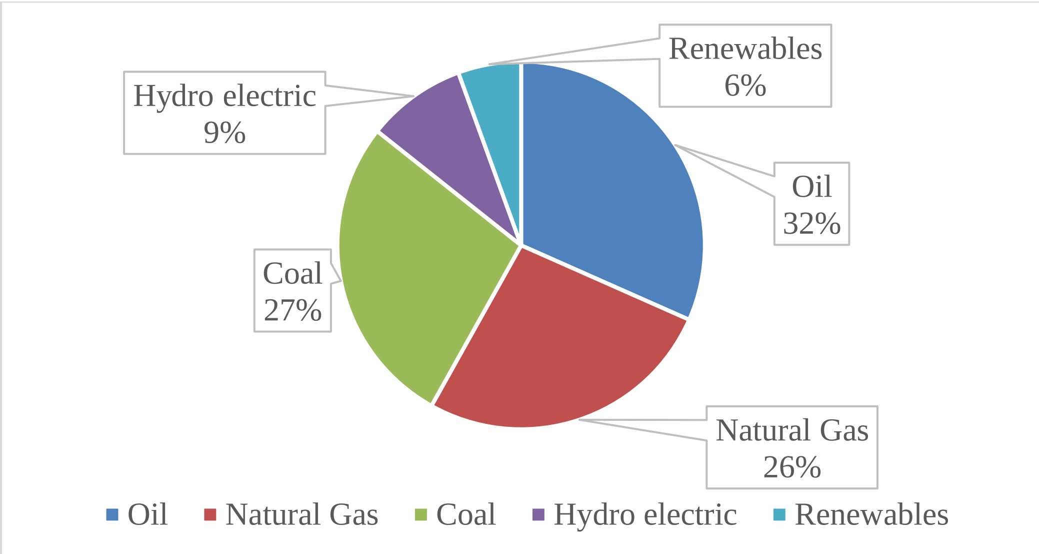

Figure 2.3: Turkey primary energy consumption by fuels at 2018.

The renewable energy generation based on BP data is 19.8 TWh of wind, 7.9 TWh of solar, and 10.0 TWh of other renewables in 2018 [8]. The percentage of renewable energy generation in Turkey is shown in Figure 2.4.

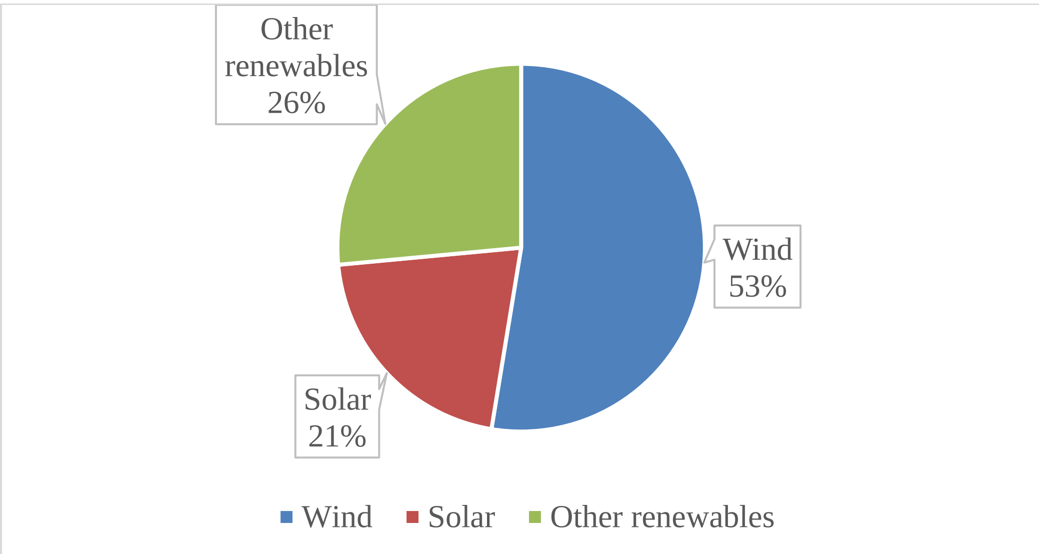

Figure 2.4: Renewable generation in Turkey.

2.3.Literature Review

Several studies are done on this subject in the literature to express energy consumption, CO_2 emissions, environmental impacts, and effects of material used in wind turbines. This literature review summarizes studies of life cycle assessment on wind turbines.

Many studies are done in order to estimate energy consumption and CO_2 emissions. Ghenai [9] mentioned that a significant amount of energy and carbon emission is produced as a result of initial production of the turbine parts. In order to decrease carbon emission and energy consumption, the turbines are recycled. For a 2 MW wind turbine, recycling of the turbine provides 54.8% total energy recovery and 55.4 % CO_2 emission reduction after the completion of their lifetime. Palomo and Gaillardon [10] stated that if the lifetime of a wind turbine is increased then the energy payback time, energy intensity and CO_2 intensity will be decreased. Ardente et. al. [11] studied on the life cycle of a wind farm in Italy, which has been shown and pollutants are indicated as air, water, and wastes. The wind farm has 3.43×10^6 kg CO_2 gas emission. According to this study, the global energy requirement range is between 42.1 TJ and 50.7 TJ, and the emission range is between 2.7×10^6 kg CO_2 and 3.7×10^6 kg CO_2. Lenzen and Munksgaard [12] mentioned that CO_2 and energy intensities have huge changes with regard to differences in material consistency. Energy intensities vary from 0.014 to 0.15 $kWh_{in}\ kWh_{el}^{-1}$ after normalization in lifetime and load factor. According to the study of Vestas [13], the energy balance of the V82.1.65 MW onshore wind turbine is 7.2 months and its CO_2 emission from electricity is 6.6 g CO_2 per produced kWh in the life cycle assessment. According to the analysis of Haapala and Prempreeda [14], the tower, nacelle, and rotor are causing the greatest environmental impact. The authors calculated the energy payback time for model 1 and model 2 as 0.43 years and 0.53 years respectively. Carr *et al.* [15] mentioned that small turbines in Thailand generate 0.29 kg CO_2- eq/L in the production of diesel fuel and 2.86 kg CO_2- eq/L in the combustion of diesel fuel. According to Siemens [16], 80 wind turbines of SG 8.0-167 DD in a wind farm save 58400000 ton CO_2 due to low greenhouse gas emission in 25 years. Mitchell, Grace, and Harrison [17] claimed that the farm on Cumbrian peatland has 27 wind turbines which provide that CO_2 payback time is 3.5 years. On the other hand, the CO_2 payback time of wind farms in Scotland peatland is 8-16 years. Thomson and Harrison [18] mentioned that carbon emissions of total manufacture and installation comprise more than 90% of the total life cycle in onshore wind turbines.

Crawford [19] inferred that 850 kW wind turbines save 35,265 t greenhouse gases and 3 MW wind turbines save 122,960 t greenhouse gases.

On the other hand, Chipindula, Sai, and Botlaguduru [20] stated that the greenhouse gas emissions are compared between onshore, shallow water and deep water locations and the minimum greenhouse gas emission is obtained from onshore locations with the interval of 5-7 gCO_2-eq/kWh. Jungbluth *et al.* [21] mentioned a comparison of the wind turbines in Europe, an onshore plant causes 11 g/kWh greenhouse gas emission and an offshore plant causes 13 g/kWh. Arvesen and Hertwich [22] mentioned that the components of a wind turbine (wind turbine, foundation, electrical collection system), installation, and decommissioning, operation and maintenance at both onshore and offshore are examined in terms of environmental impacts which are climate change, marine eutrophication, photochemical oxidant formation, and terrestrial acidification. Onshore wind turbines contribute 22.5 g CO_2-eq climate change for 1 kWh electricity generation. Offshore wind turbines contribute 21.2 g CO_2-eq climate change for 1 kWh electricity generation. Schleisner [23] revealed SO_2, NO_x, CO_2, N_2O, CH_4, VOC, CO_2 emissions per kg material. Energy payback of onshore wind turbines is 0.26 years and energy payback of offshore wind turbines is 0.39. According to the study of Bonou, Laurent, and Olsen [24], offshore wind turbines have more climate change effects than onshore wind turbines. Climate change in the studied onshore wind turbines are 6.0 CO_2 eq/kWh and 5.0 CO_2 eq/kWh. Climate change in the studied offshore wind turbines is 10.9 CO_2 eq/kWh and 7.8 CO_2 eq/kWh.

On the other hand, several studies are conducted on the effects of wind turbines on the environment. Razdan *et. al.* [25] mentioned the environmental effects of the V110 wind turbines, such as toxicity, global warming effect, eutrophication for different stages of the wind turbine from its production and plant set-up to the end of life impacts. Among the manufacturing stages, production of the tower causes the most significant effect on global warming which is 29%, per kWh of electricity produced. Sanz, Pellegrini, and Jime [26] gave information about materials, their energy payback then a life cycle assessment. Each stage of a wind turbine has different environmental impacts. Major impacts caused by the manufacturing process are inorganic respiration, climate change and reduction in mineral resources. The transportation process causes inorganic respiration, climate change, acidification, and eutrophication; operation stage causes inorganic respiration and reduction in mineral resources. Finally, the foundation affects the environment mainly due to cement material hence SO_2 and NO_x should be cautioned and observed carefully. Damien [27] mentioned that the wind and hydropower plants have insignificant effect on environmental impact such as climate change among coal, hydro, wind, and oil power plants. Recycling processes in wind turbine materials have a significant effect on providing the environmental benefit. Moreover, Tremeac and Meunier [28] stated that while selecting the location of the wind farm, the transportation and the closeness of recycling factories should be factored in, in order to reduce transportation costs and decrease environmental impact. Hertwich *et. al.* [29] signified unit environmental effects, unit energy, and material needs of renewable, and fossil energy systems. Examined environmental effects are greenhouse gases, PM_{10}, ecotoxicity, eutrophication, and land occupation. Examined material needs are iron, cement, copper, and aluminum. When wind, photovoltaics and concentrating solar power are compared with fossil fuel energy, the environmental impact of high material requirement in renewable energy systems causes less than fossil fuel energy that causes direct emission.

Various research has also been done on the materials used in wind turbines. Borup and Andersen [30] referred that the blades are a significant problem due to their uncertainty in removal and recycling phase and their main material is glass fiber which causes dust when it is cut, it results in a hazard for the environment. Andersen *et. al.* [31] stated that wind turbine components which are batteries, ferrous high alloy, ferrous metal, aluminum, copper, zinc, magnesium, nickel, and their alloys have higher than 90% efficiency in recycling. Disposal method of plastics, rubber, and other organic materials is incineration with energy recovery which has 100% efficiency. According to the study of Andersen and Borup [32], the blades of glass fiber, carbon fiber blades, cables, and similar components, nacelle result in environmental and recycling problems. According to the study of Günkaya *et. al.* [33], the construction of wind causes a high amount of carbon ferrochromium that is related with human toxicity and terrestrial ecotoxicity. In 2023, particularly wind power causes 79% human toxicity among all the energy systems. Furthermore, according to the study of Mcculloch, Raynolds, and Laurie [34], gas systems have 98.5% more greenhouse emission than wind turbine systems. The production process of three materials used in the wind turbine are responsible for 70% of total greenhouse gas emissions. These materials with the high greenhouse gas emissions are concrete, aluminum, and steel.

In the literature, a comparison of wind turbines with other energy systems has been made. Turconi, Boldrin, and Astrup [35] indicated that nearly all emissions come from the infrastructure of the wind turbines. In the comparison of life cycle emission factors for electricity generation, wind energy is the type of energy that has the least CO_2 and NO_x emissions after nuclear and hydropower. However, in terms of SO_2 emissions, natural gas, nuclear power, and hydropower have less emission than wind energy. Andersen *et. al.* [36] referenced a case study that has 5 scenarios which are base, low wind, high wind, no coal, and storage in Ireland for 2025. In Scenario 4 where there is no coal consumption and CCGT is used in its place resulting in lowest emissions among all five scenarios. When Scenario 4 is compared with Scenario 1, CO_2, NO_x, and SO_2 are decreased 23%, 57%, and 91% in Scenario 4, respectively.

3. WIND ENERGY

Wind turbine is an invention that gets its energy from the wind which ensures the energy production by rotation of the rotor blades. There are two types of wind turbines which are horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). Upwind or downwind are positions of horizontal axis wind turbines. The advantages of the vertical axis wind turbine are that the generator and gearbox are at the ground level and there is no requirement of a tower. The disadvantages are low wind speed and low efficiency [9].

Wind turbines can be further differentiated according to where they are installed. The onshore wind turbines are installed on land whereas the offshore wind turbines are installed on water. If the onshore and offshore turbines are compared in terms of technical and economic aspects, they have both advantages and disadvantages. The cost of the onshore wind turbine is less than the offshore wind turbine because of the ease of installation and maintenance. Installation of onshore wind turbines is easier because offshore wind turbines are more complex which means more technical information is required. However, if the onshore wind turbine is close to the settlement, it may disturb the residents due to noise. Moreover, offshore wind turbines provide higher energy production [37].

3.1.Wind Energy in the World

The 51.3 GW wind energy installed in 2018 but compared to the previous year, installation in 2018 is decreased by 4%. From the total installation in 2018; onshore installation is 46.8 GW of and offshore installation is 4.5 GW all over the world. However, the total installed wind power is 591 GW. China is the leading market in onshore wind energy installation since 2008 and installed 21.2 GW onshore in 2018. China has 206 GW total installations in 2018, which makes them the first market to pass the 200 GW total installation capacity. After China, the second largest market in 2018 was the USA with new 7.6 GW and a total of 96GW onshore installations. In the offshore market in 2018, China made 1.8GW installations which made them take the lead from the UK [38].

Figure 3.1 and Figure 3.2 shows the total installation of onshore and offshore wind turbines in the World.

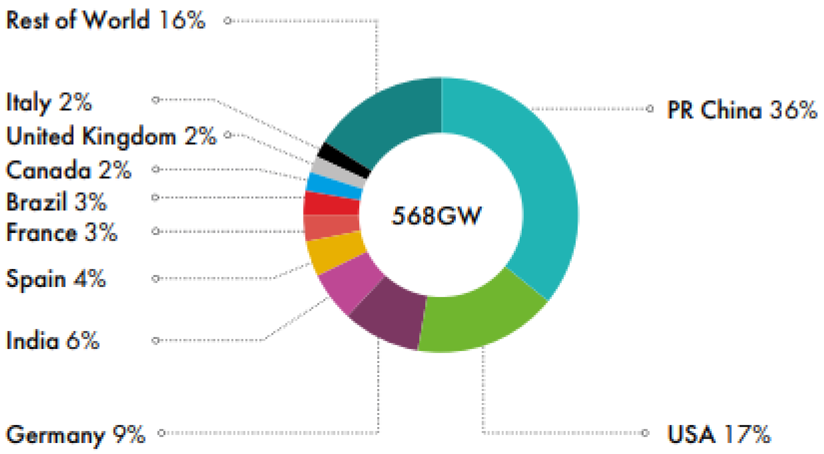

Figure 3.1: Total onshore installation [38].

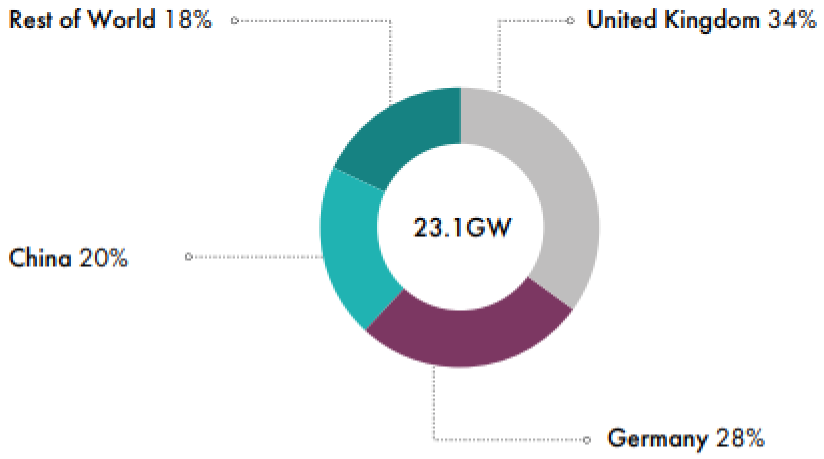

Figure 3.2: Total offshore installation [38].

3.2.Wind Energy in Turkey

Wind energy capacity of Turkey is estimated as 48,000 MW. According to this estimation, the available area for wind energy is almost 1.3% of the area of Turkey. In 2018, wind energy generation was estimated as 19,882 GWh. Active wind power plants have a potential of 7005 MW in Turkey. Moreover, wind energy in Turkey can reach 11 GW with current projects [5].

Ranking by regions of Turkey, the region with the most wind farms is in the Aegean Region, and the one with the least amount of wind farms is in the Eastern Anatolia Region. [39]. Growth rate per year for wind generation is 48.2% according to BP statistics. Figure 3.3 shows wind generation in Turkey [8].

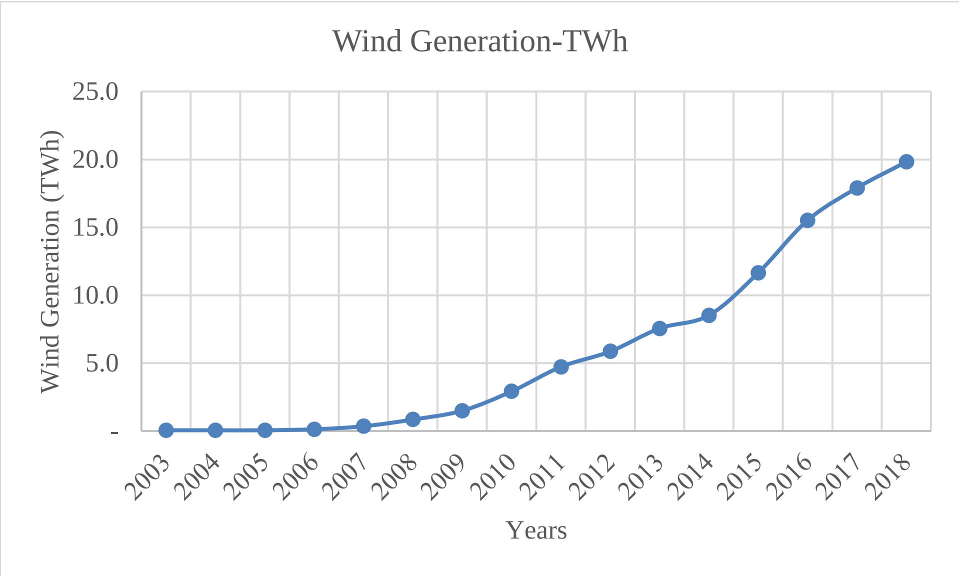

Figure 3.3: Wind generation in Turkey.

3.3.Wind Turbine Components

Wind turbines mainly have four components which are tower, foundation, nacelle and rotor.

3.3.1. Tower

The tower, while carrying nacelle and rotor, also absorbs large static loads caused by changing wind power. In the making of the tower, material of choice is concrete or steel. The tower is of a tubular shape. One of the components which bear the high loads is the tower. Nacelle is a very heavy component and is under stress due to the force from the rotor and wind. Because of its cost, it plays an important role in economic feasibility. There are different types of towers which are steel towers, concrete towers with climbing formwork, precast concrete towers, steel lattice towers, hybrid towers, and guyed poles [40].

3.3.2. Foundation

Foundation provides the stability of the turbine against the wind and it fixes the wind turbine to the ground. Mainly, there are two types of foundations which are plate foundations (also called shallow foundations) and pile foundations. Plate foundation/shallow foundation is the most commonly used method. Pile foundations are fixed with piles in soft soil [40].

3.3.3. Rotor

Rotor provides wind energy to be converted into mechanical energy by blades which is a key factor of wind turbines. Generally, rotor blades are made of synthetics reinforced with fibreglass, carbon fibers, and the layers of rotor blades which are glued with epoxy resin. The hub is located in the middle of the rotor and the blades are attached to the hub which is made of cast iron and cast steel. The hub provides the energy from the rotor blades and transmits it to the generator. If the gearbox is one of the components of the wind turbine, then it is connected to the hub through a gearbox shaft that gently turns. In this process, wind energy is converted to rotational energy. On the other hand, if the wind turbine has a direct drive, then the energy is transmitted to the ring generator through the hub. Power control which is stall control and pitch control is provided by the rotor. Stall control provides management of flow separation. If rotor blades have a stall control, it is connected to the hub at a fixed angle and it is used in large wind turbines which are higher than 1 MW. In specific wind speed, the geometry of the rotor blade is planned to bring in turbulence behind the rotor blade. Pitch control provides that the high velocity of wind moves the rotor blade around; this movement is mostly only a fraction of the degree and this process gives rise to reduction of the lift. In high velocity of the wind, the rotor proceeds to generate power at rated capacity [40].

3.3.4. Nacelle

The nacelle includes all machinery of the wind turbine. Nacelle is attached to the tower by bearings in order to follow wind direction when it needs to rotate. Components of the drivetrain are rotor shaft with bedding, gearbox, brakes and coupling, and generator [40].

The output energy of the rotor is enlarged by the gearbox which is located between the rotor and the generator. Generators can be in different sizes according to the desired power. When the rotor rotates, the electricity is produced by the generator [9].

The coupling occurs between the main shaft and the transmission. This transmission is rigid due to high torque. The control mechanism of blades is determined according to the type of brake which are aerodynamic brake systems and mechanical systems [40].

4. ENVIRONMENTAL IMPACTS

4.1.Global Warming

Global warming is caused by greenhouse gases which are CO_2, NO_2, CH_4, CFCs, HCFCs, and CH_3Br. Global warming is a worldwide scaled problem and the unit we assess it with is CO_2 equivalent. Global warming provokes melting of the polar ice caps, loss of the soil moisture, seasons getting longer, changing or loss of forests, and changing of the wind and ocean patterns.[41]. The short waves from the sun are absorbed partly and cause direct warming. The remaining waves coming from the sun are reflected. The earth's surface reflects these waves back into the atmosphere, but these waves are absorbed by greenhouse gases which are CO_2, methane, and CFCs. This interaction causes the earth to get warmer; thus, it causes global warming. On the other hand, human activities cause an increase in the amount of greenhouse gases [42]. Figure 4.1 shows the global warming potential.

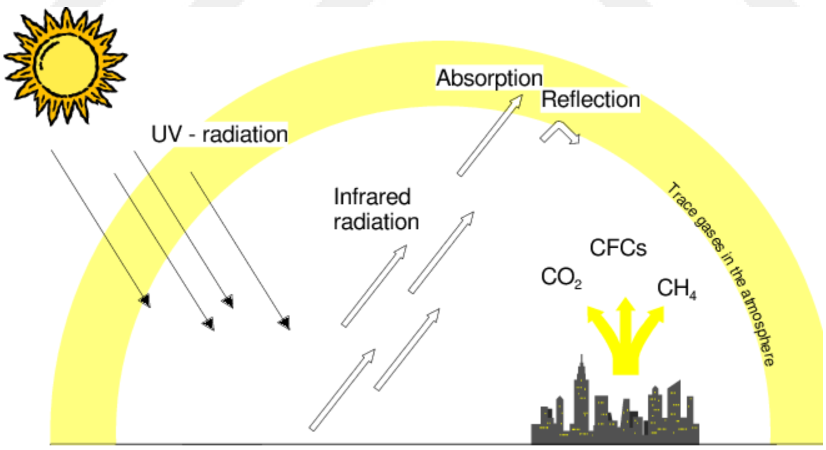

Figure 4.1: Global warming potential [42].

The equation given below is used in order to calculate Global Warming Potential for individual chemicals which is calculated as kg CO_2-eq. IS_{GW} indicates the value of the global warming impact for any greenhouse gas. EF_{GWP} is an equivalency factor for any greenhouse gas and the time frame used for this value is 100 years. Amt_{GG} is the greenhouse gas amount released into the air. [43]. Equation 4.1 shows the calculation of global warming potential.

$$(IS_{GW})_i = (EF_{GWP} \times Amt_{GG})_i \quad (4.1)$$

4.2.Ozone Depletion Potential

Stratospheric Ozone Depletion which has global impact is caused by CFCs, HCFCs, halons and CH_3Br, and shown as CFC11. Ozone depletion gives rise to increase in ultraviolet radiation [41]. Ozone is formed breaking down oxygen in the stratosphere by short-wave UV lights, which causes the creation of an ozone layer that is 15-50 km high in the stratosphere. However, 10% of this amount of ozone enters the troposphere. For the earth, ozone is very significant because short wavelengths are absorbed and long wavelengths are reflected. By this means, the earth has a little amount of UV radiation. Human activities deplete the ozone layer [42]. Figure 4.2 shows the scheme of ozone depletion potential.

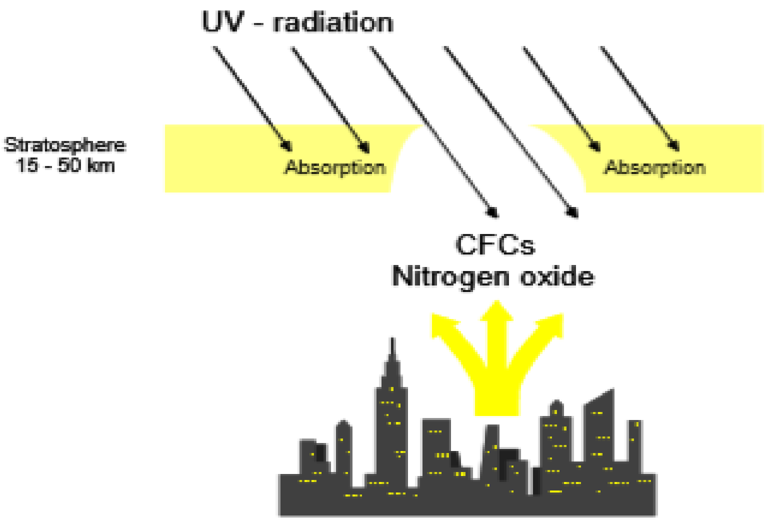

Figure 4.2: Ozone depletion potential [42].

To calculate ozone depletion potential, the equation is given for any chemical that causes ozone depletion which is calculated as CFC-11 eq. IS_{OD} indicates the amount of ozone depletion impact for any chemical. EF_{ODP} is the characterization factor of ozone depletion potential. Amt_{ODC} is ozone depleting chemical amount released into the air [43]. Equation 4.2 shows the calculation of ozone depletion potential.

$$(IS_{OD})_i = (EF_{ODP} \times Amt_{ODC})_i \quad (4.2)$$

4.3.Photochemical Smog

Photochemical smog is caused by non-methane hydrocarbons and the smog has local impact shown as ethylene-eq. The characterization factor of photochemical smog is photochemical oxidant creation potential. Photochemical smog causes decreasing visibility, eye and respiratory tract irritation, and it is harmful to vegetation and materials. Nitrogen oxides and hydrocarbons have complex reactions in the presence of UV waves from the sun and one of the products is ozone which is toxic for humans in high concentrations. When the weather has a high temperature, low humidity, and static, it will cause high ozone concentration [41, 42] Figure 4.3 shows the scheme of photochemical smog potential.

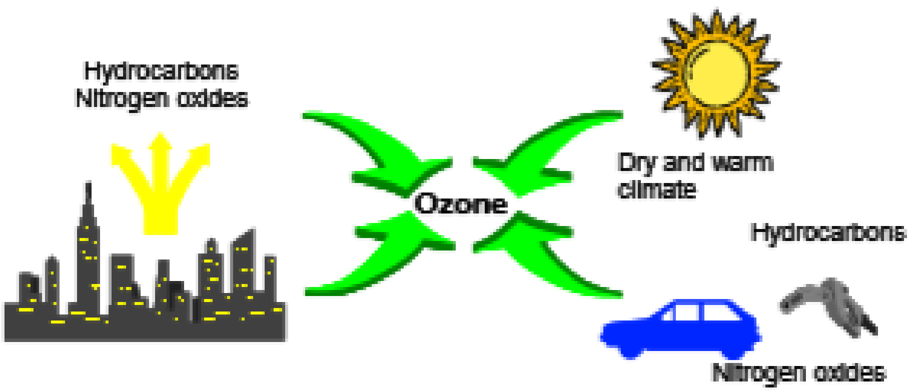

Figure 4.3: Photochemical smog [42].

The equation shows the calculation of photochemical smog. IS_{POCP} shows the effect of photochemical smog for any chemical. EF_{POCP} is a characterization factor of photochemical oxidant creation potential. Amt_{POC} is the amount of chemical that causes smog which is released into air [43]. Equation 4.3 shows the calculation of photochemical smog.

$$(IS_{POCP})_i = (EF_{POCP} \times Amt_{POC})_i \qquad (4.3)$$

4.4.Human Toxicity, Freshwater & Marine Aquatic Toxicity and Terrestrial Toxicity

Terrestrial toxicity, aquatic toxicity, and human toxicity are shown as 1,4-Dichlorbenzol. LCA includes effects of any chemical on human health and human toxicity is an estimation of negative impacts on humans. Human toxicity can be global, regional, or local due to water, soil, or air, and could give rise to an increase in morbidity and mortality [41–43]. Figure 4.4 shows the scheme of Human Toxicity.

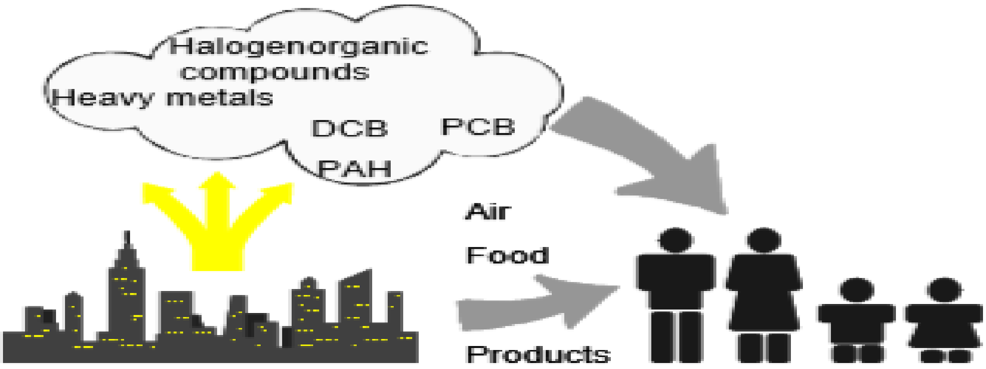

Figure 4.4: Human toxicity potential [42].

Terrestrial toxicity has a local impact on rodents causing a decrease in biodiversity. Terrestrial toxicity indicates the toxicity due to toxic chemicals. It is an approach of LCA which examines the amount of negative impact on the living organisms caused by their interaction with the toxic chemicals [41–43]. Figure 4.5 shows the Terrestrial Eco-Toxicity Potential.

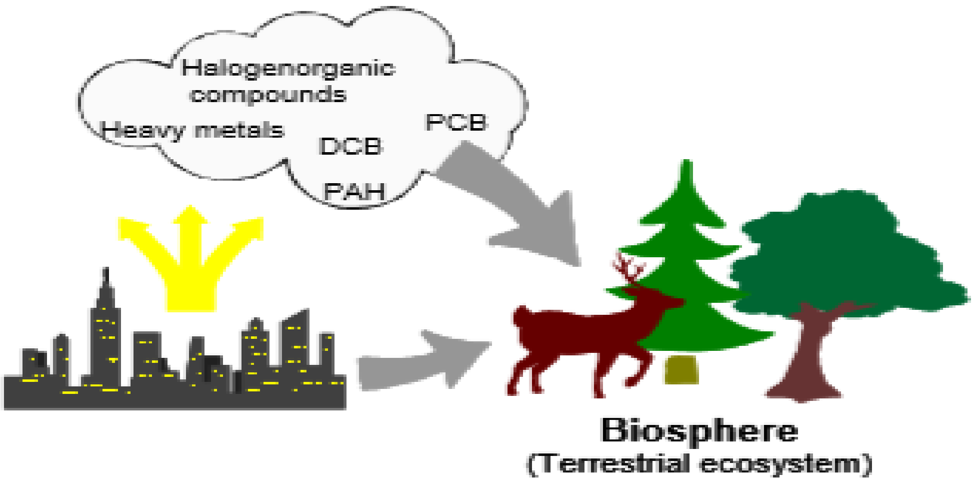

Figure 4.5: Terrestrial eco-toxicity potential [42].

Aquatic toxicity has a local impact for fish because it gives rise to decrease in aquatic plant life, food sources, and biodiversity. Aquatic toxicity considers the amount of adverse impact on the aquatic organisms caused by their interaction with the toxic chemicals [41–43]. Figure 4.6 shows the scheme of Marine & Aquatic Eco-Toxicity Potential.

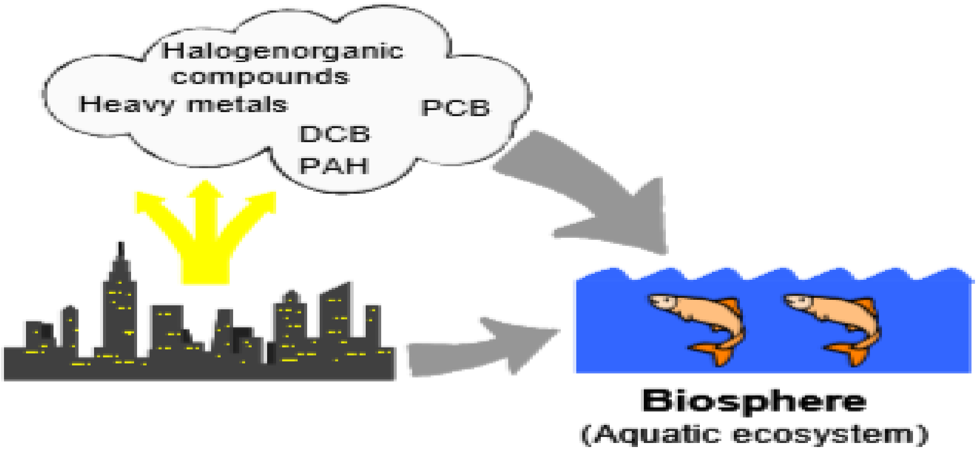

Figure 4.6: Marine & aquatic eco-toxicity potential [42].

4.5.Acidification

Acidification can be local or regional, it is caused by SO_x, NO_x, HCL, HF, and NH_4, and it is shown as SO_2-eq and release H^+ ions. The impact of acidification begets building corrosion, waterbody acidification, and damaging effects to vegetation and soil. Chemicals that cause acidification are spread through precipitation. The conversion of air pollutants to acids brings in acidification of soils and water, this will give rise to decline in pH of rainwater and fog from 5.6 to 4 and under [41–43]. Figure 4.7 shows the acidification potential.

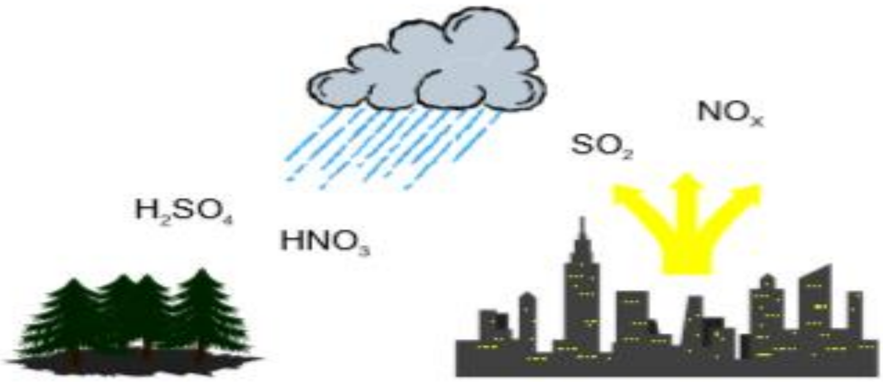

Figure 4.7: Acidification potential [42].

The equation is calculated to determine acidification. IS_{AP} is the amount of acidification for any chemical. EF_{AP} is the characterization factor of acidification potential. Amt_{AC} is a chemical amount that causes acidification [43]. Acidification potential calculation is shown in Equation 4.4.

$$(IS_{AP})_i = (EF_{AP} \times Amt_{AC})_i \tag{4.4}$$

4.6.Eutrophication

Eutrophication has local impact caused by PO_4, NO, NO_2, nitrates, and NH_4 shown as PO_4. Eutrophication triggers plant growth and causes oxygen depletion in the water body due to nutrients [41]. If a specific area has nutrient enrichment, eutrophication occurs due to air pollutants and wastewater. As a result, there will be a rapid growth of algae. Due to this effect, the sunlight cannot reach water depths and photosynthesis rates decline. Oxygen decreases; therefore, the dead algae cannot be decomposed by aerobic decomposition. The decrease in sunlight and oxygen will lead to the death of fish, anaerobic decomposition will take place which will give off H_2S and CH_4 will be produced and the ecosystem will disappear in the water body [42].

The equation gives the calculation of eutrophication potential. IS_{EUTR} gives the effect of eutrophication for any chemicals. EF_{EP} is a characterization factor of eutrophication potential. Amt_{EC} is a chemical amount released in water that causes eutrophication [43]. Equation 4.5 shows the calculation of eutrophication potential calculation.

$$(IS_{EUTR})_i = (EF_{EP} \times Amt_{EC})_i \tag{4.5}$$

4.7.Land Use and Water Use

Land use affects the quantity of disposed land, it can be seen on global, local, and regional scale. The characterization factor of land use is land availability. It causes a decrease in terrestrial habitat for wildlife and landfill space in terms of solid, radioactive, and hazardous wastes [41, 43].

Water use means consumed water, which has regional and local impacts. Water shortage potential is the unit of water use. It is a decline in the water source. In addition, water quality is another significant parameter for life cycle assessment. BOD

(Biological Oxygen Demand) and TSS (Total Suspended Solid) are two key factors for water quality [41, 43].

5. LIFE CYCLE ASSESSMENT

Life cycle assessment refers to a procedure that examines the environmental impacts of a product throughout its lifecycle from the initial stage of manufacturing to its disposal. This procedure aims to minimize the environmental impacts of a product [41].

Life cycle assessment is conducted exclusively for every stage of the wind turbine which are manufacturing, transportation, construction, operation, and disposal. These calculations are conducted under certain assumptions that are explained throughout this section. The energy consumption each stage can be found in this section whereas the wastewater generation and emissions are given at the following section. Then, the environmental effects are calculated based on these emissions and wastewater generation results.

5.1.Production of Wind Turbine

The calculations for this part is done using the properties of the wind turbine Gamesa G8X model with 2 MW. Foundation consists of iron, steel, and concrete. Foundation has two sub-components which are footing and ferrule. The used material for the ferrule is steel which is used to connect and support the wind turbine tower. The tower, which is 67 m tall, has three sections that consist of steel. The nacelle consists of a bed frame, main shaft, transformer, generator, gearbox, and nacelle cover. The bed frame consists of iron; the main shaft consists of steel; the transformer consists of silicon, copper, and steel; the generator consists of silicon, copper, and steel; the gearbox consists of iron and steel; the nacelle cover consists of fibreglass and resin. The rotor consists three blades, blade hub, and nose-cone. Three blades consist of resin and fibreglass; the blade hub consists of cast iron; the nose cone consists of fibreglass and resin [26].

Weight of materials according to components which are foundation, tower, nacelle and rotor is taken from [26] shown in Table 5.1.

Table 5.1: Weights of materials in the wind turbine.

Component	Material	Weight	Unit
Rotor	Resin	12	t
	Fibreglass	8	t
	Cast Iron	14	t
Foundation	Concrete	270	m^3
	Iron	25	t
	Steel	15	t
Tower	Steel	143	t
Nacelle	Iron	19	t
	Steel	22	t
	Silicon	0.3	t
	Copper	4	t
	Fibreglass	1	t
	Resin	1	t

On the other hand, XLPE cables have been used in the internal cabling and connection cabling of the wind turbine. Copper cable was used for internal cabling in the triple formation. The turbine connection is made by using copper or aluminum cables; however, the copper screen is used in both types of conductors and it also has triple formation. A copper cable with a cross section of 50 mm^2 is chosen for the internal cabling of the turbine. For connection, a copper or aluminum cable with a cross section of 95 mm^2, 120 mm^2, and 185 mm^2 is calculated based on 1 km of length. The 50 mm^2 cross section copper cable has a 421 kg/km conductor, while its total weight is 1390 kg/km. Aluminum cable for 50 mm^2 cross section has a weight of 128 kg/km conductor; the total weight is 1090 kg/km. The copper cable of 95 mm^2 cross section has 843 kg/km conductor, while its total weight is 1990 kg/km. Aluminum conductor cable has a weight of 256 kg/km conductor; the total weight is 1400 kg/km. For 120 mm^2 cross section cable, copper cable has 1065 kg/km conductor and its total weight is 2280 kg/km; aluminum cable has 324 kg/km conductor and its total weight is 1540 kg/km. Finally, the copper cable that has 185 mm^2 cross section has 1640 kg/km conductor and its total weight is 3030 kg/km. The aluminum conductor cable which has 185 mm^2 cross section has 499 kg/km conductor and its weight is 1890 kg/km [44, 45]. The total cable weight required for both internal and connection is shown in Table 5.2.

Table 5.2: The weights of cables.

Cable Weight (Al-conductor)		Cable Weight (Cu-conductor)
Copper(kg)	Aluminum(kg)	Copper (kg)
11532	3237	22179

Cable optimization is not made in Turkey. First of all, the position of the wind turbines is determined. Then, the road is determined for the construction equipments by examining the slope and turbine positions. Meanwhile, channels are on the road for cables, so that the cables run parallel to on-site roads. In fact, cable lengths and cross sections can be shortened by optimization.

In Turkey, Cu-conductor cables were used formerly, but in recent years it has been completely transitioned to the Al-conductor cables since the Al-conductor cable is much cheaper than Cu-conductor cable.

According to these materials, the amount of consumed energy for the production of each material has been found. In Turkey, 25.799 million ton steel is produced in 2018 by electric arc furnace which has 570 Mcal/t energy consumption. Otherwise, 11.513 million ton steel is produced by basic oxygen steelmaking and has 5450 Mcal/t energy consumption[46]. Steel energy consumption during production is calculated based on these two values, which are 8685 MJ/t. The energy required for cast iron production is 25 MJ/kg [47]. The energy requirement of resin for production is 40105 Btu/lb [48]. The energy requirement of copper for production changes between 30 and 90 MJ/kg and the average value is 60 MJ/kg. The energy requirement of silicone for production is between 1000 and 1500 MJ/kg. The average energy requirement for silicone is 1250 MJ/ kg. The energy requirement for aluminum production changes between 190 and 230 MJ/kg; the average value is 210 MJ/kg [49]. For concrete production, the energy requirement is 6.3 GJ/m^3 [50]. The energy requirement of fibreglass for production is 28 MJ/kg. The iron energy requirement for production is 25 MJ/kg [51]. The energy requirement for a wind turbine production based on these energy consumption and weight is calculated shown in Table 5.3.

Table 5.3: Energy consumption for manufacturing of wind turbine.

Material	Energy Consumption (MJ)	Energy Consumption (MWh)
	Rotor	
Resin	1108776	308
Fibre Glass	221872	62
Cast Iron	350000	97
	Foundation	
Concrete	1701000	473
Iron	625000	174
Steel	130276	36
	Tower	
Steel	1241961	345
	Nacelle	
Iron	462500	128
Steel	188378	52
Silicon	430000	119
Copper	210000	58
Fibre Glass	22400	6
Resin	111941	31

The energy consumption for both copper and aluminum cable is shown in Table 5.4.

Table 5.4: Energy consumption for cable production.

Cable	Energy Consumption (MJ)	Energy Consumption (MWh)
Cu-Conductor Cable	1330763	370
Al-Conductor Cable	1371713	381

5.2.Transportation of the Wind Turbine

Four different scenarios are given for the transportation of the four wind turbine components which are rotor, foundation, tower and nacelle separately from their respective factories. The distance and environmental effect of transportation cannot be known specifically unless there is a certain wind farm. For this reason, four possible scenarios were given for transportation and in these scenarios different modes of transportation are used such as some of them preferring only trucks and some preferring trucks and ships. Table 5.5 shows the distance scenarios between the plant and the factories.

Table 5.5: Scenarios for transportation distances.

Component	[14]		[14]		[34]		[13]	
	Truck	Ship	Truck	Ship	Truck	Ship	Truck	Ship
Rotor	4200	-	1931	-	4900	7000	1000	15566
Foundation	-	-	-	-	100	-	200	-
Tower	4200	-	2205	-	4465	-	700	-
Nacelle	4200	-	1931	-	1100	17000	1000	15566

The average of the four distances are taken and average distance is shown in Table 5.6.

Table 5.6: Selected transportation distances.

Component	Truck (km)	Ship (km)
Rotor	3007.75	11283
Foundation	150	-
Tower	2892.5	-
Nacelle	2057.75	16283

The fuel consumption of the truck is 30L/100km and it is assumed that diesel fuel is used and its net calorific value is 35.9 MJ/L [52, 53]. According to this information, the energy consumption for the transportation of the truck was found and shown in Table 5.7.

Equation 5.1 was used to find fuel consumption for ships.

$$LMPH = \frac{K \times GHP \times LP}{KPL} \tag{5.1}$$

LMPH (liters used per machine hour), K (kg fuel used per brake hp/hour), GHP (gross engine horsepower at governed engine rpm), LF (load factor in percentage), KPL (weight of fuel in kg/L). For diesel ships, weight of fuel is 0.84 kg/L; fuel consumption is 0.17 kg/brake hp-hour; the medium load factor is 0.54 [54].

Installed power for the bulk ship is 15500 hp [55]. Average speed for the bulk ship 26 km/h [56]. The net calorific value of marine diesel is 35.9 MJ/L [57]. Based on these data, the energy consumption on the ship was calculated and it is shown in Table 5.7.

Also, the total energy consumption of trucks and ships and energy consumption based on components are given in Table 5.7.

Table 5.7: Energy consumption of transportation.

Component	Truck (MJ)	Ship (MJ)	Total (MJ)	Total (MWh)
Rotor	32393	26390085	26422478	7340
Foundation	1616	-	1616	0.45
Tower	31152	-	31152	9
Nacelle	22162	38084707	38106869	10585
Total	87323	64474791	64562115	17934

5.3.Construction of the Wind Turbine

Construction equipment is required for the installation of wind turbines, and it is assumed that diesel is used for these construction equipments. The net calorific value of the diesel is 35.9 MJ/L and its density is 0.837 kg/L [53]. It is assumed that the crane works for 2 days, forklift and excavation digger work for 1 day in order to complete the construction of a wind turbine. Hourly crane, forklift and excavation digger consume 620.1L, 64 L, and 44.1 L of fuel, respectively [20]. The construction equipments are also used in the disposal stage to deconstruct the wind turbine at the end of its life. Because of this, the results have been doubled. The energy consumptions are shown in Table 5.8.

Table 5.8: Energy consumption from construction.

Construction Equipments	Fuel Consumption (L/h)	Time (h)	Energy Consumption (MJ)	Energy Consumption (MWh)
Crane	620.1	96	2137113	594
Forklift	64	48	110285	31
Excavation Digger	44.1	48	75993	21

5.4.Operation of the Wind Turbine

During the maintenance, lubricant in the gearbox and the cooling systems is changed. In the operation process, a generator is replaced once during the lifespan of the wind turbine. A generator is made of steel, copper, and silicon [26]. In total, 300.8 t lubricant oil is changed for the duration of 20 years [14].

The energy consumption for steel production is 8685 MJ/t [46]. For copper production, the energy consumption is 60 MJ/kg and for silicon production, the consumption is

1250 MJ/kg. The energy requirement for lubricant oil is 10 MJ/kg [58]. Table 5.9 shows the necessary materials and their energy consumption in the operation process.

Table 5.9: Energy consumption of operation process.

Material	Energy Consumption (MJ)	Energy Consumption (MWh)
Silicon	243750	68
Copper	120000	33
Steel	37259	10
Lubricant	3008000	836

5.5.Disposal of the Wind Turbine

The EU has published the Waste Framework Directive which is 2008/98/EC that indicates a waste hierarchy shown in Figure 5.1. According to the waste hierarchy, first of all waste should be prevented; if the waste cannot be prevented, re-use, recycling, and recovery should be done in the given order. As the last option, waste is sent to landfill. Prevention is the reduction of a product before it becomes waste. Re-use is to use a product again to reduce the amount of waste. In recycling, the waste is collected and reprocessed into a new material, which prevents waste generation. In recovery; heat, electricity, or fuel is obtained from non-recyclable wastes in the way of combustion, gasification, pyrolization, anaerobic digestion, and landfill gas (LFG) recovery [59].

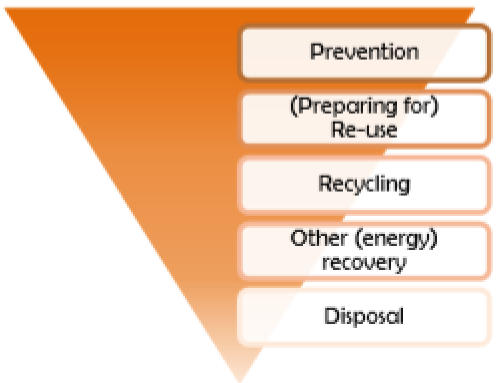

Figure 5.1: Waste hierarchy [59].

Steel, cast iron, and iron are recycled in secondary production. These ferrous metals are recycled by electric arc furnaces. Energy consumption of cast iron and iron is 19.2

MJ/kg for secondary production. However, the energy consumption of steel for secondary production is 11.7 MJ/kg. Copper needs 6.3 MJ/kg energy consumption in the secondary production which is similar to the primary copper production stage [60]. Aluminum is used in cables for this wind turbine if it is chosen. The energy requirement for secondary aluminum production is quite low and it is 2.4 MJ/kg. Also, the lubricant oil used in the wind turbine can be recycled. The energy requirement for recycling of lubricant oil is 3.4 MJ/kg [58]. The composite material that consists of fibreglass and resin is used in blades, nose-cone, and nacelle cover. The common disposal method of composite material is incineration; however, recycling and landfilling can also be used. In this study, incineration is selected as disposal method. The energy consumption for composite material incineration is 31.7 MJ/kg [58, 61].

After the wind turbine has completed its life cycle, different disposal methods are applied for the materials. These selected methods for disposal and total energy consumption of these materials are shown in Table 5.10.

Table 5.10: Disposal method and energy consumption of materials.

Materials	Method	Al-conductor cable (MJ)	Al-conductor cable (MWh)	Cu-conductor cable (MJ)	Cu-conductor cable (MWh)
Ferrous Metals	Recycling	3265452	907	3265452	907
Copper	Recycling	107304	30	174380	48
Aluminum	Recycling	7769	2	-	-
Lubricant	Recycling	1022720	284	1022720	284
Composite	Incineration	691377	192	691377	192

After the completion of its lifetime the wind turbine parts should be sent to the facilities for disposal. Since this study does not work for a specific facility, an average distance is selected. The distance of each facility is taken as 100 km. As mentioned earlier, a truck consumes 30 L of fuel per 100 km on average and the net calorific value of the diesel is 35.9 MJ/L [52, 53]. As a result, energy of 5385 MJ is used to send the parts to disposal facilities.

6. RESULTS

The calculations conducted in this section are based on the assumptions and calculations of the previous section. This section includes energy consumption and energy payback time, air emission and wastewater generation, environmental impacts, comparison of this study and Vestas V100, life cycle assessment for Turkey, and comparison of energy systems.

6.1. Energy Consumption and Energy Payback Time

In this study, a 2 MW wind turbine is used for the duration of 20 years and a capacity factor of 20% is assumed. In this case, the annual generated energy is 3504000 kWh. Energy produced during its lifetime is approximately 70080000 kWh. This means 3504 MWh per year and 70080 MWh for 20 years.

The energy consumption from every stage of the lifecycle of the wind turbine from the production of the wind turbine to its disposal is calculated separately. There are four different scenarios in this study. These scenarios are using Al-conductor or Cu-conductor and with or without transportation. Copper cable is used in the internal wiring of the wind turbine for both Al and Cu conductor scenarios.

Transportation can vary a lot since there is no specific wind farm. Energy payback time is calculated by dividing the energy consumption in all processes by the energy produced per year and it is given in Equation 6.1 [20].

$$\text{Energy Payback Time} = \frac{\text{Energy used}}{\text{Energy Produced}} \qquad (6.1)$$

The total energy consumption from manufacturing, transportation, construction, operation, and disposal stages of the wind turbine and energy payback time according to these four scenarios are shown in Table 6.1.

Table 6.1: Total energy consumption and energy payback time.

Scenarios	Total Energy Consumption (MJ)	Energy Payback Time (years)
Al conductor with transportation	83570338	6.62
Cu conductor with transportation	83588696	6.63
Al conductor without transportation	19002839	1.51
Cu conductor without transportation	19021196	1.51

In the same manner, the total energy consumption and the energy payback time of the manufacturing, transportation, construction, operation and disposal stages of the wind turbine are calculated but in this case, steel, iron, cast iron, copper, aluminum and lubricant are sent to recycling and this had an effect of decreasing the energy consumption. Table 6.2 shows the energy consumption and energy payback according to recycling.

Table 6.2: Total energy consumption and energy payback time with recycling.

Scenarios	Total Energy Consumption (MJ)	Energy Payback Time (years)
Al conductor with transportation	74763848	5.93
Cu conductor with transportation	74663591	5.92
Al conductor without transportation	10196349	0.81
Cu conductor without transportation	10096091	0.80

6.2.Air Emission and Wastewater Generation

As a result of all these processes, emissions are released. The values of these emissions are given in Appendix A-F according to each process. Each process releases a different emission. In order to calculate concrete emission, 1:1.5:3 mix ratio is selected to obtain a C30 class of concrete which indicates the composition ratio of cement, fine sand, coarse sand, and water. To obtain 700 ton concrete, 95456 kg cement is used [62, 63]. Because of this, emissions of cement are used [64, 65]. Emission factors of the iron and steel industry are used in both EAF and BOF to calculate emissions of iron, steel, and cast iron [66–69]. The emission factor is used for fibreglass to estimate emissions in the manufacturing stage [66], [70]. Resin emissions in the manufacturing process are estimated using the emission factor [66, 70]. The emissions of silicon are calculated by using emission factors [71]. Primary and secondary copper production have different emission factors to calculate air emissions [23, 66]. The aluminum is used in cables and its emission factors provide the calculation of emissions in manufacturing and disposal processes [23, 66]. CO_2 emissions in the disposal stage for copper and aluminum are taken from [60]. In order to calculate transportation emissions both ship and truck emission factor is used. The emission technology of trucks is selected as conventional [66, 72–74]. The used lubricant in the operation stage has also emission, so emission factors are used in order to calculate [75]. In the construction stage, construction equipments also have emissions that are calculated by emission factors [76]. The composite emission factor for CO_2 is taken from [61]. Also, total emissions are given in Table 6.3.

Table 6.3: Emissions based on four scenarios.

Pollutant	Wind Turbine Al Conductor with transportation	Wind Turbine Cu Conductor with transportation	Wind Turbine Al Conductor without transportation	Wind Turbine Cu Conductor without transportation	Unit
TSP	22818	22819	20330	20330	kg
NO_x	133044	133288	2723	2967	kg
CO	14394	14006	2100	1712	kg
NMVOC	4889	4889	240	240	kg
SO_2	885	885	885	885	kg
SO_x	33744	33868	569	693	kg
PM_{10}	2653	2654	165	166	kg
$PM_{2.5}$	2475	2477	148	151	kg
Pb	2493	3174	2277	2959	g
Cd	429	637	412	621	g
Hg	2677507	2677507	2677457	2677458	g
As	282	399	216	333	g
Cr	611	834	528	751	g
Cu	3185	4388	1725	2928	g
Ni	2256	2461	598	803	g
Zn	3605	3605	1615	1615	g
PCB	1272	1272	1209	1209	mg
PCDD/F	3204	4155	2878	3940	µg-I-TEQ
Total 4 PAHs	322	322	322	322	g
CO_2	6001	6062	1165	1227	t
H_2S	581	581	581	581	g
NO_2	194	194	194	194	kg

Table 6.3 (continued): Emissions based on four scenarios.

Pollutant	Wind Turbine Al Conductor with transportation	Wind Turbine Cu Conductor with transportation	Wind Turbine Al Conductor without transportation	Wind Turbine Cu Conductor without transportation	Unit
Se	167	167	1	1	g
Benzo(a)pyrene	31	2	31	2	g
Benzo(b)fluoranthene	32	3	32	3	g
Benzo(k)fluoranthene	29	-	29	-	g
Indeno(1,2,3-cd)pyrene	4	-	4	-	g
CH_4	35186	35186	35186	35186	g
N_2O	16875	18897	16625	18648	g
NH_3	458	458	433	433	g
Benz(a)anthracene	4	4	4	4	g
Dibenzo(a,h)anthracene	1	1	1	1	g
Chrysene	11	11	11	11	g
Fluoranthene	24	24	24	24	g
Phenanthene	135	135	135	135	g
HCB	16318	133	16185	-	mg

In Table 6.4, as seen in the energy consumption table, the recycled materials also have a benefit on emission, these emissions are taken as negative and the table is constructed with these values.

Table 6.4: Emissions based on four scenarios according to recycling.

Pollutant	Wind Turbine Al Conductor with transportation	Wind Turbine Cu Conductor with transportation	Wind Turbine Al Conductor without transportation	Wind Turbine Cu Conductor without transportation	Unit
TSP	22783	22790	20295	20302	kg
NO_x	132982	133225	2660	2904	kg
CO	13571	13183	1277	889	kg
NMVOC	4866	4866	217	217	kg
SO_2	856	856	856	856	kg
SO_x	33713	33810	538	635	kg
PM_{10}	2624	2629	135	141	kg
$PM_{2.5}$	2454	2456	128	130	kg
Pb	417	587	201	371	g
Cd	253	413	237	397	g
Hg	47	48	-2	-2	g
As	207	281	140	215	g
Cr	562	786	479	703	g
Cu	2522	3129	1063	1670	g
Ni	1913	2115	254	457	g

Table 6.4 (continued): Emissions based on four scenarios according to recycling.

Pollutant	Wind Turbine Al Conductor with transportation	Wind Turbine Cu Conductor with transportation	Wind Turbine Al Conductor without transportation	Wind Turbine Cu Conductor without transportation	Unit
Zn	1863	1863	-128	-128	g
PCB	62	62	-1	-1	mg
PCDD/F	-178	-65	-504	-281	µg-I-TEQ
Total 4 PAHs	89	89	89	89	g
CO_2	5943	5999	1108	1163	t
H_2S	581	581	581	581	g
NO_2	194	194	194	194	kg
Se	167	167	1	1	g
Benzo(a)pyrene	31	2	31	2	g
Benzo(b)fluoranthene	32	3	32	3	g
Benzo(k)fluoranthene	29	-	29	-	g
Indeno(1,2,3-cd)pyrene	4	-	4	-	g
CH_4	35186	35186	35186	35186	g
N_2O	16875	18897	16625	18648	g
NH_3	458	458	433	433	g
Benz(a)anthracene	4	4	4	4	g
Dibenzo(a,h)anthracene	1	1	1	1	g
Chrysene	11	11	11	11	g
Fluoranthene	24	24	24	24	g
Phenanthene	135	135	135	135	g
HCB	-16052	133	-16185	-	mg

In the production of the wind turbine materials, there is also wastewater generation along with the emission. Wastewater generation is observed during the production of steel, cast iron, iron, copper, fibreglass, and resin. Cement and aluminum production are considered dry processes compared with the other material productions, the wastewater production here is neglected [65, 77]. In order to produce 1 ton of steel, 27 m^3 wastewater is generated from the electric arc furnace; 25.3 m^3 wastewater is generated from the blast oxygen furnace [78]. Average effluent from the iron and steel industry is taken to estimate the wastewater generation [79]. The wastewater generation is taken for primary copper production. Copper production results in suspended solids, oils, and metals generation in wastewater [77]. The resin and fibreglass cause the release of BOD, COD, nitrates, and phosphates [70]. Wastewater production caused by the generator that is replaced during the operation process is also added. The produced wastewater in Al-conductor cable and Cu- Conductor cable are calculated separately, and the values are given for each conductor type in Table 6.5.

Table 6.5: The wastewater generation.

Pollutant	Al-Conductor Cable Wind Turbine	Cu-Conductor Cable Wind Turbine	Unit
Suspended Solid	366	366	kg
COD	3313	3313	kg
TOC	282	282	kg
BOD5	141	141	kg
Phenol	7	7	kg
SCN-	25	25	kg
Kjeldahl-N	41	41	kg
TNb	103	103	kg
Ammonia	252	252	kg
Nitrite	8	8	kg
Nitrate	85	85	kg
Oil and tar	63	63	kg
PAH	157	157	g
Cu	28	46	g
Pb	3	5	g
As	2	4	g
Ni	3	4	g
Cd	1	1	g
Zn	8	13	g
Phosphates	3	3	kg

6.3. Environmental Impacts

Environmental effects were calculated according to these emissions. The effect of wastewater on marine life and freshwater life is calculated separately and then the environmental effect on the total water body is calculated. The environmental effects of the lubricant are calculated for human toxicity, acidification, and global warming potentials, this calculation is done according to given data [80]. Each chemical has a different effect on the environment and these environmental effects are calculated according to the characterization factors of each chemical [81]. In this calculation, all the wastewater generations and air emissions are added to the result. Environmental impacts are calculated according to four scenarios based on energy generation for 20 years and are given in Table 6.6.

Table 6.6: Environmental impacts.

Scenarios	Al conductor with transportation	Cu conductor with transportation	Al conductor without transportation	Cu conductor without transportation
Photochemical Oxidation (kg ethylene eq./kWh)	$6.23x10^{-6}$	$6.08x10^{-6}$	$1.50x10^{-6}$	$1.35x10^{-6}$
Human Toxicity (kg 1,4-dichlorobenzene eq./kWh)	$7.29x10^{-4}$	$7.29x10^{-4}$	$7.00x10^{-4}$	$7.00x10^{-4}$
Freshwater Aquatic Ecotoxicity (kg 1,4-dichlorobenzene eq./kWh)	$8.63x10^{-5}$	$8.50x10^{-5}$	$8.63x10^{-5}$	$8.50x10^{-5}$
Marine Aquatic Ecotoxicity (kg 1,4-dichlorobenzene eq./kWh)	$1.14x10^{-3}$	$1.73x10^{-3}$	$1.14x10^{-3}$	$1.73x10^{-3}$
Terrestrial Ecotoxicity (kg 1,4-dichlorobenzene eq./kWh)	$1.26x10^{-8}$	$6.62x10^{-11}$	$1.26x10^{-8}$	$6.62x10^{-11}$
Acidification (kg SO_2 eq./kWh)	$1.82x10^{-5}$	$1.82x10^{-5}$	$1.82x10^{-5}$	$1.82x10^{-5}$
Eutrophication (kg PO_4- eq./kWh)	$5.39x10^{-6}$	$5.39x10^{-6}$	$5.38x10^{-6}$	$5.39x10^{-6}$
Global Warming (GWP_{100}) (kg CO_2 eq./kWh)	$8.73x10^{-2}$	$8.81x10^{-2}$	$1.83x10^{-2}$	$1.91x10^{-2}$

After the recycling of the materials, a gain is obtained as a result of the repurposing of the materials. For this reason, emissions from recycling are considered negative. The environmental impacts according to energy generation for 20 years resulting from this are shown in Table 6.7.

Table 6.7: Environmental impacts with recycling benefits.

Scenarios	Al conductor with transportation	Cu conductor with transportation	Al conductor without transportation	Cu conductor without transportation
Photochemical Oxidation (kg ethylene eq./kWh)	$5.90x10^{-6}$	$5.75x10^{-6}$	$1.16x10^{-6}$	$1.01x10^{-6}$
Human Toxicity (kg 1,4-dichlorobenzene eq./kWh)	$7.29x10^{-4}$	$7.29x10^{-4}$	$7.00x10^{-4}$	$7.00x10^{-4}$
Freshwater Aquatic Ecotoxicity (kg 1,4-dichlorobenzene eq./kWh)	$8.63x10^{-5}$	$8.50x10^{-5}$	$8.63x10^{-5}$	$8.50x10^{-5}$
Marine Aquatic Ecotoxicity (kg 1,4-dichlorobenzene eq./kWh)	$1.14x10^{-3}$	$1.73x10^{-3}$	$1.14x10^{-3}$	$1.73x10^{-3}$
Terrestrial Ecotoxicity (kg 1,4-dichlorobenzene eq./kWh)	$1.26x10^{-8}$	$6.62x10^{-11}$	$1.26x10^{-8}$	$6.62x10^{-11}$
Acidification (kg SO_2 eq./kWh)	$1.44x10^{-5}$	$1.44x10^{-5}$	$1.44x10^{-5}$	$1.44x10^{-5}$
Eutrophication (kg PO_4- eq./kWh)	$5.39x10^{-6}$	$5.39x10^{-6}$	$5.38x10^{-6}$	$5.39x10^{-6}$
Global Warming (GWP100) (kg CO_2 eq./kWh)	$8.33x10^{-2}$	$8.41x10^{-2}$	$1.43x10^{-2}$	$1.51x10^{-2}$

Figure 6.1 and 6.2 shows the percentage contribution of each process to the environmental impacts under all four scenarios.

Figure 6.1 shows the environmental impact contribution under transportation. In the Al-conductor cable scenario, the biggest contributor to eutrophication, acidification, terrestrial toxicity, human toxicity, freshwater, and marine ecotoxicity is the production Al-conductor wind turbine. And a major part of the negative effect on global warming and photochemical smog is due to the transportation process. The second largest contributor to global warming is the operation process followed by the production. And the second largest contributor to the photochemical smog is the production process. Under the Cu-conductor cable scenario, the only noteworthy difference from Al-conductor scenario is that terrestrial ecotoxicity is majorly caused not by the production of the wind turbine but by the construction process of the wind turbine.

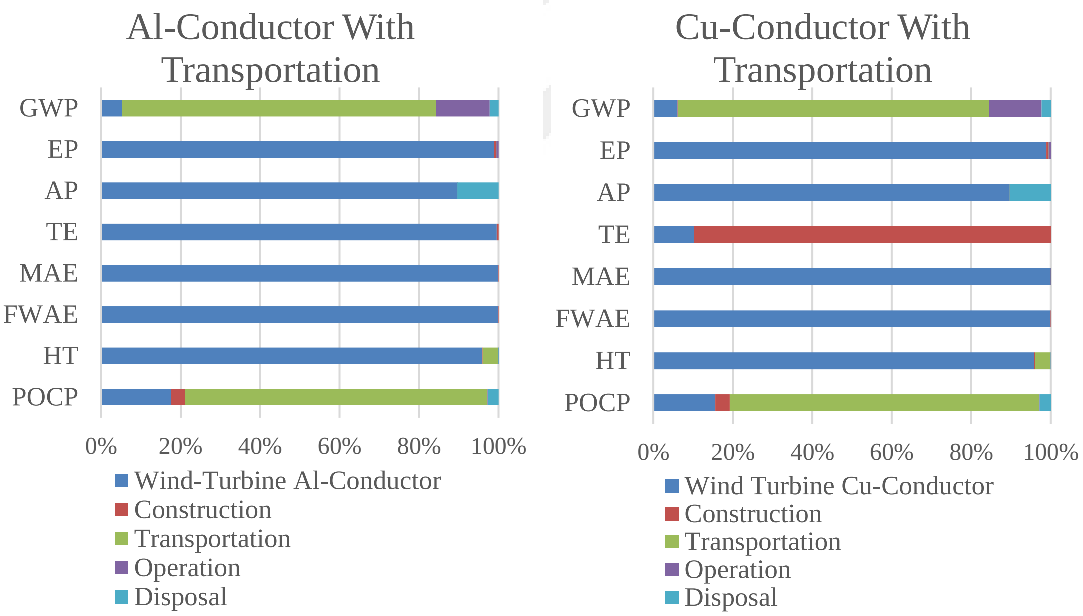

Figure 6.1: Comparison of wind turbines with transportation.

In Figure 6.2, effects of the transportation is excluded since the transportation distances in the two previous scenarios are based on other studies and these values can vary significantly. When transportation is excluded the biggest contributor to global warming is the operation process due to lubricant usage under both Al-conductor and Cu-conductor wind turbines followed by production and disposal processes. All of the remaining environmental impacts are mostly due to the manufacturing of the Al-conductor wind turbine although construction and disposal processes are the second and third largest contributors to the photochemical smog respectively after the manufacturing processes. Similar to the scenario where transportation is taken into account, the construction process of the Cu-conductor wind turbine causes the largest impact on terrestrial ecotoxicity followed by the manufacturing process.

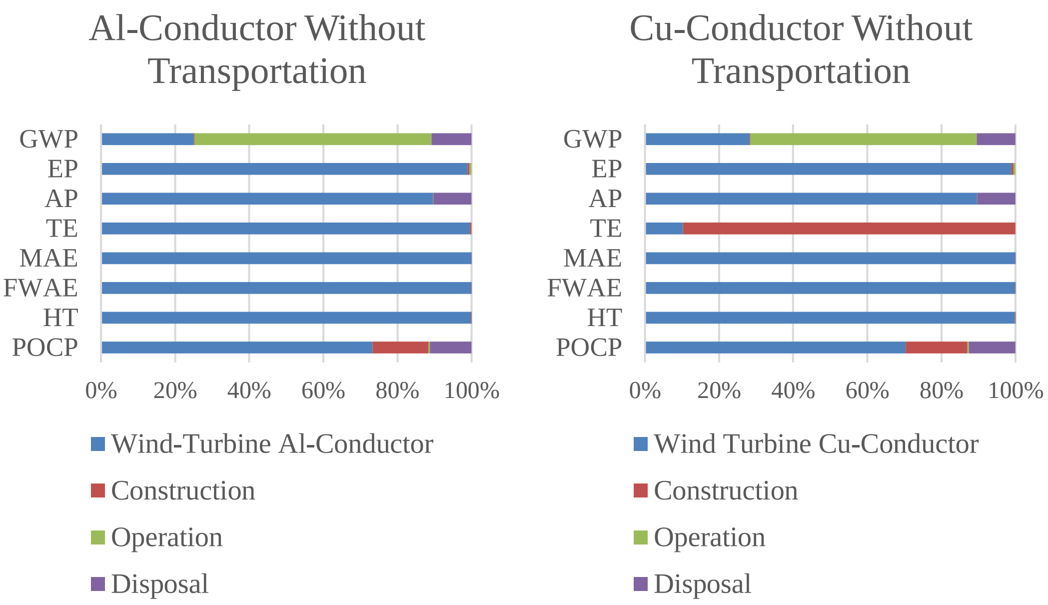

Figure 6.2: Comparison of wind turbines without transportation.

6.4.Comparison of This Study and Vestas V100

The environmental effects of 2 MW V100 wind turbines by Vestas are compared to the four scenarios analysed throughout this study on Table 6.8. The V100 wind turbines are assumed to have a life cycle of 20 years. Manufacturing consists of foundation, nacelle, blade, cables, and transformer station. Most commonly, the turbines are manufactured by using steel, iron, cast iron, aluminum, copper, polymer material, ceramic/glass, electronic, and lubricant. The transportation process consists of moving the parts of the turbine to the land and discarding them to the disposal facilities once their life cycle is completed. Both trucks and ships are used for transportation. The following distances are considered for transportation of the parts: 785 km truck and 8575 km ship for nacelle and hub; 2200 km truck 1570 km ship for blades; 2065 km truck ve 2125 km ship for tower; 50 km truck for foundation and 600 km truck for other site parts. For the construction process cranes, onsite vehicles, diggers, and generators are used. For the operation process lubricants and the replaced materials are used. And the disposal process is conducted for the whole wind farm. Steel, iron, copper, and aluminum are sent to recycling therefore the gained benefit from this process is reflected as negative on the disposal stage. Polymer is incinerated by 50% and the rest is sent to landfills. The lubricant is sent to incineration. The energy payback time of V100 wind turbines is 7 months [82].

Table 6.8: Comparison of this study and Vestas V100.

Environmental Impacts	Al conductor with transportation	Cu conductor with transportation	Al conductor without transportation	Cu conductor without transportation	Vestas V100
Photochemical Oxidation (mg ethylene eq./kWh)	5.9	5.7	1.16	1.01	3.5
Human Toxicity (mg 1,4-dichlorobenzene eq./kWh)	729.0	729.1	699.9	700.0	1256
Freshwater Aquatic Ecotoxicity (mg 1,4-dichlorobenzene eq./kWh)	86.3	85.0	86.3	85.0	54.7
Marine Aquatic Ecotoxicity (g 1,4-dichlorobenzene eq./kWh)	1.1	1.7	1.14	1.7	700
Terrestrial Ecotoxicity (mg 1,4-dichlorobenzene eq./kWh)	0.01	0.00007	0.01	0.00007	34
Acidification (mg SO_2 eq./kWh)	14.4	14.4	14.43	14.4	28
Eutrophication (mg PO_4- eq./kWh)	5.4	5.4	5.4	5.4	3.3
Global Warming (GWP_{100}) (g CO_2 eq./kWh)	83.3	84.1	14.3	15.1	6.2

6.5. Life Cycle Assessment for Turkey

Environmental impacts, energy consumption and energy payback time are calculated for Turkey and presented in this section. First, the case of domestic production of the wind turbines which will be installed in Turkey is examined. A distance of 150 km for foundation and 500 km for rotor, nacelle, and tower is assumed if the whole production process takes place in Turkey. Then the case of importing foreign manufactured wind turbines from Europe to Turkey is considered. In this case, the foundation and tower for the wind turbines are provided from Turkey and distance is considered as 150 km and 500 km respectively. It is presumed that blades are provided from the Netherlands and nacelle is provided from Spain via trucks [83]. A distance of 3500 km for the rotor and 400 km for nacelle are taken into account. The environmental impacts for the country installing the wind turbines are recalculated taking these provided information into account which can be found under Table 6.9.

Table 6.9: Environmental impacts for Turkey.

Environmental Impacts	Al conductor domestic production	Cu conductor domestic production	Al conductor imported	Cu conductor imported
Photochemical Oxidation (mg ethylene eq./kWh)	1.16	1.01	1.17	1.02
Human Toxicity (mg 1,4-dichlorobenzene eq./kWh)	699.86	700.02	699.86	700.02
Freshwater Aquatic Ecotoxicity (mg 1,4-dichlorobenzene eq./kWh)	86.30	85.03	86.30	85.03
Marine Aquatic Ecotoxicity (g 1,4-dichlorobenzene eq./kWh)	1.14	1.73	1.14	1.73
Terrestrial Ecotoxicity (mg 1,4-dichlorobenzene eq./kWh)	0.01	0.00007	0.01	0.00007
Acidification (mg SO_2 eq./kWh)	14.43	14.43	14.43	14.43
Eutrophication (mg PO_4- eq./kWh)	5.39	5.39	5.39	5.39
Global Warming (GWP_{100}) (g CO_2 eq./kWh)	14.35	15.16	14,44	15,24

The energy payback times and energy consumption calculated for both scenarios can be found on Table 6.10.

Table 6.10: Total energy consumption and energy payback time for Turkey.

Scenarios	Total Energy Consumption (MJ)	Energy Payback Time (years)
Al conductor domestic Production	10219504	0.81
Cu conductor domestic production	10119247	0.80
Al conductor from Europe	10289509	0.82
Cu conductor from Europe	10189252	0.81

6.6. Comparison of Energy Systems

In terms of lifespan, the wind turbine is one of the low life energy systems compared to other energy systems. The use of land does not show the exact result. Biomass, PV, wind, natural gas, and geothermal can vary 10%, hydropower can vary 50%, coal and nuclear can vary 100%. Land use is 2 W/m^2 in wind [84]. Capacity factor is found by dividing average power with theoretical maximum power [85]. Capacity factor of wind turbines is approximately 34.6 %. In capacity factor comparison, internal combustion is selected for natural gas [86]. In general, a comparison of energy systems is given in Table 6.11.

Table 6.11: Comparison of energy systems [84, 86–89].

Energy Systems	Life (years)	Land Use (W/m^2)	Capacity Factor (%)
Coal	30	278	53.6
Natural Gas	30	370	13
Wind	25	2	34.6
Geothermal	30	2.22	76
Hydropower	70	0.24	41.9
Solar photovoltaic	30	10	25.1
Biomass	25	0.5	61.8
Nuclear	40	966	92.5

7. CONCLUSION AND RECOMMENDATIONS

In this study, the environmental impacts of the lifecycle of the wind turbine are assessed which includes the manufacturing, transportation, construction, operation, and disposal processes. At the same time, the energy consumption of these stages is also examined and the energy payback time of the turbines in four different scenarios is calculated. In order to calculate the environmental impact, emission values of each process, and wastewater generation during the manufacturing processes are taken into account. All these calculations are conducted for Al-conductor cable and Cu-conductor cable wind turbines. After that, the scenarios are formed with and without transportation for these different conductor systems. At the same time, since a specific wind turbine is not used, the calculations of distances are made using an average distance for the transportation scenarios. In the results, two different conclusions were reached. The reason for having these two conclusions stems from the condition of sending steel, iron, cast iron, copper, aluminum, and lubricant oil to recycling and due to this recycling process, an excess of energy and released emissions are used as positive and negative values in different scenarios.

During transportation, energy consumption and energy payback time are shown to have a great effect on environmental impacts. As a conclusion, closer the producer is to the disposal facilities, less fuel is spent and therefore fewer emissions are released which provides an economic and environmental benefit. Therefore, one of the conclusions of this thesis is that closer the producer and the disposal facility are, the more efficient the entire process will be.

Energy consumption and emissions are calculated for two different cable types which are Al-conductor cable and Cu-conductor cable. However, in this study three cross sections are calculated based on 1 km length of the cable. Since the cables are added after one another three different cross sections of cables are used. The data obtained according to four scenarios are given in Table 7.1 and Table 7.2.

Table 7.1: General results.

Parameter	Al conductor with transportation	Cu conductor with transportation	Al conductor without transportation	Cu conductor without transportation
Total Energy Consumption (MJ)	83570338	83588696	19002839	19021196
Energy Payback Time (years)	6.62	6.63	1.51	1.51
POCP (kg ethylene eq./kWh)	6.23×10^{-6}	6.08×10^{-6}	1.50×10^{-6}	1.35×10^{-6}
HT (kg 1,4-dichlorobenzene eq./kWh)	7.29×10^{-4}	7.29×10^{-4}	7.00×10^{-4}	7.00×10^{-4}
FWAE (kg 1,4-dichlorobenzene eq./kWh)	8.63×10^{-5}	8.50×10^{-5}	8.63×10^{-5}	8.50×10^{-5}
MAE (kg 1,4-dichlorobenzene eq./kWh)	1.14×10^{-3}	1.73×10^{-3}	1.14×10^{-3}	1.73×10^{-3}
TE (kg 1,4-dichlorobenzene eq./kWh)	1.26×10^{-8}	6.62×10^{-11}	1.26×10^{-8}	6.62×10^{-11}
AP (kg SO_2 eq./kWh)	1.82×10^{-5}	1.82×10^{-5}	1.82×10^{-5}	1.82×10^{-5}
EP (kg PO_4- eq./kWh)	5.39×10^{-6}	5.39×10^{-6}	5.38×10^{-6}	5.39×10^{-6}
GWP (GWP_{100}) (kg CO_2 eq./kWh)	8.73×10^{-2}	8.81×10^{-2}	1.83×10^{-2}	1.91×10^{-2}

Table 7.2: General results with recycling benefits.

Parameter	Al conductor with transportation	Cu conductor with transportation	Al conductor without transportation	Cu conductor without transportation
Total Energy Consumption (MJ)	74763848	74663591	10196349	10096091
Energy Payback Time (year)	5.93	5.92	0.81	0.80
POCP (kg ethylene eq./kWh)	5.90×10^{-6}	5.75×10^{-6}	1.16×10^{-6}	1.01×10^{-6}
HT (kg 1,4-dichlorobenzene eq./kWh)	7.29×10^{-4}	7.29×10^{-4}	7.00×10^{-4}	7.00×10^{-4}
FWAE (kg 1,4-dichlorobenzene eq./kWh)	8.63×10^{-5}	8.50×10^{-5}	8.63×10^{-5}	8.50×10^{-5}
MAE (kg 1,4-dichlorobenzene eq./kWh)	1.14×10^{-3}	1.73×10^{-3}	1.14×10^{-3}	1.73×10^{-3}
TE (kg 1,4-dichlorobenzene eq./kWh)	1.26×10^{-8}	6.62×10^{-11}	1.26×10^{-8}	6.62×10^{-11}
AP (kg SO_2 eq./kWh)	1.44×10^{-5}	1.44×10^{-5}	1.44×10^{-5}	1.44×10^{-5}
EP(kg PO_4- eq./kWh)	5.39×10^{-6}	5.39×10^{-6}	5.38×10^{-6}	5.39×10^{-6}
GWP (GWP_{100}) (kg CO_2 eq./kWh)	8.33×10^{-2}	8.41×10^{-2}	1.43×10^{-2}	1.51×10^{-2}

The aim was to select an ideal cable to be used in the wind turbine by examining these two cables of different compositions. If recycling is added positively to the energy consumption, the Cu-conductor cable consumes more energy. Al-conductor cable consumes more energy if the disposal value is negative since recycling is the production of materials again. The global warming effect is greater in the wind turbine using Cu-conductor cable for connection, and there is a significant difference with the scenario without transportation. Photochemical oxidation, terrestrial ecotoxicity, and freshwater aquatic ecotoxicity are more in the wind turbines that use Al-conductor cable for connection. Human toxicity, eutrophication, and marine aquatic ecotoxicity are also higher in the wind turbines that use Cu-conductor cable. However, the acidification effect remained the same in both Al-conductor cable and Cu-conductor cable wind turbines.

While comparing this study with Vestas V100 wind turbines, the recycling is taken as negative during the disposal stage. The energy payback time of the Vestas V100 wind turbines is 7 months. The energy payback time is 10 months in this study when transportation is excluded. And global warming, eutrophication, and freshwater aquatic ecotoxicity values are also higher in this study whereas acidification, human toxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity values are higher for V100 wind turbines. When marine aquatic ecotoxicity and terrestrial ecotoxicity are compared, a big difference between the results are observed.

Recycling is also taken as negative during the disposal stage while examining setting up wind turbines in Turkey under the cases of domestic production and import from European countries. The energy payback time is 10 months under both cases which are similar to the no transportation scenario. The results of the environmental impact are also very close to the no transportation scenario. The most significant difference between the imported and domestic production cases observed in values of contribution to global warming.

Using the results obtained in this study, the topics that can be explored in future studies are listed below.

After completing their use in the turbine, cables are sent for recycling in the disposal stage. However, reuse or sale of the cables can also be considered as other viable options. The assessment of these options is not examined in this thesis and can be performed in another study.

The blades are made of composite, and this material is sent to incineration at the disposal stage. The recycling efficiency of the blades is low; therefore, it is chosen to send the blades to incineration in this study. In some other studies in the literature, the blades are sent to landfills [58]. A study assessing the productivity between these options can be performed.

After the lifecycle of the wind turbine is completed, the foundation is left in its place. There can be studies done on how to proceed with the foundation, its concrete evaluation, and other studies.

On the other hand, if we examine the disposal hierarchy, prevention and reuse of materials come before recycling. With these measures, less energy is spent and fewer pollutants are released to the environment. There could be a study conducted on the prevention and reuse strategies of the components of the wind turbine.

REFERENCES

[1] **Koyama, K.** (2017). The role and future of nitrogen fixation. *IEEJ Energy Journal*, (October), 80–84.

[2] **Martins, F., Felgueiras, C., Smitkova, M., and Caetano, N.** (2019). Analysis of fossil fuel energy consumption and environmental impacts in european countries. *Energies*, ***12*** (6), 1–11. doi:10.3390/en12060964.

[3] **The NEED.** (2009). Introduction To Energy Efficiency. *The NEED Project*, ***1*** (22), 8–11.

[4] **Turkenburg, W., Arent, D. J., Bertani, R., Faaij, A., Hand, M., Krewitt, W., … Usher, E.** (2012). Chapter 11 - Renewable Energy. *Global Energy Assessment - Toward a Sustainable Future*, 811–821.

[5] **Erdin, C., and Ozkaya, G.** (2019). Turkey's 2023 energy strategies and investment opportunities for renewable energy sources: Site selection based on ELECTRE. *Sustainability (Switzerland)*, ***11*** (7). doi:10.3390/su11072136.

[6] **Øvergaard, S.** (2008). Definition of primary and secondary energy. *Standard International Energy Classification (SIEC) in the International Recommendation on Energy Statistics (IRES)*, (Energy Statistics), 1–7.

[7] <URL-1> **Eurostat**. (2019). What kind of energy do we consume in the EU? Retrieved from https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-3a.html

[8] <URL-2> **BP**. (2018). Statistical Review of World Energy | Energy economics | Home. *Statistical Review of World Energy*. Retrieved from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

[9] **Ghenai, C.** (2015). Life Cycle Analysis of Wind Turbine, (May). doi:10.5772/29184.

[10] **Palomo, B., and Gaillardon, B.** (n.d.). Life Cycle Assessment Of A French Wind

[11] **Ardente, F., Beccali, M., Ã, M. C., and Brano, V. Lo**. (2008). Energy performances and life cycle assessment of an Italian wind farm, ***12***, 200–217. doi:10.1016/j.rser.2006.05.013.

[12] **Lenzen, M., and Munksgaard, J.** (2006). Energy and CO 2 life-cycle analyses of wind turbines — review and applications, ***26*** (2002), 339–362.

[13] **Vestas.** (2006). Life cycle assessment of electricity delivered from an onshore power plant based on Vestas V82-1.65 MW turbines, 1–77.

[14] **Haapala K. R., Prempreeda P.** (2014). Comparative life cycle assessment of 2 . 0 MW wind turbines, ***3*** (2), 170–185.

[15] **Carr, A., Drosnes, M., Glassbrook, K., and Oakley, R.** (n.d.). Life Cycle Assessment and Feasibility Study of Small Wind Power in Thailand.

[16] **Siemens** (n.d.). A clean energy solution – from cradle to grave Assessing the performance of a wind power plant.

[17] **Mitchell, J. T., Grace, J., and Harrison, G. P.** (2010). CO 2 payback time for a wind farm on afforested peatland in the UK, ***4***, 1–12.

[18] **Thomson, R. C., and Harrison, G. P.** (2015). Life Cycle Costs and Carbon Emissions of Onshore Wind Power, (June).

[19] **Crawford, R. H.** (n.d.). Life-cycle energy analysis of wind turbines – an assessment of the effect of size on energy yield, ***105***, 155–164. doi:10.2495/ESUS070161.

[20] **Chipindula, J., Sai, V., and Botlaguduru, V.** (2018). Life Cycle Environmental Impact of Onshore and Offshore Wind Farms in Texas, 1–18. doi:10.3390/su10062022.

[21] **Jungbluth, N., Bauer, C., Dones, R., and Frischknecht, R.** (2004). ecoinvent : Energy Supply Life Cycle Assessment for Emerging Technologies : Case Studies for Photovoltaic and Wind Power, ***2004***, 1–11.

[22] **Arvesen, A., and Hertwich, E. G.** (2011). Corrigendum : Environmental implications of large-scale adoption of wind power : a scenario-based life cycle assessment. doi:10.1088/1748-9326/7/3/039501.

[23] **Schleisner, L.** (2000). Life cycle assessment of a wind farm and related externalities, ***20***, 279–288.

[24] **Bonou, A., Laurent, A., and Olsen, S. I.** (2016). Life cycle assessment of onshore and offshore wind energy-from theory to application. *Applied Energy*, ***180***, 327–337. doi:10.1016/j.apenergy.2016.07.058.

[25] **Razdan, A. P., Garrett, P., Razdan, A. P., Garrett, P., Razdan, A. P., and Garrett, P.** (2015). December 2015 Life Cycle Assessment of Electricity Production from an onshore V110-2 . 0 MW Wind Plant December 2015 Authors : Priyanka Razdan , Peter Garrett Vestas Wind Systems A / S Vestas Wind Systems A / S, (December).

[26] **Sanz, F., Pellegrini, S., and Jime, E.** (2009). Life cycle assessment of a multi-megawatt wind turbine, ***34***, 667–673. doi:10.1016/j.renene.2008.05.020.

[27] **Damien, W.** (2006). Life Cycle Assessment of a Wind Turbine.

[28] **Tremeac, B., and Meunier, F.** (2009). Life cycle analysis of 4.5 MW and 250 W wind turbines. *Renewable and Sustainable Energy Reviews*, ***13*** (8), 2104–2110. doi:10.1016/j.rser.2009.01.001.

[29] **Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., and Heath, G. A.** (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies, ***112*** (20). doi:10.1073/pnas.1312753111.

[30] **Borup M., Andersen P. D.** (2016). Recycling And Removal Of Offshore Wind Turbines – An Interactive Method For Reduction Of Negative Environmental Effects., (January).

[31] **Andersen, P. D., Bonou, A., Beauson, J., & Brøndsted, P.** (2014). Recycling of wind turbines. In H. Hvidtfeldt Larsen, & L. Sønderberg Petersen (Eds.), DTU International Energy Report 2014: Wind energy — drivers and barriers for higher shares of wind in the global power generation mix. (pp. 91-97). Technical University of Denmark.

[32] **Andersen P. D., Borup M.** (2007). Managing long-term environmental aspects

of wind turbines : A prospective case study. doi:10.1504/IJTPM.2007.015169.

[33] **Günkaya, Z., Özdemir, A., Özkan, A., and Banar, M.** (2016). Environmental Performance of Electricity Generation Based on Resources : A Life Cycle Assessment Case Study in Turkey, 1–14. doi:10.3390/su8111097.

[34] **Mcculloch, M., Raynolds, M., and Laurie, M.** (2000). Life-Cycle Value Assessment of a Wind Turbine, (February).

[35] **Turconi, R., Boldrin, A., and Astrup, T.** (2013). Life cycle assessment (LCA) of electricity generation technologies : overview , comparability and limitations. doi:10.1016/j.rser.2013.08.013.

[36] **Andersen P. D., Bonou A., Beauson J., Brøndsted P.** (2014). Life Cycle Assessment of Electricity Systems.

[37] **Taylor, S. E., Birch, G. F., and Links, E.** (2004). Energy from offshore wind : an overview, ***20*** (3), 709–721.

[38] **GWEC**. (2019). Global wind energy council report 2018. *Wind Global Council Energy*, (April), 1–61. Retrieved from www.gwec.net

[39] **Turkish Wind Energy Association**. (2019). Turkish Wind Energy Statistic Report July 2019, 6–7. Retrieved from https://www.tureb.com.tr/turebsayfa/duyurular/turkiye-ruzgar-enerjisi-istatistik-raporu-temmuz-2019

[40] **BWE.** (2016). The Structure of a Modern Wind Turbine – An Overview. *German Wind Energy Association*, 1–14. Retrieved from http://www.wwindea.org/technology/ch01/en/1_2.html

[41] **Boakye-Boaten, A. (2006).** Life Cycle Assesstment: Principles and Practice

[42] **Sokka, L., Henclik, A., Goralczyk, M., Koneczny, K., Kulczycka, J., Seppälä, J., and Koskela, S.** (2005). A Life Cycle Assessment of Electricity Production from Hard Coal. *International Mining Forum 2005, New Technologies in Underground Mining, Safety and Sustainable Development*, 13–24. doi:10.1201/noe0415375528.ch3.

[43] **Barnthouse**. (1999) Chapter 3 Life-Cycle Impact Assessment, 1–215.

[44] **Nexans.** (n.d.). Nominal cross section, ***30*** (36).

[45] **ABB**. (2010). XLPE Land Cable Systems - User's Guide, 28. Retrieved from https://library.e.abb.com/public/ab02245fb5b5ec41c12575c4004a76d0/XLPE Land Cable Systems 2GM5007GB rev 5.pdf

[46] **Ministry of Industry and Technology.** (2019). Iron and Steel Department Report 2019.

[47] <URL-3> **GreenSpec** (2020). Environmental Impacts of Rainwater Goods Materials. Retrieved from: https://www.greenspec.co.uk/building-design/rainwater-goods/#iron

[48] **Office of Energy Efficiency & Renewable Energy 2017a**. (2017). Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Carbon Fiber Reinforced Polymer Manufacturing, (September), 63.

[49] **Monti, A.** (2002). Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles, *UNEP*.

[50] **Arıoğlu N., Hatipoğlu D. D., I., Salmona M. Ö. A.** (2002). Sürdürülebilirlik

Kavrami Anlayişinda Beton Endüstrisinin İrdelenmesi.

[51] **Hammond, G., and Jones, C.** (2011). A BSRIA Guide. Embodied Carbon: The Inventory of Carbon and Energy. University of Bath, UK. *Ice,* 136. doi:10.1680/ener.2011.164.4.206.

[52] **Goodyear.** (n.d.). Example : FACTORS AFFECTING DIRECTION OF TRAVEL, (352).

[53] **Staffel, I.** (2011). The Energy and Fuel Data Sheet. *Claverton Energy Research Goup*, (March), 11. Retrieved from http://www.claverton-energy.com/the-energy-and-fuel-data-sheet.html

[54] **Soleymani A. *et al.*** (2018). Linear Modelling of Marine Vessels Fuel Consumption for Ration of Subsidized Fuel. International Journal of Maritime Technology, 10 (Summer and Autumn 2018), 7–13. doi:10.29252/ijmt.10.7.

[55] **European Commission**. (n.d.). European Union Ship Emissions to Air Study Appendix 5, 1–17.

[56] **Trozzi, C.** (2010). Emission estimate methodology for maritime navigation, 6. Retrieved from http://www.epa.gov/ttnchie1/conference/ei19/session10/trozzi.pdf

[57] **Eng A. *et. al.*** (2011). Energy Information Handbook. Retrieved from http://eis.lbl.gov/energy-information-handbook.html

[58] **Jensen, J. P.** (2019). Evaluating the environmental impacts of recycling wind turbines. *Wind Energy*, ***22*** (2), 316–326. doi:10.1002/we.2287.

[59] **European Environment Agency**. (2011). The Waste Framework Directive (WFD). Retrieved from http://www.eea.europa.eu/themes/waste/policy-context

[60] **BIR.** (2008). Report on the Environmental Benefits of Recycling. *October*, (April), 49. Retrieved from http://www.thenbs.com/topics/DesignSpecification/articles/benefitsMasterSpecifications.asp

[61] **Vo Dong, P. A., Azzaro-Pantel, C., Boix, M., Jacquemin, L., and Domenech, S.** (2015). *Modelling of Environmental Impacts and Economic Benefits of Fibre Reinforced Polymers Composite Recycling Pathways*. *Computer Aided Chemical Engineering* (Vol. 37). Elsevier. doi:10.1016/B978-0-444-63576-1.50029-7.

[62] **Gutti, M. B., and Musa, A. A.** (2019). The quantities of materials in one cubic meter of concrete using different mix ratios., (January). doi:10.31219/osf.io/xcjuq.

[63] **Moore, W. M.** (2019). Concrete works. Retrieved from https://www.ilo.org/wcmsp5/groups/public/---asia/---ro-bangkok/documents/genericdocument/wcms_101286

[64] **EMEP EEA**. (2019). EMEP/EEA air pollutant emission inventory guidebook 2019: Cement production, 1–18.

[65] **Environment and Urban Ministry and ITU.** (2016). Çimento Sanayi İçin Mevcut En İyi Teknikler (MET).

[66] <URL-4> **European Environment Agency.** (n.d.) Retrieved from: https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters.

[67] **IEA.** (2000). Greenhouse Gas Emissıons From Major Industrial Sources – III Iron And Steel Productıon Report Number PH3 / 30 September 2000, (September). doi:PH3/30.

[68] **Jerry Marks, Lubetsky, J., Steiner, B. A., Faerden, T., Lubetsky, J. S., Lindstad, T., … Lubetsky, J. S.** (2006). Metal Industry Emissions. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 3: Industrial Process and Product Use*, 85. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_4_Ch4_Metal_Industry.pdf

[69] **Li, X., Sun, W., Zhao, L., and Cai, J.** (2018). Material Metabolism and Environmental Emissions of BF-BOF and EAF Steel Production Routes. *Mineral Processing and Extractive Metallurgy Review*, ***39*** (1), 50–58. doi:10.1080/08827508.2017.1324440.

[70] **Joshi, S. V., Drzal, L. T., Mohanty, A. K., and Arora, S.** (2004). Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites Part A: Applied Science and Manufacturing*, ***35*** (3), 371–376. doi:10.1016/j.compositesa.2003.09.016.

[71] **Kero, I., Grådahl, S., and Tranell, G.** (2017). Airborne Emissions from Si/FeSi Production. *Jom*, ***69*** (2), 365–380. doi:10.1007/s11837-016-2149-x.

[72] **Freese, N.** (2017). WORKING PAPER SERIES 2017 : 4 CO 2 Emissions from International Maritime Shipping.

[73] **Ambel, C. C.** (2015). Too big to ignore – truck CO 2 emissions in 2030. *Transport and Environment*, (September), 2–4. Retrieved from https://www.transportenvironment.org/sites/te/files/publications/2015 09 TE Briefing Truck CO2 Too big to ignore_FINAL.pdf

[74] **Ntziachristos, Leonidas; Samaras, Z.** (2017). Air Pollutant Emission Inventory Guidebook Guidebook 2019 (1.A.3.b). *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019*, ***8*** (9), 1–58. doi:10.1017/CBO9781107415324.004.

[75] **Perumal, A., and Timmons, D.** (2017). Contextual Density and US Automotive CO2 Emissions across the Rural–Urban Continuum. *International Regional Science Review*, ***40*** (6), 590–615. doi:10.1177/0160017615614897.

[76] **European Environment Agency.** (2013). Non-road mobile sources and machinery.

[77] **Gianluca, C., Rodrigo Gonzalo, M., Farrell, F., Roudier, S., Remus, R., and Delgado Sancho, L.** (2017). *Best Available Techniques (BAT) Reference Document for the main Non-Ferrous Metals Industries, EUR 28648*. doi:10.2760/8224.

[78] **Colla, V., Matino, I., Branca, T. A., Fornai, B., Romaniello, L., and Rosito, F.** (2017). Efficient use of water resources in the steel industry. *Water (Switzerland)*, ***9*** (11), 1–15. doi:10.3390/w9110874.

[79] **Remus, R., Roudier, S., Aguado Monsonet, M. a., and Sancho, L. D.** (2013). *Best Available Techniques (BAT) Reference Document for Iron and Steel Production. Industrial Emissions Directive 2010/75/EU* (Vol. BREF-IS). doi:10.2791/97469.

[80] **Botas, J. A., Moreno, J., Espada, J. J., Serrano, D. P., and Dufour, J.** (2017). Recycling of used lubricating oil: Evaluation of environmental and energy performance by LCA. *Resources, Conservation and Recycling*, ***125*** (January),

315–323. doi:10.1016/j.resconrec.2017.07.010.

[81] <URL-5> **CML**. (2016). CML-IA Characterisation Factors - Leiden University. *Institute of Environmental Sciences (CML)*. Retrieved from https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

[82] **Garrett, P., and Rønde, K.** (2012). Life Cycle Assessment of Electricity Production from an onshore V90-3 . 0MW Wind Plant September 2012 Authors : Peter Garrett & Klaus Rønde Vestas Wind Systems A / S. *Vestas Wind Systems A/S Vestas*, 1–106. Retrieved from https://www.vestas.com/~/media/vestas/about/sustainability/pdfs/lca_v903mw_version_1_1.ashx

[83] <URL-6> **Siemens Gamesa.** (2019). Location Finder I Siemens Gamesa. Retrieved from: https://www.siemensgamesa.com/about-us/location-finder

[84] **Buceti, G.** (2014). Sustainable power density in electricity generation. *Management of Environmental Quality: An International Journal*, ***25*** (1), 5–18. doi:10.1108/MEQ-05-2013-0047.

[85] **Boccard, N.** (2009). Capacity factor of wind power realized values vs. estimates. *Energy Policy*, ***37*** (7), 2679–2688. doi:10.1016/j.enpol.2009.02.046.

[86] **EIA.** (2019). Electric Power Monthly with Data for October 2019, (December), 1–772.

[87] **Ben Brahim, M., and Thiry, M.** (1999). Un piemont detritique a silicifications differenciees: Les Hamadas tertiaires de Boudenib-Guir (Maroc). *Zeitschrift Fur Geomorphologie, Supplementband*, ***119*** (June), 1–20.

[88] **Edenhofer, O., Madruga, R. P., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., … von Stechow, C.** (2011). *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change*. *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change*. doi:10.1017/CBO9781139151153.

[89] **Meldrum, J., Nettles-Anderson, S., Heath, G., and Macknick, J.** (2013). Life cycle water use for electricity generation: A review and harmonization of literature estimates. *Environmental Research Letters*, ***8*** (1). doi:10.1088/1748-9326/8/1/015031.

APPENDICES

APPENDIX A: Emissions of wind turbine

APPENDIX B: Emissions of cables production

APPENDIX C: Emissions of construction equipments

APPENDIX D: Emissions of operation

APPENDIX E: Emissions of transportation

APPENDIX F: Emissions of disposal

APPENDIX A

Table A.1: Emissions of wind turbine.

Pollutant	Value	Unit
TSP	20186	kg
NO_x	593323	g
CO	709838	g
NMVOC	44973	g
SO_2	870762	g
SO_x	377997	g
PM_{10}	27786	g
$PM_{2.5}$	17664	g
Pb	685	g
Cd	89	g
Hg	2677445	g
As	56	g
Cr	213	g
Cu	1	g
Ni	161	g
Zn	673	g
PCB	593	mg
PCDD/F	610	µg-I-TEQ
Total 4 PAHs	204	g
CO_2	233	t
H_2S	581	g
NO_2	194	kg
Se	0.17	g

APPENDIX B

Table B.1: Emissions of Al-conductor cable.

Pollutant	Value	Unit
NO_x	271	kg
CO	388	kg
SO_x	150	kg
TSP	10	kg
PM_{10}	8	kg
$PM_{2.5}$	6	kg
Benzo(a)pyrene	29	g
Benzo(b)fluoranthene	29	g
Benzo(k)fluoranthene	29	g
Indeno(1,2,3-cd)pyrene	4	g
CO_2	86	t
Pb	461	g
Cd	200	g
Hg	0,36	g
As	104	g
Cr	242	g
Cu	980	g
Ni	221	g
PCBs	43	µg
PCDD/F	577	µg-I-TEQ
N_2O	2191	g

Table B.2: Emissions of Cu-conductor cable.

Pollutant	Value	Unit
TSP	14195	g
PM_{10}	11311	g
$PM_{2.5}$	8650	g
SO_x	259942	g
Pb	887	g
Cd	384	g
Hg	1	g
As	200	g
Cr	466	g
Cu	1885	g
Ni	424	g
PCBs	82	µg
PCDD/F	1109	µg-I-TEQ
CO_2	145	t
NO_x	514340	g
N_2O	4214	g

APPENDIX C

Table C.1: Emissions of construction equipments.

Pollutant	Value	Unit
CH_4	2979	g
CO	580803	g
CO_2	171	kg
N_2O	7313	g
NH_3	433	g
NMVOC	183363	g
NO_x	1776	kg
PM_{10}	113	kg
$PM_{2.5}$	113	kg
TSP	113	kg
Cadmium	542	mg
Copper	92088	mg
Chromium	2708	mg
Nickel	3792	mg
Selenium	542	mg
Zinc	54169	mg
Benz(a)anthracene	4334	mg
Benzo(b)fluoranthene	2708	mg
Dibenzo(a,h)anthracene	542	mg
Benzo(a)pyrene	1625	mg
Chrysene	10834	mg
Fluoranthene	24376	mg
Phenanthene	135423	mg

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APPENDIX D

Table D.1: Emissions of operation.

Pollutant	Value	Unit
NO_x	51069	g
CO	10	kg
NMVOC	136	g
SO_2	186	g
TSP	1415	g
PM_{10}	1134	g
$PM_{2.5}$	879	g
Pb	93	g
Cd	35	g
Hg	0.2	g
As	19	g
Cr	45	g
Cu	170	g
Ni	41	g
Zn	16	g
PCB	11	mg
PCDD/F	110	µg-I-TEQ
Total 4 PAHs	1.4	g
CH_4	32207	g
N_2O	7121	g
CO_2	817	t
SO_x	25975	g
Se	0.004	g

APPENDIX E

Table E.1: Emissions of transportation.

Pollutant	Value	Unit
NO_x	130315	kg
CO	12293	kg
NMVOC	4649	kg
SO_x	33175	kg
TSP	2488	kg
PM_{10}	2488	kg
$PM_{2.5}$	2326	kg
Pb	216	g
Cd	17	g
Hg	50	g
As	66	g
Cr	83	g
Cu	1460	g
Ni	1659	g
Se	166	g
Zn	1990	g
PCB	63	mg
PCDD/F	216	µg-I-TEQ
HCB	133	mg
N_2O	235	g
NH_3	24	g
CO_2	4835	t

APPENDIX F

Table F.1: Emissions of disposal of wind turbine.

Pollutant	Value	Unit
NO_x	31462	g
CO	411	kg
NMVOC	11133	g
SO_2	14521	g
TSP	9021	g
PM_{10}	7183	g
$PM_{2.5}$	6127	g
Pb	761	g
Cd	61	g
Hg	12	g
As	15	g
Cr	24	g
Cu	159	g
Ni	170	g
Zn	871	g
PCB	605	mg
PCDD/F	1001	µg-I-TEQ
Total 4 PAHs	116	g
CO_2	22	t

Table F.2: Emissions of disposal of Al-conductor cable.

Pollutant	Value	Unit
TSP	10	kg
PM_{10}	7	kg
$PM_{2.5}$	4	kg
SO_x	15223	g
Pb	277	g
Cd	27	g
As	23	g
Cu	323	g
Ni	1	g
PCBs	43	µg
PCDD/F	690	µg-I-TEQ
HCB	16	g
CO_2	7	t

Table F.3: Emissions of disposal of Cu-conductor cable.

Pollutant	Value	Unit
TSP	7097	g
PM_{10}	5545	g
$PM_{2.5}$	4214	g
SO_x	29277	g
Pb	532	g
Cd	51	g
As	44	g
Cu	621	g
Ni	3	g
PCBs	82	µg
PCDD/F	1109	µg-I-TEQ
CO_2	10	t

Table F.4: Emissions of transportation in disposal.

Pollutant	Value	Unit
CO	1125	g
NMVOC	267	g
NO_x	6400	g
N_2O	15	g
NH_3	1	g
Pb	0.008	g
CO_2	450	kg
$PM_{2.5}$	246	g

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