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A COMPARISON OF RENEWABLE ENERGY SYSTEMS (ONSHORE WIND, OFFSHORE WIND, CONVENTIONAL PV) FOR BOZCAADA ISLAND

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
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BY

AYŞE EYLÜL ŞENTÜRK

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FOR
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IN
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ABSTRACT

A COMPARISON OF RENEWABLE ENERGY SYSTEMS (ONSHORE WIND, OFFSHORE WIND, CONVENTIONAL PV) FOR BOZCAADA ISLAND

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Renewable energy sources have been considered as a sustainable solution for energy production without polluting the environment. Shifting from fossil fuel to renewable sources has been suggested by many scientists to decrease the global warming effects. As several renewable energy sources exist such as solar, wind, hydro-power, etc., it is important to determine the appropriate option for a selected region in terms of maximizing efficiency and power output as well as minimizing life cycle costs (LCC). There are a few case studies answering this problem, and in order to address this gap, a comparison between potential renewable sources for the selected region, Bozcaada Island, has been performed in this study to determine the appropriate renewable system implementation.

The region has both wind and solar potential, therefore; two different renewable sources are evaluated with totally three distinct configurations. Onshore wind farm, which is under operation since 2000, and the proposed offshore wind farm are two distinct configurations for the island's wind potential. As an alternative option, ground-mounted on-grid photovoltaic (PV) power plant is proposed for the third configuration which will put the island's solar potential in use. All three configurations are compared with the selected impact categories which are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), cumulative energy demand (CED) and energy pay-back time (EPBT) by modelling with GaBi to evaluate environmental specifications. Life cycle cost of each system is calculated by improved equations and the results are compared in order to assess their cost characteristics. "Cradle-to grave" approach is applied in each case.

The findings revealed that offshore wind technology is more advantageous than onshore wind technology in terms of minimizing the environmental impacts except acidification potential (AP) and maximizing the use of island's wind potential whereas onshore technology is more beneficial for the environment than conventional photovoltaic (PV) system when all the selected impact categories are taken into account. In other words, the cleanest way to generate electricity in Bozcaada is utilization of the island's wind potential by offshore deployment. The most economical investment to generate 1 MWh electricity has been found as the already existing onshore wind farm configuration when costs are compared. With the same consideration, photovoltaic technology has been found to be more promising for the production of electricity than offshore wind farm for future investments in Bozcaada Island in terms of economic aspects.

Keywords: Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Offshore Wind Farm, Onshore Wind Farm, Land-Based Grid Connected Photovoltaic Plant

ÖZ

BOZCAADA İÇİN YENİLENEBİLİR ENERJİ SİSTEMLERİ (KARASAL RÜZGÂR, DENİZ ÜSTÜ RÜZGÂR VE GELENEKSEL FOTOVOLTAİK) KIYASLAMASI

Şentürk, Ayşe Eylül
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Çevreyi kirletmeksizin enerji üretimi için yenilenebilir enerji kaynakları sürdürülebilir bir çözüm olarak düşünebilir. Küresel ısınmanın etkilerini azaltmak için, fosil yakıttan yenilenebilir kaynaklara geçiş birçok araştırmacı tarafından önerilmektedir. Güneş, rüzgâr ve hidrolik güç vb. birçok yenilenebilir enerji kaynağı mevcut olduğundan, seçilen bir bölgede verimliliği ve güç üretimini en yükseğe çıkarmanın yanında yaşam döngüsü maliyetini en aza indiren uygun seçeneği belirlemek önemlidir. Bu sorunu yanıtlayan birtakım çalışmalar bulunmakla birlikte, bu boşluğu gidermek adına seçilen bölge olan Bozcaada'da uygun yenilenebilir enerji sisteminin kurulumunu belirlemek amacıyla bölgede potansiyel teşkil eden yenilenebilir enerji kaynakları arasında bir kıyaslama gerçekleştirilmiştir.

Bahsedilen bölge hem rüzgâr hem de güneş potansiyeline sahiptir bu yüzden iki farklı yenilenebilir enerji kaynağı, toplam üç farklı konfigürasyonla değerlendirilmiştir. Rüzgâr potansiyeli için, iki farklı konfigürasyondan biri 2000'den beri işletmede olan karasal rüzgâr çiftliği ve önerilen deniz üstü rüzgâr çiftliğidir. Bir diğer seçenek olarak, adanın güneş potansiyelini kullanıma almak üzere, üçüncü konfigürasyon için şebeke bağlantılı arazi tipi fotovoltaik (FV) santral önerilmiştir. Üç konfigürasyonun hepsi, küresel ısınma potansiyeli, asidifikasyon potansiyeli, ötrofikasyon potansiyeli, kümülatif enerji talebi ve enerji geri ödeme süresi olarak seçilen etki kategorilerine göre; çevresel özelliklerini değerlendirmek için GaBi ile modellenerek kıyaslanmıştır. Geliştirilen denklemlerle her bir sistemin yaşam döngüsü maliyeti hesaplanmış ve elde edilen sonuçlar, maliyet özelliklerini değerlendirmek için kıyaslanmıştır.

Bulgular; karasal teknolojinin, tüm etki kategorileri hesaba katıldığında geleneksel fotovoltaik (FV) teknolojisinden asitleştirme potansiyeli hariç çevre için daha faydalı olmasına rağmen, çevresel etkileri minimuma indirmek ve adanın rüzgâr potansiyelinin kullanılmasını maksimuma çıkarmak açısından, deniz üstü teknolojinin karasal teknolojiden daha avantajlı olduğunu göstermiştir. Yani, Bozcaada'da elektrik üretmenin en temiz yolu, adanın rüzgâr potansiyelinin deniz üstü rüzgâr teknolojisi kullanılarak değerlendirilmesinden geçmektedir. Maliyetler kıyaslandığında, mevcut olan karasal rüzgâr çiftliği konfigürasyonunun, 1 MWh elektrik üretmek için en ekonomik yatırım olduğu bulunmuştur. Ekonomik açıdan aynı şekilde bakıldığında, Bozcaada'daki gelecek yatırımlar için, FV teknolojisinin deniz üstü rüzgâr çiftliğinden daha ümit vadettiği bulunmuştur.

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To my family…

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LIST OF ABBREVIATIONS

ABBREVIATIONS

LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LCCA	Life Cycle Cost Analysis
PV	Photovoltaic
GHG	Greenhouse Gas
GWP	Global Warming Potential
AP	Acidification Potential
EP	Eutrophication Potential
CED	Cumulative Energy Demand
PED	Primary Energy Demand
EPBT	Energy Pay-Back Time
ELECTRE	ELimination and Choice Expressing REality
IIC	Initial investment cost
NE	North East
P	Production Phase
C	Construction Phase
O&M	Operation and Maintenance Phase
DorR	Decommissioning and Disposal or Recycling Phase
R	Recycling Phase
DDPMSG	Direct Drive Permanent Magnet Synchronous Generator
DDSG	Direct Driven Synchronous Generator
DFIG	Doubly-Fed Induction Generator
BOS	Balance of System
G	Ground Mounting of PV System

RF	Roof-type Mounting of PV System
mc-si	Multi-crystalline solar cell
multi-si	Multi-crystalline solar cell
CdTe	Cadmiumtellurium
CIS	Cupper Indium Selenium
LCoE	Levelized Cost of Electricity
NPV	Net Present Value
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
SO_2	Sulphur Dioxide
CO_2	Carbon Dioxide
MWh	Megawatt hour
UV	Ultraviolet
PVGIS	Photovoltaic Geographical Information System
LUCE	Levelized Unit Cost to produce 1 MWh electricity
TWEA	Turkish Wind Energy Association
OECD	Organization for Economic Co-operation and Development
CFD	Computational Fluid Dynamics
BP	British Petrol
kV	kilovolt
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
USA	United States of America
FV	Fotovoltaik

LIST OF SYMBOLS

SYMBOLS

C_{inv}	Investment Cost
$C_{O\&M}$	The cost of operation and maintenance procedures
C_{DorR}	The cost of decommissioning and disposal or recycling
C_{tr}	Total transportation expenses
LUCE	Levelized Unit Cost
LCC_{Wind}	Life Cycle Cost for a wind farm
C_{Winv}	Investment Cost for a wind farm
$C_{WO\&M}$	The cost of operation and maintenance procedure for a wind farm
C_{WDorR}	The cost of decommissioning and disposal or recycling for a wind farm
$C_{turbines}$	The total cost of the wind turbines in a wind farm
C_{Winf}	The infrastructure cost for a wind farm
C_{Welec}	The electrical equipment cost for a wind farm
C_{Wtr1}	The transportation expenses throughout the establishment period of a wind farm
C_{WM}	The material costs required for the operation and maintenance procedures of a wind farm
C_{Wtr2}	The transportation expenses for the operation and maintenance procedures of a wind farm
C_{Wtr3}	The transportation expenses for the decommissioning and disposal procedures of a wind farm
C_{Wtr}	Total transportation expenses throughout the lifespan of a wind farm
LCC_{PV}	Life Cycle Cost of a photovoltaic plant
C_{PVinv}	Investment Cost of a photovoltaic plant
$C_{PO\&M}$	The cost of operation and maintenance procedure for a photovoltaic plant

C_{DorR}	The cost of decommissioning and disposal or recycling for a photovoltaic plant
C_{panels}	The total cost of the solar panels for a photovoltaic plant
C_{Pinf}	The infrastructure cost for a photovoltaic plant
C_{Pelec}	The electrical equipment cost for a photovoltaic plant
C_{Ptr1}	The transportation expenses throughout the establishment period of a photovoltaic plant
C_{M}	The material costs required for the operation and maintenance procedures of a wind farm
C_{Ptr2}	The transportation expenses for the operation and maintenance procedures of a wind farm
C_{Ptr3}	The transportation expenses for the decommissioning and disposal procedures of a wind farm
C_{Ptr}	Total transportation expenses throughout the lifespan of a photovoltaic plant

CHAPTER 1

INTRODUCTION

Global warming is one of the most alarming problems for the future of the world. As a solution to it, the shift from fossil fuel to renewable sources in order to generate clean energy, especially large-scale implementation of wind and PV (Alsema, 2012; Hertwich et al., 2015) is strongly recommended by many researchers (Keleş & Bilgen, 2012; Larsen, 2014; Özkale et al., 2017; Pimentel Da Silva & Branco, 2018). Renewable energy technologies are suggested as a solution for the shifting procedure from fossil fuel to renewable energy sources (Santoyo-Castelazo & Azapagic, 2014; Vázquez Hernández et al., 2019) in order to decrease the air pollution and prevent the impacts of climate change especially by means of local co-production (Franzitta et al., 2016; Panwar et al., 2011). With this in mind, researchers from many countries including Greece (Orfanos et al., 2019), the United States (Mahmud et al., 2020), the United Kingdom (Stamford & Azapagic, 2014), India (Kapoor et al., 2014), Portugal (Kabayo et al., 2019) and Italy (Beccali et al., 2007; Cellura et al., 2019) firstly focus on their national grid systems by using LCA methodology. In case of Turkey, the researchers (Atilgan & Azapagic, 2016; Yilan et al., 2020) agree that the most sustainable system for the Turkish grid system is hydro power plant. However, there is limited research on the selection of most appropriate renewable source for a specific region (Oğuz & Şentürk, 2019; Schmidt et al., 2017; Siddiqui & Dincer, 2017) by using life cycle assessment (LCA) methodology prior to an investment. The only study that can be found by Erdin and Özkaya (2019) draw a framework with the application of ELECTRE (ELimination and Choice Expressing Reality), which enables large perspective for the problem of energy planning, for answering the question which renewable investments are more appropriate in any geographic region of Turkey.

In this thesis, three different configurations are analyzed by coupling LCA and LCC with the purpose of choosing the most feasible one for a specific region. The findings of the analysis carried out indicate that onshore wind farm is more cost-efficient than other two configurations. Apart from acidification potential, deployment of offshore wind is more environmental-friendly than other two configurations.

1.1 Research motivation

Hydro power plant (Atilgan & Azapagic, 2016; Yılan, 2018) is defined as the most sustainable system for Turkey's electricity in terms of environmental aspects by means of LCA results of Turkish national grid system, however; this option is not available for the water poor sides of the country. Especially for the islands of Turkey, the generation of electricity via hydraulic dam is practically impossible due to its poor water characteristics since there are rarely rivers or other water sources in the islands. For instance, there is no steady flow river on the Bozcaada Island (Hocaoğlu, 1985). However, Bozcaada Island is the selected location for this study due to its potential for solar and wind sources. In order to evaluate its renewable energy potential, three distinct configurations based on solar and wind sources are considered. The first configuration is the already operating system in the location, a land-based wind farm (Gençer, Çetin; Akkaya, Sibel; Gürkan, 2009). In addition, offshore wind farm and conventional open ground photovoltaic power plant are proposed as the other two alternatives. All of them are compared in terms of their environmental impacts and economic aspects by coupling life cycle assessment (LCA) and life cycle cost (LCC) in order to reach the purpose of the selection of the most feasible system for the electricity production in Bozcaada. Acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), energy pay-back time (EPBT) and cumulative energy demand (CED) are used to represent the results of environmental impacts whereas initial investment cost (IIC), operation and maintenance cost, decommissioning and disposal or recycling cost are the classification of the life cycle cost (LCC).

History of potential investigations for the solar and wind renewable sources in Turkey, and wind and solar potential of Bozcaada island are explained in the following section in order to provide a basis for the research motivation.

1.2 Wind potential history in Turkey and wind potential of Bozcaada Island

The investigation on the wind potential of Turkey started in the last quarter of the 20th century by processing wind data which was measured between 1989-1998 (Kaygusuz, 2009) in order to have a general notion of Turkey's wind potential. Technical potential of wind in Turkey is found as 166 TWh/year (Erdogdu, 2009). The wind potentials of different regions in Turkey were also investigated by many researchers (Akda & Guler, 2009; S. A. Akdağ & Güler, 2010; Akpinar & Akpinar, 2009; Bilgili & Sahin, 2009; Durak & En, 2002; Eskin et al., 2008; Genç & Gökçek, 2009; Karsli & Geçit, 2003; Köse, 2004; Öztopal et al., 2000; Ucar & Balo, 2009; Yaniktepe et al., 2013). While the wind potential investigations has been ongoing, the first land-based wind farm was established in 1998 in Çeşme, Alaçatı (Ilkiliç & Aydin, 2015; Kaygusuz, 2010; Kose et al., 2004). In addition, Bozcaada has been found as one of the most promising regions for wind energy installation according to some research such as Wind Potential Atlas and the articles (Incecik & Erdoğmuş, 1995; Onat & Ersoz, 2011). For this purpose, the wind data has been obtained by means of 250 kW turbine at the meteo-station (Dündar & Inan, 1996; Türksoy, 1995) in the island, and it is found that the mean energy density is 324 W/m^2, and the average wind speed is 6.4 m/s at 10 m above ground level. Average wind speeds of the island (Tuğrul Oğulata, 2003) is 6.2 m/s at 5 m and 8.4 m/s at 50 m above ground level. As a result of wind data investigations, an onshore wind farm was established on the Bozcaada island in 2000 (Ilkiliç, 2012), and it is selected as the already operational case for this study as aforementioned in the research motivation.

Gaudiosi (1994) laid emphasis on the fact that onshore wind potential is less than half of the offshore wind potential up to 30 m water depth in Turkey. Furthermore, the researchers (Argin et al., 2019; Cali et al., 2018) indicate that Bozcaada is suggested as one of the most appropriate site for the deployment of offshore wind energy. Thus, evaluation of the island's wind potential by offshore wind deployment is also considered in the context of the present study. Offshore deployment with the aid of the information that average mean wind velocity is 9.25 m/s at 100 m ground level (Emeksiz & Demirci, 2019) is proposed and compared with onshore wind farm for better evaluation of the wind potential of the island.

Wind rose for Bozcaada Island, indicating the directions and distributions of the wind over the seasons, taken from the study (Gedik et al., 2018) can be seen in Figure 1.1. The dominant wind direction of Bozcaada island is NE (Avcıoğlu et al., 2015; Cali et al., 2018).

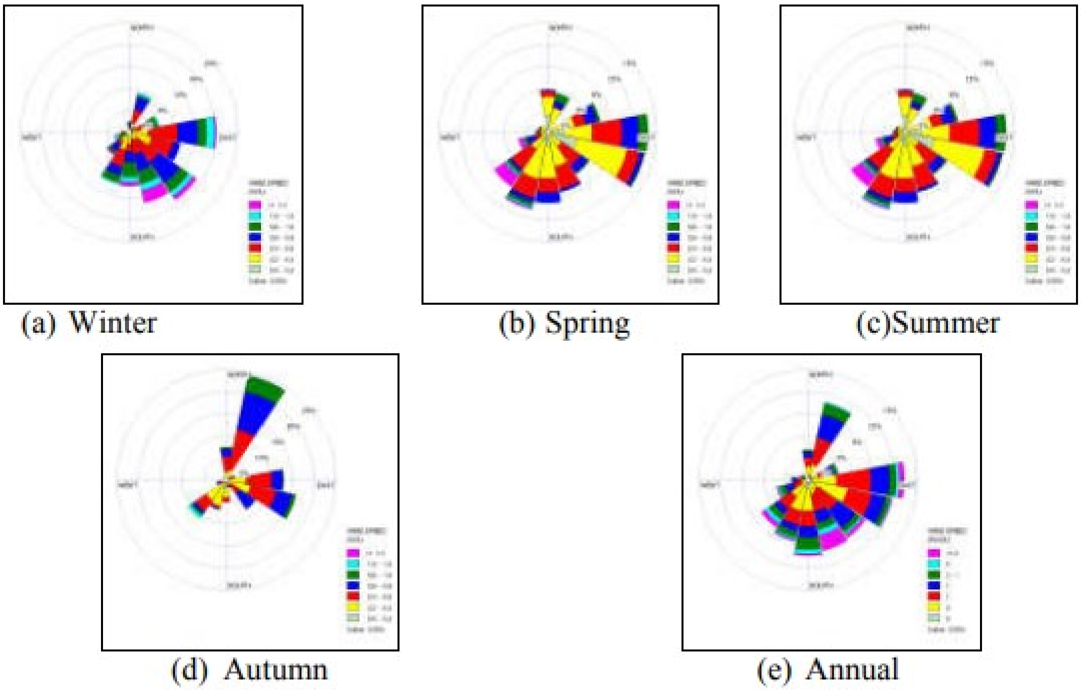

Figure 1.1 Wind directions for Bozcaada (Gedik et al., 2018)

1.3 Solar potential history in Turkey and solar potential of Bozcaada Island

The investigation related with the solar potential of Turkey started in the onset of 2000s (Balat, 2004; Tuğrul Oğulata, 2003). Until 2012, there were test projects established in Ankara and Didim Training and Research Centre (Boran et al., 2010).

The installation of grid connected PV system started in 2012 according to the study (Karadogan et al., 2014). However, there are limited studies for the solar potential of Bozcaada Island apart from Kalinci's research in the literature. Figure 1.2 taken from Kalinci's research indicates the average solar radiation of Bozcaada in 2012.

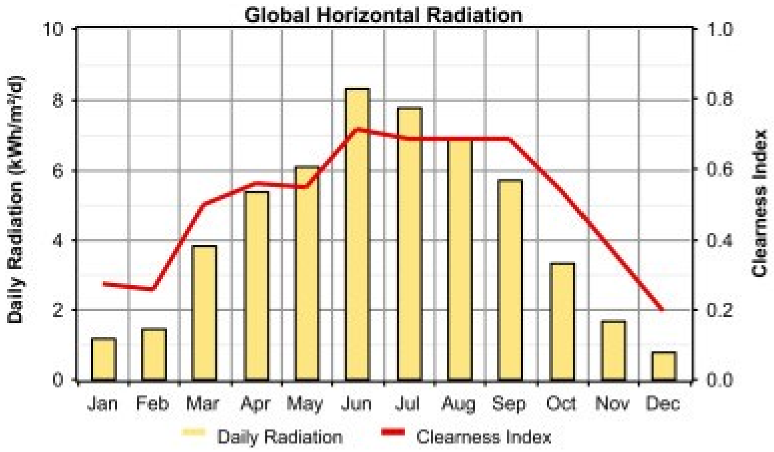

Figure 1.2 Average solar radiation for Bozcaada (Kalinci, 2015)

Furthermore, the solar energy potential of the Aegean region, where Bozcaada Island exists, is stated as 308 cal/m^2 solar energy potential per day and 7.5 hours sunshine duration per day (Tuğrul Oğulata, 2003). This is a type of proof for the further research's requirement about the island's solar potential. For this purpose, open ground photovoltaic configuration for the island is also suggested, and different aspects of land-based photovoltaic configuration in the island are examined in the context of this thesis and presented as a conference paper (Şentürk & Oğuz, 2020). In the conference paper (Şentürk & Oğuz, 2020), photovoltaic configuration proposed in Bozcaada island is evaluated by life cycle assessment method that differs from the Kalinci's research (2015) based on HOMER that is hybrid optimization for renewables. It is important that LCA methodology for PV configurations in Turkey is applied for the first time in order to evaluate solar potential of Bozcaada Island. As a result of the study (Şentürk & Oğuz, 2020), investment of onshore wind farm is more environmental-friendly than land-based photovoltaic plant for Bozcaada.

1.4 Organization of the thesis

The literature review (section 2) is divided into four subsections. The first two subsections of literature review are based on previous LCA studies for wind and photovoltaic technologies. LCA tool selection is explained in the third part, and the literature review is finalized with the previous LCC research by focusing on studies related to wind turbines and photovoltaics.

In the methodology part (section 3), application of LCA methodology for energy generation systems and selected impact categories for the comparison among the proposed configurations are explained. System boundaries for the LCA applications are also drawn for all configurations as the last part of the life cycle assessment while specific assumptions dependent to the type of renewable source are organized as the subsections of the system boundaries. In the second part of Section 3, life cycle cost concept and main equations for the calculation procedure are defined.

Fourth chapter is devoted to the analysis of all three configurations which are onshore wind farm, offshore wind farm and land-based grid-tied photovoltaic plant.

Chapter 5 is allocated for the results of the analysis and comparison of the systems in terms of environmental and economic aspects as well as the comparison with the literature including benchmarking procedures and comments on the distinctions.

Finally, discussion and future directions are given in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

In this section, firstly, previous LCA applications for photovoltaic and wind technologies are classified. Following it, appropriate LCA tool is selected with the aid of previous comparison studies among available software. Previous life cycle cost studies are the final subsection of the literature review. In that subsection, some example areas for LCC is mentioned, and the subsection is concluded with the previous cost studies about the generation of unit power, 1 MWh, by using wind and/or solar sources in Turkey.

The purpose of the same procedures of the LCA classification applied for both wind and solar PV technologies is introduced here. Following that, previous LCA studies of wind technologies are focused and listed in Table 2.1. Table 2.2 is also arranged for previous LCA applications of PV technology. Wind and solar literatures about LCA applications are given separately not to intermingle; therefore, same procedure is followed for the arrangements of the tables. All studies are tabulated based on the phases of life cycle assessment, and the considered phases of the previous studies and their results are indicated in the tables. The questions which are tried to be answered during the review of the previous LCA studies for all the selected configurations are as follows:

- Is there a cradle-to-grave approach?
- Does it initialize with production phase?
- Which phases are included in the study?
- What is the last phase of the study?
- Which methods are followed for impact assessment?

Abbreviations for the phases of the LCA for energy production systems are found in the nomenclature and are used in the tables.

2.1 Previous LCA applications of wind technologies

As seen in Table 2.1, studies are listed in line with the phases contained and their results are classified as greenhouse gas emissions (global warming potential), energy pay-back time (EPBT), eutrophication potential (EP) and acidification potential (AP).

Table 2.1 LCA applications of wind technologies

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-Back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
(Piasecka et al., 2019)	Onshore	All	Eco-indicator 99	0.351 DALY	-	29,954.917 PDF.m^2/a	
	Offshore			0.379 DALY		25,882.851 PDF.m^2/a	
(Chipindula et al., 2018)	Onshore	All	Impact 2002+	5.84 g CO_2-eq./kWh	~ 0.5	-	-
	Offshore Shallow			6.49 g CO_2-eq./kWh	~ 1.08		
	Offshore Deep			7.89 g CO_2-eq./kWh	~ 0.92		
(Reimers et al., 2014)	Offshore	All	IPCC 2007	13.2-22.2 g CO_2-eq./kWh	-	-	-

Table 2.1 LCA applications of wind technologies (continued)

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-Back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
(Tremeac & Meunier, 2009)	Onshore (4,5 MW horizontal axis)	C, O&M, DorR	Impact 2002+	15.8 g CO_2/kWhe	1.7	-	-
	Onshore (250 W vertical axis)			46.4 g CO_2/kWhe	6.5		
(Bonou et al., 2016)	Onshore (direct-drive)	All	IPCC	5.0 g CO_2-eq./kWh	0.43	-	-
	Onshore (geared)			6.0 g CO_2-eq./kWh	0.52		
	Offshore (direct-drive)			7.8 g CO_2-eq./kWh	0.83		
	Offshore (geared)			10.9 g CO_2-eq./kWh	0.93		

Table 2.1 LCA applications of wind technologies (continued)

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-Back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
(Guezuraga et al., 2012)	Onshore (geared)	All w/o R	-	9.73 g CO_2-e./kWh	0.65	-	-
	Onshore (gearless)			8.82 g CO_2-e./kWh	0.64		
(Kabir et al., 2012)	Onshore (Northern Power 100 kW)	All	-	17.8 g CO_2-e./kWh	0.6	-	4.2×10^{-2} g SO_2eq/kWh
	Onshore (Endurance 5 kW)			42.7 g CO_2-e./kWh	1.4		11.2×10^{-2} g SO_2eq/kWh
	Onshore (Jacobs 20 kW)			25.1 g CO_2-e./kWh	0.8		8.8×10^{-2} g SO_2eq/kWh

Table 2.1 LCA applications of wind technologies (continued)

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-Back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
	Onshore (DDSG)			7.25 g CO_2-e./kWh	0.87		-
(Schreiber et al., 2019)	Onshore (DDPSMG)	All	ILCD, CML, ReCiPe	12.43 g CO_2-e./kWh	0.50	-	-
	Onshore (DFIG)			7.25 g CO_2-e./kWh	0.52	-	-
(Stavridou et al., 2020)	Onshore (tubular and lattice towers)	DorR	-	-	0.48 and 0.33	-	-
(Vestas, 2015)	Onshore (North America)	All	CML 2013	7.2 CO_2-e./kWh	0.67	3.7 mg PO_4^{-3}-e/kWh	32 mg SO_2-e/kWh

Table 2.1 LCA applications of wind technologies (continued)

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-Back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
(Huang et al., 2017)	Offshore	All	Eco-indicator 99	-	1.07 and 1.2	-	-
(Gomaa et al., 2019)	Onshore	All	TRACI	0.00911 kg CO_2 e. /kWh	0.69	$8.3x10^{-6}$ kg N e. /kWh	0.00345 kg SO_2 e. /kWh
(Martínez et al., 2009)	Onshore	All	CML 2000	$6.58x10^{-3}$ kg CO_2 e. /kWh		5.86 10^{-6} kg PO_4^{-3}-eq/kWh	$5.43x10^{-5}$ kgSO_2 eq./kWh
(Zimmermann, 2013)	Onshore (Enercon E-82 E2 2.3 MW)	All	-	7.7 g CO_2-e./kWh	0.48	-	2.1×10^{-2} g SO_2 e./kWh

Table 2.1 LCA applications of wind technologies (continued)

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-Back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
(Schmidt et al., 2017)	Onshore (Siemens)	All w/o R	ReCiPe	254 DALY	-	0.0068 species.yr	0.0045 species.yr
(Demir & Taşkin, 2013)	Onshore (2050 kW-100 m)	All	CML method	1.627E-02 kg CO_2-Equiv/kWh	1.22	5.392E-06 kg PO_4^{-3} equiv/kWh	5.779E-05 kg SO_2-equiv/kWh
	Onshore (330 kW-50 m)			4.036E-02 kg CO_2-Equiv/kWh	2.97	1.269E-05 kg PO_4^{-3} equiv/kWh	1.267E-04 kg SO_2-equiv/kWh
(Zhong et al., 2011)	Onshore	DorR	Eco-indicator 99	-	-	-	-

Although there are many studies about LCA of wind technologies in the literature, the limited number of them are compared for the choice of configurations. For instance, the research (Piasecka et al., 2019) represents that an offshore wind power plant is more environmental-friendly technology compared to its onshore counterparts for the area of Poland. In case of Texas (Chipindula et al., 2018), onshore and offshore configurations are compared with different turbine sizes. Within its results, only same size turbines –namely 2.3 MW wind turbines- are listed in Table 2.1 in order to focus the importance of site selection. The study (Chipindula et al., 2018) revealed that onshore application is the most advantageous option in terms of global warming potential and energy pay-back time in Texas when the same nominal capacity turbines are deployed in three different sites- namely onshore, offshore-shallow and offshore-deep deployments as seen in Table 2.1. Another significant point of the study is that there is a contradiction between global warming impacts and energy pay-back time for the deployments of offshore configurations to be investigated further as seen in Figure 2.1 and Figure 2.2. This is, the offshore deployment having 2.3 MW turbines in shallow water gives the lowest GWP while the lowest energy-payback time is obtained by the offshore deployment having 5 MW turbines in deep water in the aforementioned study.

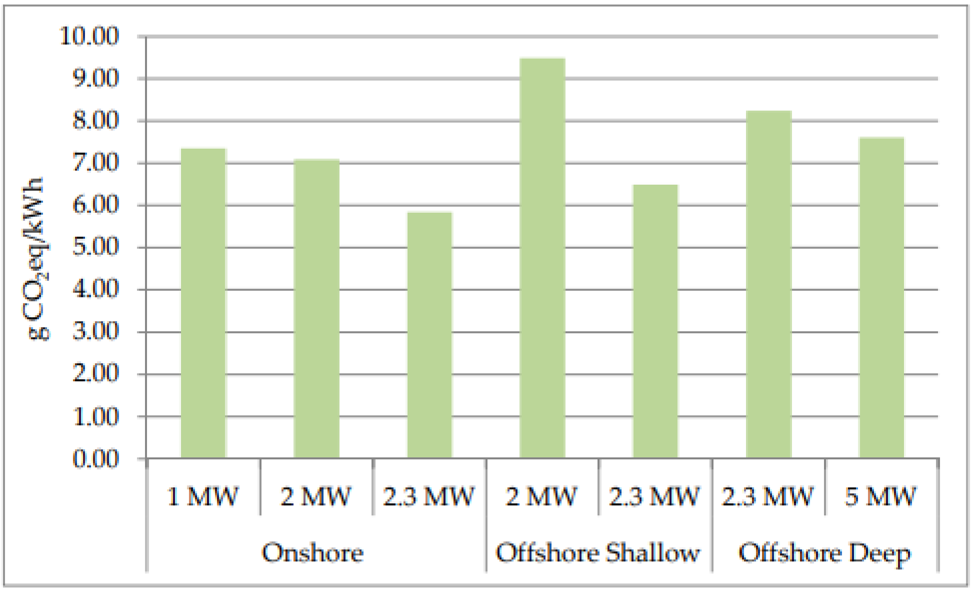

Figure 2.1 The results of global warming potential taken from the study (Chipindula et al., 2018)

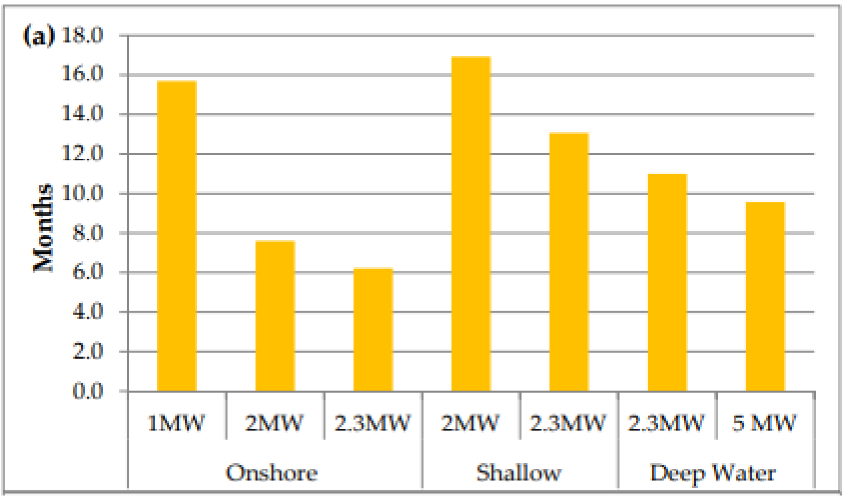

Figure 2.2 The results of EPBT obtained in the study (Chipindula et al., 2018)

In another research, the dependency of the site selection is found to be crucial for offshore wind farm deployment showing that far-shore wind parks are not declining the global warming potential due to the logistic efforts for maintenance and the raise of material requirements (Reimers et al., 2014). Furthermore, the study (Tremeac & Meunier, 2009) mentioned that transportation strategy for either small or large size wind turbines, by means of sensitivity analysis regardless of the axial types of the turbines, is crucial for the reduction of climate change.

Bonou and his colleagues (2016) compared wind source by four imaginary cases. In their study, the different mechanism types are examined as well as the distinct configurations including onshore and offshore deployment. The authors reach the conclusion that big direct drive turbines have less impacts on the environment than small geared ones. The other researchers (Guezuraga et al., 2012) also investigated the environmental impacts of the design types of wind turbines which are gearless and geared by ending their research with the support of the aforementioned study (Bonou et al., 2016). In addition, the research (Caduff et al., 2012; Kabir et al., 2012) point out that big turbines are more beneficial in terms of environmental impacts as expected. Another research related to the mechanism design of the wind turbines, whose different mechanisms defined and abbreviated as direct drive permanent magnet synchronous generator (DDPMSG), electrically excited direct driven synchronous generator (DDSG), and geared converter with doubly-fed induction generator (DFIG), is performed by the researchers (Schreiber et al., 2019) as seen in Table 2.1.

In relation to another design aspect of wind turbines, a lattice tower is proposed, and compared to the tubular tower of onshore wind farms by means of LCA (Stavridou et al., 2020) as a design improvement in order to mitigate the climate change impacts caused by turbine towers.

For the exemplification of the studies mentioning the phases of LCA, global warming potential (GWP) of manufacturing phase of wind turbine -namely, production phase for this study- is 9.7 g CO_2-e./kWh whereas plant setup of it has 0.2 g CO_2-e./kWh according to the report (Vestas, 2015). Huang and his colleagues (2017) utter that energy pay-back time depends on primary energy demand by inserting different energy inputs calculated from their scenarios for the same energy output. They also report that energy pay-back time can be shortened with the application of the proper recycling strategy that EPBT approximately is shortened 4 months, and it is decreased almost 25 % environmental impacts. Guezuraga and his colleagues (2012) demonstrate that greenhouse gas emissions can be declined with recycling although recycling raises primary energy demand, and in return, it leads to an increase in energy pay-back time for both configurations of wind turbines as shown by means of sensitivity analysis in their research.

A current LCA research (Gomaa et al., 2019) is carried out for the Tafilah Wind Farm having the same type of turbine which is chosen for the offshore configuration of this study. It is noted for the comparison of the offshore configuration of present study in the conclusion part.

Martínez and his colleagues (2009) investigated the environmental effects of onshore 2 MW rated power wind turbine with CML method. At the end of their research, it is concluded that important proportion of the impacts are caused by the turbine blades and its non-recyclable features. The LCA results of Enercon E-82 is given as an example of a home-made tool improved by Zimmermann (2013).

As probably the most similar case (Schmidt et al., 2017) to the whole scope of this study, distinct renewable sources which are the existing PV system around Toronto and proposed wind plant by authors are compared for the selected area. As an example to another similar research to the present study, the choice of the wind turbine type on the specific region, Pınarbaşı-Kayseri (Demir & Taşkin, 2013), is tried to be determined for the first time in Turkey by means of life cycle assessment method in the wind sector. At the end of the study (Demir & Taşkin, 2013), it is found that the increase in turbines' hub height leads to decrease in the environmental impacts owing to the increase in the electricity generation by means of high average wind speeds at high hub heights.

Recycling procedures for wind turbine and PV module in detail are focused in the research (Zhong et al., 2011). Further discussion related with the study is given in the following section since the research is related with not only wind turbine but also PV module.

2.2 Previous LCA applications of photovoltaic technologies

Similar procedure to the wind technology part is applied in the creation of the list summarizing the research about previous LCA applications of photovoltaic technologies as seen in Table 2.2. During the listing procedure, crystalline technologies are focused in order to compare the results with the findings of this study in the conclusion part. Each paragraph is allocated to different sides of the LCA applications since it has large and widespread features to be investigated.

It should be known that the applications for the large conventional PV system installations started in the beginning of 1990s (Yudha et al., 2018) while testbed projects for the deployment of photovoltaic system on the water started in 2007 (Trapani & Redõn Santafé, 2015). With 30 years useful life assumptions (Ito, 2011), decommissioning and disposal or recycling of these systems become a popular research area for the photovoltaic technologies since there are limited number of PV installations around the world which totally completed their lifespan as of today. To exemplify, a large application of PV system for Italy is examined (Desideri et al., 2012) by suggesting recycling of the parts. Its findings indicate only GWP and EPBT results as seen in Table 2.2 although it is the most similar study for the case which is examined in this study in terms of system's specifications.

With the purpose of guidance to policy makers about Singapore electricity, the research by Luo and his colleagues (2018) that covering the roof of the buildings with multi-crystalline PV cell technology can decline GHG emissions more than 15 times compared to Singapore's current situation. Ito and his colleagues (2003) emphasize that desert area should be used for electricity generation with the aid of LCA and LCC tools.

In another study (Ito et al., 2008), there are comparisons of solar cell types in terms of environmental and economic characteristics. As seen in Table 2.2, the range for the GWP of photovoltaic systems in the aforementioned study is 9.4-13.8 g CO_2-e./kWh while energy pay-back time ranges between 1.5-2.5 years.

Balance of system (BOS) is the definition of complementary materials required for a PV plant system except for solar modules. The thesis (Palanov, 2014) focuses on the impact assessments of the balance materials for the roof-top system via multi-crystalline cell type whereas another research (Mason et al., 2006) investigates the impacts of the balance materials for a 3.5 MW large PV installation as indicated in Table 2.2. EPBT of BOS of the large PV installation is 0.21 years while EBPT of roof-type installation is 2.3 years.

As an example of case studies of PV technology, Yu and Halog (2015) examined life cycle assessment of actual 1.2 MW grid-tied roof-mounted PV system called UQ Solar. There is another study (Wu et al., 2017) for evaluation of solar potential in China by concluding the research that the open-ground grid-connected solar station has the ability to generate clean energy more than 27 years without any energy input.

As aforementioned in the part of previous wind applications, the study (Schmidt et al., 2017) demonstrates that wind technology is more environmental-friendly than the existing PV plant to produce Toronto's electricity. In other words, it points out that the preliminary research prior to investment is so crucial for the protection the environment of the site.

According to the comparison between recycling of wind turbine and PV module, recycling of wind turbine is more beneficial to the environment (Zhong et al., 2011) than recycling of solar cells due to the unimproved recycling strategies for solar cells yet.

Table 2.2 LCA applications of photovoltaic technologies

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
(Desideri et al., 2012)	G&mc-Si	All	CML 2 baseline 2000	0.1065 kg CO_2-e./kWh	4.17	-	-
(Luo et al., 2018)	RF& multi-Si	P,C and O&M	-	20.9–30.2 g CO_2-e./kWh	1.01–1.08	-	-
(Ito et al., 2003)	G& multi-Si	P,C and O&M	Own	12.0 g CO_2-e./kWh	1.9	-	-
(Ito et al., 2008)	G& five cell types[1]	P,C and O&M	Own	9.4-13.8 g CO_2-e./kWh	1.5-2.5	-	-

[1] Including typical multi-crystalline silicon, high efficiency m-Si, amorphous silicon, CdTe (cadmiumtellurium) and CIS (Cupper Indium Selenium)

Table 2.2 LCA applications of photovoltaic technologies (continued)

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
(Palanov, 2014)	RF&mono-si	All (for BOS)	-	0.053 kg CO_2-e./kWh	2.3	1.36 x10^{-4} kg NOx- e. /kWh	2.40x10^{-4} kg SO_2 e. /kWh
(Mason et al., 2006)	G&mc-si	All (for BOS)	-	29–31 kg CO_2 e./m^2	0.21	-	-
(Yu & Halog, 2015)	RF&multi-c-Si	All	CML 2 baseline 2000	0.069393 kg CO_2 eq/kWh	2.33	0.000111 kg PO_4^{-3} eq/kWh	0.000573 kg SO_2 eq/kWh
(Wu et al., 2017)	G&multi-Si	P,C and O&M	-	-	2.3	-	-
(Schmidt et al., 2017)	G& multi-si	All without R	ReCiPe	323 DALY	-	0.0072 species.yr	0.0063 species.yr

Table 2.2 LCA applications of photovoltaic technologies (continued)

Reference	*Technology*	*Phases Included*	*Impact Assessment Method*	*Global Warming Potential*	*Energy Pay-back Time (years)*	*Eutrophication Potential*	*Acidification Potential*
(Zhong et al., 2011)	RF& Polycrystalline	DorR	Eco-indicator 99	-	-	-	-

In order to draw a conclusion for the LCA applications of wind and solar powers, there is also a need to mention about review articles in the literature.

To begin with, the important findings of the wind power reviews are emphasized. Kaldellis and Apostolou (2017) reviewed CO_2 intensities of the previous research based on the wind farm technologies. According to that study, carbon intensities range between 4.6 and 16.0 g/kWhe for onshore plants while a range between 5.2 and 32.0 g/kWhe is noted for offshore counterparts. Mendecka and Lombardi (2019) simplified LCA models for CED, AP, GWP and EP impacts which are developed with the aid of systematic approach on LCA studies of wind technologies in the literature. They observed that values for all aforementioned impact categories are higher for offshore deployments than onshore counterparts when whole range of nominal power is regarded.

In case of the solar power's reviews, LCA applications of photovoltaic system, including the results of polycrystalline module, are taken into consideration as mentioned before. For this purpose, the ranges of EPBT and greenhouse gas (GHG) emissions are noted as 1.7-1.9 years and 12.0-53.4 g-CO_2eq/kWh, respectively from the study (Sherwani et al., 2010) by focusing only on the data related to 30-year useful life assumption and standard multi-si technologies. While the range of EPBT values of multi-si PV systems is given as 1.5-5.7 years, and it is claimed that GHG emissions of multi-si type PV systems range between 9.4–104 g CO_2-eq./kWh in the review article (Peng et al., 2013).

There are research in the literature covering not only photovoltaic and/or wind energy system but also other renewable systems like nuclear and hydropower ones. For instance, a review article of LCA studies for the electricity generation from different renewable sources like wind, solar photovoltaic system etc. carried out by reviewers (Varun et al., 2009) demonstrate the literature results obtained with LCA methods for the period 1997-2005 in order to compare fossil fuel based electricity production systems and renewable energy generation systems. For the wind energy systems, energy intensities change between 0.032- 1.016 kWh/kWh while the range for greenhouse gas emissions is noted as 9.7-123.7 g CO_2/kWh. In case of photovoltaic (PV) systems, greenhouse gas emissions range between 53.4-250 g CO_2/kWh. In addition, Nugent and Sovacool (2014) focus on the LCA applications of solar PV and wind energy in their review in order to draw a road map for better deployments as well as to mitigate CO_2 emissions by means of the increase in electricity generation. The range of GWP for wind energy found as 0.4-364.8 g-CO_2-eq/kWh can be noted in order to make a comparison. However, the range found in the article for PV is beyond the scope of the present study because all PV cell technologies are included in their review. Lastly, the results of another review study for the wind and photovoltaic systems (Asdrubali et al., 2015) are summarized in Table 2.3. At the end of the present thesis, it is used for the benchmarking of LCA results due to more compehensive review than other review studies.

Table 2.3 Ranges for LCA results of PV and wind applications in the study

	Photovoltaic Systems	*Wind Systems*
Acidification Potential (AP) mg SO_2eq/kWh	78.7–979.7	28.0–115.2
Eutrophication Potential (EP) mg PO_4^{-3}eq/kWh	4.0–92.5	2.7–12.2
Global Warming Potential (GWP) g CO_2eq/kWh	9.4 -167.0	6.2–46.0
Energy Pay-Back Time (EPBT) (months)	9.6–43.9	2.4–27.5
Cumulative Energy Demand (CED) MJ/kWh	0.36–1.80	0.01–1.20

2.3 Selection of LCA tool for the study

In order to examine the environmental impacts of a product, process or a system, life cycle assessment (Singh et al., 2013) is a practical method. In order to apply this methodology, an LCA tool (Unger et al., 2004) is required. In-house LCA tools such as site-specific parametrized tools developed by Zimmermann (2013), commercially available tools like GaBi or open source tools like OpenLCA can be utilized for this purpose. Since the main goal of this study is to make a comparison between three configurations, improving a home-made tool is not preferred. Also, the notion of the comparison between available LCA software tools is also beyond the scope of this study although selection of an appropriate LCA tool is necessary. For this purpose, previous studies comparing the different LCA tools are mentioned briefly in this section.

Dasic and his colleagues (2007) studied six LCA tools including GaBi, TEAM, SimaPro, LCAiT, KCL-ECO and PEMS in terms of software properties, database, service and cost, flexibility, functionality and user-friendliness, and GaBi is found as the best one comparing the total points for the chosen characteristics. Furthermore, according to the study (Speck et al., 2015), GaBi and SimaPro are the most preferred tools by LCA practitioners. Another two studies (Speck et al., 2016; Verghese & Lockrey, 2012) compared LCA software tools for the packaging sustainability. The former compares GaBi and SimaPro whereas a comprehensive comparison of many alternative tools exists in the latter one. As a conclusion, GaBi is suggested by both of them for the LCA of packaging. Another study comparing GaBi and SimaPro (Herrmann & Moltesen, 2015) reports that large differences are caused by impact assessment part although no meaningful discrepancy exists between both software tools during the inventory level of a product system. This is, differences between the LCA results is claimed to derive from the databases by Herrmann and Moltesen (2015). ReCiPe impact assessment method is utilized for the assessment of two residential building in Finland (Emami et al., 2019) to compare GaBi and SimaPro in the construction sector, and the research is concluded that there is an urgent need to enhance the reliability of the LCA software in the building sector for policy makers. GaBi utilizes more concentrated data from industry (Jolliet et al., 2015). Furthermore, GaBi software and database system (Albrecht et al., 2013) are utilized by both scientific and industrial purposes due to its operational support. While SimaPro's cost is the best aspect, GaBi is found the best option in terms of service, functionality and being more user-friendly (Silva et al., 2017). In short, owing to user-friendliness, modelling and assessment of three configurations of this study are carried out via the GaBi software.

2.4 Previous Life Cycle Cost (LCC) Research and Costs for Wind and Photovoltaic Powers in Turkey

In this section, following the brief description of LCC and giving some example areas, research on the wind and PV system costs in Turkey are summarized.

Life cycle cost is the most common method to predict the cost throughout the lifespan of a product, a system or a process. For example, Utne (2009) is conducted LCC to improve the sustainability of the Norwegian fishing fleet. In order to produce a lightweight automotive (Delogu et al., 2016), the life cycle cost analysis is carried out between distinct composite materials which are suitable for design. In the early design step of a defense electronic (Cheung et al., 2015), a system is evaluated by means of LCC for determination of its end-of-life cost. In the shipping sector (Jeong et al., 2018), life cycle cost and life cycle assessment is tried to be coupled for a framework to choose optimum propulsion system. As another example of the trial of the coupling, Ristimäki and his colleagues (2013) carried out combined LCC and LCA for the energy system design of a new residential. In case of Turkey, Yılan (2018) is applied both LCA and LCC methodologies to the Turkish electricity mix by mentioning the levelized cost concept for the first time in order to reach the aim for more sustainable national mix.

Although there are no investments of offshore wind farm in Turkey (Cali et al., 2018), the electricity generation costs from the wind source by means of the onshore deployments (Seyit Ahmet Akdağ & Güler, 2010) range between 1.73-4.99 $ cent/kWh for the focused locations of their investigation. At the results of the study, the result of Bozcaada is given as 1.90-2.21 $ cent/kWh based on different wind shear features. In order to predict the most promising area in Central Anatolia, Gökçek and Genç (2009) carried out an economic analysis by focusing on the initial investment costs of the proposed investments with the aid of levelized cost of electricity (LCoE) concept. Unit electricity cost from a wind farm in the Cappadocia region (Taner, 2018) was found to be approximately 0.14689 $/kWh. Ozerdem and his colleagues (2006) used feasible properties of a wind farm in İzmir, and 2.68 US cent/kWh was the lowest cost they could calculate. In the end of their study, they recommended the large installations instead of the small applications. Celik (2007) found the lowest cost of the electricity generated from a wind farm in İskenderun as $ 0.15 per kWh which also contains insurance cost.

In case of offshore wind farm, Satir and his colleagues (2018) firstly make the cost estimation for the Bozcaada Island by excluding the decommissioning and disposal or recycling phase cost and by choosing LCoE and NPV as the cost evaluation tool for the determination of the most feasible alternative. In the end of their investigation, the initial investment costs established by three different turbines range between € 218,316,517- € 252,020,644. Çokyaşar and Beji (2019) are also calculated the specific investment cost of an offshore wind farm in Bozcaada Island as 1,432 $/kW by means of adoption of the data around the Baltic Sea.

As mentioned before, the network connection of large PV installations (Karadogan et al., 2014) started in 2012 in Turkey. In other words, there are limited number of studies indicating LCC of grid connected PV in Turkey. For example, Öztürk and his colleagues (2012) utilize the concept of LCC for the domestic photovoltaic system whose lifespan is assumed as 20 years. It is found that 0.40 $/kWh and 0.67 $/kWh are calculated for the on-grid and off-grid systems cost, respectively. The cost of network connected PV system designed for a greenhouse company by excluding the scrap costs are found as 7,050 $/kW (Çağlayan, 2019). The difference between the initial investment costs for 1 MW land-based and floating PV installations for İstanbul is given as 114,308 $ (Şençiçek, 2017).

In addition, the studies (Yilan et al., 2020; Yılan, 2018) utilized the levelized cost of electricity defining as the average cost of generating electricity including all costs that occur in all phases throughout the lifetime as well as CO_2 emissions cost. In these studies (Yilan et al., 2020; Yılan, 2018), LCoEs of onshore wind and solar PV are given as 73 $/MWh and 160 $/MWh, respectively. In the case of offshore technology, Cali and his colleagues (2018) found a range for LCoE of the Bozcaada Island between $/MWh 81.85 and $/MWh 109.55 while € 91.03/MWh is obtained in the another study for Bozcaada Island (Satir et al., 2018).

CHAPTER 3

METHODOLOGY
LIFE CYCLE ASSESSMENT (LCA) AND LIFE CYCLE COST (LCC)

In this section, the methodology of life cycle assessment (LCA) for the evaluation of environmental impacts and the methodology of life cycle cost (LCC) for the evaluation of economic aspects are defined and explained briefly.

3.1 Life cycle assessment (LCA)

A method for the evaluation of environmental impacts of a product, a system or a process is named as the life cycle assessment (ISO, 2006a, 2006b; Singh et al., 2013). In this study, energy generation systems are focused; thus, application procedure of life cycle assessment for the energy production systems are depicted in detail. In addition, it is required to select impact categories for the description of the assessment results as well as the choosing of impact assessment method for life cycle impact assessment (LCIA) which is the way for the expression of LCA results numerically. As the second part of this section; therefore, impacts categories are selected and explained. System boundaries of the life cycle assessment for all configurations are drawn in the last part. Renewable source assumptions are divided into two subsections based on the renewable sources.

3.1.1 LCA for the energy generation systems

In the literature, life cycle assessment methodology is applied for the energy production systems by dividing its stages into four main phases (production, construction, operation & maintenance and decommissioning & recycling) (Frischknecht et al., 2016; Lamnatou & Chemisana, 2019; Tomporowski et al., 2017; Vestas, 2015) as demonstrated in Figure 3.1.

Figure 3.1 Life cycle thinking for energy generation systems[2]

3.1.1.1 Production phase

It contains all stages perpetuating from the extraction of raw materials, including manufacturing of all parts such as transmission lines for the grid connection and infrastructure, up to the transportation of all materials to be assembled in the operation site.

3.1.1.2 Construction phase

Transportation of all materials to the operation site is the first stage for this phase. It also includes assembling of all materials and the plant installation. The construction phase ends with the generation of electricity from the plants.

[2] https://www.netl.doe.gov/LCA

3.1.1.3 Operation and maintenance phase

Electricity production is the beginning stage of it. It contains periodic controls which can be counted as cleaning of panels for PV plants and oil change for wind plants. Defect repairs like broken parts for all plants are also considered in the modeling of periodic controls. It is finalized with the end of electricity production.

3.1.1.4 Decommissioning and Disposal or Recycling Phase

Its onset is decommissioning of the plants. It perpetuates to dismantle and classify the disassembled parts either disposal or recycling materials. In this study, transportation of scrap materials is also taken into consideration by excluding the necessary processes for disposal or recycling procedures.

3.1.2 Evaluation indices for the life cycle impact assessment (LCIA)

In order to compare the results of all configurations, impact categories are chosen. Selected impact categories for this study are explained in this section.

3.1.2.1 Acidification potential (AP)

Sedimentation of inorganic materials on the earth surface composed of nitrogen oxide (NO) and nitrogen dioxide (NO_2) is named as acidification (Uctug, 2017). Acidification is the most significant cause of the air pollution (Cindoruk, 2018) since its main reason is the increase in SO_2, NO and NO_2 derived from the extensive burning of fossil fuels (Cardoso et al., 2009) in order to generate energy. The accumulation of inorganic compounds in the atmosphere also leads to acid rains (Kim & Chae, 2016). As an alternative definition, acidification (Taşkın, 2018) is the creation and the release of hydrogen ions from some inorganic compounds (Şayan et al., 2010). The changes in the amount of dissolved inorganic carbon and alkalinity of water also cause marine pollution.

3.1.2.2 Eutrophication potential (EP)

The excessive reactive nitrogen and phosphorus (Rabalais et al., 2009) and, in return, extreme loading of nutrients (Yağcı Apaydın, 2010) lead to an increase in the phytoplankton population. As a result, aquatic ecosystem quality (Frumin & Gildeeva, 2014) is spoiled, and this problem is called as eutrophication (Doğan-Sağlamtimur & Sağlamtimur, 2018).

3.1.2.3 Cumulative energy demand (CED)

The requirement of the energy for the generation of unit power (Mert et al., 2017) is cumulative energy demand. This is, each plant to be established and operated needs the primary energy before the start of electricity generation. This concept is named as primary energy demand (PED) in GaBi database while its name in Ecoinvent database is cumulative energy demand (CED) according to the research (Swart et al., 2015). Furthermore, unit power refers to the functional unit of this study which is 1 MWh. Hence, the unit of cumulative energy demand (CED) is MJ/MWh throughout the present research.

3.1.2.4 Energy pay-back time (EPBT)

Energy pay-back time is the ratio of total embedded energy, which is the primary energy needed by the plant to be initiated for production, to the annual electricity generation (Gkantou & Baniotopoulos, 2018).

3.1.2.5 Global warming potential (GWP)

It is a selected metric for the comparison of the capacity of heat retention in the atmosphere of each greenhouse gas (relative to CO_2). The ratio of the warming caused by a substance having similar mass of carbon dioxide is another definition for the term (Demirel, 2014).

3.1.3 System boundaries of LCA throughout the study and modelling procedure in GaBi

In order to draw the boundaries of the systems, general assumptions are required. For all configurations, assumptions are summarized as follows for the boundaries of the research:

- ✓ Cradle to grave perspective is considered for all configurations. In other words, all phases for each configuration are examined throughout the study.
- ✓ The configurations are modelled and assessed with GaBi software due to the user-friendly characteristics of GaBi.
- ✓ Ecoinvent database is utilized for the components and processes throughout the modelling due to the proximity of Bozcaada Island to Europe (Islam et al., 2015).
- ✓ In order to evaluate the LCA results, CML2001-Jan 2016 impact assessment method (Universiteit Leiden, 2015) was selected instead of other evaluation indices such as ReCiPe and TRACI 2 due to the close reflection features between its impact category indicators and the life cycle inventory emissions as well as the problem oriented (Demir & Taşkin, 2013) analysis of the configurations. In addition, it is one of the mid-point methods unlike ReCiPe which is one of the end-point methods, and this aspect of it enables comparison of the configurations.
- ✓ For the quantification of the results, the unit power, MWh, is defined as the functional unit of this study in order to make comparison among the configurations.
- ✓ The results are presented as a normalized single emission type by dividing with the total energy productions.
- ✓ The measure of global warming potential is kg CO_2-eq. /MWh.
- ✓ The unit of acidification potential is kg SO_2-eq. /MWh.

- ✓ kg PO_4^{-3}- eq. /MWh is the measure of eutrophication potential.
- ✓ In the evaluation of production phases, transportation of raw materials like cast iron for wind turbine and silica for solar cell are excluded due to the impossibility of correct estimation about their transportation distances. However, production processes of raw materials are taken into consideration.
- ✓ Transportation distances, utilized from the onset of construction phase to the end of the carriage of scrap materials for either disposal or recycling purposes, are measured by means of Google Maps in a similar way in the study (Sumper et al., 2011).
- ✓ Although classification and transportation of scrap parts are included, related recycling or disposal processes of scrap materials apart from the removal from the site are not considered throughout the study.

As previously mentioned before, there is a requirement of selection of LCA tool in order to apply LCA methodology. After the selection of GaBi software, modelling procedure is summarized here by giving an example (i.e. a stage in the production phase of land-based grid-tied PV plant). In the GaBi software, phases are modelled firstly. In other words, the production phase, the construction phase, the operation and maintenance phase and the decommissioning and disposal or recycling phase are modelled for each configuration.

As specific example, the manufacturing of solar cells is represented with the aid of Figure 3.2. First, the unit process of silica sand is created in the beginning of production phase of PV plant. Following process is metallurgical grade silicon and the energy need is modeled with thermal energy from hard coal which is available in GaBi as seen in Figure 3.2. In the third step, solar grade silicon process is created, and the necessary flows from Ecoinvent database are inserted in it. At the end of the production stage of solar grade silicon, the same procedure is repeated for the model of manufacturing of silicon, multi-Si casted. The energy need of the manufacturing of multi-Si wafer is obtained via China's grid mix as seen in Figure 3.2 by assemblying with multi-Si wafer with metallization pastes produced in China.

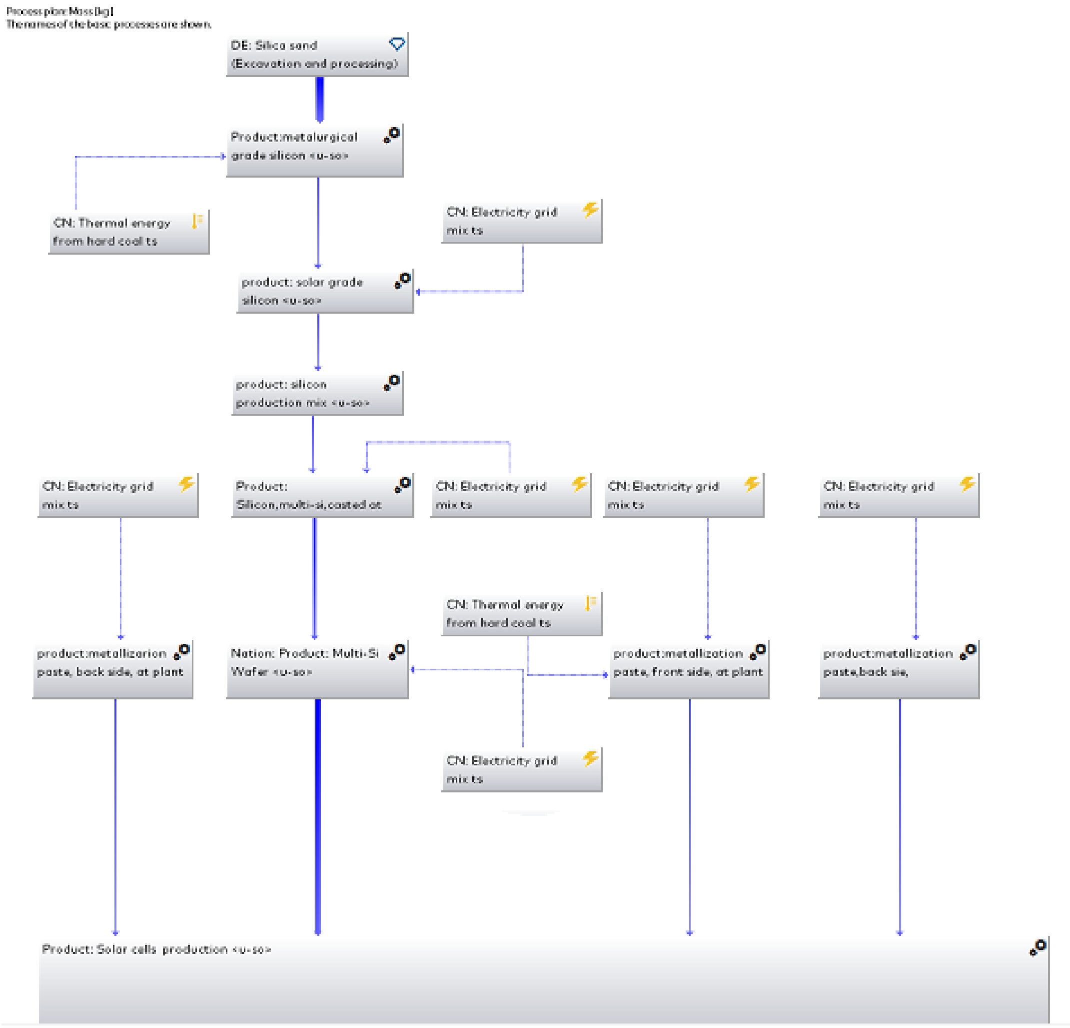

Figure 3.2 Model of manufacturing of solar cells

Specific assumptions related with the selected renewable sources are explained in the following sections.

3.1.3.1 Specific assumptions dependent to wind source

Wind related assumptions are listed as follows:

- ✓ Similar to the studies (Chipindula et al., 2018; Martínez et al., 2009) carried out, 20-year is taken as the lifespan of the wind configurations in the present study.

- ✓ Linear arrangement is assumed as the design of offshore wind farm since established onshore counterpart was also designed in a linear way.
- ✓ Production processes until the manufacturing of wind turbine are considered for both alternatives while transportation processes of raw materials until the manufacturing of wind turbine is excluded from the study.

3.1.3.2 Specific assumptions dependent to solar (PV) source

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

Degradation rates

Decrease in the solar panel efficiency because of environmental conditions named as *degradation* (Santhakumari & Sagar, 2019). Dusting of solar panels and climatic conditions like average temperature, humidity, temperature differences and ultraviolet (UV) irradiation are the main factors of degradation phenomenon (Ascencio-Vásquez et al., 2019). Testing is required to observe the decline of efficiency of solar panels particular for the region they are located at. For instance, the study (Ozden et al., 2018) focus on the different geographic regions to measure the degradation rates and degradation rate of multi-crystalline solar panel. In the aforementioned study, the degradation rate is found as 0,7 % for Central Anatolia. However, there is no measured observation and actual data for the island. Thus, the overall system degradation rate is assumed as 0,6 % based on the research article (Jordan & Kurtz, 2013).

Performance ratio

For the photovoltaic technology, it is the ratio of actual electricity generation to the electricity production expected from the ideal case. The actual production data for the performance ratio depends on geographical conditions similar to degradation rate. However, in Turkey, data for actual electricity generation from photovoltaic power plants are limited since the history of on-grid applications, triggered 2012, is relatively new for the photovoltaic technology (Karadogan et al., 2014). One of the research's findings (Karadogan et al., 2014) shows that the prediction of Photovoltaic Geographical Information System (PVGIS) database is less deviated for the actual electricity generation in Turkey than what Metronom is taken into consideration. Thus, electricity productions from the configuration is estimated with the aid of PVGIS calculator (JRC European Comission, 2017).

Specific assumptions dependent on solar (PV) source are listed below.

- ✓ Production processes up to silicon wafers are considered while transportation of raw materials up to the processes is excluded due to the impossibility of obtaining accurate values for transportation distances of the raw materials.
- ✓ Due to common usage in the literature (Gerbinet et al., 2014), multi-crystalline cells are selected as a cell type of proposed photovoltaic power plant.
- ✓ Lifespan of conventional photovoltaic system is assumed as 30 years (Ito, 2011).
- ✓ Lifespan of electric installation and mounting structure is assumed as 30 years (Frischknecht et al., 2015; Yu & Halog, 2015).
- ✓ Useful life of inverters for PV plant is suggested as 15 years (Ito, 2011). Therefore, inverters are assumed to be changed once throughout operation of PV plant (Peng et al., 2013).

- ✓ Fixed-tilt installation of the modules is chosen.
- ✓ Degradation ratio is accepted as 0,6 % although it is expected that potential induced degradation (Liu et al., 2018) for the sites near the sea will be higher than other areas. The reason of the higher potential induced degradation for the sites near the sea is the humidity which causes voltage-related system degradation on modules (Hacke et al., 2011).
- ✓ Performance ratio is accepted as 0,80 % determined by PVGIS calculator for the photovoltaic system in the light of the explanations above. For the life cycle assessment of utility scale PV installation, this performance ratio is also recommended by the researchers (Ito et al., 2008; Mason et al., 2006).

3.2 Life cycle cost (LCC)

Life cycle cost can be defined as a technique to evaluate all costs throughout the lifespan of a system (D. B. Lee, 2002). In this section, the methodology for life cycle cost analysis is described, and the procedure of calculation- namely the improved equations for each source- is explained.

3.2.1 Items of life cycle cost (LCC)

In this study, assumptions are needed for the calculation procedure. For example, there is no information about the labor costs for the offshore deployment in Turkey since there is no investment until now on. Thus, there should be common assumptions for the calculation procedure in order to be able to compare all configurations in terms of their cost aspects. In other words, boundaries are also needed for the cost calculation procedure. For this purpose, main assumptions for all configurations are listed below.

- ✓ Since one of the purpose of the study is the coupling of the life cycle assessment with the life cycle cost similar to the research on the construction sector (Ristimäki et al., 2013), project design cost are excluded from the life cycle cost calculations owing to the onset of life cycle assessment which is started with the extraction of raw material for the present study. In addition, the costs up to production phase of LCA are neglected during the calculation of LCC in order to be able to be parallel with the assumption in LCA which is the exclusion of raw materials' transportation.

- ✓ Combining the life cycle and life cycle cost in order to measure the sustainability of the system like in the study (Ristimäki et al., 2013), the costs of the material flows of each configuration are given special. In other words, the material price and the expenditure of their transportation are included throughout the configurations' life cycle cost calculations.
- ✓ The cost of labor is neglected while considering that the same impacts for each configuration will be observed throughout the calculation because all systems will require qualified labor work, and its need will be directly proportionate to the magnitude of the nominal capacity.

For this purpose, life cycle cost is categorized as follows:

3.2.1.1 Initial Investment Cost

All costs related to not only production but also construction phases are included in this item. In other words, the costs are regarded as costs of the materials in the production phase and expenses for transportation as well as expenses of assembly procedure in the construction phase.

3.2.1.2 Operation and Maintenance Cost

The costs of materials needed for maintenance procedures -namely, lubricants and oil for wind configurations and tap water for conventional PV configuration- and the replacement costs of broken parts- namely, the costs of changing spare ones instead of broken parts and transportation as well as assembly cost-.

3.2.1.3 Decommissioning and Disposal and/or Recycling Costs

Costs of disassembly procedures and expenses for the transportation of decomposed materials, either recycling scraps or disposal scraps, are regarded in the disposal or recycling costs.

3.2.2 Calculation procedure of life cycle cost (LCC)

In the light of brief descriptions of each cost item as mentioned above, equation (1) is developed to calculate life cycle costs for each configuration as follows:

$$LCC = C_{inv.} + C_{O\&M} + C_{DorR} + C_{tr} \qquad (1)$$

where $C_{inv.}$ is IIC. $C_{O\&M}$ and C_{DorR} demonstrate the operation and maintenance cost and the disposal or recycling cost, respectively. Total expenses for the transportations during all phases are expressed as C_{tr} in the equation.

Although the costs of each configuration are explained in detail in their own chapters, the developed equations to assess the planned investments for utilizing the wind and solar sources of the island are presented here in. In order to be able to compare life cycle costs of all configurations, the prices are extrapolated with the aid of the inflation calculator or producer price indices, depending on the location of their supply, in order to obtain the prices on January 2019. In other words, all costs are calculated for the onset of 2019.

$$LUCE = \frac{The\ life\ cycle\ cost\ [\$]}{The\ total\ electricity\ generation\ throughout\ the\ lifespan [MWh]} \qquad (2)$$

In order to compare the costs for the generation of 1 MWh unit electricity, levelized unit cost (LUCE) concept is introduced in equation (2) and applied to all configurations. As demonstrated in equation (2), LUCE can be defined as the ratio of the life cycle cost over total electricity generation.

3.2.2.1 Equations for the life cycle cost (LCC) of wind configurations

In order to calculate LCC for wind configurations, equations (4)-(5)-(6)-(7) are adopted by means of LCC equation in the research (Abu et al., 2020) and equation (3).

$$LCC_{Wind} = C_{Winv.} + C_{WO\&M} + C_{WDorR} \quad (3)$$

Transportation costs for the phases are indicated with the numbers. That is, C_{Wtr1} demonstrates the expense of transportation procedures during the production. The construction phases while the expenditures for operation and maintenance procedures and the expenditures of disposal or recycling procedure are shown as C_{Wtr2} and C_{Wtr3}, respectively. Due to the fact that C_{Wtr} involves C_{Wtr3}- namely C_{DorR} for this study- as the total transportation costs throughout life cycle of the configurations, C_{DorR} is not shown in the equation (3).

$$C_{Winv.} = C_{turbines} + C_{Winf} + C_{Welec.} + C_{Wtr1} \quad (4)$$

$$C_{WO\&M} = C_{WM} + C_{Wtr2} \quad (5)$$

$$C_{WDorR} = C_{Wtr3} \quad (6)$$

$$C_{Wtr} = C_{Wtr1} + C_{Wtr2} + C_{Wtr3} \quad (7)$$

Therefore, costs of processes for recycling or disposal are not included in the present study. In other words, the prices of selling procedure of recycling materials and the prices of the disposal scraps are neglected.

3.2.2.2 Equations for the life cycle cost (LCC) of photovoltaic configuration

In order to calculate LCC for photovoltaic configurations, equations (9)-(10)-(11)-(12) are adopted by means of LCC equation in the research (Abu-Rumman et al., 2017) and equation (8).

$$LCC_{PV} = C_{PVinv.} + C_{PO\&M} + C_{DorR} \quad (8)$$

Numbering of the transportation costs is as same as the case of life cycle cost of wind configurations.

$$C_{Pinv} = C_{panels} + C_{Pinf} + C_{Pelec} + C_{Ptr1}, \quad (9)$$

$$C_{PO\&M} = C_{M} + C_{Ptr2}, \quad (10)$$

$$C_{PDorR} = C_{Ptr3} \quad (11)$$

$$C_{Ptr} = C_{Ptr1} + C_{Ptr2} + C_{Ptr3}, \quad (12)$$

CHAPTER 4

ANALYSIS OF THE CONFIGURATIONS
LIFE CYCLE ASSESSMENT (LCA) AND LIFE CYCLE COST (LCC)

This chapter is devoted to life cycle assessment and life cycle cost of the configurations.

4.1 Analysis of onshore wind farm

In this part, the analysis of onshore wind farm is explained in detail.

4.1.1 Life cycle assessment (LCA) of onshore wind farm

Modelling procedure is explained for the onshore wind farm. Then, the materials and production processes used for the establishment of an onshore wind farm are presented in the life cycle inventory (LCI) part.

4.1.1.1 Structure of the model for onshore wind farm

Onshore wind farm in Bozcaada was established as seen in Figure 4.1 and has been in operation since 2000. Its installed capacity is 10.2 MW (Akova, 2011; Sahin, 2008). The farm, located on the northern west part of the island (Satir et al., 2018), includes 17 E-40 (600 kW) wind turbines (Hepbasli & Ozgener, 2004; *Turkish Wind Energy Statistic Report*, 2018) each having a tower height of 44 m.

At the time of construction of the onshore wind farm, there was no factory in Turkey which was able to manufacture the turbine parts. Thus, it is assumed that wind turbines were transferred from Enercon Company located in Germany by truck and ferry, the preferred means of transportation. The transportation distances for the wind turbines are measured as 2,640 km and 8 km by truck and ferry, respectively.

Electrical equipment including cables and inverters are assumed to be manufactured in the operating company's own cable factory located in Bilecik, and they are transferred to the construction site with the transportation distances which are 441 km by truck and 8 km by ferry. The transfer of concrete is assumed as 305 km by means of truck transportation.

Figure 4.1 Established Onshore Wind Farm[3]

During modelling of the onshore wind farm by means of GaBi, unit processes are created for demonstration of the production of all required components. Bulgarian grid mix is utilized for needed electricity throughout the manufacturing processes of all materials apart from wind turbines whereas Deutsche grid mix is preferred for production of wind turbines owing to manufacturing of the wind turbines in Germany. Greek grid mix is used for initialization of the plant due to the fact that there is no Turkish grid mix in GaBi software.

4.1.1.2 Life cycle inventory (LCI) for onshore wind farm

In order to make a correct model compatible with GaBi flows and make the model correctly, the onshore wind farm is classified into two parts named as moving parts and fixed parts. Moving parts of an onshore wind farm include rotor, cables, nacelle and inverter whereas fixed parts are composed of foundations and access roads as

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[3] http://www.demirer.com.tr/santral/bores/index.html

well as towers. Before the narration for the phases of the life cycle assessment, the main components and their functions are explained briefly in the following paragraphs.

Nacelle, a moving component and one of the main sections of a wind turbine, usually houses brakes, generator and gearbox. The other moving component of a wind turbine is the rotor, which includes a hub and blades. Foundation and roads, whose main functions are constituting the assembly procedure of a wind turbine, are required for the establishment of an onshore wind farm, and they are regarded among the fixed parts of an onshore wind turbine. The other fixed part of a wind turbine is the tower, and its main function is the carriage of the rotor and nacelle.

The Enercon E-40 specifications, used in the production phase of LCA of the onshore wind farm, are demonstrated in Table 4.1 (Y. Lee et al., 2006; Şentürk & Oğuz, 2020). In order to estimate the weight of 44 m tower utilized in the turbines, linear interpolation is applied using the weight of 46 m tower from the study (Y. M. Lee & Tzeng, 2008) since no information exists to the authors knowledge regarding the actual weight and/or geometric design of the 44 m towers.

Table 4.1 Enercon E-40 properties in the island (*Enercon E-40/6.44-600,00 KW-Wind Turbine*, n.d.; Y. M. Lee & Tzeng, 2008)

Mechanism	*Direct-Drive Mechanism (No gearbox)*
Nominal power	0.6 kW
Rotor diameter	43.70 m
Tower height[4]	44 m
Rotor weight	8.27 t
Nacelle weight	19.77 t

[4] Different from the tower height in the study (Y. M. Lee & Tzeng, 2008)

Tower weight	29.91 t
Base weight (foundation and roads)	220.00 t

As the first stage of the production phase, the processes and materials used for the manufacturing of the components are explained. For example, nacelle is produced in Germany, and steel and cast-iron parts are utilized for its production. Metal roll forming is applied for its manufacturing process (Ghenai, 2012). Nacelles are transported to the site by ferry transportation. In case of rotors, used materials are glass fiber, cast iron and epoxy resin. For modelling the manufacturing of towers, metal roll forming is utilized similar to nacelle production (Ghenai, 2012). The towers are composed of steel tubes, painted for the corrosion resistance. Deutsche grid mix is used in the model for the required energy to manufacture the nacelles and rotors since the manufacturing of them was carried out in Germany as mentioned before. In the production line in Turkey where foundations and roads are built as well as cables and inverters, Bulgarian grid mix is preferred to model the energy requirements of the processes due to the lack of Turkish grid mix in GaBi. While concrete and steel are the main raw materials used for the manufacturing process of foundation and roads, aluminum is the basic raw materials for the inverter and cables. In addition, it is assumed that only 1% of the moving parts will have a need for replacement throughout the lifespan of the plant since operating experts claim that failures typically occur at the electronic devices. Hence, spare parts as 1 % moving parts are added to the material flows in the production phase. In other words, spare parts are initially allocated for the future failures of the components.

Construction phase is started with the transfer of all materials to the site. In the stage of transportation, all components of the wind turbines are transferred from Germany to the construction site owing to the fact that they are produced in Germany. Following the transportation procedure, the turbine components and other necessary equipment are assembled in order to unite whole onshore wind farm. Excavator is used for the connection process of all components in the model because crane or lifter are not available in the educational version of GaBi. Initialization for generation of the electricity is made by Greek grid mix. They are noted as the limitations of this study.

The third phase is initialized with the electricity generation from the plant. Total electricity generation with 20-year useful life assumption is calculated as 680 GWh based on the average annual energy production of 34 GWh which is learned from the operating experts and affirmed by the research (Satir et al., 2018). Four types of maintenance procedures which are visual controls, supplement oil and lubricant, mechanical maintenance and electrical maintenance are considered in the model. The explanation for four types of maintenance procedures is given in the chapter 5 in order to clearly compare the differences between the procedures for onshore wind farm and offshore wind farm. As an important detail, the supplied lubricant and oil is assumed as 3,400 kg throughout the lifespan of the onshore wind farm with the aid of the study (Razdan & Garrett, 2015). The required transportation distance for the amendment of the broken parts and supply of oil or lubricant are assumed as 300 km. Owing to the fact that there is no traffic jam on the access roads apart from the maintenance procedure, site maintenance is not considered in the model.

Table 4.2 Summary of the end of life treatments for the components of the onshore wind farm

Materials Treated		*Ratio (%)*		*Decomposed Components*
Material Name	*Mass(t)*	*Recycling*	*Landfill*	
Iron	844.1	90	10	Nacelle and tower
Composite	142.0	-	100	Rotor
Aluminum	131.9	-	100	Electronic parts
Concrete	3,740.0	95	5	Foundation and access roads

In the decommissioning and disposal phase of the onshore wind farm, the plant is decomposed into main components such as tower and rotor. Landfill is considered as the end-of life treatment of the foundation for the future investments as suggested in the study (Haapala & Prempreeda, 2014) and DTU International Energy Report (Andersen et al., 2014). Due to the difficulty of recycling of the composite materials, the end-of life treatment for rotor and turbine blades are also considered as landfill (Andersen et al., 2014). The end of life treatments methodology and treated materials are presented in detail in Table 4.2.

4.1.2 Life cycle cost (LCC) of onshore wind farm

In this section, calculation procedure for each cost item is explained briefly for the case of onshore wind configuration.

Total turbine cost is calculated for the onshore wind farm in the year 2006 by finding the price of one Enercon E-40 turbine (Ozerdem et al., 2006). Since there was no factory in Turkey when the onshore wind farm was installed, extrapolation with Germany's price indicator (OECD, 2019) between 2006 and 2019 is applied in order to reach the prices in the year 2019.

After obtaining total turbine cost, costs of electrical apparatus in 2015 (Erdem, 2015; Erdem et al., 2015) are extrapolated with the Turkish inflation rate (*Inflation Calculator*, n.d.) to gain the costs of 2019 since electrical equipment is assumed to be manufactured in Turkey during the life cycle assessment unlike the turbine parts. The material costs of electrical equipment are found as $ 10,768,314. Spare parts are contained in the initial investment cost owing to the initial allocation of them in the life cycle assessment part.

The costs for infrastructure are calculated in a similar way to the calculation of electrical apparatus cost and by means of the same study (Erdem et al., 2015). As another part of the infrastructure, costs of the building and landscape are calculated through a similar methodology applied in the study (Oğuz & Şentürk, 2019).

Initial investment cost of the onshore wind farm is obtained by summing of all costs mentioned above.

Material costs- namely, lubricants and oil- and transportation costs that occur when spare parts are replaced with broken ones and oil and/or lubricant are supplied, are considered within the cost of operation and maintenance procedures, mainly not depending on the capacity of the wind configurations according to the working paper (Henderson, 2017). Labor costs required for the operation and maintenance are also excluded from the calculation of the operation and maintenance cost in order to focus on the costs of material flows only as assumed before. For this purpose, the maintenance cost of the Enercon E-40 turbine in the research (Fathiyah et al., 2000) for the year of 2008 is extrapolated with Germany's quarterly producer price indicator in order to gain the cost of operation and maintenance procedure of the onshore wind farm for 2019.

According to equation (6) in section 3.2.2, transportation costs occurring in the last phase are the costs of disposal and recycling. These costs neglect the resell prices of recycling scraps and focus only on the costs of disassembly and removal operations of the scrap materials. During their calculation, the total consumption of diesel is considered in order to estimate transportation costs occurred in the disassembly and removal operations. For this purpose, diesel consumptions of all scrap materials are noted from GaBi separately for their procedures. By multiplying the ultimate diesel price in Istanbul which is taken from the archived list of BP company (British Petrol, 2019) with the amount of diesel consumed, transportation costs of each scrap are obtained. As noted, transportation costs occurring at the other phases are calculated with same explained methodology. The cost of the last phase is calculated by summing the transportation costs of each scrap.

4.2 Analysis of offshore wind farm

The detailed analysis of the case is narrated following the consideration of the specific assumptions dependent to offshore configuration are listed as follow:

- ✓ How the nominal capacity of the offshore wind plant should be determined? In other words, what should be the nominal capacity of the plant in order to compare the impacts between other configurations?
- ✓ Which turbines should be selected? This is, the specification of offshore technology and onshore counterpart have main differences. In this context, there is an urgent need for the determination of the turbine type and the number of selected turbine for the LCA of offshore configuration.
- ✓ What is the applicable tower height for the selected region ? In other words, what is the upper limit of the wind speed which are measured for the wind roses around the island?
- ✓ How the selected turbines should be positioned in order to make the comparison with onshore configuration possible?
- ✓ The determination of the distance between the consecutive turbines is also needed.
- ✓ How the distance from the shore should be determined ? Is there any specific concern about Bozcaada Island like military or territorial zones?
- ✓ Following the determinations of shore distance and the nominal capacity of the plant, whether or not there should be constructed a substation.
- ✓ Which method should be preferred for the power transmission from the offshore turbines to the shore following the decisions about the substation and the distance between consecutive turbines?
- ✓ What should be suitable type of foundation for the deployment of the offshore wind farm in Bozcaada Island?

In the following subsections, the questions above are answered, and the reasons for the answers are explained in detail. This is, the answers for the questions above are supported with the literature.

4.2.1 Life cycle assessment (LCA) of offshore wind farm

Modelling procedure is applied in a similar way to the analysis of onshore wind farm.

4.2.1.1 Structure of the model for offshore wind farm

Three turbines are envisaged in the model for the offshore wind farm in order to approximately match the offshore nominal power capacity with the onshore technology. In other words, 3 Vestas V-112 turbines are considered for the offshore configuration in order to be close to the onshore wind farm's nominal power under operation. This is, Vestas V-112 3 MW turbines are chosen for the deployment of offshore wind farm instead of the E-40 (600 kW) turbines (Hepbasli & Ozgener, 2004; *Turkish Wind Energy Statistic Report*, 2018) utilized in the existing onshore wind farm owing to two main reasons. The former reason is that Enercon E-40 (600 kW) is out-of-production. The latter one is the need of bigger turbines due to the deployment location with the purpose of use the higher wind potential than the wind potential on the land.

Tower height of the offshore wind turbines is accepted as 94 m with the aid of known wind speed around the island (Satir et al., 2018) which is approximately 9.1 m/s at 94 m above ground level.

In order to be similar to the onshore wind configuration, the configuration of offshore wind turbines is considered to be positioned across the dominant wind direction, and the distance between two turbines is taken as 560 m, representing five times the rotor diameter which is suggested in the study (Koç et al., 2016) in order to minimize the impacts of wake losses.

Proximity of the military protected zones in the Mediterranean is another important aspect of the island (Soukissian et al., 2017). Hence, the distance between the offshore configuration and the coast is accepted as 10 km not only to obey the current standard territorial water range of 22 km (Argin & Yerci, 2016) but also to avoid building a substation which becomes necessary under the conditions listed below (Güzel, 2012; Huang et al., 2017).

- In case the nominal power ranges between 30 MW to 120 MW, and the distance between the closest turbine to the shore is more than 10 km or,
- The nominal power of the offshore plant has more than 120 MW.

As carried out in the study (Köroğlu & Ülgen, 2018), high voltage alternating current (HVAC) system is considered for the transmission of power from the offshore wind farm to the coast, which is the conventional way for the power transmission of small and medium capacity plants (Olguin et al., 2014). It is worth to note that there also exists another solution called high voltage direct current (HCDC) (Kirby et al., 2002) but it is usually suggested for situations where transmission line is more than 100 km which is much longer than the total transmission line of 20 km for the present case.

While moving parts are composed of nacelle, rotor and cables, fixed parts contain tower and base. Foundations and roads are required for onshore configurations whereas the basement is required for offshore deployment. There are different basement alternatives for the offshore configuration depending on the water depth. For the known water depth of 30m for Bozcaada (Satir et al., 2018), monopile (Velarde & Bachynski, 2017) is preferred among other options, which are floating (Oguz et al., 2018), gravity-based or tripod (Kaldellis & Apostolou, 2017) and suction caisson, multi-pod (tripod and jacket) (Oh et al., 2018), as in the studies about the offshore deployment in Bozcaada (Çokyaşar & Beji, 2019; Oguz & Incecik, 2014; Satir et al., 2018). Monopile foundations (Liang Tsai et al., 2016) are also suggested for near shore shallow waters like in Bozcaada. Foundation types for the deployment of offshore wind turbine are shown in Figure 4.2. Monopile is highlighted in Figure 4.2.

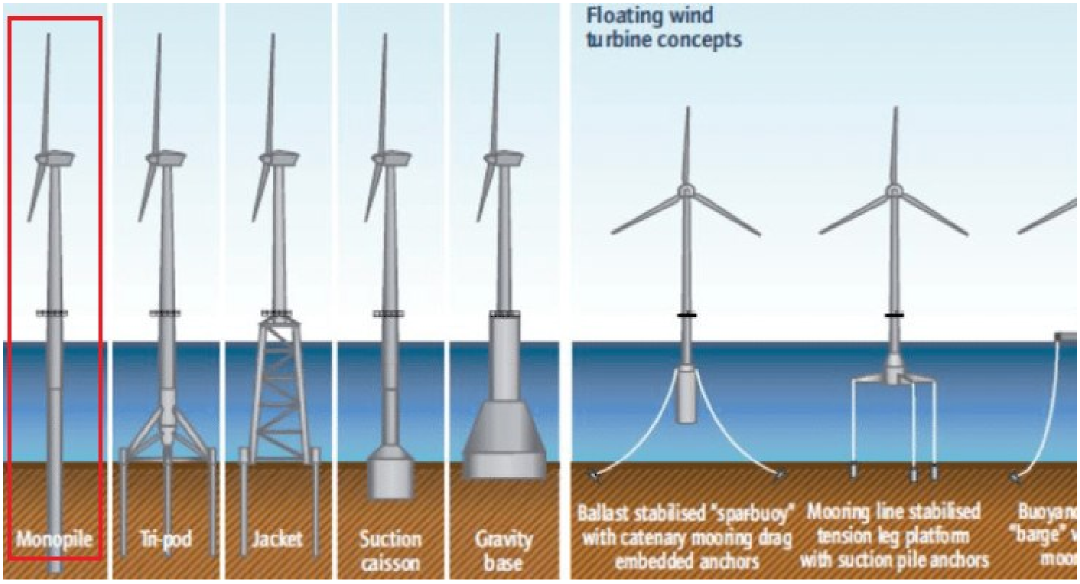

Figure 4.2 Foundation types for an offshore wind farm[5]

4.2.1.2 Life cycle inventory (LCI) for offshore wind farm

For the modelling of offshore wind farm, similar procedure used in the analysis of onshore wind farm is applied since nacelle, rotor, cables and tower are regarded as the mutual components for both onshore and offshore configurations.

Basic characteristics of the offshore wind turbine adopted from the thesis (L Tsai, 2013) -except the tower weight- are given in Table 4.3.

Table 4.3 Vestas V-112 characteristics for the proposed offshore wind farm in the island

Mechanism	*Gearbox Technology*
Nominal power	3 MW
Rotor diameter	112.0 m

[5] https://www.linkedin.com/pulse/offshore-wind-foundation-fabricator-market-risk-due-henk-de-pater

Tower height	94 m
Rotor weight	49.18 t
Nacelle weight	92.63 t
Tower weight	264.38 t
Base weight (monopile)	700.00 t

Recalculation of the tower weight is necessary before the onset of the offshore wind farm analysis due to selection of a different tower height. The tower weight of this study is recalculated based on the data provided from the research (Way & Van Zijl, 2015). By applying linear regression method to the data found, equation (13) is obtained for the selected Vestas V112-3MW offshore wind turbine where w and h indicate weight and height of the tower, respectively.

$$w = 0.26h^2 - 39.47h + 1{,}676.60 \quad (13)$$

As mentioned before, especially for the mutual components, the modelling procedure is generally similar to the modelling of the onshore wind farm. Nevertheless, there are some discrepancies between the production of non-mutual components as well as the strategies for the production of mutual components. All components of the onshore wind turbine are produced in one location. However, this is not valid for the manufacturing of the offshore wind turbine components since Vestas has produced the components in different locations. Towers are produced in U.S.A whereas rotor blades and nacelle are produced in Italy and Denmark, respectively. For this reason, European electricity grid mix is utilized for the energy need of the production processes of nacelles and rotors while American grid mix is used for the manufacturing of towers. Another main distinction between the production phases of both wind configurations is the manufacturing of the basement. Concrete and steel are the materials for the basement of onshore configuration-namely foundation and roads- while gravel is used for scour protection of monopile during the modelling of offshore basement as well as concrete and low-alloyed steel.

The other important difference is the cabling requirement on the sea for the offshore wind configuration. The 33 kV submarine cables are utilized for the cabling between the turbines as carried out in the study (Koç et al., 2016) whereas the 132 kV submarine cables are used for the transmission line from the turbines to the coast. In order to model the cables, the weights of 88 t/km and 29 t/km are considered like in the research (Birkeland, 2011) for 132 kV submarine cables and 33 kV submarine cables, respectively.

In the construction phase, transfer operations to construction site also differ from the procedure of transportation for onshore wind farm components owing to different location for the production of the offshore wind turbine parts. This is, the wind turbines are transferred from Germany while nacelles from Denmark, rotors from Italy and towers from U.S.A are transported to the site. Excavator is considered for assembling the parts together like in the assembly operation for onshore wind farm owing to the limitation of GaBi in which no crane is found. Apart from the increase in number of expeditions for transportation and assembly of parts needed for the deployment of offshore wind turbines, same procedure is applied for both wind cases.

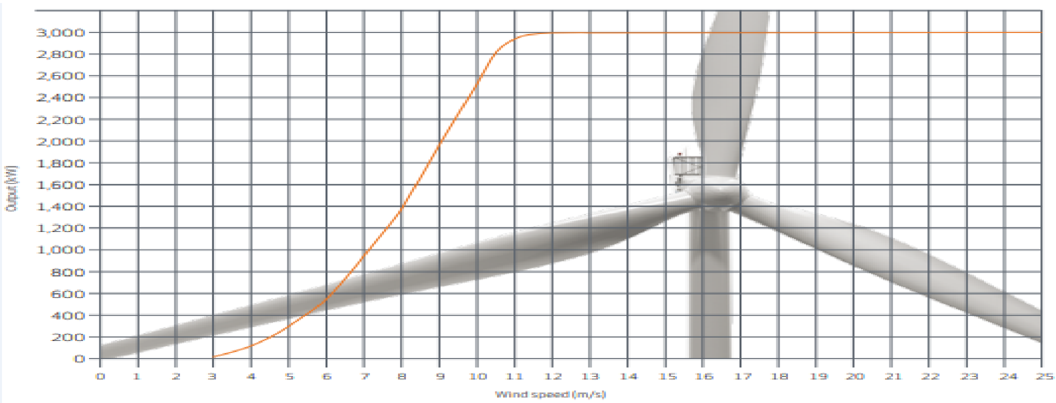

Figure 4.3 Power curve-Vestas V-112-3 MW-Offshore[6]

[6] https://www.vestas.com/en/products/4-mw-platform/v112-3_45_mw#!

The electricity production from the plant for each configuration is the onset of operation and maintenance phase. Annual electricity production for one unit of Vestas V112-3MW is estimated as 14 GWh/year from a thesis (Güzel, 2012). Based on the known wind speed of 9.1 m/s and the known tower height of 94 m (Satir et al., 2018), the applicability of the prediction of annual electricity generation is demonstrated in Figure 4.3 and Table 4.4.

Table 4.4 Power curve-Vestas V112-3 MW-Offshore[7]

Wind speed (m/s)	*Annual Energy Production (MWh)*
8.5	13.402
9.0	14.311
9.5	15.119
10.0	15.826

Total electricity generation of 840 GWh throughout the lifespan is forecasted for offshore wind farm by means of Figure 4.3 and Table 4.4.

During the operation and maintenance phase, breakage of components is expected as well as supply of lubricant and oil, when necessary. Furthermore, transportation of supplement materials is required for both onshore and offshore configurations. For this reason, spare parts are estimated and initially allocated. 1 % of all moving parts of onshore configuration as mentioned in the chapter 4 and 15 % of generator and gearbox for offshore configuration are added to material flow in the modelling procedure. Transportation distance of spare parts is applied as 40 km on the sea for the offshore configuration. The supplement of oil and lubricant are transported to offshore wind farm by ferry.

[7] https://www.vestas.com/en/products/4-mw-platform/v112-3_45_mw#!

For the inventory analysis of the operation and maintenance phase, maintenance concept of wind farms is explained briefly as indicated in the third phase of the operation and maintenance procedure of onshore wind farm. During the third phase of wind farms whether is onshore or offshore, four type of periodic controls are considered as the maintenance procedure and are applied in the modelling as follows:

- ✓ During the periodic visual controls, only transportation of the operators is required. In other words, addition of no extra material (Owens, 2019; Zeinali & Keysan, 2019) is needed to model in the light of the system boundaries drawn in chapter 3. As another important point, ferry transportation is only required for the offshore configuration.
- ✓ Supplement of oil and lubricant is required for the second kind of periodic controls. Due to gearbox mechanism used in the offshore configuration, the need for oil and lubricant change is higher than onshore configuration. According to the interviews with experts operating onshore Vestas wind farms in Turkey, one change of oil and lubricant lasts 6-7 years depending on the quality of material used. For this reason, 15,570 kg lubricant is assumed for total oil replacement considering that 3 times oil change will be required throughout the lifespan of offshore wind turbines similar to its counterparts under operation on the land in Turkey. In contrast, the need for lubrication in Enercon model is not known clearly due to the direct-drive mechanism (Owens, 2019; Zeinali & Keysan, 2019) utilized in it. Therefore, the requirement of lubricant for onshore configuration is assumed with the aid of the report (Razdan & Garrett, 2015) as 3,400 kg as mentioned in the operation and maintenance phase of onshore wind farm.
- ✓ Periodic controls of mechanic parts are called as mechanical maintenance, and they are carried out twice a year according to the study (Chan & Mo, 2017). Broken mechanical parts are replaced during these periodic controls. No material flow is created in the model for these replacements since spare parts are allocated in the production phase for each wind configuration.

Similar to visual controls, ferry is utilized only in case of mechanical maintenance of offshore wind farm.

- ✓ Similar to mechanical maintenance, electronic parts are controlled periodically, and this is named as electrical maintenance. Its modelling in the software is as same as the modelling procedure of mechanical maintenance.

Site maintenance is also neglected for the analysis of offshore wind farm similar to onshore case since access roads utilized during the lifespan of both configurations have no traffic except transportation of the parts to the wind farms.

Table 4.5 Summary of the end of life treatments for the components of the offshore wind farm

Materials Treated		*Ratio (%)*		*Decomposed Components*
Material Name	*Mass(t)*	*Recycling*	*Landfill*	
Steel alloyed	2,343.7	90	10	Nacelle, tower, rotor, cables and monopile
Aluminum	5.3	95	5	Nacelle and rotor
Copper	293.8	95	5	Nacelle and cables
Lead	220.0	90	10	Internal and grid connection cables
Polyethylene	135.2	-	100	
Polypropylene	77.1	-	100	
Polyvinylchloride	5.3	-	100	Miscellaneous
Epoxy	8.2	-	100	
Glass fiber	23.4	-	100	Rotor

The end of electricity generation is the last step of the third phase, and fourth phase analysis -the inventory analysis of decommissioning and disposal or recycling-comes after that. As the first step of the fourth phase, offshore wind farm is decomposed into their main components like nacelle and rotor. Scrap materials coming from the decomposition of main components are classified as recycling materials and disposal scraps. Their details are indicated in Table 4.5. As the main difference, the variety of scrap materials for onshore configuration is less than the variety of scrap materials for offshore configuration. Landfill, as carried out in research (Andersen et al., 2014; Haapala & Prempreeda, 2014), is the end of life treatment for concrete in both configurations, and it is regarded as one of the main similarities between the configurations. The end of life treatment for rotor and turbine blades (Jensen & Skelton, 2018) is also applied as landfill in the analysis of offshore configuration as well as in the analysis of onshore wind configuration. Scrap materials are transferred to the same area; thus, distances required for the transfer procedure are same for both configurations apart from the usage of ferry needed for what the decomposed components of offshore wind farm transferred from the coast to the shore.

4.2.2 Life cycle cost (LCC) of offshore wind farm

Each cost item is calculated for the cost analysis of offshore wind farm, and its calculation procedures are explained below.

The cost of monopile for the offshore wind farm can be considered analogous to the cost of foundation and roads in the cost analysis of the onshore system. Monopile cost for the offshore system is calculated for 30 m water depth by means of equation (14) obtained from the report (Rosenauer, 2014). After updating the cost of monopile to 2019 prices by European producer price indices- in order to be able to be parallel to the life cycle assessment part-, the cost of monopile for the present case is found as \$ 20,693,864.3.

$$\text{The cost of monopile} = 2{,}242{,}483.33 + 7.236d_{shore} + 986{,}059\exp(0.0182d) \quad (14)$$

In equation (14) (Rosenauer, 2014), d_{shore} indicates the distance of the shore, and d shows water depth. The cost of monopile can be obtained per nominal power of the system by using the equation (14).

Equation (15) from the report (Kolios & Brennan, 2018) is used for calculation of the total costs of the parts including nacelles and rotors for the whole farm. Nominal power is indicated with x in equation (15), and the cost is calculated in € from equation (15).

The total costs of nacelle and rotor per turbine = (3.106.ln (x.MW)-662,400) € (15)

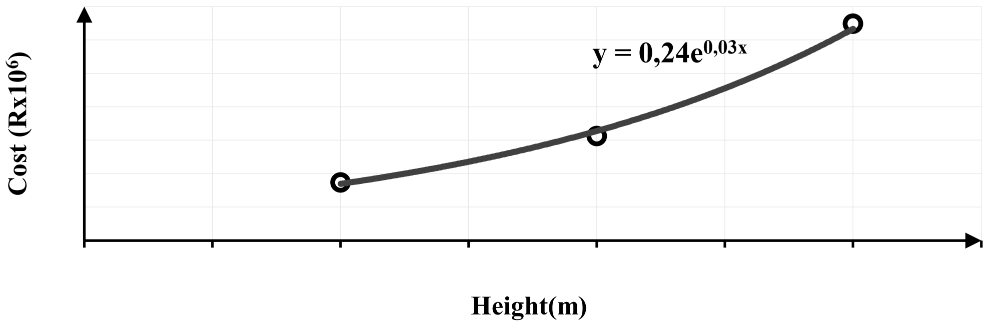

Figure 4.4 Tower cost vs. height for Vestas V-112 3 MW (Way & Van Zijl, 2015)

For the cost of turbine, the parts of nacelle and rotor are considered together. With the aid of equation (15) (Kolios & Brennan, 2018), total cost of nacelles and rotors for all turbines is calculated in €. After converting the cost from euro to dollar, in order to obtain the cost of 2019, European Union producer price indices (OECD, 2019) is applied, and current total costs of nacelle and rotor parts for 2019 are calculated as $ 7,900,311.

The total tower cost of the offshore wind farm, obtained by means of Figure 4.4 adopted from the research (Way & Van Zijl, 2015), is converted from Randi to dollar, and it is updated to reach the cost of 2019. As a result, total turbine cost is found as $ 9,382,956.0 for 2019.

The costs of 33 kV cables gained from the study (Judge et al., 2019) in 2016 and the costs of 132 kV cables obtained from the study (Gonzalez-Rodriguez, 2017) in 2017 are updated by European producer price indices (OECD, 2019) for the calculation of the total costs of internal cables and grid connection cables, respectively. As a result, the total cost of internal cables is $ 147,993.5, and the total cost of grid connection cables is $ 13,737,648 for the year of 2019.

For the cost of operation and maintenance phase, obtained costs from a thesis (Puglia, 2013) in 2013 for Vestas V-112- 3 MW are updated by European producer price indices (OECD, 2019), and the cost of the phase is calculated as $ 4,960,320.0.

In order to calculate the last phase's cost, amount of diesel for each transportation process is noted from GaBi similar to the cost analysis of onshore wind farm. Same procedure in the cost calculation of onshore system is applied again, and the total cost of the fourth phase for offshore wind farm is found as $ 101,052.2.

4.3 Analysis of land-based grid connected photovoltaic (PV) plant

This chapter is allocated for the detailed analysis for the life cycle assessment (LCA) and life cycle cost (LCC) of a land-based on-grid proposed photovoltaic system.

4.3.1 Life cycle assessment (LCA) of land-based on-grid photovoltaic (PV) plant

Model structures of the system described for the proposed PV plant and inventory of life cycle assessment are explained in the following sections.

4.3.1.1 Structure of the model for conventional land-based on-grid photovoltaic (PV) system

One of the important types of photovoltaic systems is suggested as "land-based grid connected" although there have been other choices depending on the deployment location and connection issues to the grid. In other words, the specifications of the proposed system for this study is land-based deployment instead of roof-type or floating deployments regarding the application site. In addition, grid-tied system –

meaning that there is no storage unit due to direct connection to the grid- is the other crucial feature of the proposed PV plant of this study.

In order to compare the PV plant with the wind farms, the established wind farm area of 20,560 m^2 is also utilized for the application of land-based PV plant. The land needed to establish an open-ground mounting photovoltaic system in United States with the selection of fixed-tilt installation type is forecasted as 3.8 acres/MWac (Denholm & Margolis, 2008) whereas the land use of a PV plant for the Konya Plain Region is found as 17,391 m^2/MW in the project (Ministry of Development Regional Development Administration for Konya Plain Project, 2012) which is similar to selected area of this study in terms of some characteristics such as being a flat land and having close longitude and latitude. Therefore, the nominal capacity of the proposed photovoltaic deployment in Bozcaada is determined as approximately 1.2 MW by means of the average of the values mentioned above such that 16,400 m^2 land is needed for 1 MW nominal capacity of on-grid open ground PV plant.

As mentioned in "specific assumptions dependent to solar (PV) source" section giving the concept definitions, degradation rate and performance ratio of proposed PV installation is taken as 0.6 % and 0.80 %, respectively. Optimum fixed-tilt properties for Bozcaada Island is determined with the aid of PVGIS calculator (JRC European Comission, 2017) similar to the performance ratio. 3° azimuth and 32° slope angles determined by PVGIS are the features for the optimum design of the solar arrays in order to establish an open ground and grid connected PV plant in the island.

The number of solar modules are calculated as 4615 for the determined nominal capacity since the PV plant is composed of 265 kWp solar modules. Solar modules include 60 cells each of which having 243 cm^2 of wafer area. In addition, zinc coated steel and aluminum are the materials for the support frames used to hold the solar modules in place.

4.3.1.2 Life cycle inventory (LCI) for conventional land-based on-grid photovoltaic (PV) system

In the raw material extraction for the proposed PV plant-namely production phase-, solar cells that are the most important parts of the system are assumed to be brought from Taiwan to Tekirdağ factory to be manufactured into solar modules. Although production processes of the wafer are inserted into the model, the transportation of related silicon is not inserted owing to the lack of accurate information as indicated in Figure 3.2. Silicon wafer is produced in Taiwan by utilizing Chinese grid mix since no Taiwanese grid mix is available in GaBi. Following the manufacturing of the silicon wafer, silicon wafers are transferred to Tekirdağ by 8689 nautical miles ocean-going ship transportation. Related processes in order to manufacture solar modules such as metallurgical grade silicon are inserted in the model. After the solar cells are transferred to Tekirdağ, the rest of the processes are inserted in the production phase of the PV plant. There is no requirement for the comprehensive site clearance prior to the installation of PV plant since no vegetation exists on the selected area whereas there is a need for a building in order to operate the system properly. In addition, frames composed of steel and aluminum are required to make arrangement of solar modules. For this purpose, a unit process is created and called as open ground mounting structure in GaBi. All required materials like concrete for the roads and foundations for the frames, steel and aluminum for the mounting frames as well as building for the operation are added to the open ground mounting structure unit processes. In case of production of the inverters, Ecoinvent database is used for the materials and related processes. As mentioned in the related chapters, spare parts for wind configurations are allocated initially and added to the material flows of the production phases. Due to the difficulty of PV plant spare parts' preservation properly, the inverters and the solar modules are not allocated initially in the modelling of grid connected open ground PV system. Hence, it is not added to material flows in the production phase.

Following the end of production phase by means of manufacturing the necessary components, which are solar modules, inverters and open ground mounting structure; all of the components are transported to the site in the onset of construction phase in order to unite the plant. The distances for the transportations of the components are measured via Google maps. The transportations of the components in the appropriate order are listed as follows:

- For solar modules,
  - 228 km by truck from Tekirdağ to Kilitbahir ferry dock station
  - 2 km by ferry to cross the Dardanelles.
  - 54 km by truck from the Çanakkale dock station to Geyikli dock station
  - 8 km by ferry from Geyikli dock station to Bozcaada dock station
  - 9 km by truck from Bozcaada dock station to construction area
- For inverters,
  - Totally 390 km by truck from the inverters' factory to construction site
  - Totally 8 km by ferry in order to reach the construction area
- For open ground mounting structure including foundation and fences,
  - Totally 390 km by truck to the site
  - Totally 8 km by ferry to the area (only from Geyikli dock station to Bozcaada dock station)

Only manual work is necessary in order to assemble the components whereas excavator is utilized for the wind configurations. In order to model cabling and initialization, another unit process called electric installation is created. The extrapolated values from 570 kWp photovoltaic plant (Jungbluth et al., 2010) for cabling and fuse box are inserted to the electric installation unit process in order to depicture the mass and energy flows throughout necessary lighting and cabling which includes cables from the module to inverter, cables from the inverter to the electric meter and cables for the connection between solar panels as well as low and medium switchboards. As the assembly procedure of the model, a unit process named as PV plant installation is created, and all aforementioned components are connected to this process. For the energy needed to initialize the system, which is the final stage of construction phase, Greek grid mix is utilized due to the limitation of GaBi.

In the operation and maintenance phase, the total electricity production is forecasted based on the assumed degradation ratio and annual production estimate taken from PVGIS calculator. The change in the amount of electricity generation vs. years due to degradation are demonstrated in Figure 4.5. Total electricity production is calculated as 52.31 GWh for 30-year life span of the plant. In the maintenance stage for the grid-tied land-based photovoltaic plant, cleaning of the dust accumulated on the solar panels are mandatory. Tap water usage is assumed for the case of this study, and the truck transportation distance for the carriage of tap water throughout the useful life is accepted as 80 km. As another maintenance step, the inverters are replaced once owing to the limitation of their life-span. Replacement of inverters is modelled the same way that their supply is modelled in the production phase. The required transportation distance from the operation building to the construction site for inverter replacement is assumed as 80 km similar to the carriage of tap water. During the lifetime of the PV plant, 15 solar modules are assumed to be broken and replaced with spare ones. However, there is a crucial distinction between the procurement strategies of spare parts for PV and the procurement strategies of spare parts for wind configurations as mentioned in the explanation of the production phase of the PV plant. For the supply of spare parts in the use phase of PV system, 371 km by truck and 10 km by ferry transportation are considered.

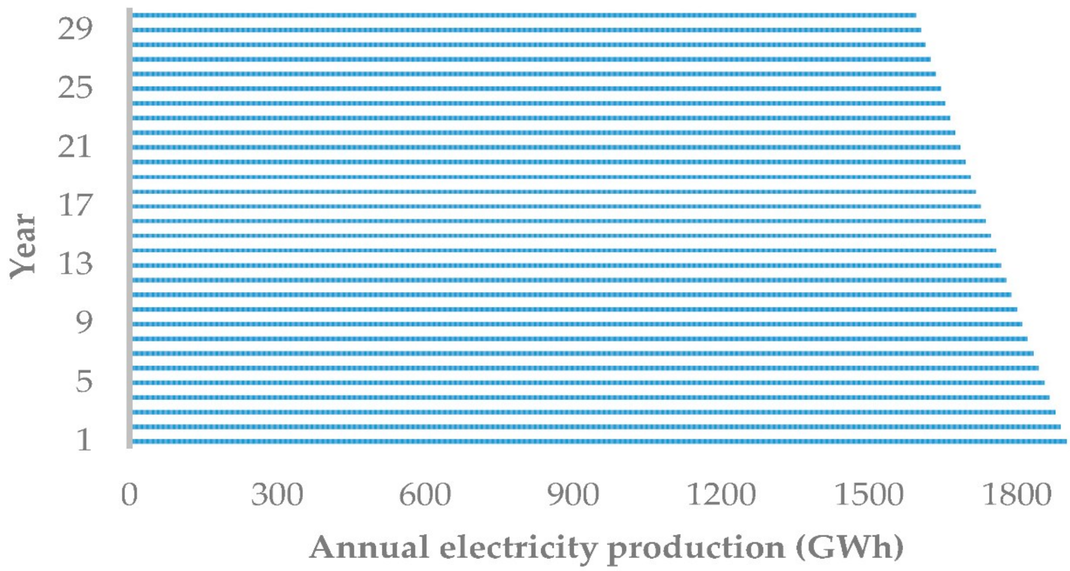

Figure 4.5 Change in the amount of electricity generation due to degradation

Decommissioning and disposal or recycling phase starts with the finalization of the electricity generation. Basic onsite deconstruction is applied to the on-grid open mounted photovoltaic plant in order to classify the scraps into disposal or recycling. Aluminum, copper and steel scraps are regarded as the recycling materials, which are deriving from the equipment required for the balance of PV system such as support frames, cables and inverters. Unit processes are created for each type of scrap materials in GaBi by inserting their own weights. Open loop recycling is preferred as the recycling strategy for the decomposed parts apart from solar panels following their transfer to the recycling plant by 8 km ferry and 300 km truck transportations. In other words, no recycled material is bounded to the production phase except for the decomposed and recycled solar modules. It is worth here to note that the unit process created for the scrap solar panels is named as decomposed solar panels. The decomposed solar modules are transferred to Deutsche Solar AG recycling plant (Appleyard, 2009) by a cargo plane as in the article (Desideri et al., 2012). After the procedure in the recycling plant, recycled solar panels containing 3.48 % decomposed panels by mass are returned to the material flow of solar modules in the production phase. The transfer procedures of the recycled solar panels by truck and ferry transportation are neglected since the cargo plane is the dominant cause of the emissions compared to truck and ferry.

4.3.2 Life cycle cost (LCC) of conventional land-based on-grid photovoltaic (PV) system

For calculation of the life cycle cost of proposed PV plant on site, the price of solar panels produced in Tekirdağ is taken into consideration.

In case of infrastructure, site clearance costs are neglected since construction site is already available for the deployment of conventional PV plant due to the established onshore wind farm. In other words, as seen in Figure 4.1, there is no slope and vegetation which are the main obstacles prior to installation of PV plant. Hence, no material flows are considered for the site clearance stage. Other items for the infrastructure of land based PV plant can be regarded as settings, wiring and supporting structures on which solar panels are mounted. For the cost of open ground mounting, costs of settings and wirings for 1 kW (Batman et al., 2012) is extrapolated by using Turkish inflation rate (*Inflation Calculator*, n.d.) in order to be parallel to the assumption that all supporting structures are manufactured in Turkey in the part of the life cycle assessment of PV plant. Building and landscape are regarded as other sources for the infrastructure costs. Same cost calculation procedure used in the case of onshore wind farm is also applied here for these items.

The replacement of broken parts with spare parts and cleaning of solar panels from the accumulated dust are performed throughout the operation and maintenance phase of the conventional PV plant. The spare parts including spare inverters and spare solar panels are not allocated initially; therefore, their transportation distances are assumed as the sum of initial supply distance and distance required for the replacement process. Utilization of 46.6 tons of tap water and 80 km of transportation distance for the cleaning procedure are also assumed.

Due to the manual operations for the decomposing of the plant, no costs are considered for this step. For the disposal and recycling costs, transfer stage for scrap materials except scrap solar panels is as same as the transfer stage in the cost calculation procedure of onshore wind farm. As mentioned before, the scrap solar panels are transported to a recycling plant by a cargo plane. The transportation cost for the transfer of scrap solar panels is calculated with $ 300/tons Kerosen price taken from Alibaba website (Kerosen, 2019).

CHAPTER 5

COMPARISON OF THE CONFIGURATIONS AND RESULT ANALYSIS

Chapter 5 is divided into two main subsections in order to examine and compare the results of the life cycle impact assessments (LCIA) and life cycle cost analysis (LCCA) for all configurations. The results of the life cycle assessment (LCA) are interpreted and compared with the results found in the literature for the similar cases in section 5.1.1. The costs of the configurations are firstly compared by LUCE in section 5.2. Following that, there is another subsection of LCCA for the benchmarking of the calculated costs for the present study's configurations with the results found in the literature for the similar cases.

5.1 Life cycle impact assessments (LCIA)

With the guidance of ISO 14042 (Ryding, 1999), the order of evaluation indices for the life cycle impact assessment part is followed in the narration of this section. As mentioned before, CML2001-Jan 2016 impact assessment method is preferred as the impact assessment method. Also, it should be noted that demonstrations related to the LCA phases include the results of the grid-tied open ground PV plant in which recycled solar panels are considered in the material flow for the production phase.

As seen in Figure 5.1, the production phase of onshore wind farm causes the highest acidification while the construction phase of the offshore wind farm leads to the highest acidification in the life cycle comparison due to excessive usage of fuel for the transportation and assembly process. Although the unit process of aluminum ingot mix is the main reason for the highest level acidification in the model for the production phase of onshore wind farm, the difference between the acidification level between two wind configurations can be explained by the excessive requirement of aluminum for the establishment of onshore configuration (see Table

4.2 and Table 4.5 for aluminum weights). In the case of land-based PV plant, production phase and last phase (decommisioning and disposal or recycling phase) have the highest acidification potential share throughout its lifespan. It is important to note that total acidification of the grid connected land-based PV system is lower than the total acidifications of two wind farms owing to lower material weights of PV plant than the material weights of wind configurations. Further details and comments related to acidification potentials can be found in Appendix C.

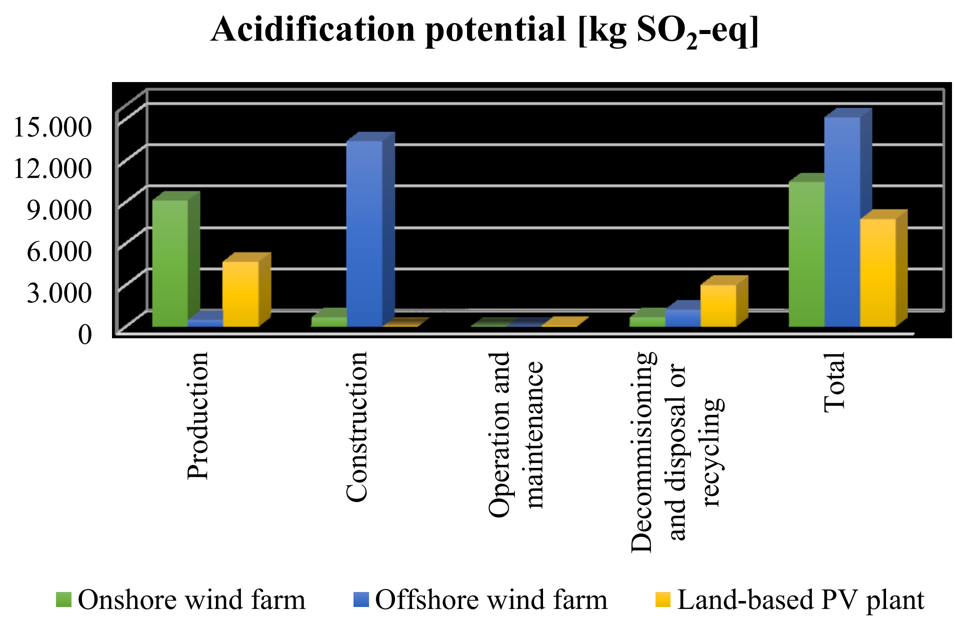

Figure 5.1 AP of three configurations based on the LCA phases

As seen in Figure 5.2, the lowest total eutrophication among the configurations is caused by the grid connected open ground PV system. The production phase and decommissioning and disposal or recycling phase of the land-based photovoltaic system are the main reasons of the eutrophication during its lifecycle. Decommissioning and disposal or recycling phase is more dominant than the other phases of the onshore wind farm owing to the municipal solid waste unit process for the scrap of the concrete (see Table 4.2) whereas construction phase is more dominant in the offshore wind farm configuration. In Appendix D, further details and further comments on the eutrophication potential can be shown.

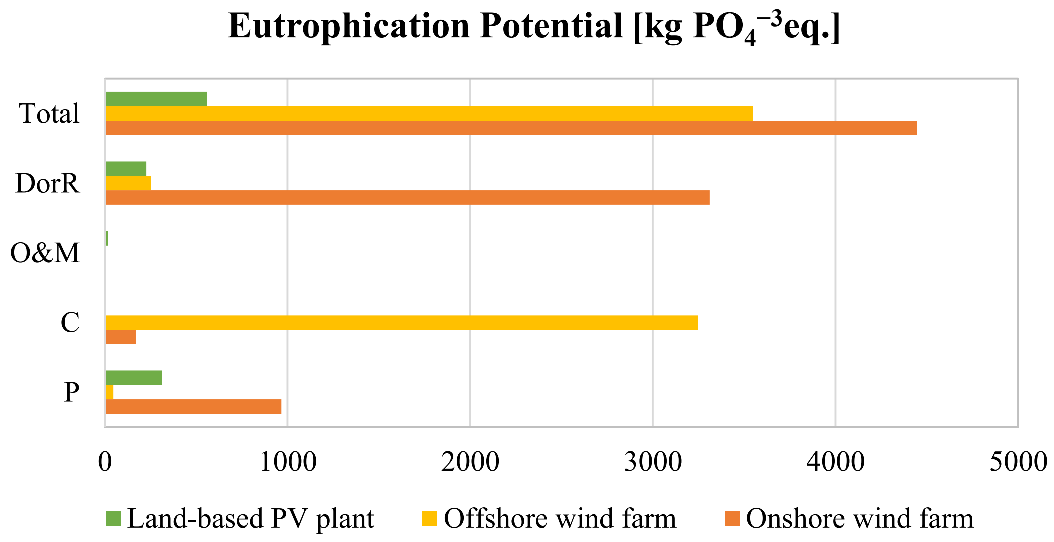

Figure 5.2 EP of three configurations based on the LCA phases

In Figure 5.3, the total energy requirements of the configurations are demonstrated. During its lifetime, the offshore wind farm needs the highest energy with a value of 87,352,073.0 MJ whereas the primary energy need of the on-grid land-based PV plant is the lowest with 12,268,379.4 MJ. The lowest weight of the configuration is PV plant; hence, primary energy requirement of the PV plant gives the lowest result as seen in Figure 5.3. From the definition of the cumulative energy demand (see also Table 5.4), onshore configuration needs 111.0 MJ primary energy in order to generate 1 MWh electricity. The primary energy requirement of offshore configuration is 104 MJ/MWh. In addition, 234.5 MJ is required to be produced 1 MWh electricity from the land-based PV plant. The difference between the results of wind configurations can be explained by the fact that direct-drive mechanism turbines are heavier than its gearbox counterparts (Marx, 2018; Preiss et al., 2008).

In order to make a comment about energy pay-back time (see also Table 5.4), estimated total electricity generation should be reminded for each configuration. The total forecasted electricity production is 680 GWh for the onshore wind farm whereas 840 GWh and 52.31 GWh are the predicted electricity generations for the offshore wind farm and grid connected land-based PV plant, respectively. Therefore, energy pay-back time is found as 0.62 years for the onshore wind farm while 0.58 years is the energy pay-back time of offshore wind farm. For the solar configuration, it is founded as 2.06 years. The CED results for the phases of each configuration are tabulated in Appendix E.

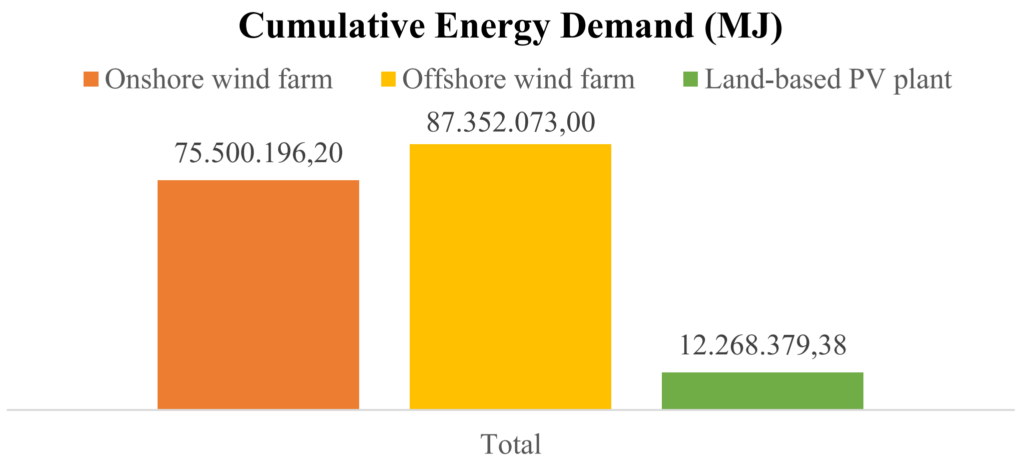

Figure 5.3 CED of three configurations based on the LCA phases

In terms of greenhouse gas emissions (GHGs), the construction phase of the offshore wind farm and the production phases of both the onshore wind farm and the grid connected land-based PV plant have the highest proportion for the global warming potential as indicated in Figure 5.4. Operation and maintenance phases of all configurations lead to approximately zero emissions. While the total greenhouse gas emissions of each configurations are indicated in Table 5.4, detailed results of the phases for each configuration are indicated in Table 5.1.

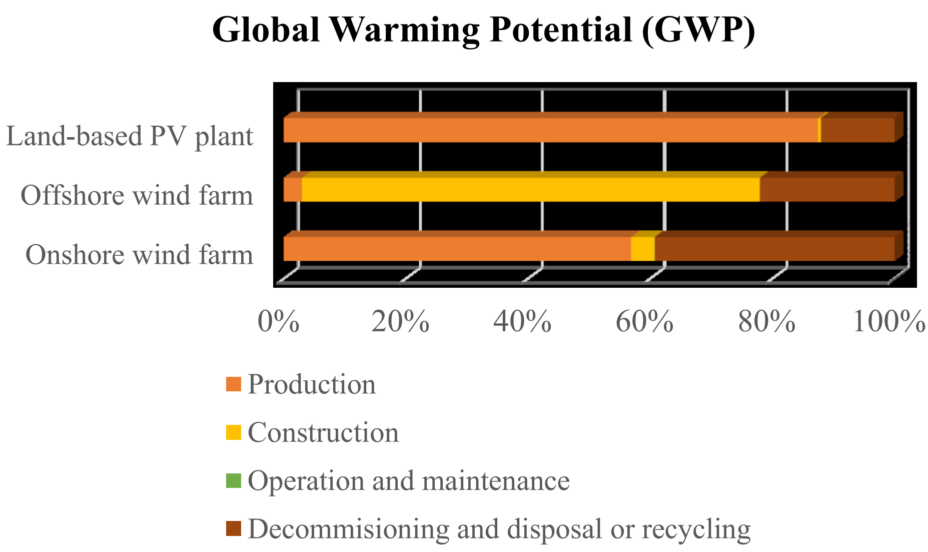

Figure 5.4 GWP of three configurations based on the LCA phases

Table 5.1 Global warming potential of each configuration based on the phases [kg CO_2-eq./MWh]

	Land-based PV plant	*Onshore wind farm*	*Offshore wind farm*
Production	16.0291	6.0102	0.2256
Construction	0.0854	0.4077	5.7367
Operation and maintenance	0.0028	0.0062	0.0004
Decommissioning and disposal or recycling	2.2130	4.1554	1.6911

5.1.1 Interpretation of the life cycle assessments (LCA)

The purpose of this section is the benchmarking for the results of the present study and comment on the reasons for discrepancies between the present study's results and the results in the literature. Following this, onshore wind farm for the comparison with the literature, the results of offshore wind farm results as well as offshore wind farm results which are drawn from the present thesis are compared with the results found in the literature. As the last comparison with the literature, the results of the PV plant of this study is presented. In order to conclude the section, all results of the present study are compared with the results in a review article (Asdrubali et al., 2015) to make a more comprehensive comparison with the literature.

It can be suggested that Bozcaada Island is more appropriate site than Pınarbaşı-Kayseri region (Demir & Taşkin, 2013) for the onshore deployment of wind technology since wind velocity and wind potential of Bozcaada Island according to wind potential investigations (Dündar & Inan, 1996; Ilkiliç & Aydin, 2015; Türksoy, 1995) in Turkey is higher than Pınarbaşı-Kayseri region. According to the findings of the present study, onshore wind farm in Bozcaada is found to be more environmental-friendly than the counterpart in the Pınarbaşı-Kayseri region in terms of GWP, EP and EPBT as expected. Total GWP is 10.64 kg CO_2/ MWh for this study whereas the best result of the study (Demir & Taşkin, 2013) is 16.27 kg CO_2/ MWh. In the case of eutrophication potential, the range of the research is 0.00539-0.01269 kg PO_4^{-3}/MWh. The eutrophication of the present study is 0.00651 kg PO_4^{-3}/MWh. Energy pay-back time is found as 7,4 months for the present study, and it is lower than the best results found in Pınarbaşı-Kayseri region whose EPBT is 14.6 months. However, the acidification potential of onshore deployment in the present study is 0.01545 kg SO_2/MWh while the best result of the mentioned research is 0.05779 kg SO_2/MWh. In other words, the result of the acidification potential is deviated from the result of the research carried out by Demir and Taşkın. The comments on this discrepancy between the results noted here can be found in the following paragraph.

As the tower height increases for the onshore deployments with direct-drive mechanism turbines, the decrease in the greenhouse gas emissions is more dramatical than the decrease in energy pay-back time. The results of GWP and EPBT from the study (Bonou et al., 2016) for a direct-drive turbine having 92.5 m tower height are given as 5.0 kg CO_2-eq./MWh and 5.2 months, respectively (see also Table 2.1). On the other hand, GWP and EPBT results of the present study having 44 m tower height are found as 10.64 kg CO_2-eq./MWh and 7.4 months, respectively. The height increase of the tower causes a dramatic decrease in the greenhouse gas emissions while it leads to a relatively significant decrease in energy pay-back time for onshore deployments utilizing direct-drive mechanisms as indicated in Table 5.2.

In the case of offshore deployments having geared turbine, the relation mentioned previous paragraph occurs oppositely. As seen in Table 5.2, EPBT and GWP of the present study having 94 m tower height and geared turbine are found as 5.3 months and 7.65 kg CO_2-eq./MWh, respectively. 11.1 months for EPBT and 10.9 kg CO_2-eq./MWh for GWP are the results of the research (Bonou et al., 2016) (see also Table 2.1) for offshore deployment having 68.25 m tower height and geared turbine. That is, EPBT is affected more dramatically than GWP by the height increase of the tower for the geared turbine deployed as an offshore application.

Table 5.2 Results based on deployment locations, mechanisms and tower heights

Deployment[8]	*Tower height (m)*	*GWP (kg CO_2-eq./MWh)*	*EPBT (months)*
Onshore (this study)	44	10.64	7.4
Onshore (Bonou et al., 2016)	92.5	5.0	5.2
Change rate (%)	110.23	- 53.01	-29.73
Offshore (Bonou et al., 2016)	68.25	10.9	11.1
Offshore (this study)	94	7.65	5.3
Change rate (%)	37.73	- 29.82	- 52.25

In addition, GWP and EPBT results of the case study (Gomaa et al., 2019) for Tafilah wind farm under operation since 2015 are given as 9.11 kg CO_2 eq. /MWh and 0,69 years, respectively. As a remainder, this farm was established on a land where the average wind speed is 7-8 m/s with Vestas V112-3MW turbines, and tower height of the turbines is 119 m. When the results of the Gomaa's study (2019) and the results of offshore wind deployment for the present study seen in Table 5.2 are compared, it can be suggested that increase in the tower height in order to reach higher wind potential has a limited effect in order to decrease greenhouse gas emissions. Hence, an optimum point for the tower weight of a configuration should be determined carefully not only having higher wind velocity but also avoiding the worst effect of the increase in the tower materials prior to make an investment.

For the another benchmarking of offshore deployment results, GWP impact of offshore wind farm for this study is assessed with another evaluation indices, TRACI 2. The results are compared with the results of the study (Liang Tsai et al., 2016) that focuses on the sitting effects of an offshore wind farm by carrying out LCA. The reevaluated results of the present study with TRACI 2 impact assessment method are calculated as 7.64 kg CO_2-eq./MWh. Hence, it is seen that there are no significant

[8] Onshore deployments have direct-drive turbines while offshore deployments have geared turbines.

differences between the results of TRACI 2 and CML 2001-Jan 2016 impact assessment methods (see Table 5.2 or Table 5.4 for the present results with CML 2001-Jan 2016) for the evaluation of greenhouse gas emissions (GHGs). Comparison in terms of GWP is now possible between the results of the research (Liang Tsai et al., 2016) and the results of present study. Results for 20 different cases are listed in the thesis (Liang Tsai et al., 2016) in order to observe the sitting effects such as locational factors, lake depth, and distance from shore. Selecting the appropriate one out of 20 cases is necessary for the comparison with this study's results; thus, the results of the Berrien County's second case is selected. Its system characteristics are similar to the features of offshore wind configuration in the present study as demonstrated in Table 5.3. In addition, same turbine model, Vestas V-112 3 MW, is used in both cases. As seen in Table 5.3, the major differences between the two cases arise from cabling due to number of turbines and forecast of total electricity generation. In order to eliminate the effects of vastly between different total electricity production estimations, which are 7.88 GWh for Berrien County and 14 GWh for the offshore configuration in the present study, it is assumed that the turbines in Berrien County produce 14 GWh/year annually like the offshore wind farm case, and the GWP results related with this assumption are summarized in Table 5.3 for better understanding the procedure of the elimination of different predictions for the total electricity generation.

As seen in Table 5.3, there is still a huge difference between the GWP results even though the annual electricity production are assumed to be equal for both cases. The reasons of this difference can be regarded as cabling and distinctions in the modelling of construction phase for the offshore wind farm compared to the selected case of Berrien County. The former reason can be explained by the total cable length since higher number of turbines in Berrien County case requires extremely higher cabling than the offshore deployment case of the present study. That is, the total cabling is 94 km for the Berrien County case while the offshore deployment needs only 20 km cables as indicated in Table 5.3. Hence, it can be claimed that the cabling due to the increase in the number of turbines leads to an increase in the greenhouse gas emissions (GHGs) contrary to the expectation of the decrease in the global warming potential with the increase in the number of turbines. From this point of view, the number of turbines should be carefully determined prior to the investment in order to avoid the unfavorable impacts of excessive cabling. The latter reason why the result of GWP for the offshore deployment of the present study is lower than the case of Berrien County is the differences during the modelling, especially during the modelling of construction phase. There are two main distinctions between the construction phase modelling of the Berrien County and present research cases. The first one is the assumption that no substations are needed as demonstrated in Table 5.3. This is, Berrien County case requires a substation owing to its higher nominal power than 120 MW (Güzel, 2012; Huang et al., 2017). However, there is no need to build a substation for the case of offshore deployment during the modelling procedure. The impact of substation occurs especially from the onset of production phase to the end of construction phase. Hence, it is claimed that the second reason of the differences between the GWP results is the limitation in GaBi faced during the modelling of the offshore deployment. As mentioned before, only excavator and ship could be used as the required transportation equipment in the model of offshore deployment. However, the jack-up boat and tugboat as well as truck (Liang Tsai et al., 2016) are utilized in the construction phase of Berrien County case since it is modelled by another LCA software which is SimaPro 7.0. In other words, the second reason of the distinctions between the GWP results of the cases can be derived from the differences between the database of the distinct LCA software. To sum up, the discrepancies of the GWP results between the Berrien County and the present thesis comes from the number of turbines- namely, the need of cabling- and the modelling procedures.

Table 5.3 Comparison with study (Liang Tsai et al., 2016)

Cases *System properties and GWP results*	*Berrien County Case*	*Offshore Wind Farm*
Number of turbines	100	3
Nominal power of the farm (MW)	300	9
Shore Distance (km)	10	10
Water Depth (m)	30	30
Tower weight (m)	100	94
Internal cables (km)	80.92	1.12
Submarine cables (km)	10	10
Transmission cables on the land (km)	3	9
Total cabling (km)	93.92	20.12
Substation	Yes	No
Annual electricty production per turbine [GWh/year]	7.88	14.00
GWP [kg CO_2/MWh] (with their own assumptions)	27.98	7.64
GWP [kg CO_2/MWh] (14 GWh/year per turbine)	15.75	7.64

In case of benchmarking of the open-ground grid tied system, there are many significant differences during the modeling with the most similar study (Desideri et al., 2012) to present analysis. In order to make a comment, some of them are listed as follows:

- Site clearance was neglected in the present study. However, Desideri and his colleagues (2012) considered it in their research.
- In the construction phase, only truck was utilized to carry the materials in this thesis. However, they used excavator for the excavation process (Desideri et al., 2012) in order to prepare the land for the installation of the PV plant.
- Lifespan is assumed as 25 years in their research. However, useful life is considered as 30 years in the present study.

From the items listed above, it can be claimed that LCIA results are highly sensitive to the system boundaries such as land preparation and initial assumptions such as lifetime in case of LCA of PV systems.

The more comprehensive benchmarking than previous ones is made by the review article (Asdrubali et al., 2015) and results are tabulated as Table 5.4. The results deviated from the present study are indicated as italic style, and the reasons of the deviations are examined while the results of the review article are highlighted with the bold style.

Table 5.4 Comparison with the review (Asdrubali et al., 2015)

	Land-Based PV Plant	***PV Systems***	***Wind Systems***	*Onshore Wind Farm*	*Offshore Wind Farm*
AP [kg SO_2eq/MWh]	0.0982	0.0787-0.9797	0.0280-0.1152	*0.0155*	*0.0180*
EP [kg PO_4^{-3}eq/MWh]	0.0079	0.0040-0.0925	0.0027-0.0122	0.0065	0.0042
GWP [kg CO_2eq/MWh]	18.3	9.4-167.0	6.2-46.0	10.6	7.7
EPBT [months]	24.4	9.6-43.9	2.4-27.5	7.4	6.9
CED [MJ/MWh]	*234.5*	360-1800	10-1200	105.0	97.0

There are three deviated results as seen in Table 5.4. The first one is the acidification potential of the onshore wind farm, and the second one is the acidification potential of the offshore wind farm. In other words, acidification potentials of wind configurations are deviated. The main reasons for these deviations can be explained by the utilization of only excavator for the transportation on the land instead of crane or lifter and usage of only ferry for the transportation on the sea instead of the utilization of tug-boat, jack-up and ferry together in the model of construction phases. As mentioned before, the usage of the excavator for the transportation on the land and the modelling of the transportation on the sea by only ferry are caused by the limitation of GaBi Education version. However, it is known that fossil fuels, required to operate heavy machinery used in this study for the assembly process, should have led to raise the acidification (Cardoso et al., 2009). This is, the deviations of the acidification results of the wind configurations derive from the limitation of GaBi. This notion is also supported with the comparison made by the LCA study of the onshore wind system in Turkey (Demir & Taşkin, 2013) mentioned in the second paragraph of this section. While other impacts of the present study except for AP is in the ranges found in that research (Demir & Taşkin, 2013), the result for acidification potential of the onshore wind configuration also deviated from the ranges determined for the wind farms in the mentioned study (Demir & Taşkin, 2013) due to the utilization of different versions of GaBi software for the modelling.

The third deviated result is the cumulative energy demand of the land-based grid connected PV system. The basic reason for this can be explained by the absence of site clearance in the modelling for the production phase of present onshore wind deployment.

To summarize, all results except for three of them mentioned above are in the range of the review article (Asdrubali et al., 2015).

5.2 Life cycle cost analysis (LCCA)

Life cycle cost items mentioned in the related chapter are listed in Table 5.5 for all configurations. The unit of all costs in Table 5.5 is $ except for LUCE. The unit of LUCE is $/MWh.

Table 5.5 List of the each cost items for all configurations

Cost Items	*Land-based PV plant*	*Onshore wind farm*	*Offshore wind farm*
$C_{panels/turbines}$	650,000.0	12,696,331.4	9,382,998.3
$C_{elec.}$	709,502.0	10,768,314.0	13,885,641.2
$C_{inf.}$	743,682.0	271,638.0	20,693,864.3
C_{tr1}	1,185.1	98,263.0	483,857.7
$C_{inv.}$	2,104,369.1	23,838,415.9	44,446,361.5
C_{M}	712,024.7	106,786.6	5,008,292.1
C_{tr2}	1,623.5	237.8	321.6
$C_{O\&M}$	713,648.2	107,024.4	5,008,613.7
$C_{tr3} = C_{DorR}$	8,742.0	7,530.0	101,052.2
C_{tr}	11,550.5	106,030.8	585,231.5
LCC	2,826,759.2	23,952,970.3	49,556,027.4
LUCE	54.0	35.2	59.0

While the initial investment cost of the land-based PV plant is cheaper than other two alternatives, levelized electricity production cost-LUCE- gives the best result for onshore wind farm as shown in Table 5.5. The comparison between offshore wind farm and land-based PV plant indicates that land-based PV plant is more promising technology for the island than offshore wind farm in terms of economic aspects. The percentages of cost items, including their own transportation expenses, are shown in Table 5.6 for the all configurations. Initial investment costs have the highest ratio for all configurations. The initial allocation strategy of spare parts is the reason why the ratios of land-based PV plant cost is distributed more evenly compared to wind configurations. In order to explain the differences of the cost items in the wind configurations, further analysis is required. For this purpose, the cost breakdowns of the initial cost investments are shown in Figure 5.5.

Initial investment cost of the onshore wind farm is found as $ 23,838,415.9 while it is $ 44,446,361.4 for offshore wind farm, and the cost breakdown of initial investment costs for each configuration is indicated in Figure 5.5. Transportation costs of every items are added to their own material costs to obtain the total costs in Figure 5.5. As seen in Figure 5.5, the highest cost item is the cost of infrastructure- namely the monopile- for the offshore configuration whereas the cost of turbines has the highest ratio in the case of onshore wind farm. From this point of view, the installation of the offshore configuration is more expensive than onshore deployment due to expensive installation equipment not the turbines. In other words, the infrastructure and electrical equipment for the offshore deployment should be developed for the cost-efficient options rather than the decreasing the offshore turbine costs.

Table 5.6 Percentages of the costs for all configurations

Cost Items *Configuration types*	*Initial investment costs*	*Operation and maintenance costs*	*Decommissioning and disposal or recycling costs*
Land-based PV plant	74.44 %	25.25 %	0.31 %
Onshore wind farm	99.52 %	0.45 %	0.03 %
Offshore wind farm	89.69 %	10.11 %	0.21 %

Operation and maintenance procedure costs are $ 107,024.4 and $ 5,008,613.7 for onshore and offshore wind farms, respectively. In addition, the ratios of transportation costs over material costs for the procedure are 0.223 % and 0.006 % for onshore and offshore wind farms, respectively. In other words, the material costs of the offshore wind farm are considerably higher than the material costs of the onshore wind farm, and it can be explained by the spare parts assumptions.

According to these assumptions, 15 % replacement of generator and gearbox and usage of 15,570 kg lubrication are assumed in the life cycle assessment of offshore configurations owing to the geared technology. Whereas, the required lubrication as 3,400 kg and the replacement of 1% of all moving parts are assumed for onshore configuration having direct-drive mechanism.

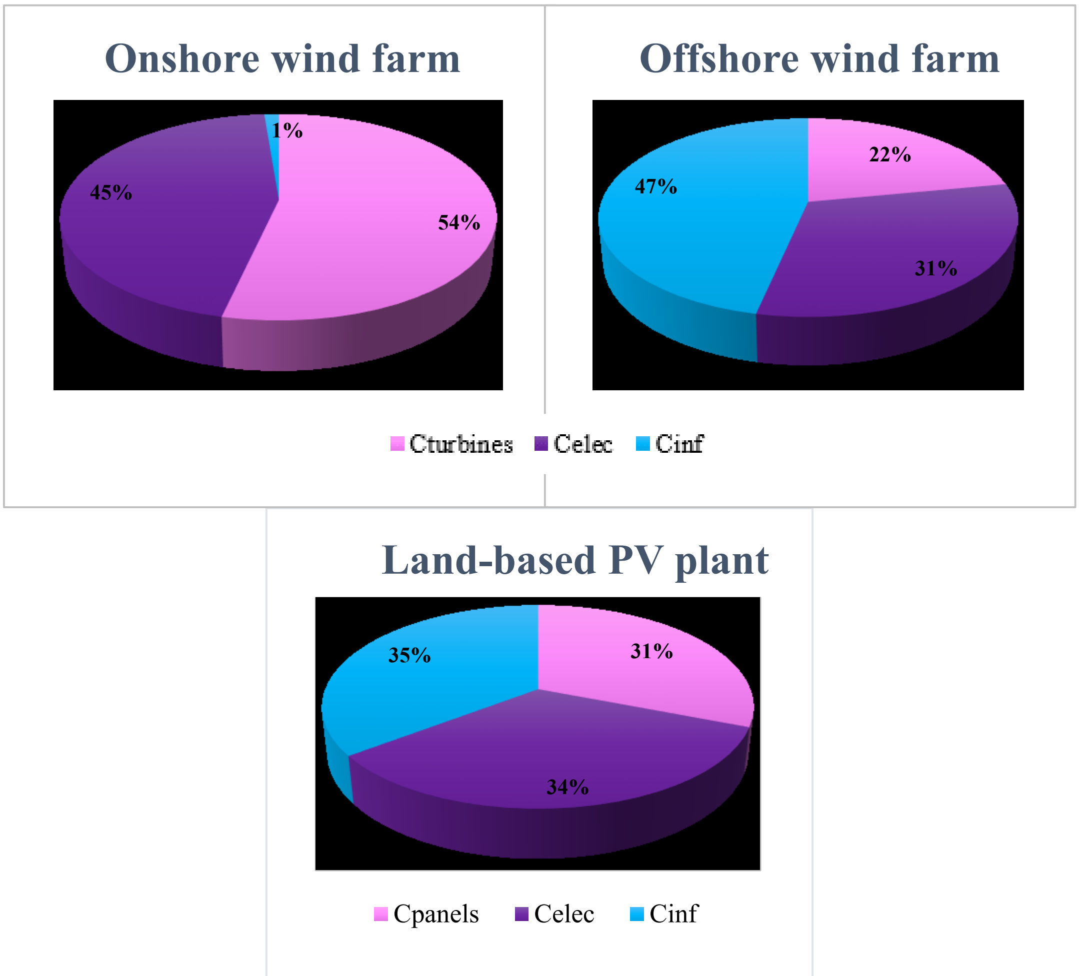

Figure 5.5 The cost breakdown of initial investment costs for all configurations

In case of disposal and recycling costs, transportation and decommissioning costs are taken into consideration for both configurations as indicated in equation (6). The costs of disposal and recycling for onshore wind farm is $ 7,530.0 while the disposal and recycling phase of offshore wind farm costs $ 101,052.2. It can be explained that the higher total weights of scrap materials and the requirement of ferry transportation leads to higher costs in the fourth phase of offshore wind farm than the costs occurred in the last phase of onshore wind farm.

In case of the grid-tied open ground PV system, cost items of the initial investment are almost equally distributed as seen in Figure 5.5.

Operation and maintenance phase needs more planned consideration in terms of investors in case of land-based PV plant since the replacement and, in due, procurement of the spare parts are required in the maintenance procedure.

Although solar panels are delivered to the recycling plant in the decommissioning and disposal or recycling phase, the expenses are relatively cheaper since the weights of the materials and parts of the solar configuration is generally lower than the materials and parts of the wind configurations.

5.2.1 Benchmarking of the costs

For benchmarking of the life cycle cost calculations, firstly, the same procedure aforementioned in the section 3.2.2 is applied to calculate only the initial investment cost without the transportation expenses for the established onshore wind farm in 2000. The initial investment cost of the onshore wind farm is calculated as $ 11,417,765.0 in June 2000. The cost of the onshore wind farm is declared as approximately $ 13,000,000.0 as mentioned in the thesis (Koçaslan, 2006) and in the website of operating company indicated with the screenshot (Demirer Holding A.Ş., 2019) in Appendix A. When the excluded costs, which involve costs of project development stage and labor costs during the calculation strategy, are considered together with the excluded transportation expenses, the estimation of the initial investment costs can be considered as acceptable.

For benchmarking of the offshore cost calculations, as the second part of this section, the research about CAPEX model of the European offshore wind farm (Vieira et al., 2019) and its data set amassed from the website (4C Offshore Ltd., 2018) are utilized. By filtering the related parameters in order to reach the closest case to the offshore deployment of the present study, the cost of Rampion offshore wind farm is examined in detail. The reason of this selection is due to the fact that its shore distance is 13 km, and that its average water depth for the deployments of the wind turbines is 29.5 m. The investment cost of the Rampion offshore wind farm with Vestas V 112-3.45 turbine models is found as € 1900 million for 400,2 MW nominal capacity. Following the exchange between the currencies with the rate of January 2019, its cost is inflated with the European price indices (OECD, 2019) in order to obtain the cost of Rampion offshore wind farm in 2019. The cost of Rampion Offshore Wind Farm per MW is $ 5,586,413.20 while the cost of offshore configuration of the present study is $ 4,938,484.61 per MW. In other words, the initial investment cost of offshore deployment of this study per turbine is $ 14,815,453.83 whereas the reference case cost is calculated as $ 19,273,125.56 per turbine (Vieira et al., 2019). When the exclusions of the project design cost and the labor cost in the construction phase during the calculation of the investment cost of the offshore deployment considered in this study, it is claimed that the difference between the reference case cost and the offshore wind farm cost of this study are caused by the system boundaries applied for the cost calculation procedure.

The last part of this section is the benchmarking of the PV plant costs. In case of open ground on-grid photovoltaic system, the cost is abstained to be validated since there is no consensus about the basic features of the land based grid connected PV systems, even in the land use requirement of a conventional PV plant, around the world as mentioned in the second paragraph of 4.3.1.1 section.

In order to make a more comprehensive comments on the costs of the configurations, the definition of LCoE concept and the results of LCoE found in the literature should be reminded here. LCoE is levelized cost of electricity which means that the unit cost of the electricity from a power plant. It is worth to note that LCoE generally includes more costs items than the costs considered in this study. For example, LCoEs in the thesis (Yılan, 2018) include even CO_2 emissions costs, and LCoEs of onshore wind farm and PV plant are given as 73 $/MWh and 160 $/MWh, respectively. According to Cali and his colleagues (2018), LCoEs of offshore wind farm located in Bozcaada range between $/MWh 81,85 and $/MWh 109,55 although it is found as € 91.03/MWh in another study (Satir et al., 2018). With the aid of the calculation procedure explained in chapter 3, the costs for the configurations of this study are calculated as 54,0 $/MWh for PV plant, 35,2 $/MWh for onshore wind farm and 59,00 $/MWh for offshore wind farm (see Table 5.5). As narrated in chapter 3, the calculation procedure used LUCE definition and some assumptions whose main purpose are the coupling of LCA and LCC. With this in mind, the costs obtained via equation improved for LUCE should be lower than the costs calculated by means of LCoE concept. As expected, the costs for each configuration are lower than the costs calculated with the aid of LCoE, which are found in the literature. This is, all costs calculated in the present study are in the safe region according to the related literature results (Cali et al., 2018; Satir et al., 2018; Yılan, 2018).

CHAPTER 6

CONCLUSION AND FUTURE DIRECTIONS

6.1 Conclusion

The thesis is aimed to determine the most environmental-friendly and the most economical alternative in order to produce electricity in Bozcaada by evaluating the wind and solar potential of the island. During the life cycle assessment, cradle-to-grave approach is carried out. In case of life cycle cost calculation, the cost of material and the cost of material flow- namely, transportation and assembly procedures- are focused on in order to couple the life cycle cost with the life cycle assessment. As a result of the analysis of three distinct configurations by means of LCA and LCC, onshore wind farm, the already existing case, is the most economic option in order to generate 1 MWh electricity in the island –followed by the PV and offshore wind system, respectively. On the other hand, the offshore wind farm demonstrates the best trend in terms of environmental aspects apart from the acidification potential. That is, the onshore wind farm has less acidification potential than the proposed offshore wind farm for the island. The open ground grid connected photovoltaic plant is less expensive than the offshore wind farm although offshore wind farm is less harmful to the island's environment than suggested PV system as well as the onshore wind farm already in operation.

Although the results of the present study indicate that the evaluation of wind source for Bozcaada's electricity generation is more advantageous than the assessment of the island's solar potential by a photovoltaic plant as in the Canadian case (Schmidt et al., 2017) in terms of environmental features, there is still a requirement to carry out further investigations. In other words, further research is needed in order to state whether or not the making use of solar source by means of photovoltaic systems are more harmful to the environment than wind and/or any other renewable sources as well as other configurations utilized solar source such as solar thermal systems and floating PV plant.

Last phase of onshore wind farm and land-based grid connected PV plant lead to significant greenhouse gas emissions. Thus, it should be considered in detail before the installation of the plants. In other words, the transportation of waste materials is planned during the project design step. Furthermore, the recycling technologies for solar cells and the recycling of composite materials utilized for the manufacturing of wind turbine blades have not been improved yet. Research on the recycling technologies in both wind and PV systems should be increased in order to reduce negative impacts of their production phase on the environment. In the case of offshore wind farm, the construction is the most detrimental phase to the environment among other phases although there were limitations about its modelling. In fact, it would have led to higher impacts than the impacts determined in the end of analysis carried out for this thesis. Hence, strategies for the construction phase of an offshore wind deployment should be investigated further in order to find cleaner ways for that.

6.2 Future directions

Throughout the thesis work, the useful lives are considered as 20 years for wind configurations, and 30 years for photovoltaic configurations as suggested in the literature. As one of the future directions of the study, all configurations should be assessed for the same lifespan, for example 60 years, with the aid of sensitivity analysis for better recognition of the economic and environmental impacts of the investments utilizing the renewable sources of Bozcaada Island. Furthermore, evaluation of the island's other potentials such as wave energy or other configuration types for the island's solar potential like floating photovoltaic plant should be evaluated with the aid of LCA and LCC methodologies for the future research in order to be able to determine the most environmental-friendly and/or the cost-efficient technology for the production of electricity in Bozcaada.

The need for risk assessment of an energy production system is inevitable as well as assessment of environmental and economical aspects in order to determine the most sustainable alternative. Hence, the risk assessment of the systems such as the possibilities of incidents throughout their lifespan should be considered in order to make comprehensive evaluation for the energy production systems throughout their lifespan.

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APPENDICES

A. Declaration of the operating company

BORES BOZCAADA RÜZGAR ENERJİ SANTRALI SAN. VE TİC. A.Ş.

Türkiye'nin 3.ncü, Demirer Holding A.Ş.'nin 2.nci Rüzgar Enerji Santralı olan Bozcaada Rüzgar Enerji Santralı'nın rüzgar ölçüm direği 1996'da dikilmiştir. 1998 yılında fizibilite çalışmalarına başlanan proje, gerekli yasal izinler tamamlandıktan sonra 3 ayda bitirilmiş ve Haziran 2000'de hayata geçirilmiştir.

Bozcaada Rüzgar Enerji Santralı 17 adet türbinden oluşmakta ve yılda 35 milyon kilovat saat elektrik üretmektedir. Kurulu gücü 10.2 MW olan santral, 13 Milyon USD'na mal olmuştur. Santral, adanın enerji ihtiyacının 30 kat fazlasını Çanakkale'ye iletmekte ve böylece yaklaşık 30.000 kişinin elektrik ihtiyacını karşılamaktadır.

Bu santral için Bozcaada'nın tarım ve hayvancılığa müsait olmayan en ücra köşesi, adanın sakinliği düşünülerek dünyanın en sessiz çalışan türbin modeli seçilmiştir. Proje hazırlanırken estetik hususlar gözönüne alınarak kafes kuleler yerine konik silindir kuleler kullanılmıştır. Ayrıca bu kuleler yurt dışından getirilmek yerine ülkemizde üretilmiştir. Doğal güzelliği korumak amacıyla, üretilen elektrik dağıtım merkezine havai hat yerine daha pahalı olan yeraltı kablosu ile iletilmiştir.

Santralı ziyaret edenlerin görüşlerini yazabilecekleri bir ziyaretçi defteri tutarak bu çabalarımızın nasıl değerlendirildiğini tesbit etmeye çalışıyoruz. Bu konudaki görüşler bize daha iyilerini yapmak için güç veriyor.

Yap-İşlet-Devret Statüsünde kurulan ve ülkemizin yenilenebilir enerji kaynaklarını değerlendiren bu proje 20 yıl sonra Enerji ve Tabii Kaynaklar Bakanlığı'na bedelsiz devredilecektir.

B. Initial investment cost at June 2000 with the exclusion of transportation expenses

Cost item	*Year (Found)*	*Cost (Found) [$]*	*Cost at 2000 (June) [$]*
$C_{turbines}$	2006	11.172.280	10.471.708
C_{inf}	2015	170.904	23.278
C_{elec}	2015	6.775.000	922.779

Without transportation expenses, initial investment cost is represented as follow:

$C_{Winv.} = C_{turbines} + C_{Winf} + C_{Welec.}$

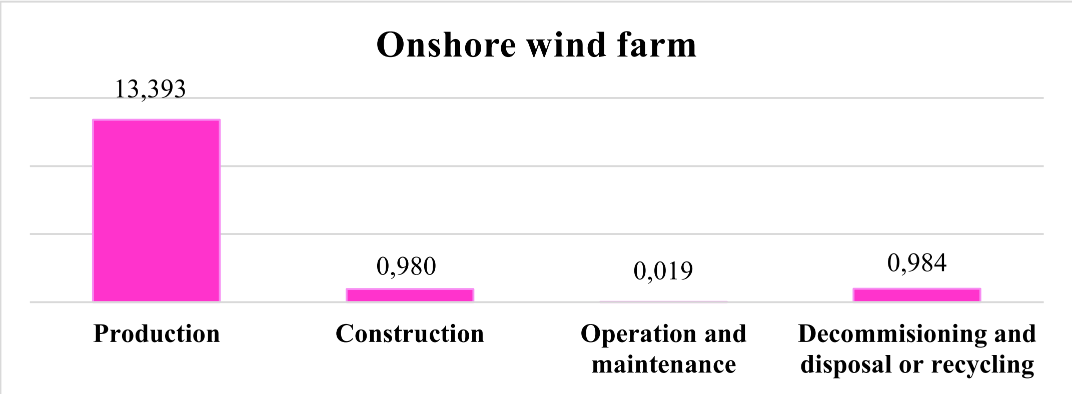
For June 2000,

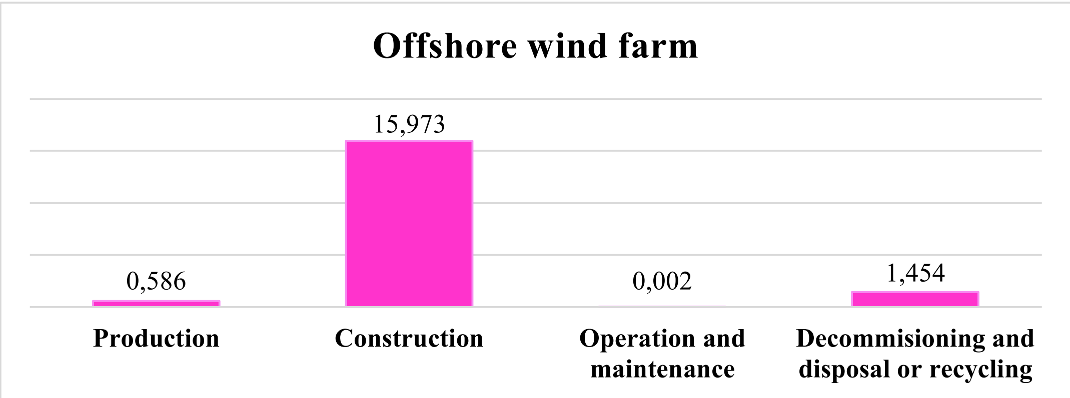
$C_{Winv.} = 10.471.708 + 23.278 + 922.779$

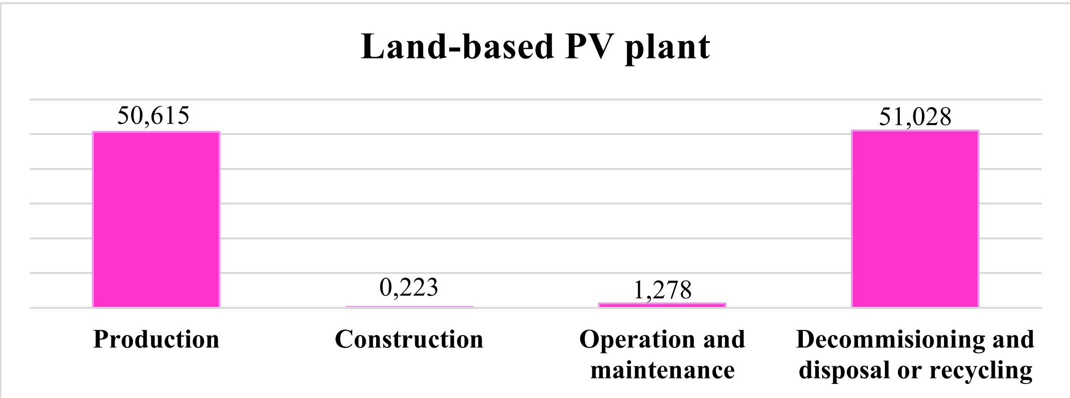
$C_{Winv.} = \$ 11.417.765$

C. Acidification potential (AP)

All units are given as kg SO_2-eq./GWh.





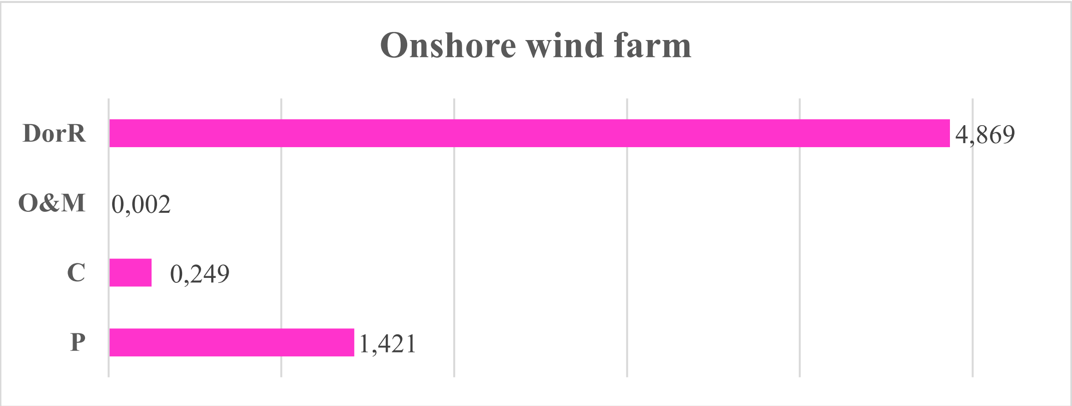


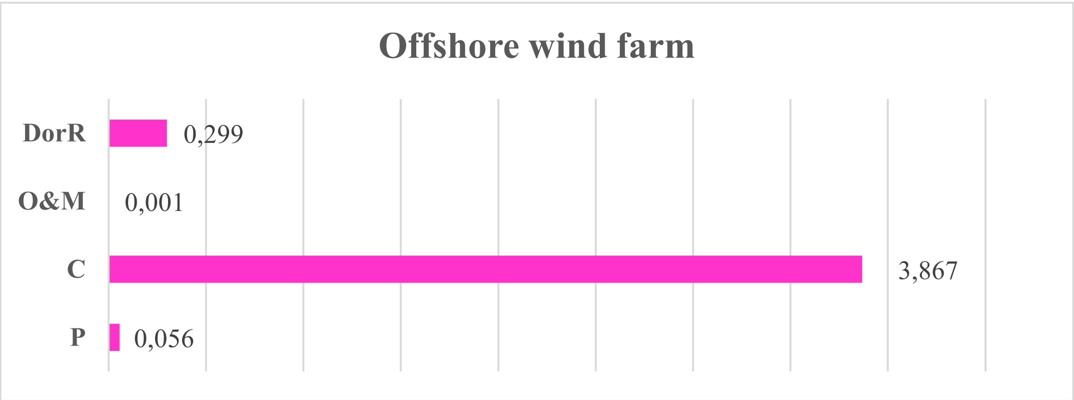
The unit process of aluminum ingot mix in the modelling of the production phase of onshore wind farm is the basic reason for the highest acidification level than other phases of onshore wind farm.

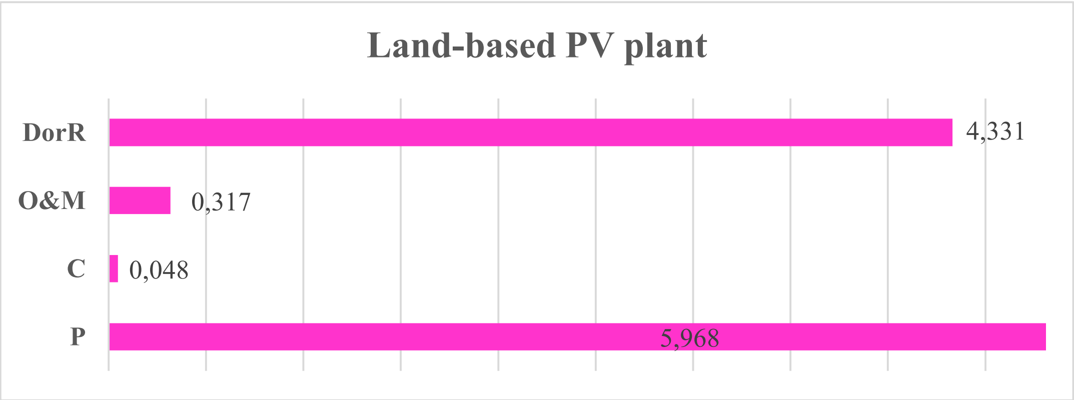
The production phase of the open ground grid tied PV plant cause the highest acidification since it needs extensive energy from distinct sources like thermal energy and electricity. In other words, the processes of energy need which are electricity and thermal energy as well as the unit process of float flat glass are the major contributors of the acidification of its production phase. Furthermore, disposal or recycling phase of the land based grid connected PV plant leads to a high acidification level because it requires fuel for transportation of scrap solar panels. This is, the high acidification share of the disposal and decommissioning phase is the transportation of scrap materials to recycling plant by airline.

D. Eutrophication potential (EP)

All units are given as kg PO_4^{-3} eq./GWh.







The highest level for the eutrophication for the onshore wind farm occurs in the decommissioning and disposal or recycling phase. The main reason is the unit process of municipal solid waste on landfill since foundations and roads have left on the construction site while modelling this phase. Although there is a dominant cause for the eutrophication in the decommissioning and disposal phase of onshore wind farm, there is no specific unit process which is the main reason for the eutrophication in the production phase of onshore wind farm. This is, the distribution of the eutrophication of the unit processes in the production phase of the onshore wind farm occurs almost equally when examined in detail.

In the case of open ground grid connected PV plant, the manufacturing processes of the multi-Si wafer, the unit process of float flat glass are the main contributor as well as the energy needs of the processes for the high eutrophication level observed in the production phase of the system. However, the cargo plane utilized for the transfer of the scrap solar panels to the recycling plant is the basic source of the high eutrophication level faced in the decommissioning and disposal or recycling phase of the plant similar to the trend occurred in the case of high acidification level of the PV plant's last phase.

E. Cumulative Energy Demand (CED)

All units are given as MJ/MWh. Cumulative energy demands for the configurations based on the phases are shown.

	Land-based PV plant	*Onshore wind farm*	*Offshore wind farm*
Production	203,7367	100,0291	5,6088
Construction	1,1390	6,2496	88,3580
Operation and maintenance	0,0249	0,2956	0,0054
Decommissioning and disposal or recycling	29,6316	4,4554	10,0183

CURRICULUM VITAE

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EDUCATION

Degree	Institution	Year of Graduation
BS	Anadolu Uni. Business Administration	2013
BS	METU Mechanical Engineering	2012
High School	Ankara Science High School, Ankara	2007

WORK EXPERIENCE

Year	Place	Enrollment
2014-Present	T.C. Sağlık Bakanlığı, Ankara	Health Specialist
2013-2014	Öz-Ka Grup İnşaat Elekt.Gıd.Taah.San.Tic.Ltd.Şti., Ankara	Building Maintenance Officer
2013 March	Mitaş Cıvata, Ankara	Quality Control Engineer
2012 November	Beyçelik Gestamp Kalıp ve Oto Yan Sanayii Pazarlama ve Ticaret A.Ş., Bursa	Planning Engineer
2011 August	Bahadır Tıbbi Alet Cihaz ve İnşaat Makina Sanayi ve Ticaret A.Ş., Samsun	Intern Eng. Student
2010 August	Türk Traktör ve Ziraat Makineleri A.Ş., Ankara	Intern Eng. Student

FOREIGN LANGUAGES

Advanced English, Beginner Italian

PUBLICATIONS

1. Şentürk A. E. and Oğuz E. "Life cycle assessment of two different renewable energy systems for a selected region: Bozcaada island", Sustainable Development and Innovations in Marine Technologies Proceedings of the 18th International Congress of the Maritime Association of the Mediterranean (IMAM 2019), September 9-11, 2019, Varna, Bulgaria

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