# FEASIBILITY OF GÖKÇEKAYA PUMPED STORAGE HYDROPOWER PLANT AND METRİSTEPE WIND POWER PLANT

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**FEASIBILITY OF GÖKÇEKAYA PUMPED STORAGE HYDROPOWER PLANT AND METRİSTEPE WIND POWER PLANT**

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## ABSTRACT

### FEASIBILITY OF GÖKÇEKAYA PUMPED STORAGE HYDROPOWER PLANT AND METRİSTEPE WIND POWER PLANT

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Population increment, industrialization, and developments in technology cause increase in energy demand. In order to meet this demand, fossil fuels are used excessively despite being exhaustible and harmful to environment. It is necessary to decrease use of fossil fuels to meet energy need without causing burdens on environment. Thus, renewable energy sources such as wind, solar, biomass, and geothermal has been started to use significantly. From renewable energy sources wind energy has taken considerable attention to generate electricity due to being developed technology. Moreover, wind power plants (WPPs) are installed in many countries to benefit from clean source of electricity. Also, it is known that to meet increasing demand in peak hours energy storage has become crucial and many energy storage systems are utilized. Since environmental concerns have been risen over time, necessity of using environmentally friendly energy storage systems such as pumped storage hydropower (PSH) has been one of the major issues. In this dissertation, emissions of two environmentally friendly systems Gökçekaya PSH (not commissioned yet) and Metristepe WPP (commissioned) both located in Turkey are investigated and compared by using life cycle assessment (LCA) method. To carry out LCA studies, one of the most common software GaBi is used and CML impact categories are considered to evaluate emissions. In addition, to have comprehensive comparison of systems, cost of the systems are calculated and compared. Besides, whether these systems compensate their investments in 20 years lifetime or not is revealed.

Keywords: Life Cycle Assessment, Wind Energy, Pumped Storage Hydropower, Turkey, Cost

# ÖZ

## GÖKÇEKAYA POMPAJ DEPOLAMALI HİDROELEKTRİK SANTRALİ VE METRİSTEPE RÜZGAR SANTRALİNİN FİZİBİLİTESİ

Ağdoğan, Özge
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Nüfus artışı, endüstriyelleşme ve teknolojik gelişmeler enerji talebinin artmasına neden olmaktadır. Bu talebi karşılamak için, fosil yakıtlar tükenebilir ve çevreye zararlı olmasına rağmen aşırı derecede kullanılmaktadır. Enerji ihtiyacını çevreye yük olmayacak şekilde karşılayabilmek için fosil yakıtların kullanımının azaltılması gereklidir. Bu sebeple, rüzgar, güneş, biyokütle ve jeotermal gibi yenilenebilir enerji kaynakları önemli seviyede kullanılmaya başlanmıştır. Yenilenebilir enerji kaynakları içinden rüzgar enerjisi gelişmiş bir teknoloji olmasından dolayı fazla dikkat çekmiştir. Ek olarak, temiz elektrik enerjisi kaynağından yararlanmak için birçok ülkede rüzgar santralleri kurulmuştur. Ayrıca, enerji ihtiyacının yüksek olduğu zamanlarda artan ihtiyacı karşılamak için enerji depolamak önem kazanmıştır ve birçok enerji depolama sistemlerinden yararlanılmıştır. Pompaj Depolamalı Hidroelektrik Santraller gibi çevre dostu enerji depolama sistemleri kullanma ihtiyacı çevresel kaygıların artması nedeniyle önemli konulardan biri olmuştur. Bu tezde, Türkiye'de yer alan iki çevre dostu sistemin Gökçekaya Pompaj Depolamalı Hidroelektrik Santral (PHES- inşa edilmemiş) ve Metristepe Rüzgar Santralinin (RES- inşa edilmiş) emisyonları yaşam döngüsü analizi (YDA) metoduyla araştırılmış ve karşılaştırılmıştır. YDA çalışmaları için en yaygın yazılımlardan biri olan GaBi kullanılmış ve emisyonları değerlendirmek için CML etki kategorileri dikkate alınmıştır. Ek olarak, sistemlerin kapsamlı bir şekilde karşılaştırılması için maliyetleri hesaplanmış ve maliyetler karşılaştırılmıştır. Ayrıca, bu sistemlerin 20 yıllık ömründe yatırımlarını karşılayıp karşılamadığı açıklığa kavuşturulmuştur.

Anahtar Kelimeler: Yaşam Döngüsü Analizi, Rüzgar Enerjisi, Pompaj Depolamalı Hidroelektrik Santraller, Türkiye, Maliyet

To people passed away due to COVID-19

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ABBREVIATIONS

PSH: Pumped storage hydropower

WPP: Wind power plants

LCA: Life cycle assessment

CML: Centrum voor Milieuwetenschappen in Leiden

IPCC: International Panel on Climate Change

LCCA: Life cycle cost assessment

ISO: International Standardization Organization

MRI: Midwest Research Institute

REPA: Resource and Environmental Profile Analysis

EMPA: Swiss Federal Laboratories for Materials Testing and Research

SETAC: Society of Environmental Toxicity and Chemistry

GWP: Global Warming Potential

DOD: Department of Defense (in US)

IEC: International Electro technical Commission

NORSOK: The Competitive Standing of the Norwegian Offshore Sector

A-CAES: Adiabatic Compressed Air Energy Storage

C-CAES: Conventional Compressed Air Energy Storage

CAES: Compressed Air Energy Storage

PV: Photo Voltaic

USA: United States of America

NPP: Nuclear Power Plant

DSİ: General Directorate of State Hydraulic Work

EİE: Electric Power Resources Survey and Development Administration

JICA: Japan International Cooperation Agency

FA: Fly Ash

PEMFC: Proton Exchange Fuel Cell

LMSWTs: Locally Manufactured Small Wind Turbines

LMPHPs: Locally Manufactured Pico-Hydro Plants

DFIG: Doubly-Fed Induction Generator

DDSG: Direct Driven Synchronous Generator

DDPMSG: Direct Drive Permanent Magnet Synchronous Generator

WPHCIES: Wind Power-Hydrogen Coupled Integrated Energy System

LCOE: Levelized Cost of Energy

TLWT: Tension-Leg-Wind-Turbine

TLB: Tension-Leg-Buoy

VAWT: Vertical Axis Wind Turbine

HAWT: Horizontal Axis Wind Turbine

BC: Before Christ

AD: Anno Domini

IRENA: International Renewable Energy Agency

UK: United Kingdom

US: United States

FAETP: Freshwater Aquatic Eco Toxicity

EPBT: Energy Payback Time

FOWT: Floating Offshore Wind Turbine

LCIA: Life Cycle Impact Assessment

LCC: Life Cycle Cost

GHG: Green House Gas

## LIST OF SYMBOLS

SYMBOLS

$SO_x$: Sulphur Oxides

$NO_x$: Nitrogen Oxides

$NH_3$: Ammonia

HCl: Hydrochloric acid

$CO_2$: Carbon dioxide

N: Nitrogen

P: Phosphorus

$PO_4$: Phosphate

Sb: Antimony

UV lights: Ultraviolet lights

CFCs: Chlorofluorocarbons

HCFFs: Hidrochlorofluorocarbons

DCB: Dichlorobenzene

$C_2H_4$: Ethylene

CO: Carbon monoxide

$CH_4$: Methane

$SO_2$: Sulphur dioxide

NO: Nitrogen oxide

$NH_4$: Ammonium

PbAC: Advanced lead acid batteries

NaS: Sodium Sulphur batteries

Li-ion: Lithium-ion batteries

NaNiCI: Nickel-sodium-chloride batteries

m: Meter

$m^2$: Square meter

$m^3$: Cubic meter

MWh: Megawatt hour

MW: Megawatt

kWh: Kilowatt hour

kWh/kg: Kilowatt hour/ kilogram

kWh/year: Kilowatt hour/ year

MJ: Mega Joule

$C_{total}$: Total Cost

$C_{initial\ material}$: Initial Material Cost

$C_{O\&M}$: Operation and Maintenance Cost

$C_{tr}$: Transportation Cost

$C_{EoL}$: End of Life Cost

$Q_{pump}$: Pump Discharge

$H_{pump}$: Head of Pump

$M_{euro}$: Million Euro

P: Power

H: Head

$C_1$: First cost value

$C_2$: Second cost value

$S_1$: First power value

$S_2$: Second power value

n: Number of years

$d_{real}$: discount rate

a: inflation rate

i: interest rate

km: Kilometer

ton-km: Ton-kilometer

$: Dollar

€: Euro

R: Rotor Radius

$P_r$: Turbine Rated Power

H: Hub height

$EI_t$: Environmental Impact

$\epsilon_e$: Amount of pollutant in given span

$N_e$: Normalization Factor

EoL: End of Life

# CHAPTER 1

# INTRODUCTION

## 1.1 General

Energy is one of the most important factors that affect modern life in today's world. Energy demand increases significantly depending on population growth and it is challenging to supply required energy in peak hours. When numerical values are considered, it is expected that world population will reach 8.3 billion in 2030 and energy demand will increase about 40 percent (Lloyd's Register, QineticQ, & University of Strathclyde Glasgow, 2013). As energy source fossil fuels such as coal, natural gas have been used from past to present. Since fossil fuels are both exhaustible and harmful to environment, renewable energy such as wind, solar, biomass, and geothermal are started to use in a considerable extend. Although use of renewable energy increases, according to IPCC (Intergovernmental Panel on Climate Change, 2011) only 13 percent of energy demand meet by renewable energy. Therefore, use of renewable energy sources have to be maximized due to being inexhaustible and environmentally friendly. From renewable energy sources, wind energy has been developed rapidly such that in 2009, 1.8 percent of electricity demand in world met by wind and it is predicted that in 2050, 20 percent of electricity demand in the world will be met by wind (Intergovernmental Panel on Climate Change, 2011). To generate electricity using wind potential, installation of wind power plants (WPPs) has been practiced all over the world. Also, to meeting energy demand, storage is an effective solution and environmentally friendly energy storage systems for instance pumped storage hydropower (PSH) plant can be utilized to achieve it. In order to mitigate effects of climate change and decrease burdens on environment, wind power plants can be used to generate electricity and pumped storage hydropower can be used to store energy. Thus, in this thesis Gökçekaya PSH (not commissioned yet) and Metristepe WPP (commissioned in 2011) both located in Turkey are investigated to compare emissions of systems using life cycle assessment (LCA) method. In LCA method, emissions from production phase to decommissioning phase are considered (from cradle to grave) to identify emissions throughout life time. In addition, to compare these two systems comprehensively, cost analysis is carried out using life cycle cost assessment (LCCA) method.

## 1.2 Scope of the Thesis

In this thesis, aim is to find and compare environmental burdens of Gökçekaya PSH and Metristepe WPP using LCA method. To our knowledge, in literature despite comparing many systems using LCA method, comparison of PSH and WPP has not been practiced yet. Comparing PSH and WPP is crucial because effects of wind power intermittency can be mitigated using PSH to store energy. Intermittency of wind power can cause blackouts and PSH can be a solution to this problem due to having advantage of storing energy when wind is available and electricity is cheap (at off-peak hours). After that, stored electricity can be used to meet demand in peak hours (when electricity is expensive) or when wind does not blow. Since hybrid WPP-PSH system has not been practiced yet in Turkey and due to not having study related to site selection to construct hybrid PSH-WPP system, separate but close PSH and WPP systems are investigated. In this way, it is possible to compare and have an insight about possible environmental effects of PSH and WPP systems in Turkey. For this purpose, a proposed PSH (Gökçekaya PSH) and a commissioned WPP (Metristepe WPP which is the closest WPP to Gökçekaya PSH) are selected to investigate environmental burdens of these two systems. Also, it is known that due to not being commissioned yet, in literature LCA study related to Gökçekaya PSH has not been carried out up to the present. To give an insight about environmental burdens of Gökçekaya PSH, before construction of the system LCA study should be carried out. This will provide an opportunuity to change processes that cause environmental pollution with more environmentally-friendly processes before its construction. Due to abovementioned reasons, in this thesis Gökçekaya PSH and Metristepe WPP are investigated using LCA method and their emissions to environment are found. Moreover, when emissions are compared it is found that Metristepe WPP is more environmentally friendly compared to Gökçekaya PSH. In addition, to have comprehensive comparison, cost of these systems are found by using LCCA method. Besides, in 20 years whether these systems can compansate their investments or not is revealed. Findings showed that while Metristepe WPP can compansate its investments in 20 years, Gökçekaya PSH cannot compansate its investments in 20 years life time.

Following this chapter, LCA and LCCA methods are described in Chapter 2. Firstly, definition of LCA method is provided. After that, development of LCA method, software selection to carry out LCA, and impact categories are explained. Lastly, LCC method is introduced and application areas are given.

In Chapter 3, general information about PSH system, types of PSH, historical developments of PSH in world and PSH status in Turkey are explained. Also, advantages and disadvantages of PSH are provided in this chapter. In addition to this, available studies in literature about LCA and LCC of PSH are given.

In Chapter 4, general information about wind power plants, historical developments of wind power, and types of wind power plants are discussed. Moreover, advantages and disadvantages of wind power plants are given. Also, in this chapter LCA and LCC studies in literature about WPP are presented.

Following this, in Chapter 5 LCA and LCC analysis of Gökçekaya PSH and in chapter 6 LCA and LCC findings of Metristepe WPP are presented. In both chapters, site selection, system boundary, and resulted emissions are discussed. After that, LCC study of systems are provided in detail.

Finally, comparison of two systems, conclusions, and recommendations for future works are given in Chapter 7.

# CHAPTER 2

# LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST ASSESSMENT

## 2.1 Introduction to LCA

LCA is a method to find environmental burdens of a system or a product throughout its lifetime from production to end of life, in other words, cradle-to-grave. In order to carry out an LCA study following phases can be utilized according to International Organization for Standardization (ISO 14040): goal and scope definition, inventory analysis, impact assessment, and interpretation. Relation between these phases is shown in Figure 2.1 and it is revealed that all phases affect each other (The International Standards Organisation, 2006).

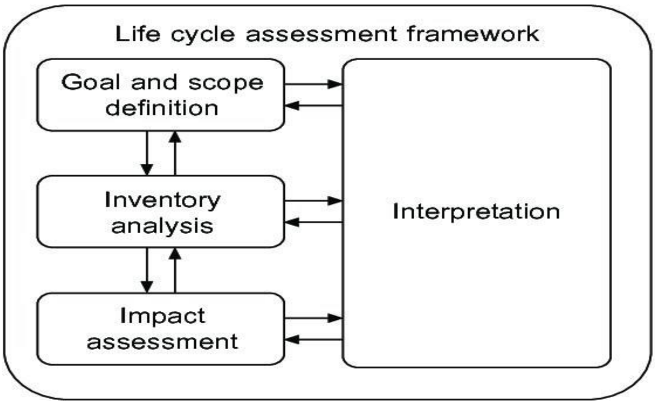



Figure 2.1. Phases of LCA (Ouellet-Plamondon & Habert, 2015)

Goal and Scope Definition: Aims of the study are identified and details of the system with specified boundary are provided in this phase. System boundary can be selected deeper or focusing on certain subjects related to predefined scope. Moreover, assumptions are generally given in this phase to describe breadth of the LCA study.

Inventory Analysis: In this phase required data to carry out LCA study are collected. Inventory data includes input data such as material inputs, energy inputs and output data such as emissions to air, emissions to water, and wastes in considered boundary. Two types of data can be used: primary data which is collected from manufacturer directly or secondary data which is taken from literature or used from the databases (for example Eco invent).

Impact Assessment: Input and output of inventory analysis are expressed in terms of environmental impact categories to understand effects on environment. While compulsory parts of impact assessment are classification of inventory analysis results and characterization, optional parts are normalization, grouping, and weighting.

Interpretation: Results of impact assessment are discussed and presented within the predefined scope of LCA and these results can be used by decision-makers.

One of the main aims of carrying out LCA studies is to eliminate processes or products that will damage environment. Another aim is to mitigate environmental burdens of a product by identifying and replacing processes that are harmful to environment. Also, LCA studies can be used to give insights to decision makers about taking precautions or planning of a project (The International Standards Organisation, 2006).

## 2.2 Development and Application Areas of LCA

To find environmental impacts of a product and compare different products, first studies using basic components of LCA were started to carry out in the late 1960s. Time span from 1970 to 1990 was classified as decade of conception due to developing different approaches and finding terminology. Then from 1990 to 2000 was the decade of standardization due to studies related to finding common methodology for LCA. Between 2000 and 2010 books and papers describing methodology in more detail were published and this decade named as decade of elaboration (Jacquemin, Pontalier, & Sablayrolles, 2012).

In 1969, Midwest Research Institute (MRI) carried out an unpublished study for Coca Cola Company to specify required sources, emissions, and waste of different containers. After this study, depth and breadth of studies were increased (from cradle to grave) and named as Resource and Environmental Profile Analysis (REPA) by MRI. In 1984, Swiss Federal Laboratories for Materials Testing and Research (EMPA) identified necessary data for carrying out LCA studies and found first impact assessment method by classifying emissions due to air and water separately. When 1990s were considered, studies related to LCA increased and different guidelines for LCA published due to rising interest to LCA method. In North America and Europe, Society of Environmental Toxicity and Chemistry (SETAC) had become a pioneer to study structure and methodology of LCA. In addition to SETAC, ISO started to investigate methodology of LCA in 1994. After that, standardization of methodology for LCA was accomplished by ISO, then both ISO 14040 and ISO 14044 were published. After 2005, LCA networks such as American Center for LCA, Australian LCA, and Thai network were established. Following this, a great number of carbon footprint standards were introduced using LCA method (Guinée et al., 2011).

In recent years, methodology of LCA has been developed significantly due to obtaining enhanced databases and compatibility of used methods. Also, it is noticed that application area of LCA has become wider compared to past (Finnveden et al., 2009). At first, LCA is utilized in fields such as plastics, detergents, automobiles, and cosmetic industry. Following this, LCA method has been started to use in construction materials, agriculture, mining, oil and gas extraction, production of materials, energy supply, and transportation. In the fields related to engineering main LCA users can be given as energy, waste water treatment, and product engineering. It is predicted that LCA application will be wider in the future (Jacquemin et al., 2012).

## 2.3 Software Selection

There are many software to carry out life cycle assessment such as CES EDUPACK, Solidworks sustainability, Sustainable Minds, OpenLCA, SimaPro, and GaBi ( Silva et al., 2019; Ren & Su, 2014). From these software, Gabi and SimaPro are the most commonly used software both in academia and industry ( Silva et al., 2019) and they are completely developed tools in which ISO 14040 and ISO 14044 are used (East, Samarakoon, Pranamornkith, & Bronlund, 2015).

Although database of CES EDUPACK 2010, Solidworks 2010, and Sustainable Minds cannot be modified by user, database of both GaBi and SimaPro can be modified. Also, results of CES EDUPACK 2010 contains only energy and carbon footprint which are not sufficient to understand all environmental impacts. Solidworks is a drawing program and modelling has to be carried out before sustainability analysis. Also, in order to use Sustainable Minds for sustainability analysis internet connection is necessary because use of data is not possible without internet connection (Ren & Su, 2014). When SimaPro, which is developed by Pre Consultants, is considered, it is stated that user have to fill areas for material, process, transport, recycle, reuse and disposal to find environmental impacts (Ren & Su, 2014). Also, both in GaBi developed by PE International and SimaPro users can add material or process into database (Herrmann & Moltesen, 2015; Ren & Su, 2014). Unlike SimaPro, GaBi includes biotic carbon dioxide ($CO_2$) and biotic carbon monoxide (CO) and GaBi gives carbon in the biomass separately (Speck, Selke, Auras, & Fitzsimmons, 2016). In addition, only in GaBi software life cycle of a product can be expressed by graphs (Ren & Su, 2014). In this study, GaBi software is selected to use not only for abovementined superiority, but also having large database, being user-friendly, and being available more than 25 years in the market. Comparison of these softwares are given in Table 2.1 to understand their influence.

Table 2.1 Comparison of LCA software (Ren & Su, 2014)

| Considerations | CES EDUPACK | SolidWorks | Sustainable Minds | SimaPro | GaBi |
|---|---|---|---|---|---|
| Product Definition Based on LCA (Defining amount of elements in product life cycle) | ** | * | ** | *** | **** |
| LCIA Method | * | *** | ** | **** | *** |
| Database | *** | *** | ** | **** | *** |
| Database Modification | * | * | * | **** | *** |
| Report Presentation (pie charts, bar, data sheet) | ** | ** | *** | **** | ** |
| Details in results | * | ** | ** | **** | **** |

## 2.4 CML Impact Categories

There are many impact assessment methods such as CML, ReCiPe, and Eco indicator 99 to express input and output data of LCA in terms of environmental impact categories. In this study, CML 2001 impact categories are used and their definitions are provided below.

### 2.4.1 Acidification Potential

Substances which produce acids such as $SO_x$ (Sulphur Oxides), $NO_x$ (Nitrogen Oxides), $NH_3$ (Ammonia), and HCl (Hydrochloric acid) cause acid rains which are harmful to ecosystem, water, and soil. Acidification potential (AP) shows formation potential of these substances. (Unit is kg-$SO_2$-equivalent) (Alqub, 2017; Martínez, Sanz, Pellegrini, Jiménez, & Blanco, 2009).

### 2.4.2 Global Warming Potential

Main reason of climate change is emissions of greenhouse gases to air that causes rise in temperature which results in rising sea levels and desertification. Greenhouse gases which cause climate change can be measured by global warming potential and it is generally expressed for 100 years (GWP100). (Unit is kg- $CO_2$-equivalent) (Alqub, 2017; Martínez et al., 2009).

### 2.4.3 Eutrophication Potential

Enriching water with N (Nitrogen) and P (Phosphorus) causes excessive growth of algae and this causes decrease in oxygen level in water. Consequently, many livings die due to lack of oxygen. Eutrophication impact category shows potential of increasing N and P (Unit is kg-$PO_4$ (phosphate)-equivalent) (Alqub, 2017; Martínez et al., 2009).

### 2.4.4 Abiotic Depletion

This category includes two subcategories: abiotic depletion element (unit is kg- Sb (Antimony)-equivalent), and abiotic depletion of fossil (unit is MJ). Since both elements and fossils are exhaustible sources, extinction of these sources depends on amount of reserves and required time for accumulation of them. Therefore, depletion of elements and fossils are provided in this category (Alqub, 2017; Martínez et al., 2009).

### 2.4.5 Ozone Layer Depletion Potential

Depletion of ozone in stratosphere causes emissions of Ultraviolet (UV) lights to atmosphere. Gases such as CFCs (Chlorofluorocarbons), halons, and HCFFs (Hidrochlorofluorocarbons) result in ozone layer depletion and effects of combination of these gases have not been known yet but it is certain that they are harmful to environment. This impact category shows ozone layer depletion in stratosphere (Unit is kg $R_{11}$ or CFC-11 equivalent) (Alqub, 2017; Martínez et al., 2009).

### 2.4.6 Fresh Water Aquatic Ecotoxicity

This category shows impacts of toxic substances on freshwater ecosystems (Unit is kg- DCB (dichlorobenzene) – equivalent) (Alqub, 2017; Martínez et al., 2009).

### 2.4.7 Marine Aquatic Ecotoxicity

In this category, impacts of toxic substances on sea water are expressed. (Unit is kg-DCB-equivalent) (Alqub, 2017; Martínez et al., 2009).

### 2.4.8 Human Toxicity

This category represents impacts of released unit chemicals on environment and human health (Unit is kg-DCB-equivalent) (Alqub, 2017; Martínez et al., 2009).

### 2.4.9 Terrestrial Toxicity

Terrestrial Ecotoxicity shows impacts of toxic substances on land organisms. (Unit is kg-DCB-equivalent) (Alqub, 2017; Martínez et al., 2009).

### 2.4.10 Photochemical Ozone Creation Potential

Although ozone is required in stratosphere to prevent reaching of UV lights to atmosphere, ozone is toxic and harmful for human in atmosphere. Photochemical ozone creation potential shows amount of ozone in atmosphere and it causes release of gases such as CO (carbon monoxide), $SO_2$ (Sulphur dioxide), NO (Nitrogen oxide), and $NH_4$ (Ammonium) (Unit is kg-ethylene ($C_2H_4$) equivalent) (Alqub, 2017; Martínez et al., 2009).

## 2.5 Introduction to LCC

Life Cycle Cost (LCC) is a method to investigate feasibility of systems and required budget to construct, operate, and decommission the system. Although components of LCC study depend on scope and change for each project, in general LCC consists of initial cost, operation and maintenance cost, repair costs, replacement costs, and residual (salvage) values (Ma, Yang, & Lu, 2014). LCC is utilized to find and compare costs of projects and alternatives in order to select economically feasible option. Also, it is possible to minimize costs of a project before construction of it.

The first application of LCC dates back to end of 1960s in military for logistics and operation by US Department of Defense (DOD). After that, from 1970s to 1980s application of LCC in military field had been increased. While in 1980s LCC is utilized in electrical power plants, oil and chemical industries, during 1990s LCC had been started to use in railway industry (Kawauchi, Cooperation, & Rausand, 1999). At the end of 1990s, LCC was started to use widely and standards were prepared by organizations such as International Electrotechnical Commission (IEC), ISO, and The Competitive Standing of the Norwegian Offshore Sector (NORSOK). Despite these standardization studies, it is known that finding same proceedings for different projects is not straightforward due to dependency of the system. Therefore, at first definition of problem, then finding cost of elements and collection of required data, and lastly evaluation can be basic procedures to apply (Kawauchi et al., 1999).

In this chapter LCA and LCC methods are described and required information are supplied. PSH technology, its development and literature study of both LCA of PSH and LCC of PSH will be discussed in the following chapter.

# CHAPTER 3

# PUMPED STORAGE HYDROPOWER PLANTS

## 3.1 General Description of PSH

PSH is the most developed and common (approx. 99%) method to store electricity in large scale compared to flywheels, batteries, and compressed air energy storage (CAES) (International Energy Agency, 2014). A PSH system generally has two reservoirs located in different elevations. Electricity in off-peak time when electricity has low cost is used to pump water from lower to higher reservoir to store it temporally and then in peak hours when electricity has high cost, stored water is released back to generate electricity (NHA, 2013; Rehman, Al-Hadhrami, & Alam, 2015). When water is stored in higher elevation, electrical energy stored as potential energy and in required times released back to lower reservoir to generate electricity as conventional hydropower plants. As seen in Figure 3.1, pumped storage power plant consists of six main components: upper reservoir, headrace, penstock, pump-turbine, tailrace, and lower reservoir. Headrace carries water between upper reservoir and upper end of penstock (a vertical tunnel) and lower end of penstock is connected to pump-turbine which is located on same shaft with motor-generator. Then, pump-turbine is united with tailrace tunnel which is slightly higher than powerhouse and tailrace tunnel attached to lower reservoir (Pickard, 2012).

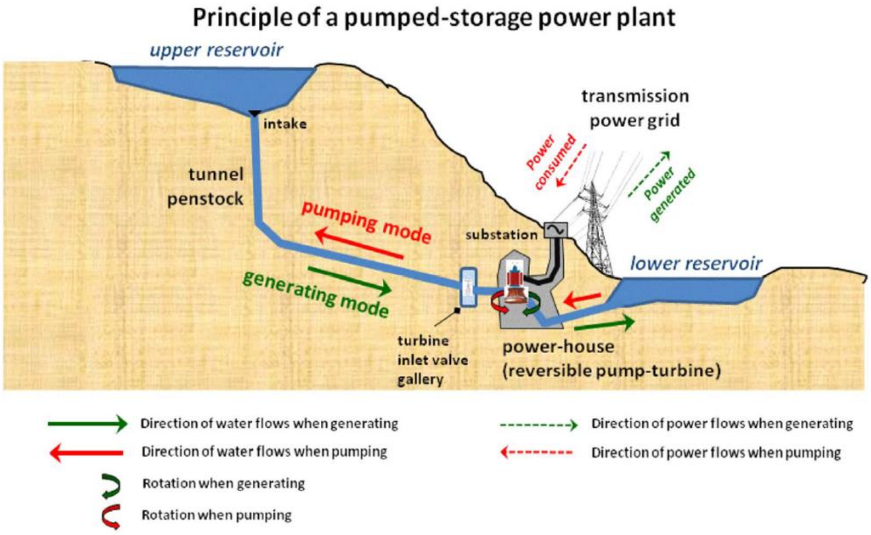



Figure 3.1. A Pumped Storage Hydropower Plant (Abdellatif, AbdelHady, Ibrahim, & El-Zahab, 2018)

There are three types of PSH system: pure pumped storage (off-stream), pumped-back storage, and hybrid systems. In pure pumped storage upper reservoir is on off-stream; therefore it can be named as off-stream pumped storage. Although some researchers called pure pumped storage same as closed-loop, others defined closed-loop as both upper and lower reservoirs are not located on river instead located in an isolated area. From environmental aspect, a closed-loop system is more preferred due to not being harmful to aquatic ecosystem as a result of locating in isolated area instead of river. Nevertheless, it should be pointed that efficiency of closed-loop system can be lower than pure pumped storage system due to high rate of evaporation and leakage on upper and lower reservoirs. Another system is pumped-back storage in which pumped storage and conventional hydroelectric power plants are used. Common application is to convert an existing dam to one of the PSH reservoirs and adding pump-turbine. Hence, construction cost of PSH system is decreased due to utilizing an existing dam. Last type is hybrid system where PSH is used together with WPP or Photovoltaic (PV) system. Intermittent nature of wind and solar system is compensated by storing energy using PSH system. Challenge of this system is finding suitable location for both PSH and WPP (or PV) due to hardness of finding a place with potential of two system at the same time (Barbaros, 2019; Cetinkaya, 2014; Yang, 2016).

### 3.2 Historical Development of PSH

Application of the first PSH dates back to 1890s, in the alpine regions of Switzerland, Austria, and Italy (Yang, 2016). Also, Whittingham claims that the first PSH was constructed in Schaffhausen (Switzerland) in 1909 (Whittingham, 2012). After application of PSH in Europe, the first PSH of USA which was located on Housatonic River was built in 1930.

Although until 1960s Europe and USA were leading places of PSH, after 1960s construction of PSH had increased due to increase in nuclear power plant (NPP) construction as a consequence of 1970s oil crisis. It was known that the first PSH of Japan was constructed in 1934 and to supply required power to NPPs, Japan increased number of PSH after 1960s (Barbaros, 2019; Yang, 2016). Despite its first PSH construction was as late as 1968, PSH application of China has grown significantly. Besides, China has many PSH projects most of them in off-stream and has high-capacity.

Until 1990s, high number of PSH were constructed in USA, Europe, Japan, and China. In 1990, since natural gas prices had been decreased, gas turbines become more preferable than PSH in order to store energy (Yang, 2016). After that, technological developments had been increased to make PSH technology more efficient and in order to increase efficiency of PSH systems, a number of studies were carried out focusing on pump and generator. Since adjustment of input power is not possible using a constant speed motor-generators, adjustable-speed pumped storage systems are started to use. After invention of adjustable-speed turbine, number of constructed PSH has increased (Nagura, Higuchi, Tani, & Oyake, 2010). Advantages of adjustable-speed turbines are their high efficiency due to operating at optimal efficiency point of turbine, working without hydraulic instability and cavitation, adjusting fluctuations in power and used energy when pumping (Cetinkaya, 2014). Also, adjustable-speed pumped storage systems have shorter response time than constant speed motor-generators (Nagura et al., 2010). The first adjustable-speed pumped storage system deployed in 1987 as a pilot project by Hitachi (22 MVA) in Narude Hydro Plant. Following this, the first full scale PSH with adjustable speed pumped storage was installed in Japan, Yagisawa PSH which was started to operate in 1990 (Koritarov, 2014).

Energy generation from renewable sources has been increased in 21$^{st}$ Century to mitigate environmental pollutions. As described in Chapter 1,being intermittent is the most important challenge of renewable energy sources such as wind and solar. To compensate their intermittency, energy storage has become more vital and PSH has been used more compared to past due to being environmentally-friendly solution (Barbaros, 2019). Rise in interest result in more developments in PSH technology. For instance, Okinawa Yanboru seawater PSH was built in Japan in 1999. This PSH was the first PSH in which ocean was utilized as lower reservoir (International Energy Agency, 2014).

According to published technical report (Ayder, 2015) with 26.7 GW installed PSH, Japan is on the first rank which is followed by China (24.8 GW), and USA (22.8 GW) in the world. In Europe, Italy (7.2 GW), Germany (6.7 GW), Spain (6.5 GW), and France (5.2 GW) have highest total capacity of installed PSH (Guittet et al., 2016). More than 50% of installed PSH in Europe are in Germany, Italy, Spain, and France. When France is considered, it can be understandable that high number of NPP caused increase in number of required PSH. Also, Austria and Switzerland will increase construction of PSH due to both having suitable geographical places and having high number of investors. Despite not being developed as other parts of Europe in terms of electricity generation, in East Europe construction of PSH is expected to rise especially in Romania due to having suitable conditions. In addition to these, in Scotland number of PSHs are planned to design in order to compensate intermittency of increasing wind power in United Kingdom (UK). Furthermore, to meet peak demand hydropower plants are sufficiently used in Scandinavian countries, therefore; PSH has not been constructed yet. Moreover, USA has planned to increase its PSH capacity to compensate intermittency of wind energy because of aiming to meet 20% electricity demand of country by wind in 2030. Since Japan has limited sources to generate electricity, NPPs are used in high amount but after Fukushima NPP disaster, Japan has aimed to increase the number of PSHs and use it instead of NPP. When China is considered, it is revealed that coal is used to generate electricity due to having high amount of coal reserves. In spite of this, China is willing to increase use of renewable energy, therefore; energy storage has become a necessity and PSH is the most suitable option to store energy in large capacity (Cetinkaya, 2014).

### 3.3 PSH Technology Status in Turkey

Conventional hydro power plants (HPPs) are the most used renewable energy sources in Turkey. The country has high hydroelectric potential and 683 HPPs are in operation. In addition, 47 HPPs are under construction according to report prepared by DSİ (State Hydraulic Works) (State Hydraulic Works, 2019a). Since NPPs have not been constructed in the country up to now and use of renewable energy sources have not been in large amount, PSH construction has not been practiced yet in Turkey.

It is predicted that electricity demand of Turkey will increase significantly in 2023 and renewable energy share in electricity generation has been targeted to increase about 30% in 2023 (Sogukpinar, Bozkurt, & Cag, 2018). In addition to this, two NPPs one of them located in Mersin (Akkuyu NPP) and other one in Sinop (Sinop NPP) have been planned to construct. In order to store energy to solve intermittency problem of renewable sources and to supply quick energy to planned NPPs, construction of PSH is a necessity in Turkey.

A study to identify suitable sites for PSH construction was carried out by EİE (Electric Power Resources Survey and Development Administration) in 2005 and identified sites are given in Table 3.1 (Unver & Bilgin, 2015).

Table 3.1 Potential Sites for PSH Systems (Unver & Bilgin, 2015)

| Name of PSH Site | Location |
|---|---|
| Kargı PSH | Ankara |
| Sarıyar PSH | Ankara |
| Gökçekaya PSH | Eskişehir |
| İznik I PSH | Bursa |
| İznik II PSH | Bursa |
| Yalova PSH | Yalova |
| Demirköprü PSH | Manisa |
| Adıgüzel PSH | Denizli |
| Burdur PSH | Burdur |
| Eğirdir PSH | Isparta |
| Karacaören II PSH | Burdur |
| Oymapınar PSH | Antalya |
| Aslantaş PSH | Osmaniye |
| Bayramhacılı PSH | Kayseri |
| Yamula PSH | Kayseri |
| Hasan Uğurlu PSH | Samsun |

Following this, a comprehensive study with Japan International Cooperation Agency (JICA) was carried out in 2011 and a report (Study on Optimal Power Generation for Peak Demand in Turkey) was prepared by JICA (Barbaros, 2019). At first stage of their study, 28 potential sites which had sufficient elevation for PSH construction were identified. Since Turkey, which is located on North Anatolian and East Anatolian active faults, is prone to earthquake, sites that were close to active faults less than 10 km were eliminated. In addition to this, sites that were located in national park region were eliminated due to being area of many living species. The remaining options were scored by considering whether they were located in limestone zone or not. Also, places that require minimum numbers of house resettlement are selected for construction. After these eliminations, three sites were remained: Altınkaya, Gökçekaya, Karacaören II Dam regions. Then, conceptual designs of Gökçekaya and

Altınkaya PSH were carried out (Japan International Cooperation Agency, 2011). Lastly, feasibility study of Gökçekaya PSH was carried out in 2016 due to being close to high amount of electricity consumption areas and transmission lines center (Barbaros, 2019).

## 3.4 Advantages and Disadvantages of PSH

In this section, advantages and disadvantages of PSH system are given.

### 3.4.1 Advantages of PSH

1. PSH has faster response to electricity demand fluctuations and blackouts in grid compared to other energy storage systems (Barbaros, 2019; Cetinkaya, 2014).

2. PSH has capability of storing large amount of electricity (Yang, 2016).

3. PSH has a potential to balance the grid in case of demand fluctuations by consuming energy in times of low-cost and generating energy in times of high-cost (Barbaros, 2019).

4. Efficiency of PSH is high (about 80%) (Yang, 2016).

5. Operation and maintenance costs of PSH are low (Cetinkaya, 2014).

6. Consumption of water is minimized by taking advantage of using same water many times (Cetinkaya, 2014).

### 3.4.2 Disadvantages of PSH

1. Initial investment cost of PSH is high despite having low operation and maintenance cost (Barbaros, 2019; Cetinkaya, 2014).

2. It is challenging to find suitable location to construct PSH due to requirement of mountainous region to provide elevation difference (Barbaros, 2019; Cetinkaya, 2014).

3. Since required mountainous regions are natural habitat of many livings, PSH may destroy their habitats. Also, changing natural way of water might be harmful to aquatic ecosystem and water quality may decrease due to sedimentation in reservoir bottom (Cetinkaya, 2014).

## 3.5 LCA of PSH

There is limited number of studies related to LCA of PSH in literature, therefore; publicly available studies are summarised in the following.

LCA of Tonstad III PSH in Norway was examined by (Torres, 2011) to understand environmental effects of source of used electricity (generated by wind or thermal power plant) to pump water for storage (charging). When wind power is used to operate the plant instead of gas turbine, it is found that negative impacts of wind generated power on environment are 50-70% less than gas turbine generated. Also, in terms of climate change impact category, PSH operated using wind generated electricity rather than using gas turbine plant generated has 60 times less effects. Due to lack of required data in utilized database, underground tunnel construction and reversible Francis Turbine were investigated in detail to obtain required data. Based on these results, it was revealed that both underground tunnel construction and reversible Francis Turbine have negative impacts on environment due to high amount of metal and material usage (Torres, 2011).

A PSH system for Nablus Western Wastewater Treatment Plant in Palestine was designed, and LCA of the designed PSH was investigated by (Alqub, 2017). It was highlighted that production phase had the highest negative effects on environment, followed by end of life and maintenance phases. Moreover, it could be pointed out that excavation and transportation phases had negligible contributions compared to other phases. Since other phases of PSH did not have as significant contribution as production phase, only production phase of PSH was compared to lead acid batteries. It was found that lead acid batteries had higher contribution than PSH to global warming potential (62% higher), and acidification (99% higher) impact categories and PSH had higher contribution than lead acid batteries in eutrophication (17% higher), and human toxicity (70% higher) impact categories (Alqub, 2017).

Required metal and energy for three different mechanical energy storage systems: PSH, A-CAES (Adiabatic Compressed Air Energy Storage), C-CAES (Conventional Compressed Air Energy Storage) was examined in addition to their GHG emissions by (Kapila, Oni, Gemechu, & Kumar, 2019). Net energy ratio (output energy/ input energy (construction energy + maintenance + operational)) was found as: PSH 0.778, C-CAES 0.542, and A-CAES 0.702. It could be concluded that net energy ratio of PSH and A-CAES were higher than C-CAES due to minimal losses compared to C-CAES. When greenhouse gas (GHG) emissions were taken into account, emissions of operation stage was higher than both construction and decommissioning in all systems. Among these storage systems, PSH had the least GHG emissions (205 kg$CO_2$ equivalent/kWh), followed by A-CAES (227 kg$CO_2$ equivalent /kWh), and C-CAES (365 kg$CO_2$ equivalent /kWh) (Kapila et al., 2019).

LCA of two energy storage systems which were PSH and utility-scale battery storage were compared by (Immendoerfer, Tietze, Hottenroth, & Viere, 2017). Among impact categories, only in natural land transformation, PSH had 5% higher impacts than utility-scale battery storage. In other categories, GWP (15%), cumulative energy demand for fossil (13%), cumulative energy demand for metals (90%), cumulative energy demand for minerals (45%), eutrophication (20%), and human health in terms of carcinogenic materials (25%) were higher in utility-scale battery storage. Two additional cases were examined for sensitivity analysis: in first option life span of PSH was taken as 150 years while assessment period was kept same (80 years), in second option larger size battery was considered. As a result of these analyses, it was concluded that benchmark case had higher impacts than both options but still utility-scale batteries had higher negative impacts on environment than PSH technology (Immendoerfer et al., 2017).

PSH and CAES as mechanical energy storage systems, advanced lead acid (PbAC), sodium sulphur (NaS), lithium-ion (Li-ion), nickel-sodium-chloride (NaNiCI) batteries, and Proton Exchange Fuel Cell (PEMFC) were examined to determine their effects on environment by considering their construction, disposal/end of life, and use phases. In climate change impact category, PEMFC had the highest impact, and its effect was approximately 44% higher than other systems. When human toxicity impact category was considered Lead, Li-ion, NaNiCI had about 10% higher effects than other systems. In particular matter formation PEMF (40% higher), and in fossil depletion PEMF approximately 2 times higher compared to other systems in this study. For end of life case (Oliveira et al., 2015) stated that battery storage cases had more impacts than mechanical systems due to lower number of cycles. Overall, it is possible to conclude that NaS battery had the lowest effects on environment, followed by PSH (Oliveira et al., 2015).

## 3.6 LCC of PSH

It is necessary to determine required cost in order to understand required budget and identify feasibility of the project. Since there is not many publicly available study about LCC of PSH, some of them are found and described below.

LCC of advanced deep cycle lead battery (option1), conventional battery (option2), pump storage with a combination of battery tank (option3), and pumped storage without battery (option4) were compared to each other for 25 years lifetime in a remote island in Hong Kong by (Ma et al., 2014). It is found that option 4 had the lowest life cycle cost followed by option 3, option 1, and option 2 from low to high cost. It was stated in the paper that reversible pump turbine usage could enhance efficiency of the system compared to separate pump and turbine due to decrease in cost of machines although it was not used due to unavailability. Also, it was given by authors that when power supply stability, energy conservation, and technology usage were calculated with costs, option 3 would have the lowest LCC (Ma et al., 2014).

LCA impact categories which could be affected by transportation were considered by (Panesar, Kanraj, & Abualrous, 2019) for 100 years. Moreover, LCC of concrete mix designs 100 GU (0% fly ash), 25 FA (25% fly ash), 35 FA (35% fly ash), 50 FA (50% fly ash) were investigated. When environmental impact categories such as particulate air, GWP, human toxicity were considered and 100 GU was taken as the benchmark case, it is found that 50FA (40-60% of 100GU) had the least burden on environment, followed by 35 FA(60-75% of 100GU), 25 FA(70-85% of 100GU). As percentage of fly ash increased, global warming potential of concrete decreased due to decrease in amount of cement. In addition, since cost of fly ash was less than cost of cement, 50 FA had the lowest LCC compared to others in this study (Panesar et al., 2019).

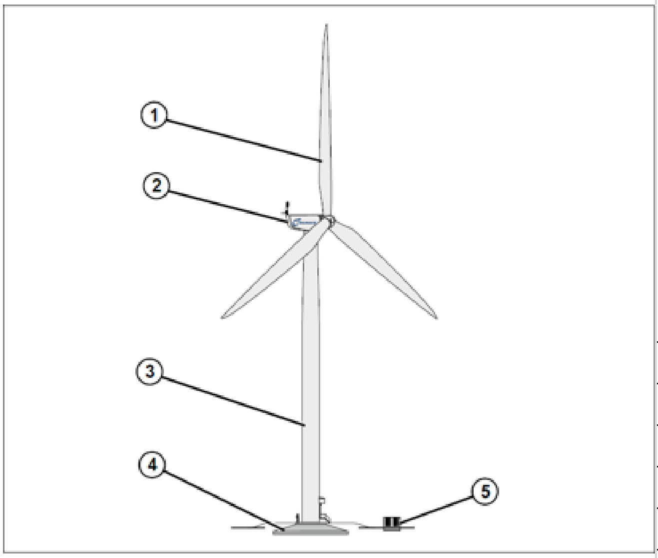
In this chapter, information related to PSH which is one of the main systems investigated in this thesis are given. Since PSH has been older system compared to wind turbines which is another main system to investigated in this thesis, firstly PSH is described and following this chapter, description of wind turbines will be given.

# CHAPTER 4

# WIND ENERGY AND WIND POWER PLANTS

## 4.1 General Description of WPP

Wind energy is one of the renewable energy sources to generate electricity without giving harm to environment. In order to generate electricity from wind, wind turbines which converts kinetic energy of wind to electrical energy are used (Zafar, 2018). Wind turbine consists of five main parts: 1- rotor and blades, 2-nacelle, 3-tower, 4-foundation, and 5-transformer (can be outside or inside wind turbine) as seen in the Figure 4.1 (Zander, 2014).




| | |
|---|---|
| 1 | Rotor and Blades |
| 2 | Nacelle |
| 3 | Tower |
| 4 | Foundation |
| 5 | Transformer |

Figure 4.1. Components of Wind Turbine (Zander, 2014)

Description of main components of wind turbine is provided as follows:

Tower is the part that carries components of wind turbine. Furthermore, it is utilized to lighten and carry wind and vibration loads to foundation. Towers can be steel, concrete, steel lattice, and hybrid. Both steel towers and steel lattice towers are prepared before construction and assembled in site. There are differences between them: steel lattice towers are more economical and require less material compared to steel towers. Although concrete towers are mostly used in countries where steel prices are high, it is known that at high towers steel is more economical and steel can be reused in end of life of turbine. Another option that is not common is hybrid tower which can consist of concrete and steel tower or concrete and steel lattice (Zafar, 2018).

Second main part is nacelle that covers components of wind turbine such as generator, gearbox, yaw mechanism, and brake system. Mechanical and electronical components of the turbine are located in nacelle and nacelle is placed on tower (Zafar, 2018).

Foundation is a part of turbine that supply stability of turbine by transferring loads (dead load, wind load, overturning, and bending moments) and vibration to ground. Monopile, bucket, jacket (tripod), and gravity based foundation types are commonly used in offshore industry. In onshore wind footings are used for light turbines and for heavy turbines pile foundations are preferred (Zafar, 2018).

Rotor is another main part that converts kinetic energy of wind to mechanical energy. Rotor includes blades (usually three blades), rotor shaft, and hub (Dang & Rashid, 2009).

Lastly, anemometer to detect wind speed, wind wanes to adjust direction of wind turbine parallel to wind direction, and brakes to stop turbine can be classified as auxiliary mechanisms of wind turbine (Zafar, 2018).

Two main types of wind turbine exist: vertical axis wind turbine (VAWT) and horizontal axis wind turbine (HAWT). Difference between two types is their spinning axis: VAWT spins around a vertical axis as shown in Figure 4.2 and HAWT spins around a horizontal axis as shown in Figure 4.3.

Figure 4.2. Vertical Axis Wind Turbine (Aboufares, 2015)

Figure 4.3. Wind Farm with Horizontal Axis Wind Turbines (Arı, 2019)

Though VAWT has advantages such as to generate energy at lower wind speeds and ability of utilizing wind without depending on direction of wind, disadvantages such as supplying less power and less efficiency compared to HAWT are reasons of not being used for commercial purpose. Thanks to variable blade pitch of HAWT, blades can be adjusted in different conditions and this cause increase in efficiency. Commercially, HAWT is more preferable than VAWT due to above mentioned reasons (Dang & Rashid, 2009).

Wind farms can be located not only onshore (on land) but also offshore as shown in Figure 4.4 and application of offshore wind farms has been increased in recent years. Despite having stable wind and higher wind speed, being expensive and having difficult maintenance are the main drawbacks of offshore wind farms. Also, its maintenance has been required longer time compared to onshore wind turbines.

Figure 4.4. Offshore Wind Farm (Fard, 2018)

## 4.2 Historical Development of WPP

Before using to generate electricity, wind is used for irrigation, water pumping, and navigation. While wind energy was used to supply energy for boots in Nile River (Egypt) in 5000 BC, in China and Persia it was utilized to pump water in 200 BC. Also, in Middle East wind was used for irrigation. In addition to these, in seventh century BC to grind grains wind energy was benefited using vertical-axis mills in Iran and Afghanistan (Ackermann, 2012; Ilkilic, Aydin, & Behcet, 2011; Zafar, 2018). First application of horizontal windmills were carried out in Persia, Tibet, and China in 1000 AD. After that, in Mediterranean Countries and Europe horizontal windmills were found. From twelfth to nineteenth centuries, performance of windmills were developed gradually having a rotor diameter of 25 m (Ackermann, 2012).

Dane Poul La Cour was the first who built a wind turbine to generate electricity in 1891. After that, F.L. Smith which was a Danish company, produced modern wind turbine (with modern air foils) in 1941. This developments were followed by Palmer Putnam who built a bigger size wind turbine (53 m rotor diameter) using a new design approach for an American Company (Morgan Smith) (Ackermann, 2012; Ackermann & Soder, 2000). While design approach of Danish company was taken upwind rotor and slow speed operation as a baseline, Putnam's approach was used downwind rotor and variable pitch operation. After using these two different approaches, Danish approach had been chosen to practice in turbine development and Danish approach was further developed by Johannes Juul at the end of World War II. This turbine generated 2.2 million kWh energy from 1956 to end of 1960s. In the meanwhile a turbine with high efficiency was developed by Heutter. In 1970s, power generation by wind increased due to oil crises and countries such as USA, Germany, and Sweden made investments to develop large wind turbines. Moreover, in 1970s the first large scale wind farm was installed in USA with 50 kW and then turbine size was reached 200 kW in 1980s. In 1990s, investments in wind energy in the USA had fallen and investments in Europe had increased (Ackermann, 2012).

After 1990, not only onshore wind energy was utilized but also offshore wind energy was started to use. The first offshore wind farm was installed in Denmark in 1991 and after that installation of offshore wind farms was increased significantly in Europe and USA. When both onshore and offshore wind sectors are considered, it was revealed that global capacity of wind power had become 100 GW. These developments were followed by generating 4% of electricity used in world from wind in 2016. After that, the first floating offshore wind farm (Hywind) was installed in Scotland in 2017. According to IRENA (International Renewable Energy Agency), total installed onshore wind power worldwide was 542 GW in 2018 and it is expected to rise up to 1787 GW in 2030. Also, annual deployment of onshore wind farm was 45 GWh in 2018 and it is predicted that this number will reach 147 GWh in 2030. When rate of wind power to meet electricity need of countries are taken into account, in 2030 it is predicted that UK (37%), Germany (32%), China (29%), USA (28%), France (13%) and India (3%) will reach to meet their electricity demand (International Renewable Energy Agency, 2019).

### 4.3 WPP Technology Status in Turkey

Turkey has high wind energy potential and 48000 MW wind energy potential exists in total (both onshore and offshore). While 30000 MW portion has wind velocity between 7 m/s and 7.5 m/s, remaining 18000 MW has 7.5 m/s and higher wind velocity (Sogukpinar et al., 2018).

According to wind atlas of Turkey (see Figure 4.5), Marmara and Aegean Regions have the highest wind potential and cities with the greatest wind potential are Balıkesir, İzmir, and Manisa. In addition, despite having 3500 m coastline, Turkey has not been installed offshore wind farm yet (Kaplan, 2015).

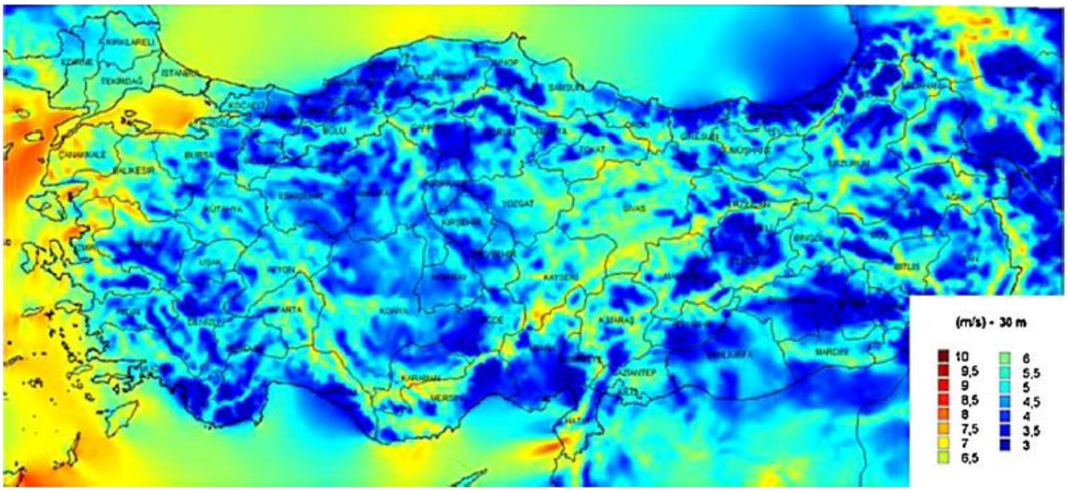



Figure 4.5. Wind Atlas of Turkey (Kaplan, 2015)

The first wind farm which was Germiyan WPP installed in 1998, in Çeşme having 3 turbines (each has 500 kW power capacity). The second important attempt was installation of Ares WPP in 1998, in Çeşme with 12 turbines (each has 600 kW power capacity). After that Bozcaada WPP in Bozcaada Island was installed with 17 turbines (each has 600 kW power capacity) in 2000 (Baskaya, 2017). From 2006 to end of 2019, number of WPPs has been increased significantly and power obtained from wind is shown in Figure 4.6.

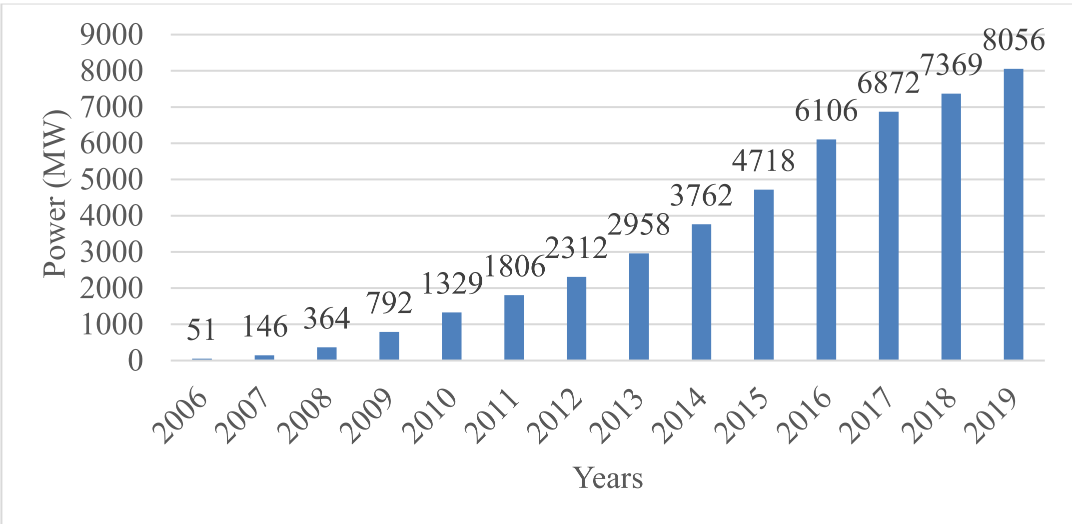



Figure 4.6. Amount of Wind Power Obtained with Years (*Turkish Wind Energy Association*, 2020)

According to Turkish Wind Energy Association report published in January 2020, 198 WPPs are operational in Turkey. Distribution of WPPs with regions of Turkey can be seen in Figure 4.7 and it is clear that most of the plants are located in Aegean and Marmara Regions due to high wind potential (Turkish Wind Energy Association, 2020). Despite providing strong winds in winter, Black Sea region has not been used to install WPP due to being rough region and not having flat terrains to locate wind farm. The most suitable sites to install wind farm are Marmara Region, Mediterranean Coast, Aegean Sea Coast, and Central Anatolia (Ilkilic et al., 2011).

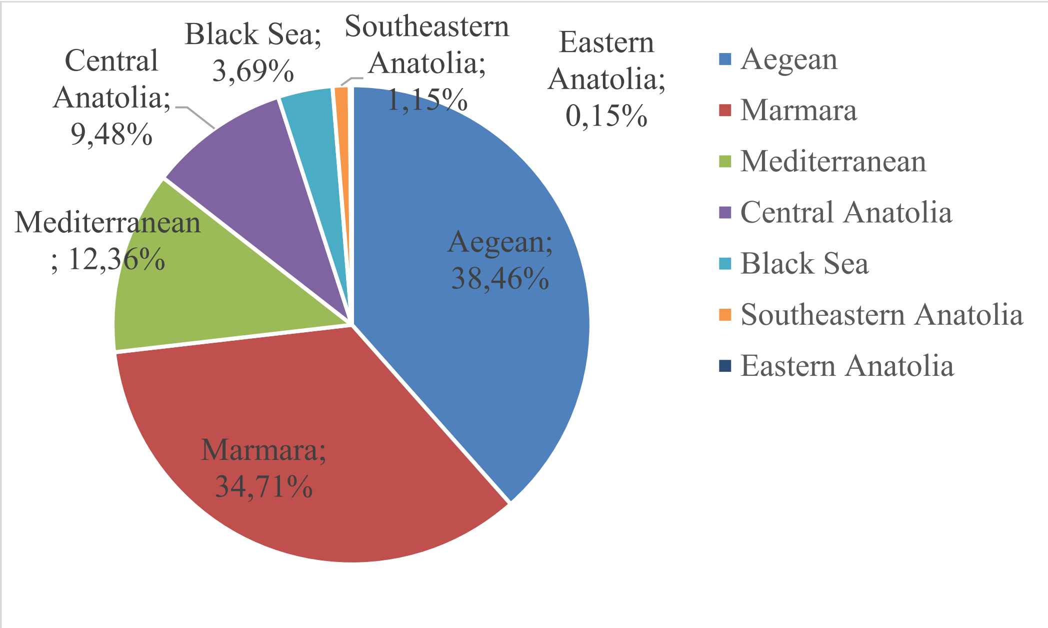



Figure 4.7. Distribution of Operational WPPs in regions of Turkey (*Turkish Wind Energy Association*, 2020)

One of the Turkey's 2023 targets is to obtain 125000 MW of energy from renewable energy sources and to obtain 20000 MW power from wind. In order to achieve this target, number of WPPs have been increased significantly (Sogukpinar et al., 2018).

## 4.4 Advantages and Disadvantages of WPP

In this section, advantages and disadvantages of WPP are given.

### 4.4.1 Advantages of WPP

1. Wind energy is environmentally-friendly and inexhaustible source of energy (Baskaya, 2017; Kaplan, 2015).

2. Wind energy is one of the lowest price renewable energy source (Umair Shahzad, 2016).

3. Wind Power Plants have caused increase in employment such as installation and maintenance of turbine sector. Also, since wind power plants are installed to rural areas, people who lives in these rural areas may have job opportunities (Baskaya, 2017; Kaplan, 2015; Umair Shahzad, 2016).

4. Due to being free, electricity costs generated from wind power do not fluctuates but electricity costs generated from fossil fuels fluctuates due to change in costs of mining and transportation (Kaplan, 2015).

5. Using wind energy decreases source dependency due to not depending on sources of other countries (Kaplan, 2015).

6. Wind power plants not only reduce depletion of fossil fuels but also has advantage of quick installation and disassembly (Baskaya, 2017).

### 4.4.2 Disadvantages of WPP

1. Wind turbines cause noise pollution and disturbs people living close to power plant side (Baskaya, 2017; Shahzad, 2016).

2. Wind turbines cause drawbacks to bird life such as killing and injuring birds (Baskaya, 2017; Shahzad, 2016).

3. Wind energy is not predictable and stable, instead it is intermittent which causes blackouts ( Shahzad, 2016).

4. Wind turbines cause statics in radio and television in close sites about 2-3 km (Baskaya, 2017).

5. One of the argued disadvantage is that wind turbines cause visual impact and aesthetic related problems (Baskaya, 2017; Shahzad, 2016).

## 4.5 LCA of WPP

Large amount of studies related to LCA of wind turbines are carried out, therefore; some of the available studies are provided below. Studies are classified whether they include raw material extraction phase or not. First, studies with raw material extraction phase is considered are given.

LCA of small scale VAWT with primary data of 5 kW wind turbine installed in Poland was investigated by (Kouloumpis, Sobolewski, & Yan, 2020). In end of life two main scenarios: do nothing (scenario A), recycling of metals and incineration (scenario B) were taken into consideration with three sub scenarios using different capacity factors (0.5%, 9.0%, 20.5%). Results of this paper demonstrated that the subscenarios with the lowest capacity factor (0.5%) caused highest emissions in main scenarios (A and B) due to low electricity generation. Except freshwater aquatic eco toxicity (FAETP), in other impact categories scenario A had higher impacts than scenario B due to lowering effect of recycling and incineration. Besides, usage of high amount of steel and concrete to produce mast and foundation (about 60%) was main cause of contribution to global warming potential (GWP). It was declared that producing VAWT with capacity factor more than 12% reduced environmental impacts and further studies were necessary (with primary data) to confirm VAWT as environmentally friendly energy system (Kouloumpis et al., 2020).

To study energy consumption and GHG emissions of HAWT, a Taiwanese-built off-grid small scale 600 W HAWT (12 m/s wind speed) was studied by (W. C. Wang & Teah, 2017). It was found that the highest GHG emissions were in production phase in which manufacturing, machinery, and packaging were included. In the study, two cases were investigated: shipping turbines to local markets in Taiwan and exporting turbines to US markets. In US case, GHG emissions of wind turbine was 5.47 kg $CO_2$ equivalent higher than Taiwan local market case. The main reasons of this difference could be transportation distances, disposal and incineration differences between two countries. In addition, four components of wind turbine were investigated and among them generator had the highest GHG emissions due to high amount of steel usage followed by tower, rotor, electric components respectively (Wang & Teah, 2017).

A study was carried out by (Alsaleh & Sattler, 2019) for 2 MW onshore wind turbines (Gamesa G83 and G84) which were installed in Lone Star wind farm in Texas. When findings of this study was analysed, it was indicated that the highest emissions were in material acquisition and manufacturing phase (about 65%-90% of all emissions). Being independent from the used processes (recycled, disposal, incineration), end of life phase had the lowest emissions. While diesel usage was the main reason of high emissions in installation phase due to high weight of installed equipment, it caused the highest ozone smog formation (5.9%) emissions in transportation phase. In addition, operation and maintenance had the highest contribution rate to non-carcinogens category (6.8%) due to replacement of control system after 10 years. Furthermore, impacts of the turbine parts were tower (>40% due to steel processing), nacelle (>20%), rotor (>10%), foundation (>6%) from highest to lowest. In order to carry out sensitivity analysis two parameters were considered: turbine life span (20-25-30 years) and wind speed (8 m/s- in the farm site). In terms of life span, it was stated in the paper that despite increase in lifespan of turbine caused increase in impacts of operation and maintenance, per kWh impacts were lower when lifespan is longer (30 years) due to generation of more energy. Also, in terms of wind speed, increase in wind speed caused increase in energy production; nevertheless, electricity generation was overestimated in optimum wind speed (8 m/s) about 2.3 times more than wind velocity measured from the farm (Alsaleh & Sattler, 2019).

Studies without raw material extraction phase are described as follows.

LCA of a wind turbine (Gamesa Onshore Wind Turbine, model G8x with 2 MW rated power) which had doubly fed inductor generator (DFIG) in the Munilla wind farm in Spain was carried out by ( Martínez, Sanz, Pellegrini, Jiménez, & Blanco, 2009). They carried out their first study using Eco indicator 99 methods and it was found that manufacturing phase (at least 60%) has the highest emissions. Also, transport phase had minor environmental effects (30-50% less than other phases), and in use phase, inorganic respiration (1500 eco-points) and reduction of mineral resources (1600 eco-points) categories were high due to replacement of components when turbine is in operation. Due to recycling of materials and leaving foundation with covering, emissions in end of life were negative (Martínez et al., 2009). In their second study using CML method, emissions due to wind turbine and electricity mix of Spain in Eco invent database (with same power level) were compared. This comparison revealed that emissions due to wind turbine were less than Spain electricity mix in abiotic depletion (98.99%), Global Warming Potential for 100 years (98.76%), ozone layer depletion (96.73%), human toxicity (89.26%), freshwater aquatic eco-toxicity (94.06%), marine aquatic eco-toxicity (99.34%), terrestrial eco-toxicity (92.68%), photochemical oxidation (99.24%), acidification (99.28%), and eutrophication (97.78%). Furthermore, in the paper it is stated that main parts causing environmental impacts are rotor (due to amount of fiberglass), tower (due to steel) and nacelle (due to copper and fiberglass) ( Martínez et al., 2009).

Two electricity generation sources: locally manufactured small wind turbines (LMSWTs) and locally manufactured pico-hydro plants (LMPHPs) were examined by (Troullaki, Latoufis, Marques, Freire, & Hatziargyriou, 2019). For LMSWTs (900 W at 11 m/s turbines) a project in Ethiopia and for LMPHPs (450 W and run-off river type) a project in Greece were utilized to collect necessary data. Findings revealed that LMPHP had significantly lower (approximately 88%) environmental impacts than LMSWT in all considered impact categories. In addition, manufacturing of electric-electronic parts and production of construction materials: steel, concrete to build tower and foundations were the main reasons of high emissions in LMSWT systems. Another point is that environmental impacts of LMPHP system were mainly caused by manufacturing of batteries, inverter, and cables. After that, LCA results of both LMSWTs and LMPHPs were compared with a small petrol generator as an alternative to generate electricity in off-grid. It is found that 2 kW petrol generator had about 90% higher environmental impacts than LMSWT and LMPHP in all considered impact categories (Troullaki et al., 2019).

Environmental impacts of three medium scale: 330 kW ($T_1$), 500 kW ($T_2$), 810 kW ($T_3$), and two large scale: 2050 kW ($T_4$), and 3020 kW ($T_5$) wind turbines with changing hub heights (50, 80, 100 m) were compared by (Demir & Taskin, 2013). When findings were interpreted it was found that increase in hub height caused decrease in both environmental impacts and energy payback times of turbines due to high amount of electricity generation. Also, comparison of results with fossil fuel generated electricity revealed that wind had less effects than fossil fuel. As a result of this study, it was stated that $T_4$ at 100m hub height had the best performance in terms of energy payback times, energy consumption, and environmental impacts (Demir & Taskin, 2013).

LCA of two onshore (V80-2.0 MW and V90-3.0 MW) and two offshore (V80- 2.0 MW and V90-3.0 MW) wind turbines were compared by (Noori, Kucukvar, & Tatari, 2015). It was revealed that the highest emissions in construction phase could be due to high amount of materials used. Furthermore, since weight of materials, and foundation of onshore wind turbines were greater than offshore, GHG emissions of onshore were at least 50% (or more) higher than offshore. Also, findings of this research indicated that offshore wind turbines generated less environmental impacts than onshore wind turbines (GHG emissions for onshore 17.37 equivalent/kWh and 7.44 equivalent /kWh for offshore). When produced electricity in entire life time was considered it was stated in the paper, offshore V80-2 MW wind turbine generated

1.43 times more electricity than onshore wind turbine and offshore wind turbine V90- 3 MW generated 1.77 times more electricity than onshore. In conclusion it was stated that V90 wind turbines were more environmentally friendly than V80 wind turbines per kWh of generated electricity and V90 wind turbines had 14% less GHG emissions in onshore and 30% less in offshore compared to V80 wind turbines due to generating more electricity (Noori et al., 2015).

An LCA study was carried out to investigate environmental burdens of 3 MW power wind turbines: Geared converter with doubly-fed induction generator (DFIG), direct driven synchronous generator (DDSG) electrically excited, and direct drive permanent magnet synchronous generator (DDPMSG) assumed to install an imaginary onshore site in Germany (North German Plain) by (Schreiber, Marx, & Zapp, 2019). In manufacturing, while nacelle and rotor (52%- 99%) impacts were the highest in all turbine types, and tower had approximately 30% impacts. It was discussed in the paper that in all impact categories of CML (except abiotic depletion potential), DDSG had (20%-90%) higher values than DDPMS and DFIG. Furthermore, in all impact categories DFIG and DDPMSG have 5% or less difference. As an exception to this generalization, in human toxicity with cancer effects, DFIG has 10% higher impact than DDPMSG. Overall, DDSG had the highest impacts in all categories and followed by DDPMSG and DFIG respectively and all three wind turbines performed better than other renewable power generation technologies (Schreiber et al., 2019).

In a report written by (Petruneac, 2015), a case study of two wind turbines ( 2 MW onshore Turbine A, 2 MW offshore Turbine B) in Cornwall were examined to find sources of $CO_2$ emissions and compare their emissions with the UK's electricity grid. Since foundation of Turbine A (60% steel) was composed of reinforced concrete, and foundation of Turbine B (85% steel) was composed of steel, turbine B had higher steel amount and GHG emissions in manufacturing phase. Results were revealed that emissions of Turbine A were transport (29.3%), tower (36.3%), nacelle (17.2%), rotor (15.7%), foundation (11.5%), and emissions of Turbine B were transport (81%), foundation (11%), tower (4%), nacelle (2%), and rotor (2%). In conclusion, it was expressed that carbon footprint of Turbine A is 10.4 g/kWh, Turbine B is 43.5 g/kWh, and UK electricity grid 448 g/kWh. Thus, both Turbine A and Turbine B were more environmentally-friendly than UK electricity grid (Petruneac, 2015).

A review article was written by (Raadal, Gagnon, Saur, & Hanss, 2011) to investigate GHG emissions of wind and hydropower. When LCAs of wind turbine were reviewed, large variations was found: 3 MW wind turbines had 4.6 $gCO_2$-equivalent emissions and 30 kW wind turbine had 55.4 $gCO_2$-equivalent emissions. LCA studies related to hydropower were reviewed and it was found that run-off type hydropower plants had approximately 8 $gCO_2$-equivalent ,reservoir type hydropower plants has 30 $gCO_2$-equivalent emissions. The reason for the high emissions in reservoir type hydropower plants was high amount of concrete usage in construction of reservoir. Also, in this study it was stated that when capacity of WT increased, GHG emissions decreased (For example wind turbine with capacity factor 0-15% caused 35 $gCO_2$-equivalent and wind turbine with capacity factor 46-55% caused 8 $gCO_2$- equivalent emissions) (Raadal et al., 2011).

### 4.6 LCC of WPP

There is a limited number of studies for LCC of wind turbines so that available studies are presented in the following.

Fang proposed a model for life cycle cost of grid connected wind power-hydrogen coupled integrated energy system (WPHCIES) to increase quality of utilized wind power. A 9.5 MW wind power plant located in South China is used to validate model. It was found that payback period for capital is 11 years for wind farm and 8.13 years for WPHCIES (Fang, 2019).

Cost of wind turbines in Europe (including Norway, Switzerland, and Turkey) with power equal or greater than 3 MW (hub heights between 99-120 m) were investigated by (McKenna, Hollnaicher, Ostman, & Fichtner, 2015). Reduction in cost of electricity was carried out by classifying wind turbines utilizing wind speed and available areas. In conclusion, it was found that UK, Poland, and Sweden has largest wind potentials and lowest cost of energy generation (0.06-0.08 Euro/kWh) compared to countries in Europe. When results of this study were compared to other studies, it was revealed that costs were not different and potential of wind energy was considerable higher than other available studies (20 PWh-petawatt hour) due to difference in system boundaries and considering short term market potential (McKenna et al., 2015).

Levelized Cost of Energy (LCOE) is a method to estimate cost of unit energy generated and used to compare cost of systems utilized to generate energy (Lerch, De-Prada-Gil, Molins, & Benveniste, 2018).

Lerch et al. investigated LCOE for three floating wind turbine concepts: semi-submersible (concrete), tension leg platform (steel), and spar (concrete) and three offshore sites (each 500 MW): Golfe de Fos, Gulf of Marine, West of Barra. In three floating wind turbine concepts West of Barra had the highest cost, and followed by Gulf of Marine. For sensitivity analysis, parameters related to cost and energy were used. It was concluded that discount rate had the highest influence on LCOE. Also, cost of turbine, substructure, mooring, and power cable had the highest contribution to total cost (Lerch et al., 2018).

LCOE of following 5 MW floating offshore wind turbines were investigated: Hywind II (spar), Sway (tension-leg-spar), WindFloat (Semi-submersible), Tension-leg-wind-turbine (TLWT), and Tension-Leg-Buoy (TLB). Also, as a base case available data of jacket and monopile (bottom-fixed turbines) were utilized. Depth of FOWTs was taken as 200 m and depth of bottom-fixed turbines taken as 30 m. LCOE of systems from highest to lowest could be given as: WindFloat (287.8€/MWh), Hywind (243.4€/MWh), Sway(233.6€/MWh), TLWT(232.2€/MWh), and TLB(225.9€/MWh). In all types, production of turbine and grid connection were the highest LCOE value. Since cost of mooring lines and length of export cable were the most important parameters, depth of deployment and distance from shore were main factors to increase LCOE values. In addition, it is stated that systems with lowest steel mass had lower LCOE values (Myhr, Bjerkseter, Ågotnes, & Nygaard, 2014).

Conceptual background to introduce PSH and WPP systems are supplied in the first four chapters. Case studies and results of analysis will be given in the following chapters.

# CHAPTER 5

# LCA and LCC of GÖKÇEKAYA PSH

## 5.1 Site Selection and Description

Locations that has potential to construct PSH are defined in Turkey by JICA as discussed in Chapter 3. In JICA report, three suitable locations: Gökçekaya Dam, Altınkaya Dam, and Karacaören II Dam are found as the most suitable sites among alternatives due to their geological and topographical convenience. From these three sites, Gökçekaya Dam region is selected in this study because of being close to places that have high amount of electricity consumption and being located in intersection of transmission lines as mentioned in Chapter 3 (Barbaros, 2019). Gökçekaya PSH is planned to construct utilizing existing Gökçekaya Dam (a concrete arch dam) which is on Sakarya River, Eskişehir province as highlighted in Figure 5.1. Gökçekaya Dam was started to operate in 1973 with installed power 278 MW and 562 GWh/year annual electricity production (State Hydraulic Works, 2019b).


Figure 5.1. Location of Gökçekaya Dam in Map of Turkey (“Google Earth Pro,” n.d.-a)

Preliminary design of Gökçekaya PSH was carried out by JICA and dimensions of this design is provided in Table 5.1.

Table 5.1 General Information and Dimensions of Gökçekaya PSH (Japan International Cooperation Agency, 2011)

| Description | | Unit | Gökçekaya PSH |
|---|---|---|---|
| General | Installed Capacity (P) | MW | 1400 |
| | Designed Discharge ($Q_d$) | $m^3/s$ | 428 |
| | Effective Head ($H_d$) | m | 379.5 |
| | Peak Duration Time | hrs | 7 |
| Upper Dam Reservoir | Type | | Full Face Pond (Asphalt) |
| | Height (H) | m | 35 |
| | Crest Length (L) | m | 2700 |
| | Dam (Bank) Volume (V) | $m^3$ | 1557000 |
| | Excavation Volume ($V_e$) | $m^3$ | 10310000 |
| | Reservoir Area ($R_a$) | $km^2$ | 0.5 |
| | Catchment Area ($C_a$) | $km^2$ | 4.8 |
| | Usable Water Depth | m | 30 |
| | Effective Reservoir Capacity | $mil.m^3$ | 10.8 |
| Lower Dam Reservoir | Usable Water Depth | m | 11.5 |
| | Effective Reservoir Capacity | $mil.m^3$ | 214 |
| Waterway | Intake (L x n) | m | Bellmouth 34 x 1, Tunnel 396 x 1 |
| | Headrace (L x n) | m | 2028 x 1 |
| | Penstock (L x n) | m | 662 x 2, 110 x 4 |
| | Tail-bay (L x n) | m | 125 x 4, 116 x 2 |
| | Tailrace (L x n) | m | 476 x 1 |
| | Tailrace (L x n) | m | Tunnel 53 x 1, Open 51 x 1 |
| | Total Length (Lt) | m | 4051 |
| Powerhouse | Type | | Egg-shape (Underground) |
| | Overburden | m | 365 |
| | Height | m | 57.5 |
| | Width | m | 37 |
| | Length | m | 210 |
| | Cavern Volume | $m^3$ | 266000 |
| Turbine | Type | | Single-Stage Francis |
| | Number | Unit | 4 |
| | Unit Generating Capacity | MW | 350 |

## 5.2 Methodology

In order to find environmental burdens of the Gökçekaya PSH applied methodology is LCA as described in Chapter 2 and to perform economic analysis of the system applied methodology is LCCA. ISO 14040 and ISO 14044 are utilized to carry out LCA analysis.

### 5.2.1 Goal and Scope

Main purpose of this study is to find environmental burdens of Gökçekaya PSH and Metristepe WPP and to compare their emissions in order to give an insight to both decision makers and researchers. In this chapter, emissions of Gökçekaya PSH are found and presented by using GaBi software. Since Gökçekaya PSH has not been constructed yet, determinig emissions and economic feasibility of system are important in order to identify environmental problems and economic concerns related to system.

### 5.2.2 System Boundary

In this study, main focus is from construction to end of life; therefore, raw material extraction has not been taken into consideration and it is assumed that construction materials and other equipment are taken from manufacturer (Demir & Taşkin, 2013; Kapila et al., 2019). As shown in Figure 5.2, system boundary consists of construction, operation, maintenance, and end of life phases. Also, components of each phase are shown in the figure. In addition, functional unit is taken as 1 MWh and after finding total emissions of the system for considered lifetime (20 years), all emissions are expressed for 1 MWh electricity production.


Figure 5.2. System Boundary

Assumptions are summarized in the following.

1. Transmission lines and grid connections are not included in the boundary (Alsaleh & Sattler, 2019).

2. Lifetime of Gökçekaya PSH is taken as 20 years and transportation of materials are considered (Ma et al., 2014).

3. For transportation, diesel powered Euro 5 truck in GaBi is used.

4. Electricity mix of Germany is used due to absence of electricity mix of Turkey in GaBi database. Since electricity mix of German is cleaner than Turkey, results might change when electricity mix of Turkey is used and this is one of the limitations of this study.

5. All materials and equipment are assumed to taken from Turkey Branch Office, when equipment are bought from companies located in abroad. Hence, factories and brands located in Turkey are utilized.

6. Time required to replace pump, turbine, and generator is taken as 25 years, since in this study 20 years life time is considered replacement of the equipment is not taken into consideration (Immendoerfer et al., 2017).

7. 1.35 MW electricity consumption per hour to pump water to upper reservoir is assumed (Barbaros, 2019).

### 5.2.3 Phases of LCA

Primary data of Gökçekaya PSH are taken from the JICA report such as dimensions of constructed parts and power of machines (Japan International Cooperation Agency, 2011). Besides, some primary data are taken from the manufacturers. When primary data are not available, data from literature and Eco invent database in GaBi software are utilized. Phases of LCA are described in following subsections.

#### 5.2.3.1 Construction Phase

Construction phase of PSH consists of three stages: construction of pipes, construction of upper reservoir, and construction of powerhouse. In all construction phases, dimensions such as length of pipes, cross sections and dimensions of powerhouse are taken from JICA report. In addition to the report, amount of reinforcement, concrete, asphalt, and membrane are calculated.

In construction of pipes phase headrace, tailrace, tail-bay, and penstock are taken into consideration. Since headrace and tailrace are reinforced concrete pipes, both required reinforcement and concrete are considered in their construction. Tail-bay and penstock are welded steel pipes and support is prepared for these pipes by using reinforced concrete. Based on discussions with experts, the largest available welded steel pipe having 16 mm wall thickness and 3048 mm outer diameter was used. Besides, suitable dimensions of an egg-shaped underground powerhouse (57.5 m height, 37 m width, 210 m length) are taken from JICA report. Required material amounts are calculated accordingly. Also, excavation is carried out for construction of upper reservoir and powerhouse by using hydraulic digger in GaBi. After excavation of upper reservoir, discussions with experts show the necessity of membrane coating on upper reservoir before asphalt lining. For this purpose, asphalt lining is applied on membrane. Calculated amount of required materials are presented in Table 5.2.

Table 5.2 Required Material Amounts in Construction Phase

| **Construction of Powerhouse** | **Unit** | **Amount** |
|---|---|---|
| 1. Excavation of Powerhouse | $m^3$ | 266000 |
| 2. Reinforcement | Ton | 6993.47 |
| 3. Concrete | Ton | 906992.16 |
| **Construction of Upper Reservoir** | | |
| 1. Excavation of Upper Reservoir | $m^3$ | 10310000 |
| 2. Wet Area Membrane | $m^2$ | 500000 |
| 3. Asphalt Lining | Ton | 312000 |
| **Construction of Pipes** | | |
| 1. Headrace | | |
| Concrete of Headrace | Ton | 362863.39 |
| Reinforcement of Headrace | Ton | 15421.20 |
| 2. Tailrace | | |
| Concrete of Tailrace | Ton | 85169.11 |
| Reinforcement of Tailrace | Ton | 3619.57 |
| 3. Tail-bay | | |
| Concrete of Tail-bay | Ton | 133078.30 |
| Reinforcement of Tail-bay | Ton | 4031.39 |
| Welded Steel Pipe | Ton | 880.48 |
| 4. Penstock | | |
| Concrete of Penstock | Ton | 188236.02 |
| Reinforcement of Penstock | Ton | 8074.98 |
| Welded Steel Pipe | Ton | 21244.63 |

#### 5.2.3.2 Operation Phase

In operation phase of PSH, pumping mode electricity requirement for the power plant is considered. Pumping mode efficiency of Gökçekaya PSH is taken as 89.09% for 5 hours electricity generation and 7 hours pumping where $Q_{pump}$=305.71 $m^3$/sec, $H_{pump}$= 402.40 m and total pumping capacity considering efficiency losses is 1354.22 MW. It is assumed that operation of Gökçekaya PSH will start in 2025 and 1.350 MWh electricity consumption occurs in pumping mode (Barbaros, 2019). As can be seen in equation (1), one cycle consists of 12 hours. Hence, there are 2 cycles in a day (14 hours pumping).

$\text{Generation hours (5 hours)} + \text{Pumping hours (7 hours)} = \text{12 hours (1 cycle)}$ (1)

$20 * 365 * 14 = 102200$ hours pumping is required. (2)

$102200 * 1.35 = 137970\ \text{MWh}$ (In 20 years life time required total electricity consumption). (3)

In addition to electricity consumption, transportation of electromechanical equipment: generator (4585 tons), transformer (341.25 tons), and reversible Francis turbine (84000 tons) are considered in this phase.

#### 5.2.3.3 Maintenance Phase

In this phase lubrication of generator and reversible Francis turbine are considered.

According to JICA, 1400 MW reversible Francis turbine with 380 m effective head should be used in Gökçekaya PSH (Japan International Cooperation Agency, 2011).

Weight of spiral casting per MW capacity is 0.3 tons/MW (Torres, 2011).

$0.3\,\frac{\text{tons}}{\text{MW}} * 1400\ \text{MW} = 420\ \text{tons}$ (4)

Since fraction of weight of spiral casting in turbine is 0.5%, weight of reversible Francis turbine is calculated as 84000 tons (Torres, 2011).

Although 525 MW generator is suggested in JICA report, a generator model from AKSA (1.5 MW) is selected (model: APD 2100 M) to scale properties properly due to data unavailability of 525 MW generator. A linear relation between weight and capacity of motor-generator is assumed (Kapila et al., 2019). Using this assumption, weight of 525 MW generator is found as 4585 tons. Also, it is assumed that linear relationship exists between power and oil capacity of both generator and reversible

Francis turbine. Furthermore, frequency of oil refilling of generator and reversible Francis Turbine is taken as 500 hours (Palmera, n.d.).

#### 5.2.3.4 End of Life Phases

In end of life phase, disposal (landfilling) of main construction materials: concrete, reinforcement bars, and asphalt are considered in this research. Also, reinforced concrete is transported to site, after that separation of them is carried out by using magnet in the factory.

In order to identify effect of recycling to emissions, recycling of concrete is taken into account. Therefore, instead landfilling of concrete completely, 60% of concrete is landfilled and 40% of concrete is recycled to use as aggregate. According to (Tam, 2011), concrete recycling rate can change between 5% - 90% and concrete recycling rate is selected as 40% in this study. Besides, in order to crush concrete, 34 MJ per ton energy consumption is assumed (Panesar et al., 2019).

Disposal of main construction materials case will be named as base case and case that include recycling of concrete will be named as alternative case in the following sections. In base case, disposal amount (landfill) of concrete is 167638.99 tons, reinforcement bar is 38140.61 tons, and asphalt is 312000 tons. In alternative case disposal amount (landfill) of concrete is 100583.394 tons, recycling amount of concrete is 67055.596 tons and both asphalt and reinforcement bar disposal amounts remain same.

#### 5.2.3.5 Transportation

Transportation is not considered as a separate phase, instead in each phase transportation is included. In Table 5.3, transportation distances of materials and equipment are given.

Table 5.3 Transportation Distance of Gökçekaya PSH

| Material or equipment | Unit | Distance |
|---|---|---|
| Concrete | km | 66.9 |
| Reinforcement Bars | km | 73.1 |
| Asphalt | km | 73.8 |
| Membrane | km | 380.0 |
| Welded Steel Pipe (spiral) | km | 194.0 |
| Reversible Francis Turbine | km | 201.0 |
| Generator | km | 205.0 |
| Transformer | km | 581.0 |
| Generator Oil | km | 205.0 |
| Reversible Francis Turbine Oil | km | 80.1 |
| End of life company (Anket A.Ş.) | km | 216.0 |

### 5.2.4 Description of GaBi Working Principles for Gökçekaya PSH

In order to understand GaBi inputs and outputs, it is necessary to define following terms.

Functional Unit: It is a selected unit to compare two or more systems and in this study, functional unit is selected as 1 MWh electricity generation.

Process: Every system composed of many processes and to model a system in GaBi, it is necessary to use processes. It is possible to create processes or use processes in the database if necessary process exists in database. In Figure 5.3, grey boxes represent processes and shown in the legend. For instance, in Gökçekaya PSH concrete lining of pipes is a process to construct pipes; therefore, concrete lining of pipes is a necessary step to construct pipes.

Flow: It is utilized to connect processes and shows transition of materials and energy from one process to another. In Figure 5.3, all arrows represent flows and shown in the legend.

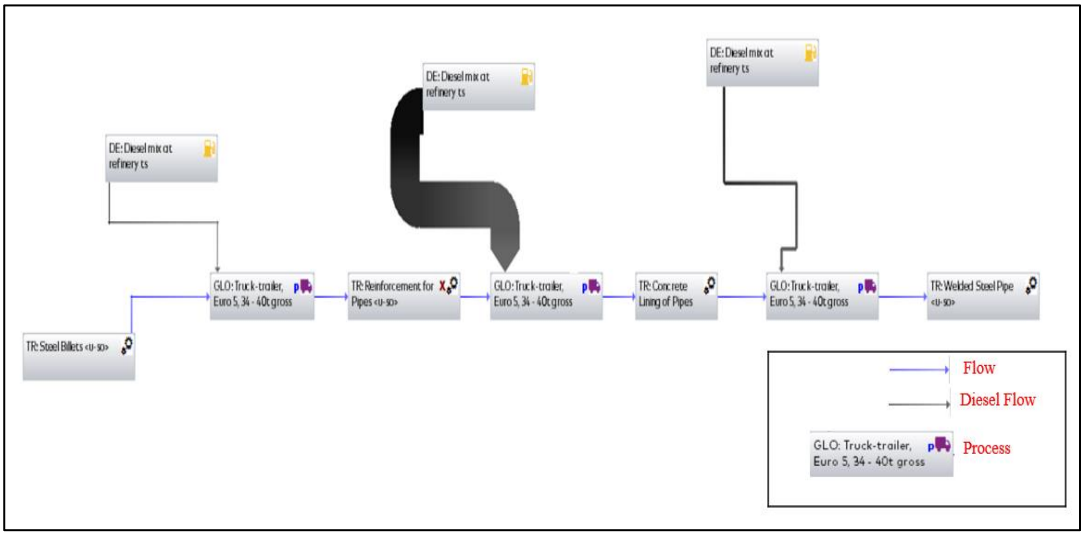



Figure 5.3. Flow chart of LCA processes and established model in GaBi (Construction of Pipes in Gökçekaya PSH)

Plan: It consists of flows and processes, as an example Figure 5.3 shows a plan of construction of pipes and it includes all processes and flows. Also, inside a plan, more than one plan can connect to obtain total results. In Figure 5.4, construction phase of Gökçekaya PSH is shown and it connects three different plans: construction of pipes, construction of powerhouse, and construction of upper reservoir. In addition, each plan has to contain at least one fixed process to carry out analysis and during calculation of results fixed process or processes taken as reference which means results are calculated with respect to fixed process. As seen in Figure 5.4, a red cross exists if process is fixed and construction of powerhouse is a fixed process in this plan.

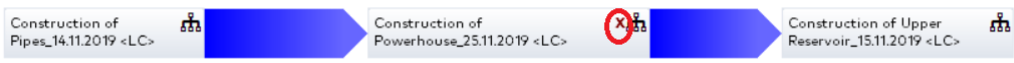



Figure 5.4. Construction Phase of Gökçekaya PSH (in total)

After generating phases separately, in order to find total emissions of Gökçekaya PSH all phases are combined in one plan as seen in Figure 5.5.


Figure 5.5. All phases of Gökçekaya PSH

Each process has input and output flow information as seen in Figure 5.6 and flow data are entered manually to this tab in GaBi.

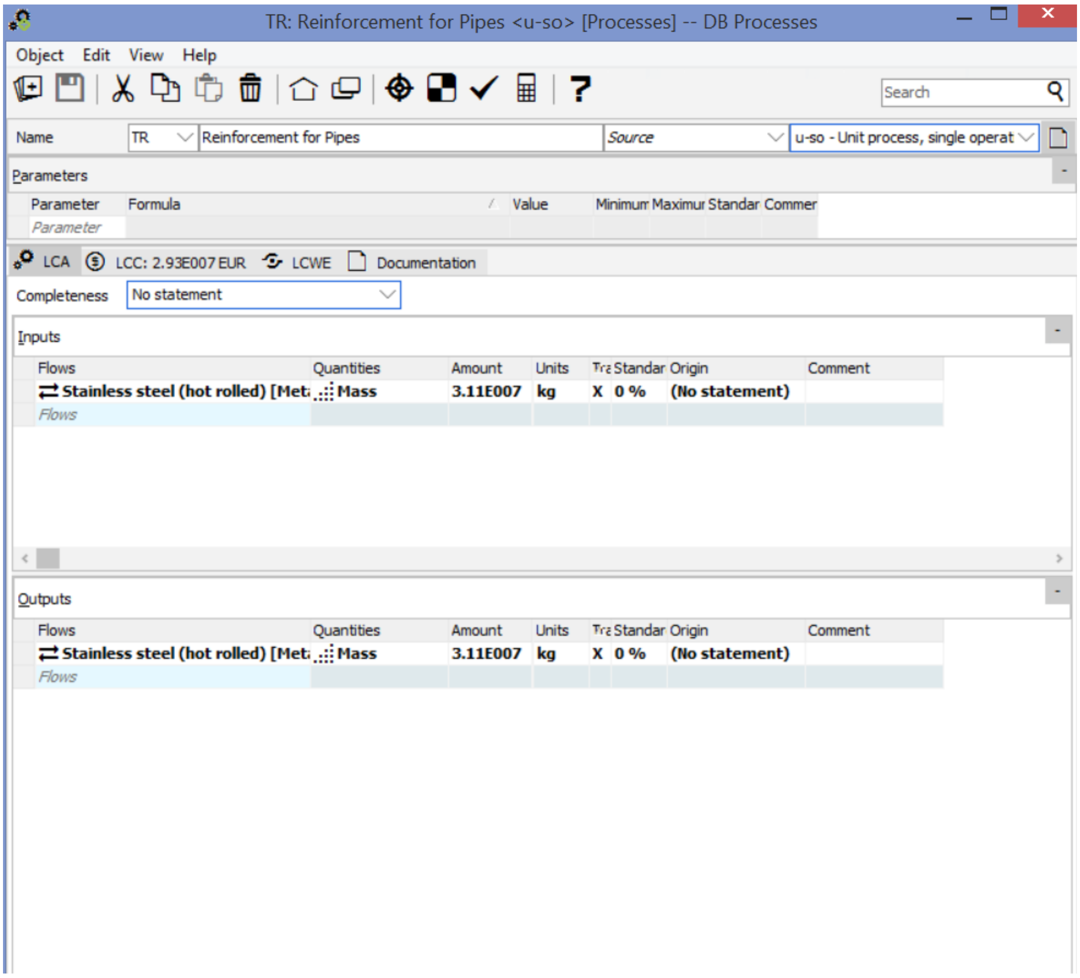



Figure 5.6. Flow of Reinforcement for Pipes Process (GaBi)

Although each process has same flow information tab, transportation processes have different tab as seen in Figure 5.7. In this tab distance is entered manually and it should be known that distance driven by single truck multiplied by truck number to model more than one truck. After that, result of multiplication can be entered to distance value. In this study, Euro 5 truck with 27 tons payload capacity is used and apart from distance, all other data related to transportation processes exist in database and used directly.

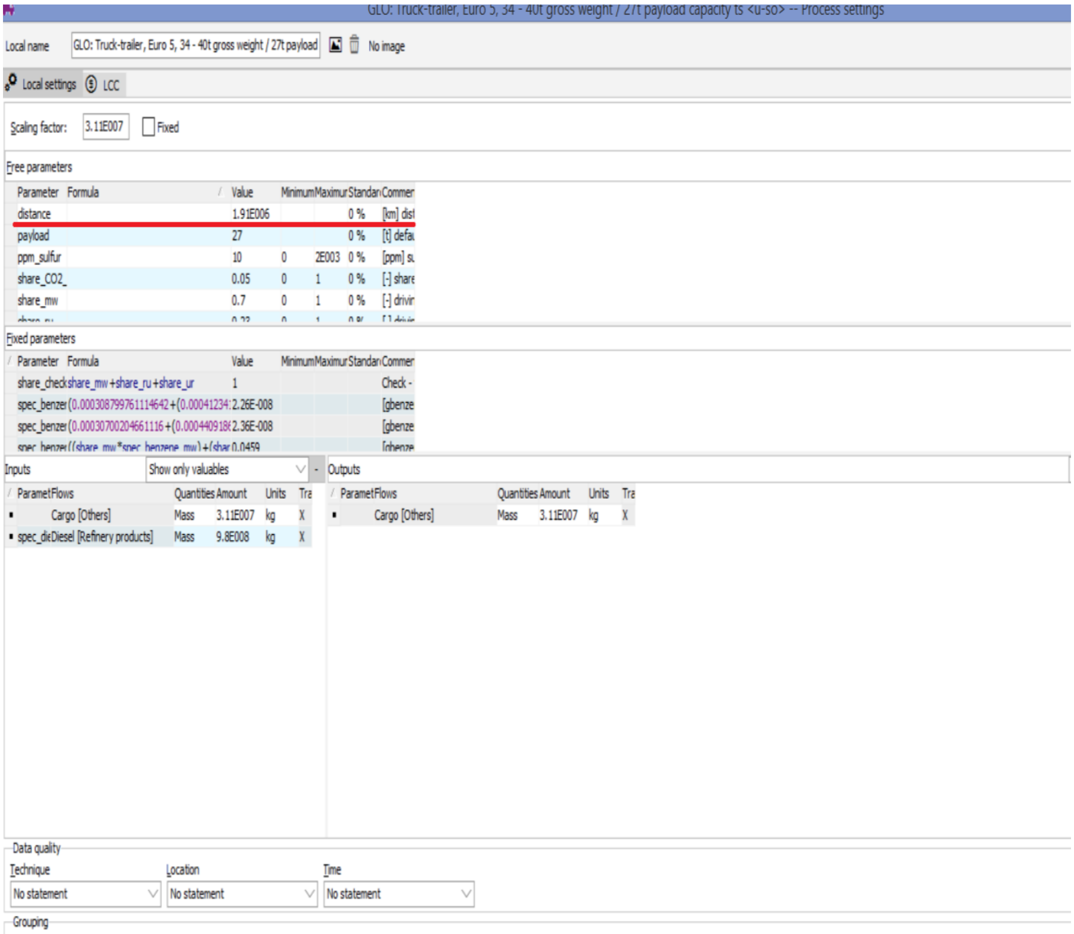


Figure 5.7. Transportation Process of Concrete for Lining of Pipes (GaBi)

After completing modelling in GaBi, results can be obtained as graphs. Software takes entered Life Cycle Inventory (LCI) data and convert them to Life Cycle Impact Assessment (LCIA) results which means express results in terms of impact categories such as GWP, EP, AP. In order to convert results two operations are carried out by software: classification and characterization. As given in Chapter 2, according to ISO 14040/14044 while classification and characterization, are compulsory parts of impact assessment: normalization, grouping, and weighting are optional parts (The International Standards Organisation, 2006). In order to obtain results, GaBi carries out classification and characterization.

Classification: Substances are classified by considering their contribution to impact categories. For instance, as seen in Figure 5.8 $CO_2$, CO, and $CH_4$ contributes to GWP but do not contribute to EP.

Characterization: In order to express one impact category with same unit, one substance is taken as reference and other substances are multiplied by characterization factors which are determined by scientists. For instance, to express GWP, $CO_2$ is selected as reference and CO emissions multiplied by 3 to convert emissions kg.$CO_2$ – equivalent as can be seen in Figure 5.8. Also, characterization factors might be different depending on impact methods such as CML, TRACI, and ReCiPe.

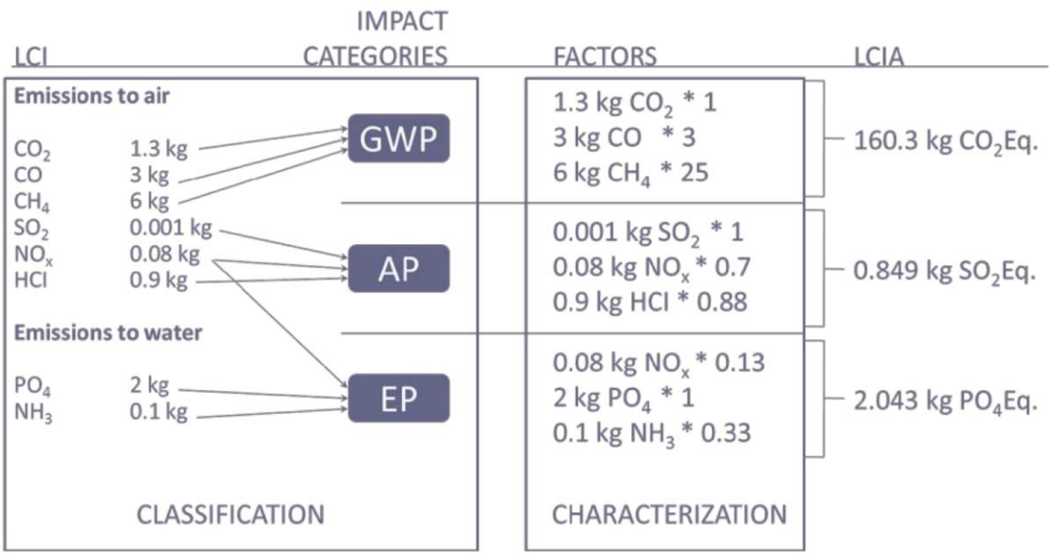



Figure 5.8. Classification and Characterization (PE International, 2013)

In this thesis graphical GaBi results that include compulsory parts of impact assessment (classification and characterization) are used. Although not being used, optional parts (normalization, grouping, and weighting) are defined and discussed in the following.

Normalization: Taking a reference such as emissions of a location in certain time interval, emissions can be expressed without dimension. Also, it is possible to show results of investigated impact categories in one graph using normalization (PE International, 2013).

Normalization process is carried out using equation (5) (Jeong, Wang, Oguz, & Zhou, 2018) where $\epsilon_e$ is amount of pollutant for the given time span, $N_e$ is normalization factor for impact categories such as GWP, AP, EP for each pollutant, and $EI_t$ is environmental impact for impact categories such as GWP, AP, EP for each pollutant.

$$EI_t = \epsilon_e * N_e \qquad (5)$$

Grouping: Impact categories can be ranked depending on preferences of organizations and a number of parameters such as their global or local scale. Results of grouping depend on choices of organizations so that it is possible to have different ranking on same results (PE International, 2013).

Weighting: Impact results can be compared to each other in terms of their importance and weighting factors (PE International, 2013).

According to (Pizzol et al., 2017), reason of being optional for normalization and weighting is being tendentious due to commercial issues. Normalization have been thought tendentious because of having different results depending on choice of reference and weighting has been defined as non-scientific according to ISO 14044 (Pizzol et al., 2017). In order to give unbiased results, in this thesis optional parts of LCA have not been applied to results.

### 5.2.5 Impact Assessment Results

In this study, impact categories that have significant contribution are taken into account. Hence, the most significant three impact categories: Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) are discussed. Materials that cause increase in emissions in these impact categories and effects of these categories are discussed previously in Chapter 2. In addition, there are two cases: base case and alternative case. While in base case disposal (landfill) of concrete is investigated, in alternative case recycling of concrete (40%) is considered. Since investigating effect of recycling on emissions is an interesting concept, base and alternative cases are taken into consideration. First, total emissions of base case GaBi graphs (Figure 5.9, Figure 5.11, and Figure 5.13) and then total emissions of alternative case GaBi graphs (Figure 5.15, Figure 5.17, and Figure 5.19) will be given. Also, in order to show emission of construction, end of life, and maintenance phases graphs are prepared using Excel. Base case graphs (Figure 5.10, Figure 5.12, and Figure 5.14) and alternative case graphs (Figure 5.16, Figure 5.18, Figure 5.20) are provided below in each impact category.

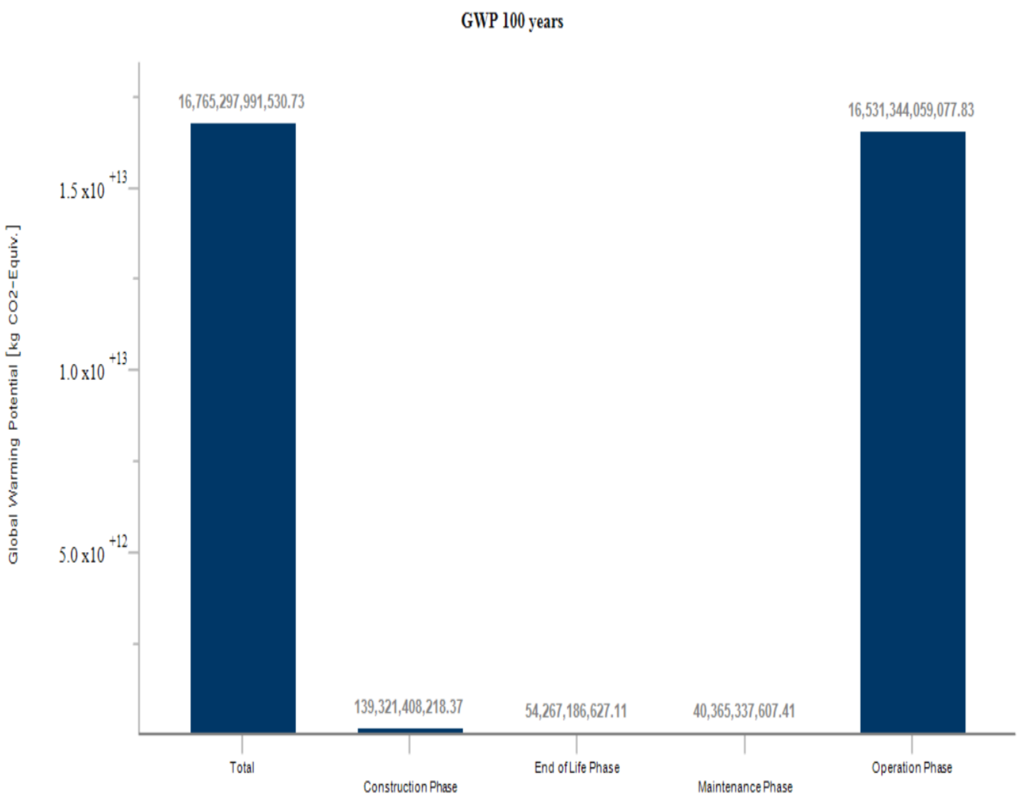



Figure 5.9. Global Warming Potential of Base Case

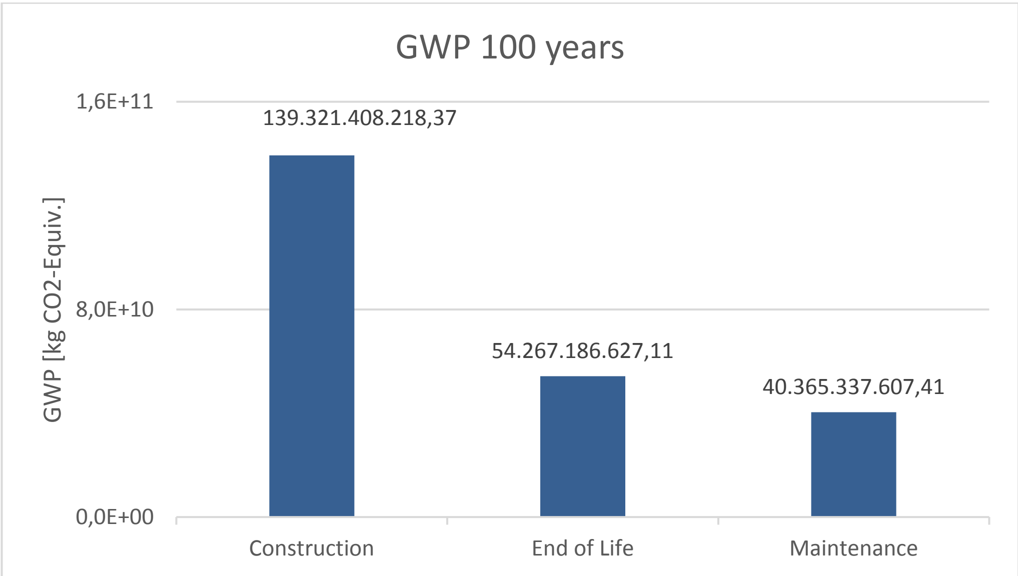



Figure 5.10. GWP of Construction, End of Life, Maintenance Phases (Base)

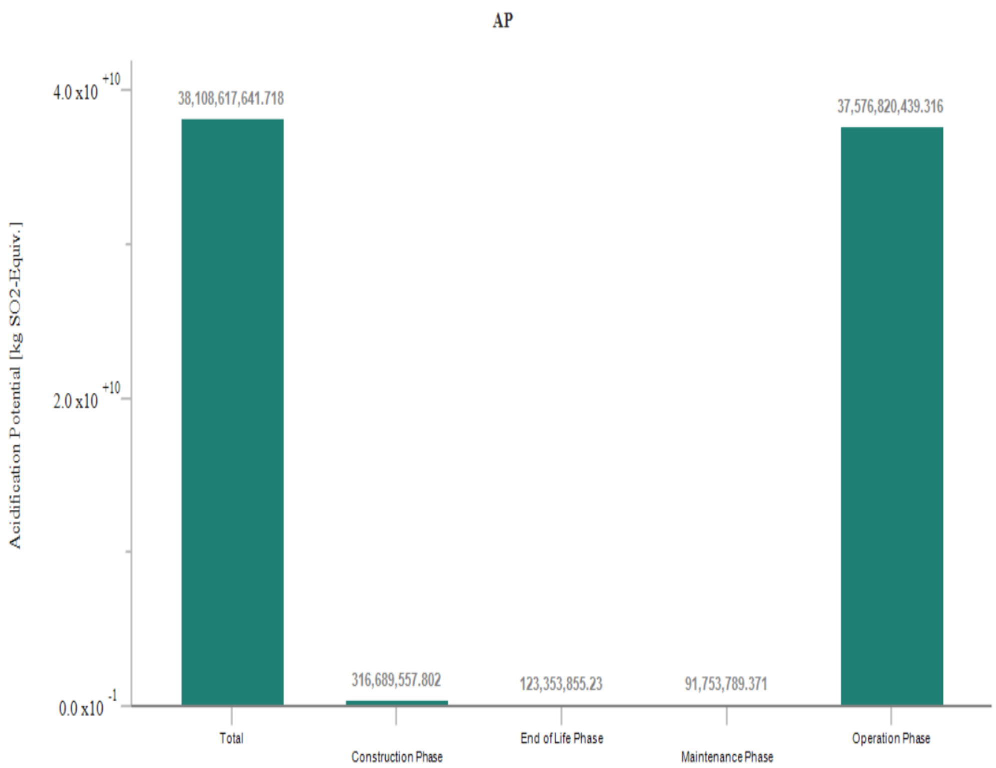



Figure 5.11. Acidification Potential of Base Case

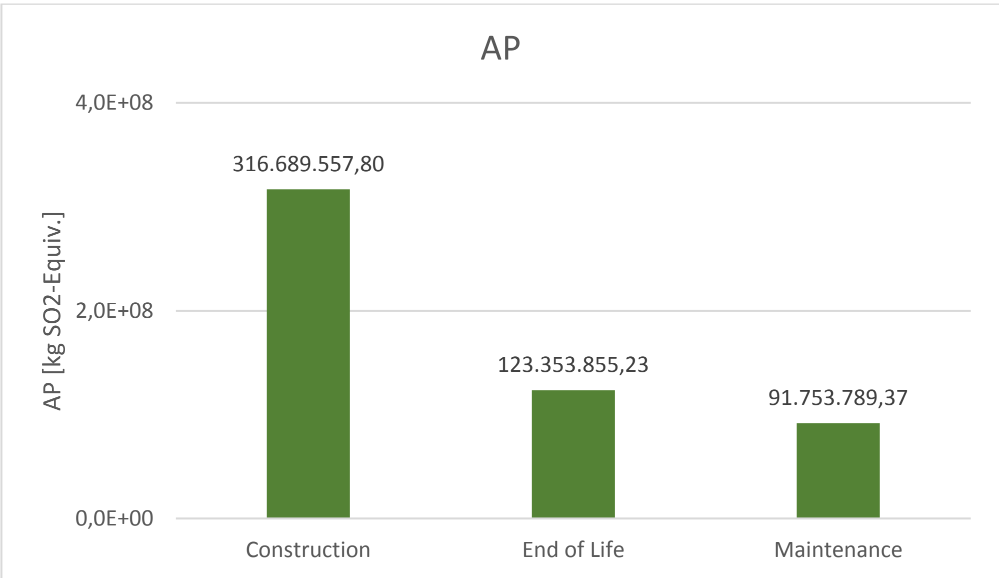



Figure 5.12. AP of Construction, End of Life, Maintenance Phases (Base)

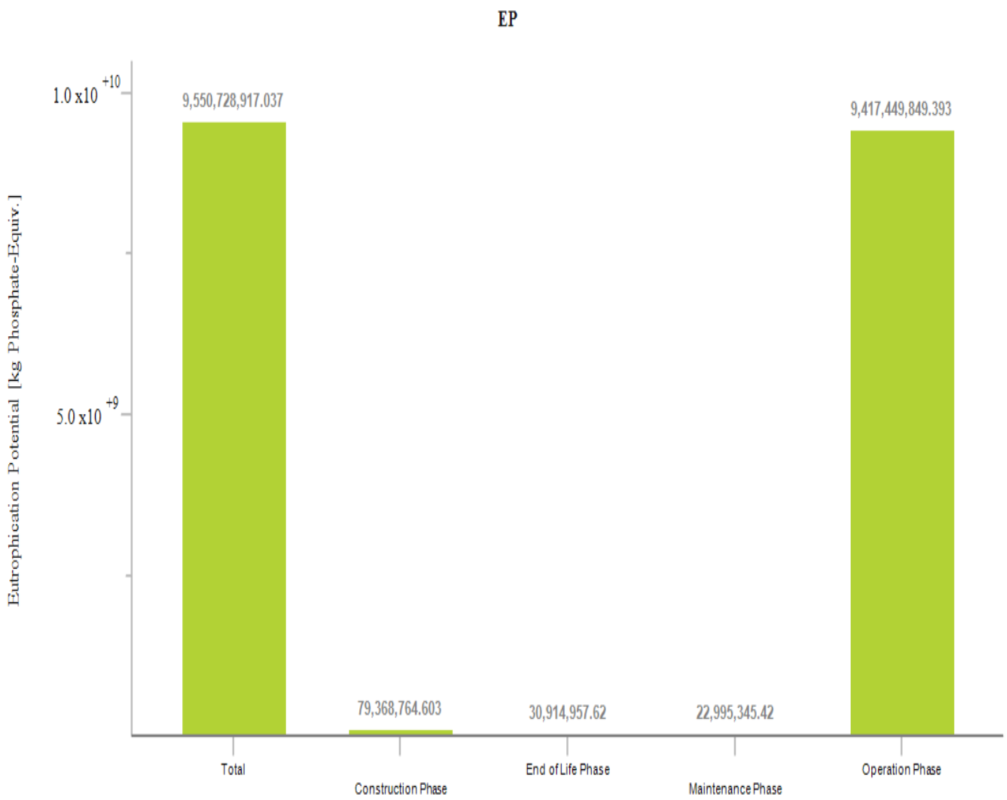



Figure 5.13. Eutrophication Potential of Base Case

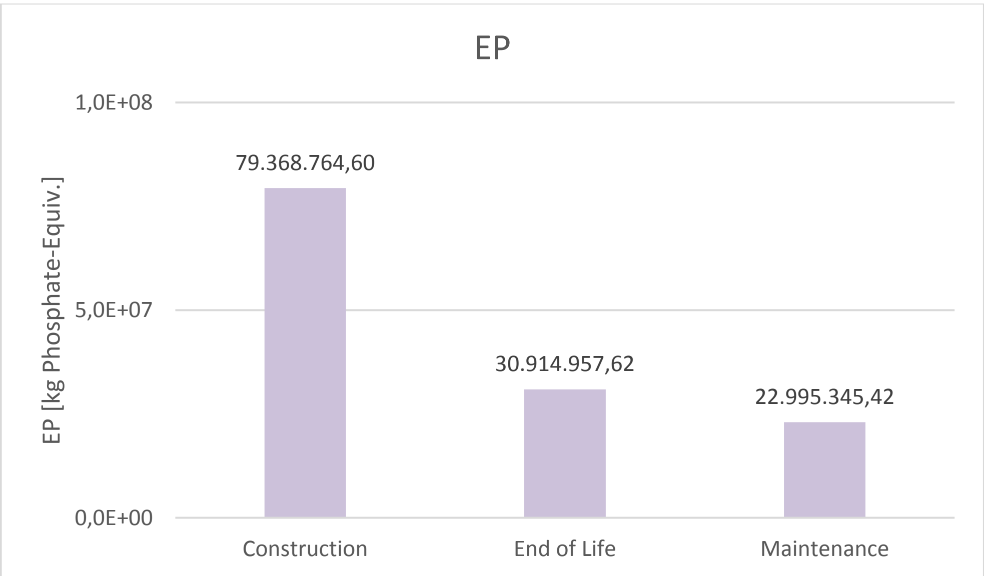



Figure 5.14. EP of Construction, End of Life, Maintenance Phases (Base)

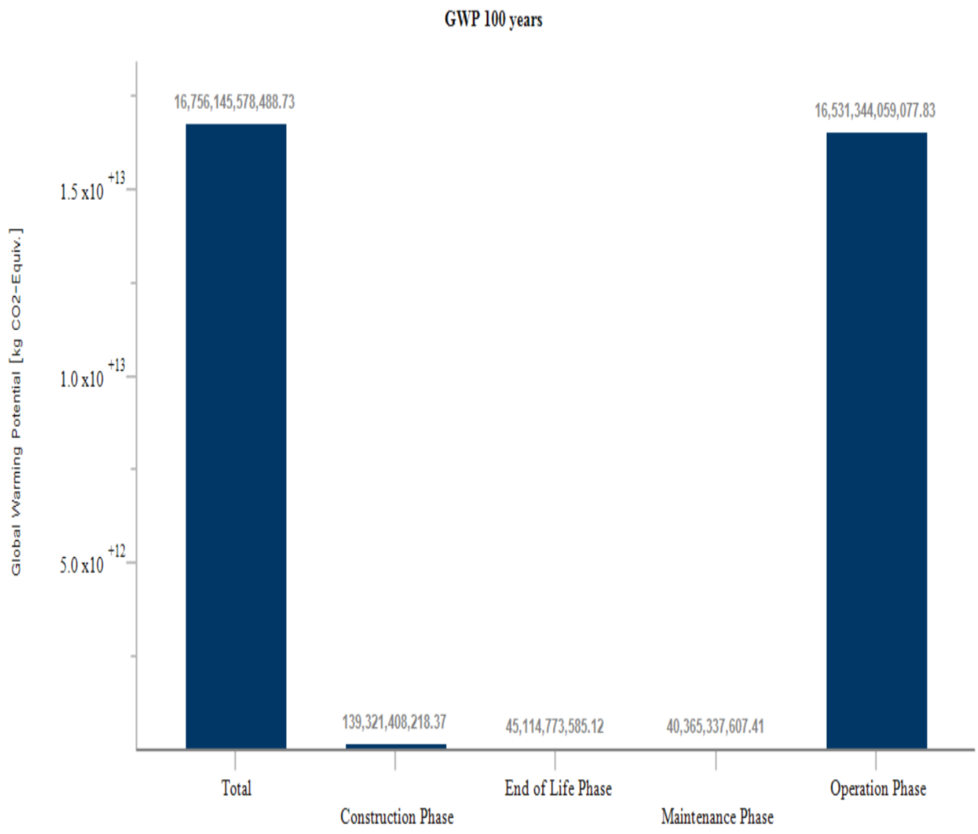



Figure 5.15. Global Warming Potential of Alternative Case

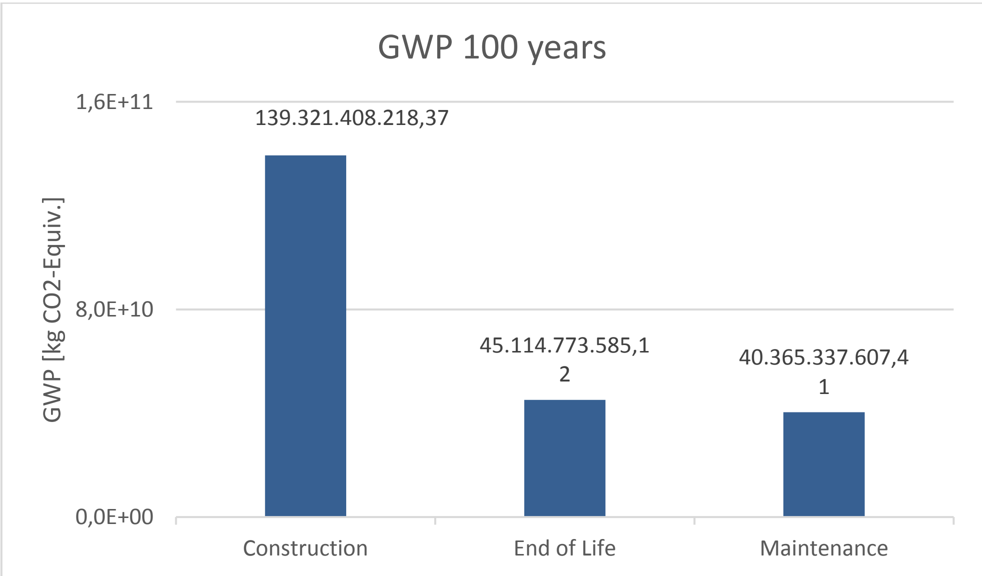



Figure 5.16. GWP of Construction, End of Life, Maintenance Phases (Alternative)

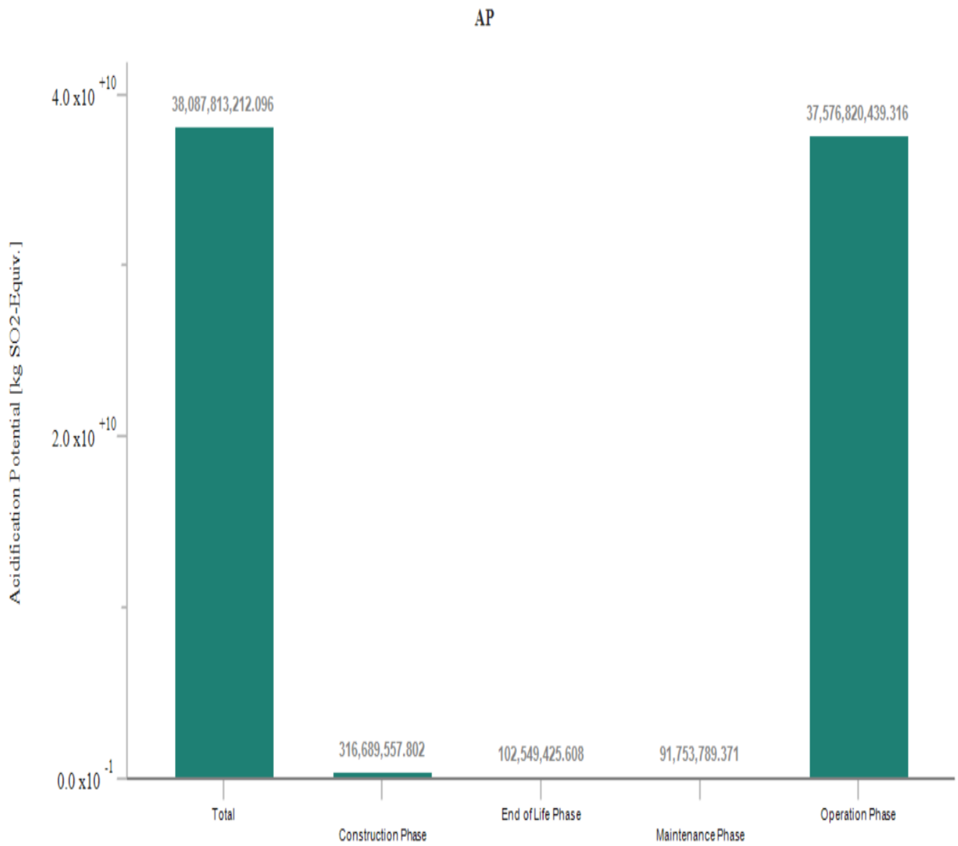



Figure 5.17. Acidification Potential of Alternative Case

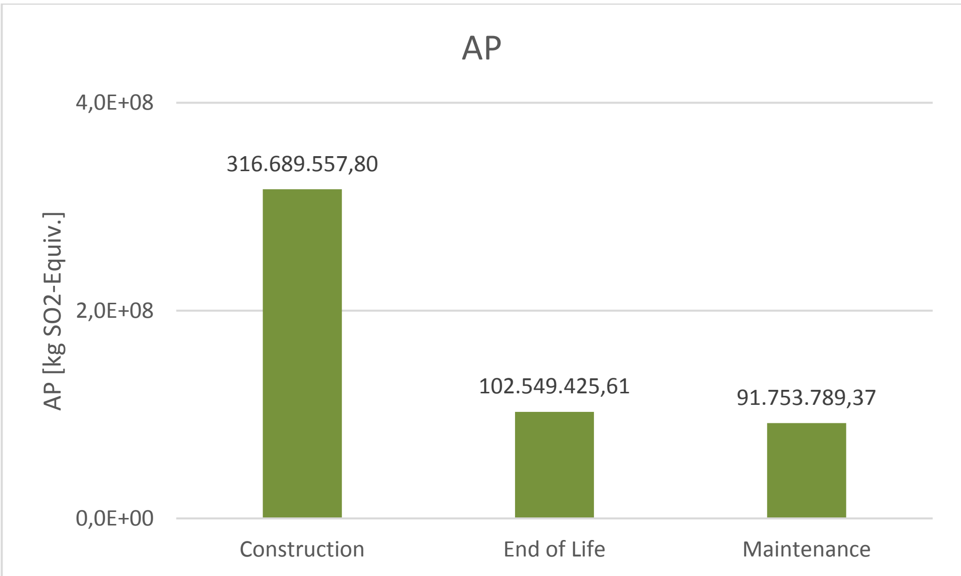



Figure 5.18. AP of Construction, End of Life, Maintenance Phases (Alternative)

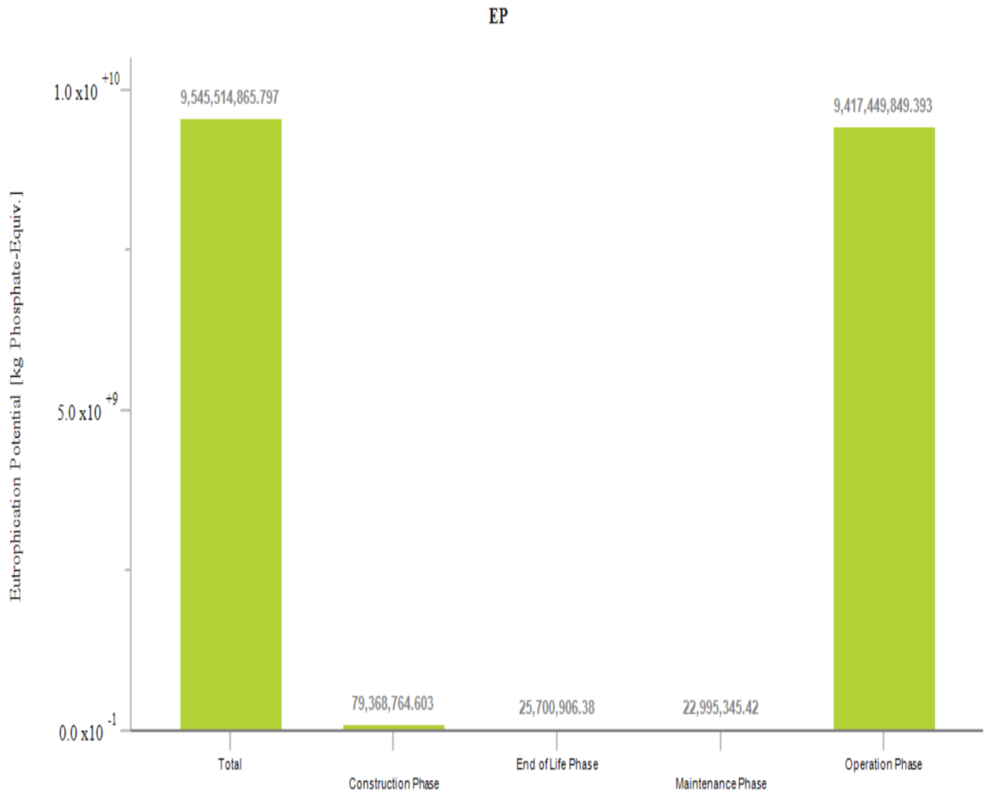



Figure 5.19. Eutrophication Potential of Alternative Case

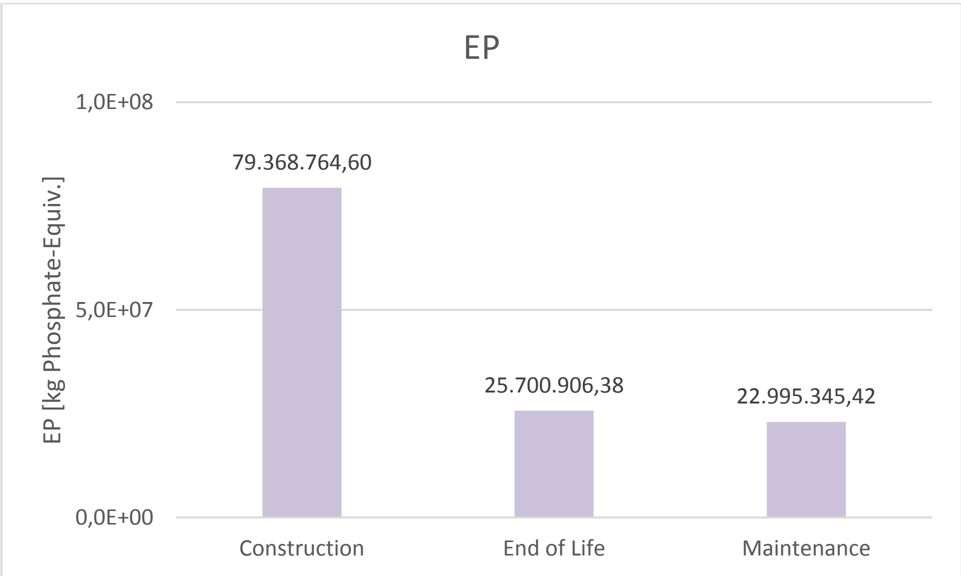



Figure 5.20. EP of Construction, End of Life, Maintenance Phases (Alternative)

Results indicated that operation phase has the highest emissions in both base case and alternative case. After operation phase, emissions of phases from highest to lowest are construction phase, end of life phase, and maintenance phase respectively. End of life phase in base case has higher emissions than end of life in alternative case due to having recycling of concrete in alternative case.

### 5.2.6 Results Interpretation

It is critical to express impact assessment results in terms of functional unit in order to compare different systems. Since aim of this study is to compare emissions of Gökçekaya PSH and Metristepe WPP, it is necessary to express results in terms of functional unit which is 1 MWh for this study.

In order to find environmental burdens of Gökçekaya PSH for 1 MWh, following calculations are carried out.

Capacity factor of 1400 MW Gökçekaya Francis pump-turbine is calculated using equation (6).

$$\text{Capacity Factor} = 100 * \frac{\text{Actual Output}}{\text{Potential Output}} \quad \text{(Neill \& Hashemi, 2018)} \quad (6)$$

$$Capacity\ Factor = 100 * \frac{98550\ MWh}{20\ years * 365\ days * 24\ hours * 1400\ MW} = 0.04\%$$

Total energy production in Gökçekaya PSH (for 20 years) can be calculated using equation (7).

$$1400\ \text{MW} * 20\ \text{years} * 365\ \text{days} * 24\ \text{hours} * 0.04\ (\text{Capacity Factor}) = 9811200\ \text{MWh} \quad \text{(Rosenbloom, 2006)} \quad (7)$$

Total emissions of base case are given in Table 5.4 and total emissions of alternative case are given in Table 5.5 as represented in figures. To find emission results for 1 MWh energy storage, total emissions are divided by 9811200 and final results are shown in Table 5.6. It is revealed that results of base and alternative case are same apart from end of life phase as expected. In the case of end of life phase, emissions are less in alternative case than base case due to recycling of concrete (40%).

Table 5.4 Total Emissions of Gökçekaya PSH (Base Case)

| | GWP | AP | EP | % |
|---|---|---|---|---|
| Construction | 139,321,408,218 | 316,689,558 | 79,368,765 | 0.83 |
| Operation | 16,531,344,059,078 | 37,576,820,439 | 9,417,449,849 | 98.60 |
| Maintenance | 40,365,337,607 | 91,753,789 | 22,995,345 | 0.24 |
| End of Life | 54,267,186,627 | 123,353,855 | 30,914,958 | 0.32 |
| TOTAL | 16,765,297,991,531 | 38,108,617,642 | 9,550,728,917 | 100.00 |

Table 5.5 Total Emissions of Gökçekaya PSH (Alternative Case)

| | GWP | AP | EP | % |
|---|---|---|---|---|
| Construction | 139,321,408,218 | 316,689,558 | 79,368,765 | 0.83 |
| Operation | 16,531,344,059,078 | 37,576,820,439 | 9,417,449,849 | 98.66 |
| Maintenance | 40,365,337,607 | 91,753,789 | 22,995,345 | 0.24 |
| End of Life | 45,114,773,585 | 102,549,426 | 25,700,906 | 0.27 |
| TOTAL | 16,756,145,578,489 | 38,087,813,212 | 9,545,514,866 | 100.00 |

Table 5.6 Emissions of Gökçekaya PSH for 1 MWh

| | GWP (kg $CO_2$-equivalent) | | AP (kg $SO_2$-equivalent) | | EP (kg $PO_4$-equivalent) | |
|---|---|---|---|---|---|---|
| | Base Case | Alt. Case | Base Case | Alt. Case | Base Case | Alt. Case |
| Construction | 14,200.2 | 14,200.2 | 32.3 | 32.3 | 8.1 | 8.1 |
| Operation | 1,684,946.2 | 1,684,946.2 | 3,830.0 | 3,830.0 | 959.9 | 959.9 |
| Maintenance | 4,114.2 | 4,114.2 | 9.4 | 9.4 | 2.3 | 2.3 |
| End of Life | 5,531.2 | 4,598.3 | 12.6 | 10.5 | 3.2 | 2.6 |
| TOTAL | 1,708,791.8 | 1,707,858.9 | 3,884.2 | 3,882.1 | 973.5 | 972.9 |

Operation phase has the highest emissions as expected and summarized in Chapter 3. In this study reasons of highest emissions in operation phase are high amount of electricity consumption in pumping mode of PSH and transportation of electromechanical equipment with diesel truck. Also, it should be noted that used electricity mix from grid in pumping mode causes high amount of emissions. After operation phase, construction phase has high emissions due to high amount of construction material usage. Also, end of life and maintenance phases do not have high emissions compared to both operation and construction phases. In end of life main reason of low emissions is considering primary construction materials instead of considering all materials and in maintenance phase not considering replacement of equipment is the reason of low emissions. Taking 20 years lifetime for PSH is the cause of not considering replacement of equipment in maintenance phase and parallel to scope of the study results are acceptable. In case of considering replacement of machines and equipment, emissions in maintenance phase may be higher than end of life phase.

Since recycling is more environmentally-friendly solution than disposal (landfilling), recycling of concrete in alternative case is investigated by taking 40% recycling and 60% disposal (landfilling) to demonstrate change in emissions. In this study, main focus is determining environmental effects of construction materials in end of life phase. For this purpose, one of the construction materials, concrete is selected to determine change in emissions as a result of recycling. As a result of analyses, it is revealed that emissions of end of life in alternative case are about 17% less than emissions of end of life in base case. Furthermore, in other phases (operation phase, maintenance phase, and construction phase) emissions of base case and alternative case are same in all impact categories (GWP, AP, EP). It can be concluded that 40% recycling of concrete and 60% landfill of concrete reduce end of life emissions about 17% compared to 100% landfilling of concrete.

## 5.3 LCC of Gökçekaya PSH

In this study exchange rate of 20 November 2019 are used and all monetary values are given after conversion to Euro (1$ = 5.7 TL, 1 Euro = 6.3 TL, 1 Euro = 0.9$). When prices belong to past years, they are converted by using online inflation calculator (Brueau of Labor Statistics, n.d.).

LCCA studies are carried out parallel to LCA phases for 20 years lifetime. The following equation is used to calculate total cost of systems:

$$C_{Total} = C_{Initial\ Material} + C_{O\&M} + C_{tr} + C_{EoL} \quad (8)$$

In order to find total cost of PSH, initial material costs of concrete, reinforcement bars, welded steel pipe, membrane, and asphalt are considered. Reason of referring this component as initial material cost is not considering cost of labor and operation cost of construction equipments. Then, costs of generator, reversible Francis turbine, and transformer costs are chosen to consider as electromechanical equipment. In maintenance phase, lubricant oil for generator and for reversible Francis Turbine are taken into account. Furthermore, in operation phase, required electricity cost to store water in power plant is considered (Ma et al., 2014). Finally, in end of life phase cost of landfill (disposal) of concrete, ribbed bar, and asphalt are taken into account. In addition, for cost calculation of end of life phase recycling cost of concrete is taken into account.

Calculation of cost is given in the following in detail.

1. Cost of concrete (39.68 €/m$^3$) (Küpeliler C., personal communication, November 11,2019), reinforcement bars (469.84€/ton) (Abaklılar R., personal communication, November 11,2019), welded steel pipe (720 €/m) (Akmermer P., personal communication, November 11,2019), and asphalt (46.34 €/ton) (Esfalt A., personal communication, November 11,2019) are obtained from manufacturing companies.

2. Cost of wet area membrane is taken as 5.52 €/m$^2$ from supplier website (Istanbulteknik.blue, n.d.).

3. Cost of excavation of upper reservoir and powerhouse are taken as 15.48 €/$m^3$ (Planning, 2019).

4. Electricity consumption cost is taken as 56.35 €/MWh during operation phase (Barbaros, 2019).

5. Maintenance phase consists of two types of cost of oil for lubrication of turbine (554.66 €/barrel) and generator (18.61€/bottle). Costs are taken from suppliers website (Oil Markt, n.d.).

6. To find cost of transformer, motor-generator capacity is used as capacity of transformer (525 MW) due to not having transformer capacity in JICA report. Details of 500 MW transformer such as its cost ($5,000,000.00 in 2011) its weight (325 tons) are taken from electrical engineering website (Csanyi, 2013). Then, price manipulations are carried out by using inflation calculator (Brueau of Labor Statistics, n.d.). As a result of these calculations, it is found that price of 500 MW transformer is $5,840,000.00 having weight of 325 tons. It is assumed that transformer price and transformer weight linearly proportional to capacity of transformer, therefore; price of 525 MW makes 6,132,000.00$ (5,518,800.00€) with weight 341.25 tons.

7. *Cost of Reversible Francis Turbine*

Cost of reversible Francis turbine is calculated using the formula in (Alzohbi, 2018).

$$\text{Cost}\ (\text{M}_{\text{euro}}) = 13.39 * \text{P}^{0.5825}(\text{MW}) * \text{H}^{-0.3359}\ (\text{m}) \qquad \text{(Alzohbi, 2018)} \quad (9)$$

Power of turbine (P) is taken as 350 MW and turbine head (H) is taken as 380 m in equation (9).

$$\text{Cost}\ (\text{M}_{\text{euro}}) = 13.39 * 350^{0.5825}(\text{MW}) * 380^{-0.3359} = 55.2269301\ \text{M}_{\text{euro}}$$
$$= 55{,}226{,}930.1€ * 4\ (\text{Units}) = 220{,}907{,}720.40\ €$$

8. *Cost of Generator*

Since properties of required 525 MW generator is not specified in JICA report, an available model of (APD 2100 M) diesel generator is selected which has 1.5 MW power to use and cost of it taken from authorized officer of producer company (Wang, Lam, Hsu, & Chen, 2019).

In order to calculate reliable approximation to generator cost, linear approach is not used, instead, nonlinear approach is used. The formula in the original study is used to scale processes of power plants and most common scale factor (n=0.6) for energy plants are used. Equation (10) is taken from (Wang et al., 2019).

$$C_2 = C_1 * (\frac{S_2}{S_1})^n \qquad (10)$$

Where $C_1$ is known input process, $C_2$ is required input process, $S_1$ is size of first process (process which information is known), $S_2$ is second process (which information is required to find), and n is scale factor.

In this study, $C_1$ and $C_2$ values are used as cost values, $S_1$ and $S_2$ are used as power value of generators.

$$\mathrm{C}_2 = 313{,}529.40€ * (\frac{525}{1.5})^{0.6}$$

In conclusion, 525 MW generator cost is found as 10,537,051.39 €.

9. Transportation unit cost (by truck) is taken as 0.077$/ton-km (0.07 €/ton-km) based on study carried out by (Panesar et al., 2019). Transportation cost details are given in Table 5.7.

Table 5.7 Transportation Cost Details

| | **Total Amount (ton)** | **Distance(km)** | **Unit cost (€)** | **Total cost (€)** |
|---|---|---|---|---|
| Concrete | 167639 | 66.9 | 0.07 | 785,053.37 |
| Reinforcement Bar | 38140.6 | 73.1 | 0.07 | 195,165.48 |
| Asphalt | 312000 | 73.8 | 0.07 | 1,611,792.00 |
| Welded Steel Pipe | 880.479 | 194 | 0.07 | 11,956.90 |
| Wet Area Membrane | 135 | 380 | 0.07 | 3,591.00 |
| | | Transportation Cost (Total) | | 2,607,558.74 |

10. Cost of landfilling (disposal) for main construction materials: concrete, asphalt, and reinforcement bars are taken as 0,4 €/ton based on private communication with factory (Anket A.Ş., personal communication, November 13,2019).

For alternative case, 40% of concrete is recycled and 60% of concrete is landfilled. Cost of concrete recycling is taken as 28$/ton in 2018 and using inflation calculator (Brueau of Labor Statistics, n.d.) it becomes 25.8 €/ton ("Riverside Recycling Facility," 2018).

Total cost of Gökçekaya PSH and its components are given in Table 5.8 while cost of end of life phase of alternative case is given in Table 5.9. Also, cost summary of Gökçekaya PSH is shown in Table 5.10.

Table 5.8 Total Cost and Components of Gökçekaya PSH

| ***Construction of Powerhouse Phase*** | | | |
|---|---|---|---|
| **Name of Material** | **Unit** | **Quantity** | **Cost (€)** |
| Concrete | $m^3$ | 377913.4 | 14,996,563.49 |
| Reinforcement Bars | ton | 6993.47 | 3,285,820.83 |
| Excavation of Powerhouse | $m^3$ | 266000 | 4,118,777.78 |

Table 5.8 (continued)

| | | | |
|---|---|---|---|
| | **Construction of Powerhouse Total** | | 22,401,162.10 |
| ***Construction of Pipes Phase*** | | | |
| **Name of Material** | **Unit** | **Quantity** | **Cost (€)** |
| Concrete | $m^3$ | 320561.177 | 12,720,681.63 |
| Reinforcement Bars | ton | 31147.135 | 14,634,209.46 |
| Welded steel pipe | m | 2496 | 1,797,120.00 |
| | **Construction of Pipes Total** | | 29,152,011.09 |
| ***Construction of Upper Reservoir Phase*** | | | |
| **Name of Material** | **Unit** | **Quantity** | **Cost (€)** |
| Membrane | $m^2$ | 500000 | 2,760,317.46 |
| Asphalt | ton | 312000 | 14,460,952.38 |
| Excavation of Upper Reservoir | $m^3$ | 10310000 | 159,641,349.21 |
| | **Construction of Upper Res. Total** | | 176,862,619.05 |
| ***Electromechanical Equipments*** | | | |
| **Name of Machine** | **Unit** | **Quantity** | **Cost (€)** |
| Generator | number | 1 | 11,707,834.87 |
| Francis Pump-Turbine | number | 1 | 220,907,720.40 |
| Transformer | number | 1 | 5,518,800.00 |
| | **Electromechanical Equipments Total** | | 238,134,355.27 |
| ***Maintenance Phase*** | | | |
| **Name of Material** | **Unit** | **Quantity** | **Cost (€)** |
| Generator oil (as lubricant) | number of bottle | 7411112 | 170,290,884.62 |
| Turbine oil (as lubricant) | number of barrel | 2503579 | 1,388,635,922.93 |
| | **Maintenance Phase Total** | | 1,558,926,807.55 |
| ***End of Life Phase*** | | | |
| **Name of Process** | **Unit** | **Quantity** | **Cost (€)** |
| Concrete | ton | 167638.985 | 66,523.41 |
| Reinforcement Bars | ton | 38140.60516 | 15,135.16 |

Table 5.8 (continued)

| | | | |
|---|---|---|---|
| Asphalt | ton | 312000 | 123,809.52 |
| | **End of Life Total** | | 205,468.09 |
| ***Operation Phase*** | | | **Cost (€)** |
| Electricity consumption | | | 7,774,500.00 |
| ***Transportation Cost*** | | | |
| **Name of Process** | **Unit** | **Quantity** | **Cost (€)** |
| Concrete | ton | 167638.99 | 785,053.37 |
| Reinforcement Bar | ton | 38140.61 | 195,165.48 |
| Asphalt | ton | 312000 | 1,611,792.00 |
| Welded Steel Pipe | ton | 880.4786 | 11,956.90 |
| Wet Area Membrane | ton | 135 | 3,591.00 |
| | **Transportation Total** | | 2,607,558.74 |
| | | **TOTAL** | 2,036,064,481.89 |

Table 5.9 Cost in End of life of Alternative Case

| Alternative Case | Unit | Quantity | Cost (€) |
|---|---|---|---|
| Concrete landfill (60%) | ton | 100583.391 | 40,233.36 |
| Concrete recycle (40%) | ton | 67055.594 | 1,730,034.33 |
| | **Concrete EoL Total** | | 1,770,267.68 |

Table 5.10 Total Cost of Base and Alternative Case of Gökçekaya PSH

| Components of Cost | Cost (€) |
|---|---|
| **Construction Cost of Powerhouse** | 22,401,162.10 |
| **Construction Cost of Pipes** | 29,152,011.09 |
| **Construction Cost of Upper Reservoir** | 176,862,619.05 |
| **Cost of Electromechanical Equipment** | 238,134,355.27 |
| **Operation Cost** | 7,774,500.00 |
| **Maintenance Cost** | 1,558,926,807.55 |
| **Transportation Cost** | 2,607,558.74 |
| **End of Life Cost** | 205,468.09 |
| **End of Life Cost (Alternative)** | 1,909,212.36 |
| **Total Cost** | 2,036,064,481.89 |
| **Total Cost (Alternative)** | 2,037,768,226.16 |

After calculation of total cost, it is necessary to find total incomes of PSH due to electricity production in 20 years lifetime. Since electricity generation time span is 5 hours and pumping time span is 7 hours, 1 cycle includes 12 hours which means 2 cycles occur in a day. In total 73000 hours electricity generation is obtained in 20 years. Electricity production cost assumed as 56.35 €/MWh and in 1 hour 1.35 MW electricity production assumed (Barbaros, 2019). As a consequence, total income of Gökçekaya PSH is found 5,553,214.59 €.

Present value of total expenses and incomes are found. In order to compare their values after 20 years, it is necessary to find their future value.

Equation (11) is used to find future values (20 years lifetime) (Consulting, 2006).

$$\text{Present Value} = \frac{\text{Future Value}}{(1+d_{real})^n} \qquad (11)$$

(Where n is number of years, $d_{real}$ is the discount rate (including effect of inflation))

Equation (12) is used to find discount rate including effect of inflation:

$$d_{real} = \frac{1+i}{1+a} - 1 \qquad (12)$$

(Where a is inflation rate and i is interest rate)

In equation (11), average interest rate of Euro (i) is taken as 1.84% (“Fxempire,” 2020) for years between 1998 and 2020. Inflation rate of Euro is taken as 1.6% according to The World Bank (“The World Bank,” 2020).

$$d_{real} = \frac{1+0.0184}{1+0.016} - 1 = 0.00236$$

It is possible to find future value of expenses of a project (i.e. at the end of life time, 20 years later) by using equation (10).

$$2{,}036{,}064{,}481.89 = \frac{\text{Future Value}}{(1+0.00236)^{20}}$$

Future Value = 2,134,352,155 € (Future value of expenses)

For incomes due to storage of electricity, same formula (equation 10) can be utilized.

$$5{,}553{,}214.59 = \frac{\text{Future Value}}{(1 + 0.00236)^{20}}$$

Future Value = 5,821,286.92 € (Future value of incomes)

$$\text{Future Value of Expenses} - \text{Future Value of Incomes} = 2{,}128{,}530{,}868\ € \quad (13)$$

When equation (13) is interpreted, it is revealed that Gökçekaya PSH cannot compansate its initial investments in 20 years lifetime.

## 5.4 Results and Discussion

Gökçekaya PSH is planned to construct utilizing existing Gökçekaya Dam as lower reservoir and construction of upper reservoir is required. After specifying scope of the study, system boundary of the PSH is specified and impact assessment results are obtained. When impact assessment results are interpreted it is revealed that operation phase has the highest emissions in three impact categories: GWP, AP, and EP. It is known that cement is one of the components of concrete and causes emissions of $CO_2$, $CH_4$, and $SO_2$. The highest contribution of cement is to GWP and cement also cause acidification due to realeasing $SO_2$. In addition, aggregate in concrete causes eutrophication due to emission of both $PO_4$ and $NH_3$. Moreover, despite having less emissions compared to concrete, asphalt has contribution to GWP. From construction materials steel increase emissions in GWP and in Gökçekaya PSH welded steel pipes are highly used. Although construction materials are the main reason of the emissions in construction phase, the highest emissions are in operation phase due to using electricity grid mix to pump water from lower reservoir to upper reservoir. Also, it should be highlighted that lubricants in maintenance phase contribute to eutrophication because of releasing them to water without control. Since in transportation diesel trucks are used and they release CO, HC, and $NO_x$ gasses, they cause increase in GWP and AP significantly. Lastly, it should be emphasized that landfilling (disposal) of construction materials especially concrete cause increase in emissions in GWP impact category.

One of the precautions to reduce emissions in operation phase can be using more environmentally-friendly electricity sources such as wind to pump water for storage instead of using electricity grid mix. Increasing rate of recycling and recycling of more material in end of life phase may be the ways to decrease emissions. Using today’s technology, it does not seem possible to reduce emissions in construction and maintenance phase. Although it is not possible now, it may be possible in coming years due to developments in technology.

Economical feasibility study of Gökçekaya PSH is revealed that the PSH cannot compensate its investments in 20 years. Besides, it is known that construction of PSH is expensive and this is one of the disadvantages of PSH construction as described in section 3.4. Although PSH cannot compensate its investments in 20 years and have lower income than expenses, the PSH can make a profit in longer lifetime studies. Also, it should be noted that electricity consumption and production prices are taken as same in this study. However, PSH consumes electricity in off-peak hours when prices are lower and PSH generate electricity in peak hours when prices are higher as previously stated in Chapter 5. Although this causes a slight difference in short life time span, it may cause greater difference in longer life time span. This is one of the limitations in this study. In conclusion, construction of Gökçekaya PSH might be more feasible for longer lifetime.

CHAPTER 6

# LCA and LCC OF METRISTEPE WPP

## 6.1 Site Selection and Description

In order to carry out LCA of a wind power plant, Metristepe WPP is selected for this thesis due to being close to Gökçekaya PSH. Metristepe WPP is located in Metristepe Martyrs Memorial, Bozüyük, Bilecik which is the best place of the city to install a WPP due to being mountainous and having high wind speed. Location of the Metristepe WPP is shown in Figure 6.1.

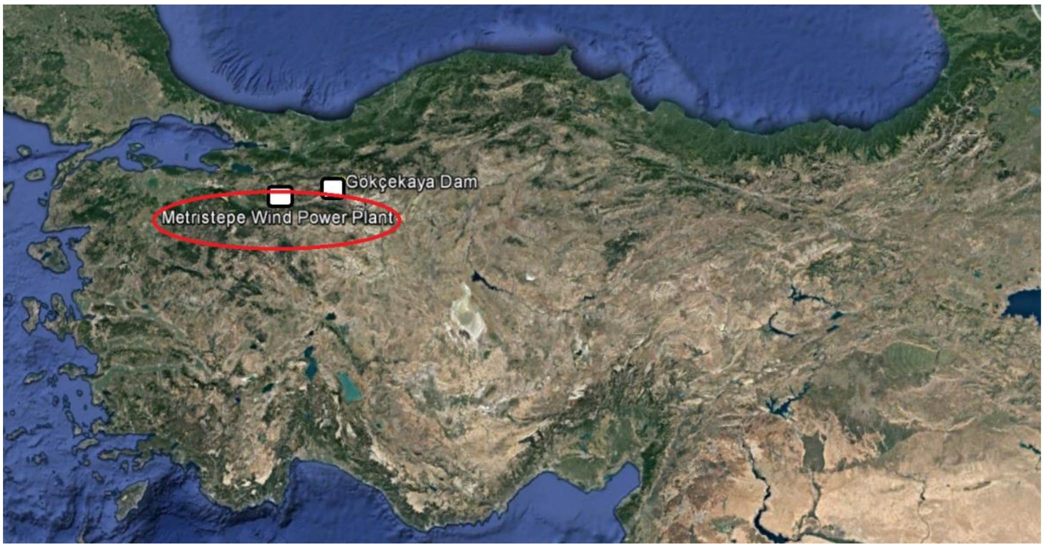



Figure 6.1. Location of Metristepe WPP (“Google Earth Pro,” n.d.-b)

Metristepe WPP was installed in 2011 by Can Energy and general properties of the WPP are given in Table 6.1.

Table 6.1 General Properties of Metristepe WPP (Baskaya, 2017)

| | |
|---|---|
| **Number of Wind Turbines** | 16 |
| **Turbine Type** | Nordex N100/2500 |
| **Nominal Power of Each Turbine** | 2.5 MW |
| **Nominal Power of the Wind Farm** | 40 MW |
| **Hub Height** | 80 m |
| **Rotor Diameter** | 99.8 m |
| **Average Annual Electricity Generation** | 104691.192 MWh |

## 6.2 Methodology

LCA method which is described in Chapter 2 is used to determine environmental burdens of Metristepe WPP and ISO 14040/ISO 14044 are utilized to carry out LCA. In addition, to study economic feasibility of the WPP, LCCA method is applied.

### 6.2.1 Goal and Scope

As previously stated in Chapter 5, main purpose of this study is to find environmental burdens of both Gökçekaya PSH and Metristepe WPP and to compare their emissions. In this chapter, emissions of Metristepe WPP are found by using GaBi software. Although Metristepe WPP was constructed in 2011, LCA of Metristepe WPP has not been carried out yet. It is important to determine emissions and to carry out an economic feasibility of the WPP in order to compare it with Gökçekaya PSH.

### 6.2.2 System Boundary

In this study, main focus is construction; therefore, raw material extraction has not been taken into consideration and it is assumed that construction materials and other equipment are taken from manufacturer as assumed in Chapter 5 for Gökçekaya PSH (Demir & Taskin, 2013; Kapila et al., 2019). System boundary of each phase is shown in Figure 6.2. In addition, functional unit is taken as 1 MWh and after finding total emissions of the system for considered lifetime, all emissions are expressed for 1 MWh electricity production.

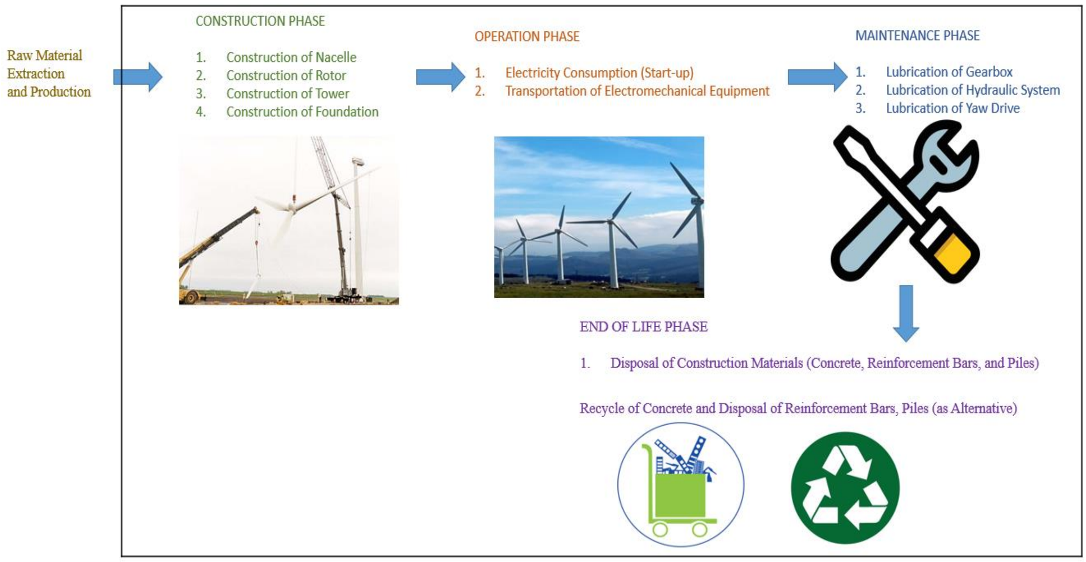



Figure 6.2. System Boundary

Assumptions are summarized in the following.

1. Transmission lines and grid connections are not included in the boundary (Alsaleh & Sattler, 2019).

2. Lifetime of each turbine in Metristepe WPP is taken as 20 years and transportation of materials are considered (Alsaleh & Sattler, 2019; Demir & Taşkin, 2013).

3. For transportation, diesel powered Euro 5 truck in GaBi is used.

4. Electricity mix of Germany is used due to absence of electricity mix of Turkey in GaBi education database. It is known that electricity mix of German is cleaner compared to Turkey, results might change when electricity mix of Turkey is used, therefore; this is one of the limitations of this study.

5. All materials and equipment are assumed to taken from Turkey Branch Office, when equipment are bought from companies located in abroad. Hence, factories and brands located in Turkey are utilized.

6. Since replacement of turbine moving parts such as generator, gearbox, and rotors is generally carried out at the end of 20 years (lifetime) is considered, replacement of equipment and parts are not taken into account in this study (Alsaleh & Sattler, 2019).

7. It is assumed that electricity consumption of turbines are 1% of the electricity generation of turbines (Guezuraga, Zauner, & Polz, 2012).

8. Main concern in cut-off criteria is weight of each component with respect to total weight of turbine (components which have high weight portion in total weight are taken into account) (Martínez et al., 2009).

9. Surface treatment of tower is not considered in this study (Martínez et al., 2009).

10. It is assumed that linear relationship exists between power and material quantity. Also, 0.5 kWh/kg energy is consumed to assembly components (assembly place is assumed as wind farm site) (Schreiber et al., 2019).

### 6.2.3 Phases of LCA

Primary data of Metristepe WPP such as dimensions of foundation, amount of lubrication oil, and properties of turbines are taken from the Nordex Technical Specification for N100/2500 Wind Turbine (Zander, 2014). When primary data are not available, available data from literature and Eco invent database in GaBi software are utilized as secondary data. LCA phases are described in following parts.

#### 6.2.3.1 Construction Phase

To construct a wind turbine, required parts can be given as nacelle (bed frame, nacelle cover, generator, main shaft, gearbox, and other auxiliary parts), rotor (hub, blades, and rotor shaft), tower (tubular steel tower), and foundation (bored pile). Required data about material types and amounts are taken from Nordex (Zander, 2014) and a study with 2 MW turbine (Martínez et al., 2009). Furthermore, 0.5

kWh/kg energy consumption is taken into account to assemble parts of turbine (Schreiber et al., 2019). Since parts such as nacelle, rotor, and tower are assumed to be taken from a factory, only their transportation and assembly is considered. Construction phases such as excavation, pile installation (used piles have 20 m depth and each piles has 0.8 m diameter), reinforcement preparation, and casting concrete are taken into account for foundation. Amount of required materials and material components of equipment are given in Table 6.2.

Table 6.2 Amount and Components of Turbine Materials

| **Construction Phase** | | | | |
|---|---|---|---|---|
| | Material 1 | Material 2 | Material 3 | TOTAL (Tons) |
| **Nacelle Parts** | | | | |
| Bed Frame | iron | | | 210 |
| Nacelle Cover | fiberglass (16 t) | resin (24 t) | | 40 |
| Main Shaft | steel | | | 122 |
| Generator | Silica (4.8 t) | Copper (49.28 t) | Steel (105.92 t) | 160 |
| Gearbox | iron (160 t) | Steel (160 t) | | 320 |
| Other Parts (Auxiliary Systems) | Steel | | | 604 |
| **Rotor Parts** | | | | |
| Rotor Hub | cast iron | | | 457.6 |
| Blades | Glass reinforced plastic | | | 537.6 |
| Rotor Shaft | Steel | | | 164.8 |
| **Tower** | Tubular steel tower | | | 4960 |
| **Foundation** | | | | |
| Pile | Steel | | | 30863 |
| Reinforcement | Steel | | | 840 |
| Concrete | | | | 16819.2 |

#### 6.2.3.2 Operation Phase

In operation phase of WPP, start up electricity of wind farm is taken into consideration for 20 years. It is known that annual average electricity generation of power plant is 104691192 kWh/year (Baskaya, 2017) and it is assumed that electricity consumption of turbines are 1% of the electricity generation of turbines (Guezuraga et al., 2012). Hence, start-up electricity of wind turbine for 20 years is found as 20938238.4 kWh. In addition, transportation of transformer (silica (2.98 tons), copper (30 tons), and steel (66 tons)) is considered in this phase due to being external (not locating in nacelle). Also, generator is not included in this phase due to being located in nacelle.

#### 6.2.3.3 Maintenance Phase

Maintenance phase includes lubrication of gearbox (52800 litter), hydraulic system (720 litter), and yaw drive (2016 litter). Amount of lubrication oil are taken from Nordex turbine for 20 years (Zander, 2014). In addition, lubrication frequency of all turbine parts is taken as 3.2 years (Coronado & Wenske, 2018). Since replacement of turbine moving parts such as generator, gearbox, and rotors are generally carried out at the end of 20 years and in this study 20 years lifetime is considered, replacement of equipment and parts are not taken into account (Alsaleh & Sattler, 2019).

#### 6.2.3.4 End of Life Phase

In end of life phase, disposal (landfilling) of main construction materials: concrete, reinforcement bars, and piles are considered in this research. Also, reinforced concrete is transported to site, after that separation of them carried out by using magnet in the factory.

In order to identify effect of recycling to emissions, recycling of concrete is considered in end of life phase. Therefore, instead landfilling of concrete completely, 60% of concrete is landfilled and 40% of concrete is recycled to use it as aggregate. According to (Tam, 2011), concrete recycling rate can change between 5% - 90% and concrete recycling rate is selected as 40% in this study. Same recycling ratios are used in case of Gökçekaya PSH as given in Chapter 5. Besides, in order to crush concrete, 34 MJ per ton energy consumption is assumed as stated previously in Chapter 5 (Panesar et al., 2019).

Disposal of main construction materials case will be named as base case and case that include recycling of concrete will be named as alternative case in the following sections. In base case, disposal amount (landfill) of concrete is 16819.2 tons, reinforcement bar is 840 tons, and piles are 30863 tons. In case of alternative case, disposal amount (landfill) of concrete is 10091.52 tons, while recycling amount of concrete is 6727.68 tons and both piles and reinforcement bar disposal amounts remain same.

#### 6.2.3.5 Transportation

Transportation is not considered as a phase, instead in each phase transportation is included separately. Transportation distances of materials and equipment are provided in Table 6.3.

Table 6.3 Transportation Distance of Metristepe WPP

| Material or equipment | Unit | Distance |
|---|---|---|
| Concrete | km | 47.3 |
| Reinforcement Bars | km | 42.7 |
| Piles | km | 253.0 |
| Nacelle and Rotor | km | 437.0 |
| Tower | km | 264.0 |
| Transformer | km | 437.0 |
| Gearbox Lubrication Oil | km | 17.1 |
| Hydraulic System Lubrication Oil | km | 17.1 |
| Yaw Drive Lubrication Oil | km | 136.0 |
| End of life company (Anket A.Ş.) | km | 301.0 |

### 6.2.4 Description of GaBi Working Principles for Metristepe WPP

Some necessary terms such as functional unit, process, flow, and plan are described in Chapter 5 (section 5.2.4) and one representative example for each case from Gökçekaya PSH model is presented. In this section, terms and working principles of GaBi is not described again instead an example of each term is presented using GaBi model of Metristepe WPP.

As seen in legend of Figure 6.3, flow and process are shown and as mentioned in Chapter 5 arrows show flows, grey boxes show processes.

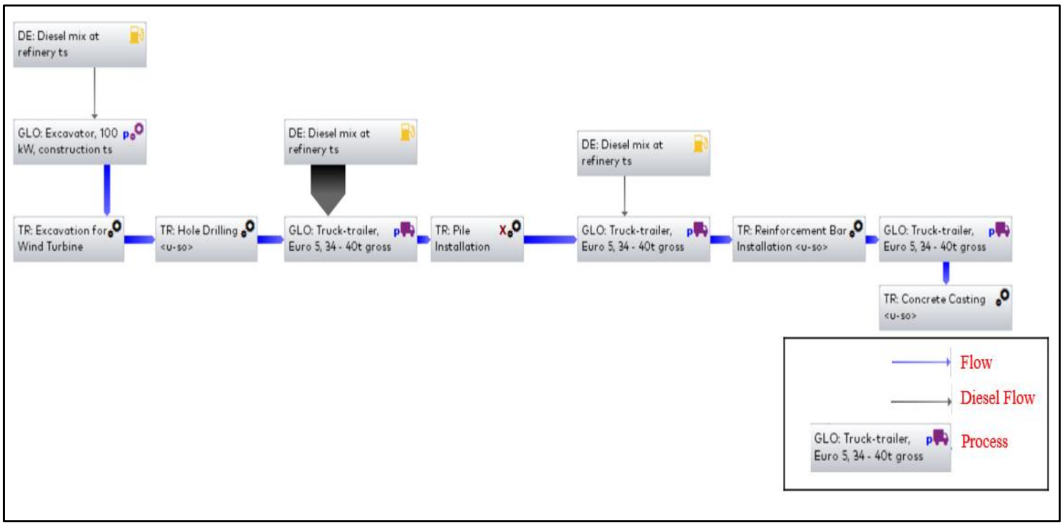



Figure 6.3. Flow Chart of LCA Processes and Established model in GaBi (Foundation Construction of Metristepe WPP)

Construction of foundation, tower, nacelle, and rotor are combined to obtain emissions of construction phase. Plan of construction phase is shown in Figure 6.4 and fixed process is marked with red circle. In addition, all phases of Metristepe WPP are combined in Figure 6.5 to obtain total emissions.


Figure 6.4. Construction Phase of Metristepe WPP (in total)


Figure 6.5. All phases of Metristepe WPP

Each process has a separate tab to enter flow information and pile installation process of Metristepe WPP can be seen in Figure 6.6.

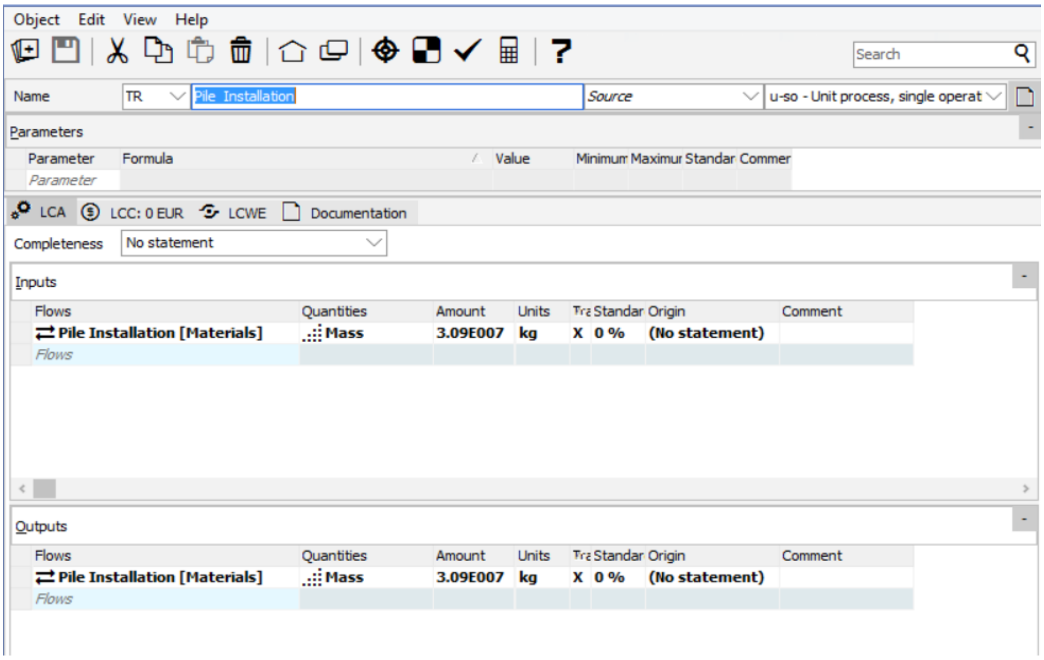



Figure 6.6. Flow of Pile Installation Process (GaBi)

Transportation processes have different data such as distance, pay load capacity. An example of transportation process tab is shown in Figure 6.7.

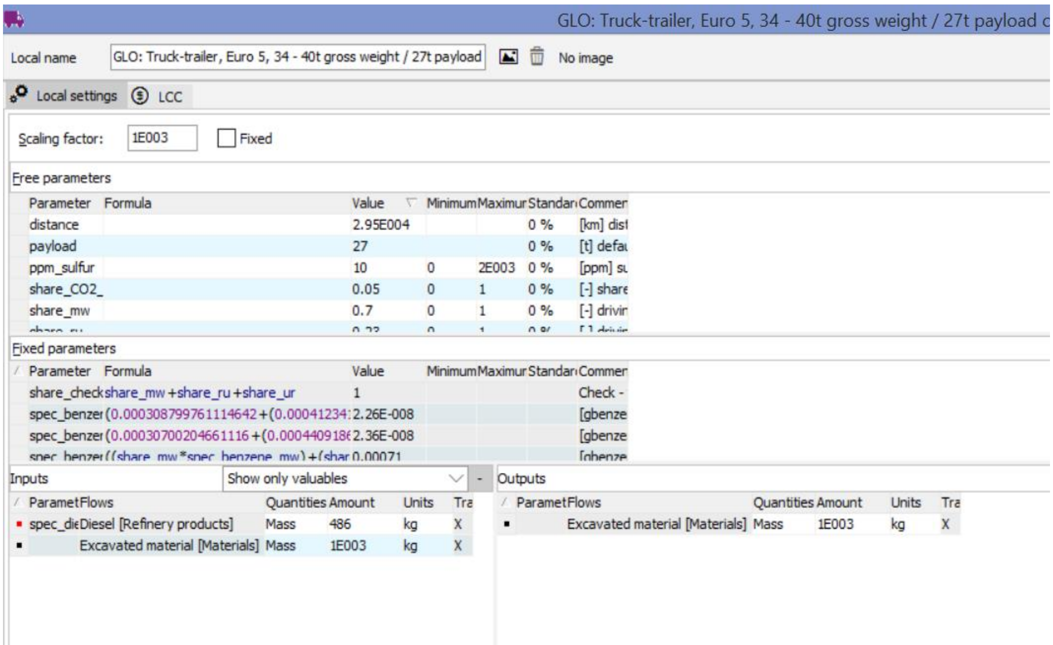



Figure 6.7. Transportation Process of Concrete Casting for Foundation (GaBi)

### 6.2.5 Impact Assessment Results

In this study, impact categories that have significant contribution are taken into account. The most significant three impact categories: Global Warming Potential, Acidification Potential, and Eutrophication Potential are discussed. Definition of these impact categories and substances that cause these emissions were discussed in Chapter 2. In order to investigate effect of recycling on emissions, base case and alternative case are investigated. In base case disposal (landfill) of concrete is considered and in alternative case recycling of concrete (40%) is taken into account. At first, total emissions of base case GaBi graphs (Figure 6.8, Figure 6.10, and Figure 6.12) and then total emissions of alternative case GaBi graphs (Figure 6.14, Figure 6.16, and Figure 6.18) are given. Moreover, emissions of operation, end of life, and maintenance phases are shown separately for each impact category. Base case graphs (Figure 6.9, Figure 6.11, and Figure 6.13) and alternative case graphs (Figure 6.15, Figure 6.17, and Figure 6.19) are shown below total emissions.

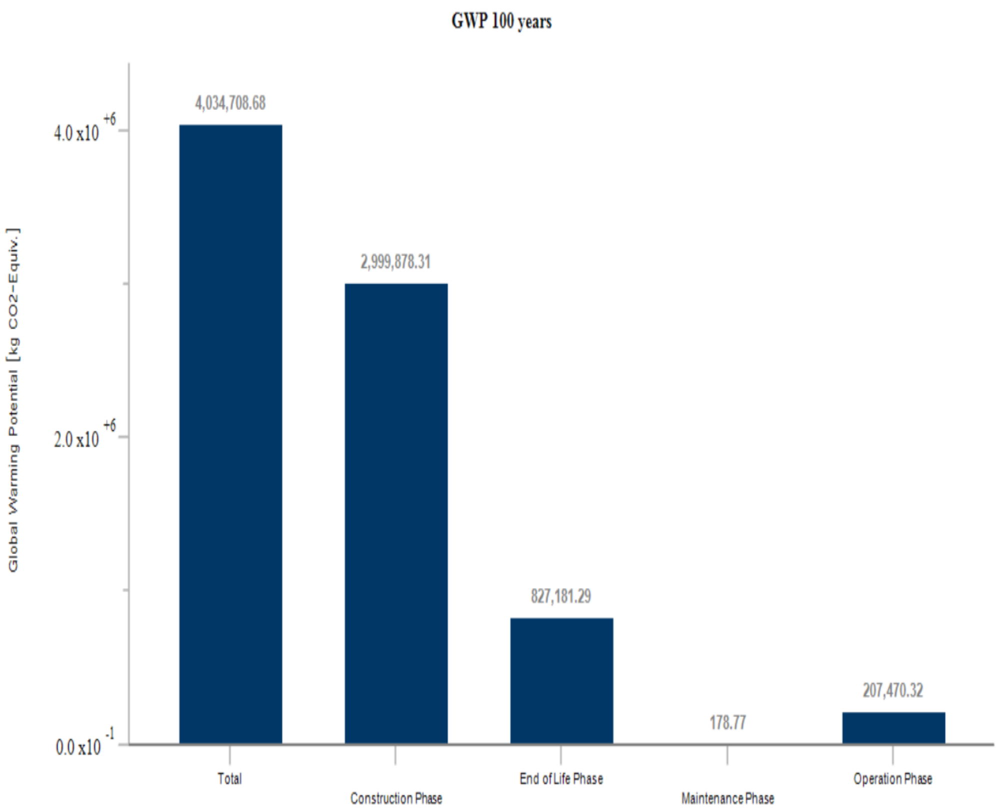



Figure 6.8. Global Warming Potential of Base Case

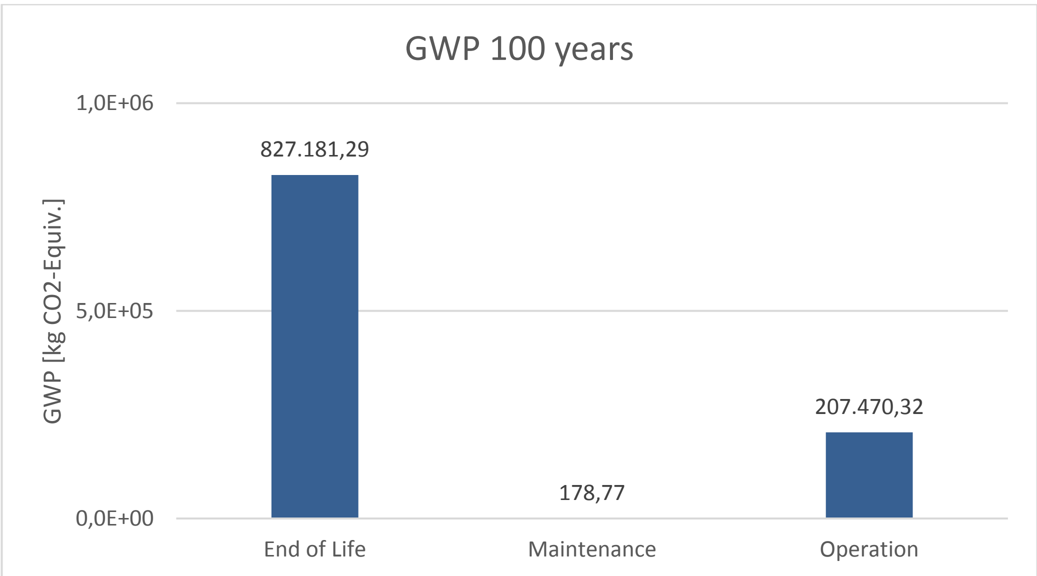



Figure 6.9. GWP of End of Life, Maintenance, and Operation Phases (Base)

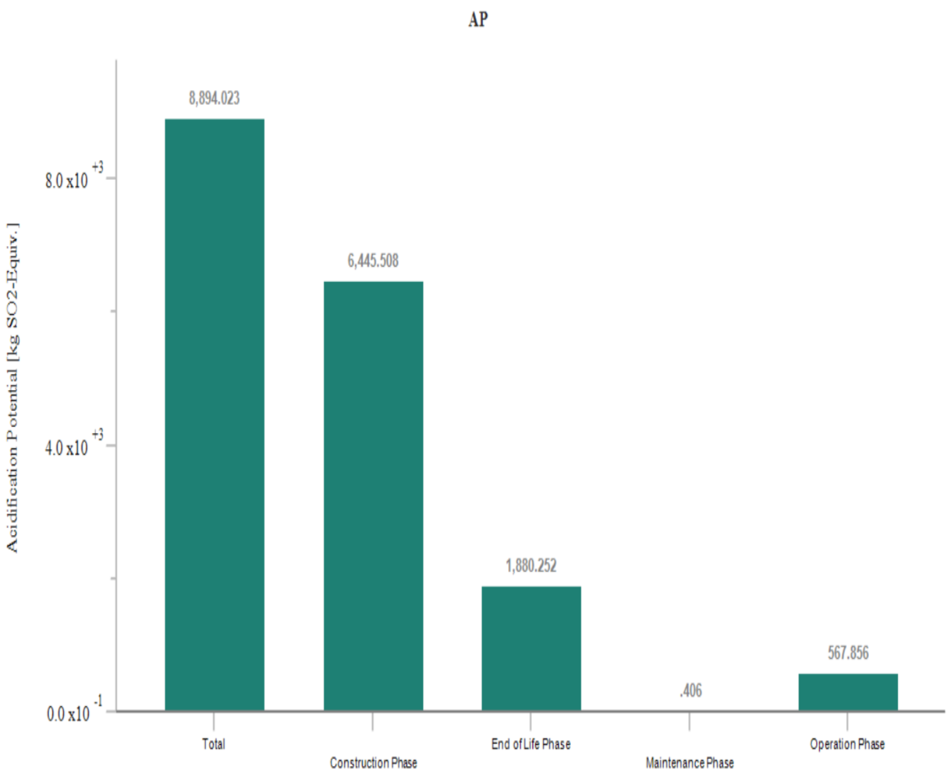



Figure 6.10. Acidification Potential of Base Case

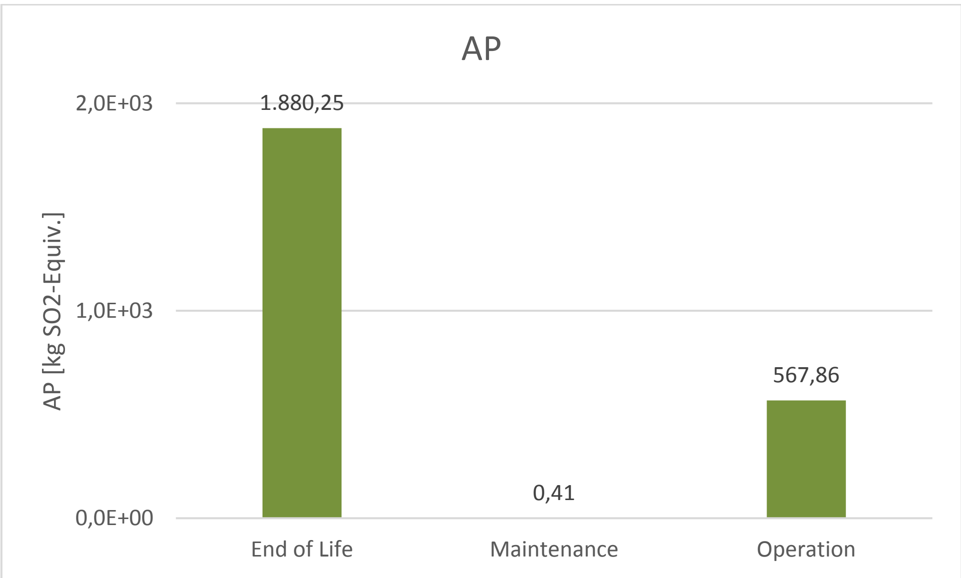



Figure 6.11. AP of End of Life, Maintenance, and Operation Phases (Base)

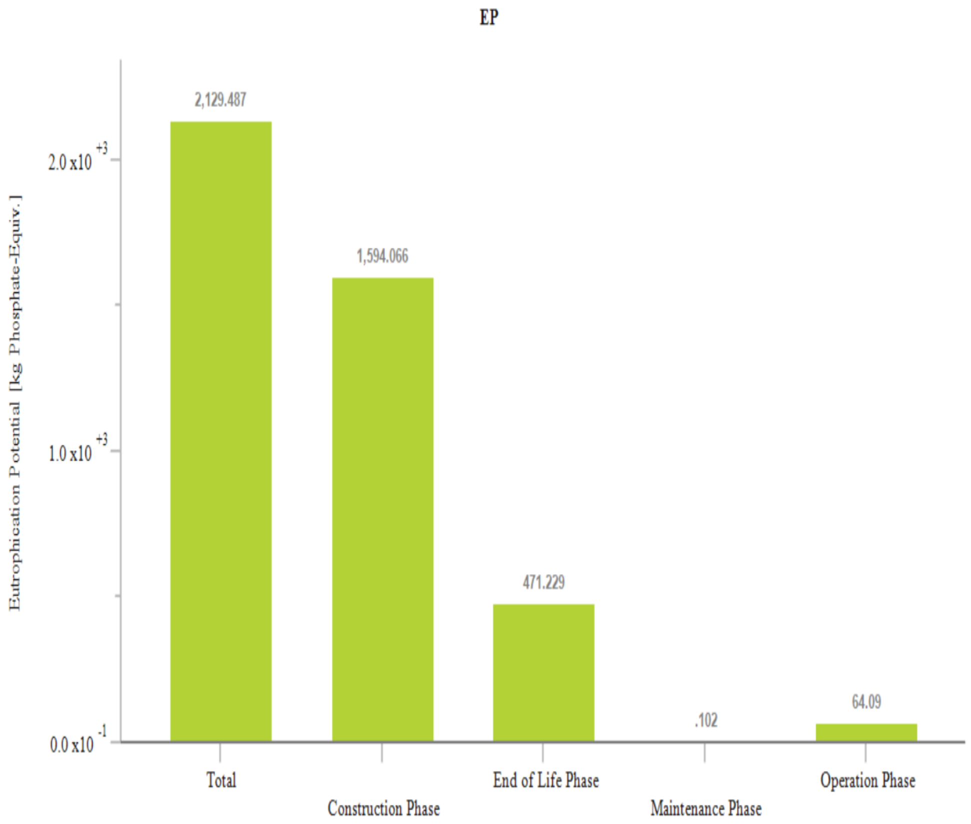



Figure 6.12. Eutrophication Potential of Base Case

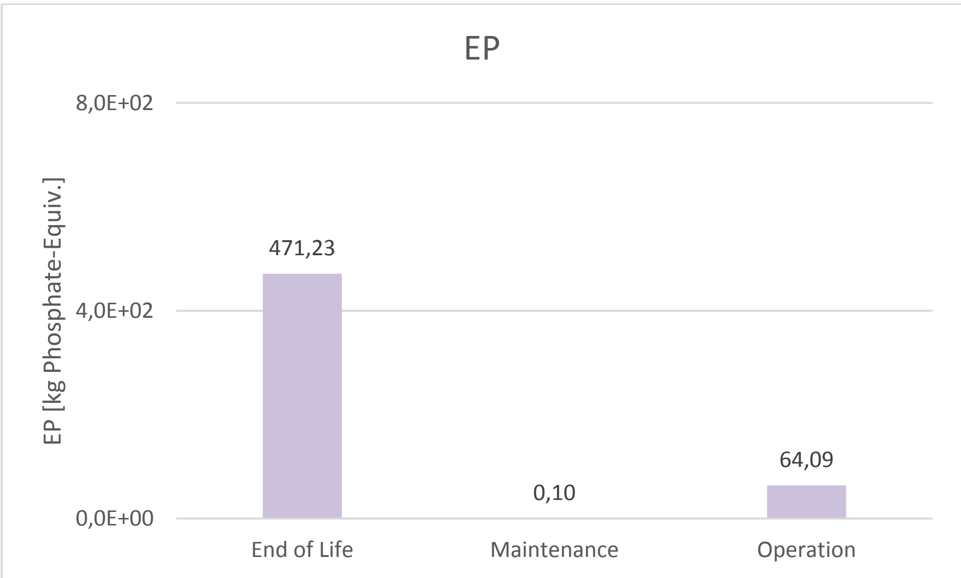



Figure 6.13. EP of End of Life, Maintenance, and Operation Phases (Base)

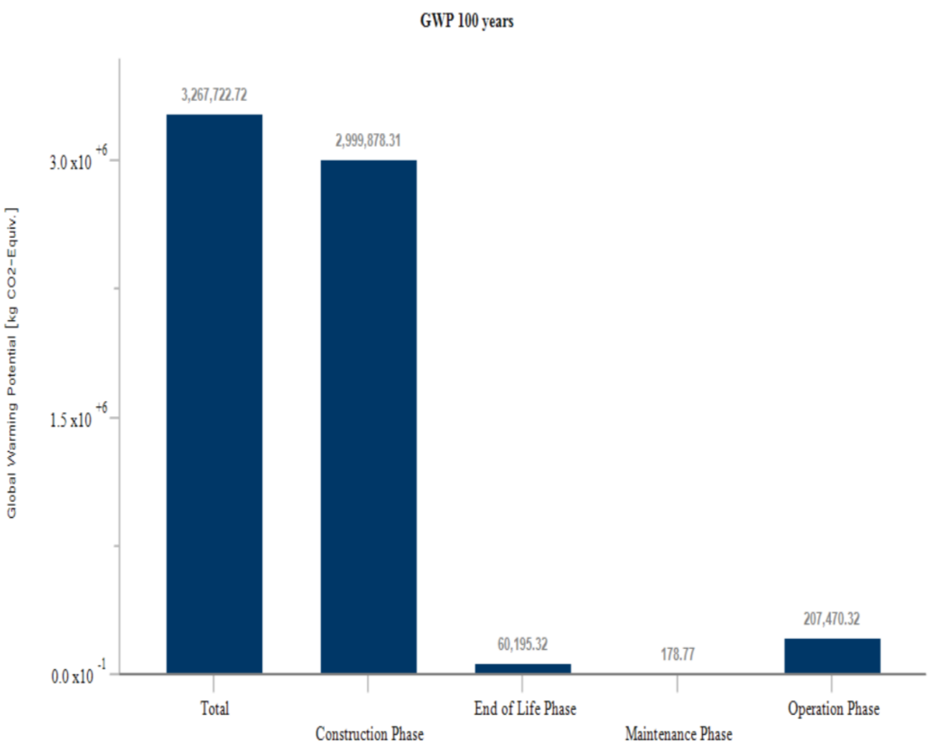



Figure 6.14. Global Warming Potential of Alternative Case

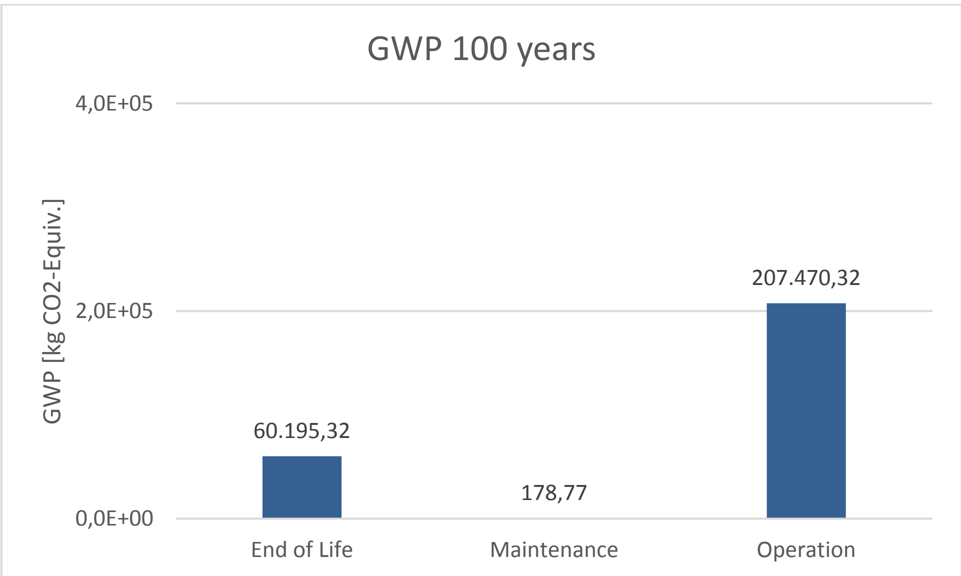



Figure 6.15. GWP of End of Life, Maintenance, and Operation Phases (Alternative)

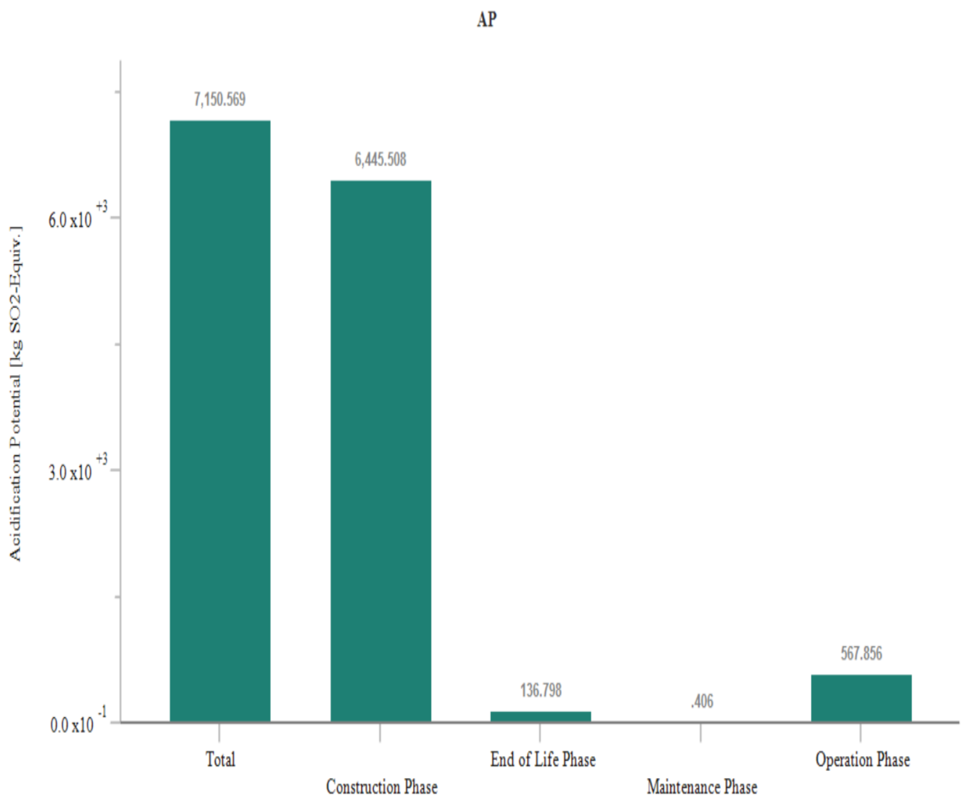



Figure 6.16. Acidification Potential of Alternative Case

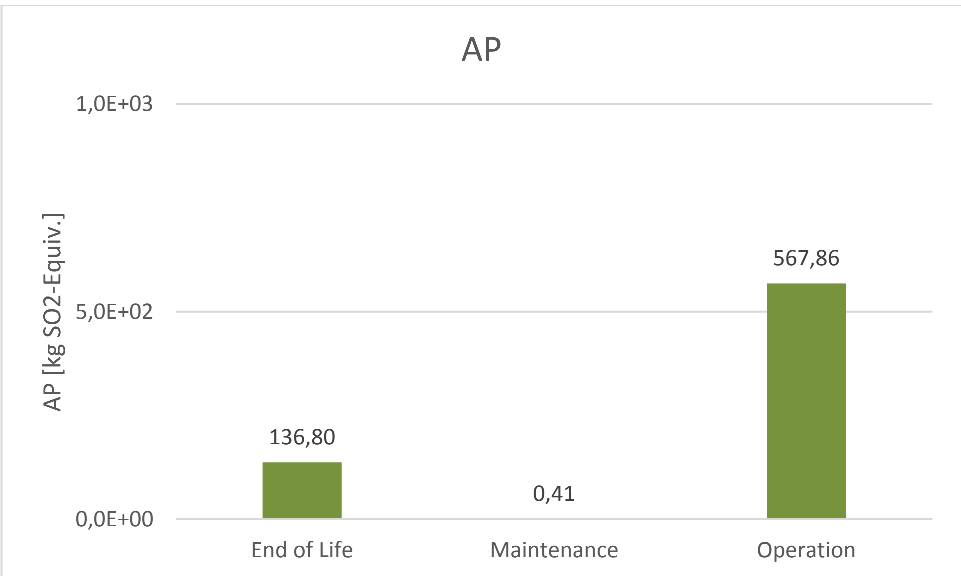



Figure 6.17. AP of End of Life, Maintenance, and Operation Phases (Alternative)

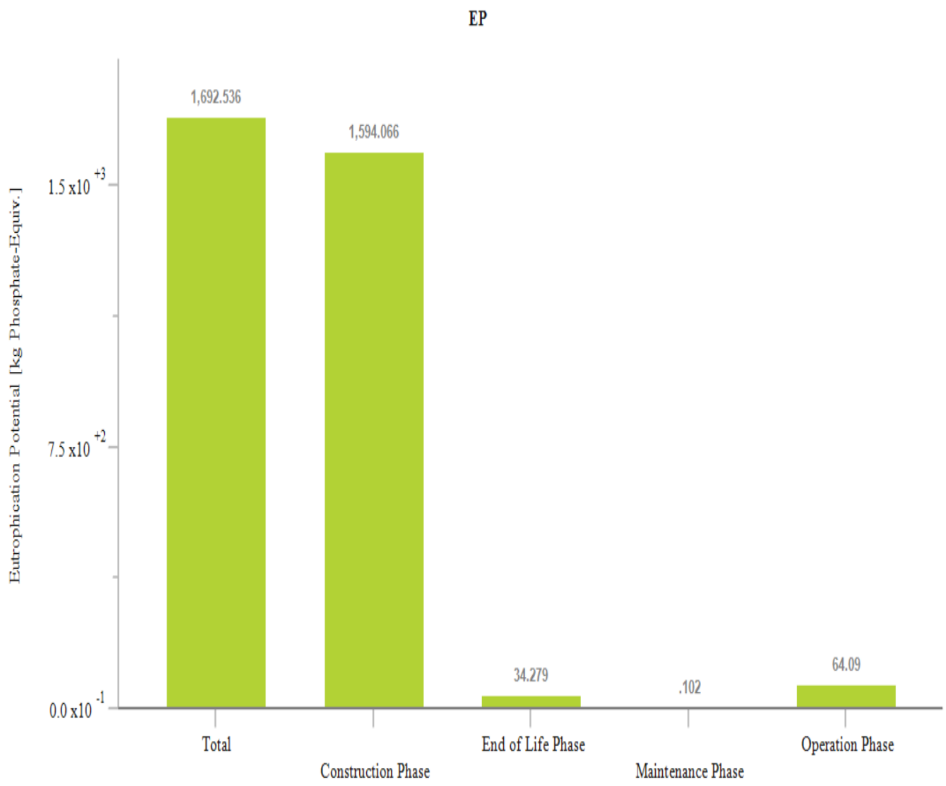



Figure 6.18. Eutrophication Potential of Alternative Case

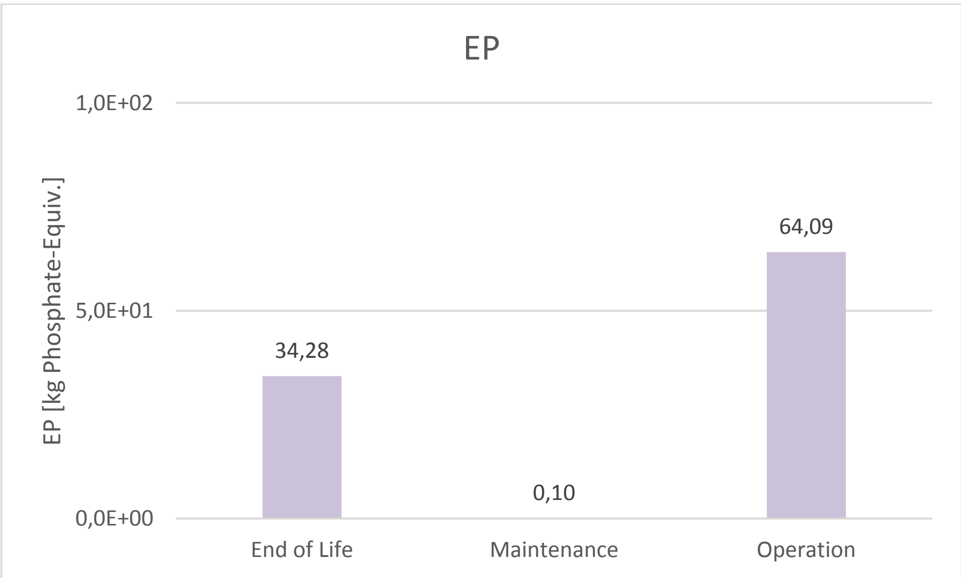



Figure 6.19. EP of End of Life, Maintenance, and Operation Phases (Alternative)

Results indicated that construction phase has the highest emissions which is similar to studies from literature given in Chapter 2. After construction phase, emissions of phases from highest to lowest are end of life phase, operation phase, and maintenance phase respectively in base case. End of life phase in base case has higher emissions than end of life in alternative case due to having recycling of concrete in alternative case. After construction phase, emissions of phases from highest to lowest are operation phase, end of life phase, and maintenance phase respectively in alternative case.

### 6.2.6 Results Interpretation

It is necessary to express results in terms of functional unit which is 1 MWh for this study in order to compare emissions of Gökçekaya PSH and Metristepe WPP.

In order to find environmental burdens of Metristepe WPP for 1 MWh, following calculations are performed.

Capacity factor of Metristepe WPP is calculated as 29.87% using equation (6) given in Chapter 5.

$$\text{Capacity Factor} = 100 * \frac{2093823.84\ \text{MWh}}{20\ \text{years} * 365\ \text{days} * 24\ \text{hours} * 16 * 2.5\ \text{MW}} = 29.87\%$$

Total energy production in Metristepe WPP (for 20 years) can be calculated using equation (7) given in Chapter 5.

$$16 * 2.5\ \text{MW} * 20\ \text{years} * 365\ \text{days} * 24\ \text{hours} * 29.87\ (\text{Capacity Factor}) = 209328960\ \text{MWh}$$

Total emissions of base and alternative case are given respectively in Table 6.4 and Table 6.5. These results represent emissions for 209328960 MWh, to convert emission results to 1 MWh, results are divided by 209328960 and final results are shown in Table 6.6. It is revealed that results of base and alternative case are same except end of life phase as expected. In the case of end of life, emissions are less in alternative case than base case due to recycling of concrete (40%).

Table 6.4 Total Emissions of Metristepe WPP (Base Case)

| | GWP | AP | EP |
|---|---|---|---|
| Construction | 2,999,878.31 (74.35%) | 6,445.51 (72.47%) | 1,594.07 (74.86%) |
| Operation | 207,470.32 (5.14%) | 567.86 (6.38%) | 64.09 (3.01%) |
| Maintenance | 178.77 (0.004%) | 0.41 (0.005%) | 0.10 (0.005%) |
| End of Life | 827,181.29 (20.50%) | 1,880.25 (21.14%) | 471.23 (22.13%) |
| TOTAL | 4,034,708.69 (100%) | 8,894.02 (100%) | 2,129.49 (100%) |

Table 6.5 Total Emissions of Metristepe WPP (Alternative Case)

| | GWP | AP | EP |
|---|---|---|---|
| Construction | 2,999,878.31 (91.80%) | 6,445.51 (90.14%) | 1,594.07 (94.18%) |
| Operation | 207,470.32 (6.35%) | 567.86 (7.94%) | 64.09 (3.79%) |
| Maintenance | 178.77 (0.01%) | 0.41 (0.01%) | 0.10 (0.01%) |
| End of Life | 60,195.32 (1.84%) | 136.80 (1.91%) | 34.28 (2.03%) |
| TOTAL | 3,267,722.72 (100%) | 7,150.57 (100%) | 1,692.54 (100%) |

Table 6.6 Emissions of Metristepe WPP for 1 MWh

| | GWP (kg $CO_2$-equivalent) | | AP (kg $SO_2$-equivalent) | | EP (kg $PO_4$-equivalent) | |
|---|---|---|---|---|---|---|
| | Base Case | Alt. Case | Base Case | Alt. Case | Base Case | Alt. Case |
| Const. | $1.4x10^{-2}$ | $1.4x10^{-2}$ | $3.1x10^{-5}$ | $3.1x10^{-5}$ | $7.6x10^{-6}$ | $7.6x10^{-6}$ |
| Operation | $9.9x10^{-4}$ | $9.9x10^{-4}$ | $2.7x10^{-6}$ | $2.7x10^{-6}$ | $3x10^{-7}$ | $3x10^{-7}$ |
| Maint. | $9.0x10^{-7}$ | $9.0x10^{-7}$ | $2x10^{-9}$ | $2x10^{-9}$ | $5x10^{-10}$ | $5x10^{-10}$ |
| EoL | $3.9x10^{-3}$ | $2.9x10^{-4}$ | $9x10^{-6}$ | $7x10^{-7}$ | $2.3x10^{-6}$ | $1.6x10^{-7}$ |
| TOTAL | $1.9x10^{-2}$ | $1.6x10^{-2}$ | $4.2x10^{-5}$ | $3.4x10^{-5}$ | $10x10^{-5}$ | $8.1x10^{-6}$ |

Construction phase has the highest emissions in both base case and alternative case as expected from previous studies in literature. Use of high amount of construction materials and transportation of both turbine parts and construction materials are main reasons of highest emissions in construction phase. After construction, end of life phase has high emissions due to disposal (landfilling) of materials in base case. Operation and maintenance phases have low emissions compared to construction and end of life phases. Maintenance phase has the lowest emissions due to excluding replacement of pieces such as generator, gearbox, and bearings in 20 years lifetime. In case of considering replacement of turbine parts, emissions in maintenance phase may be higher than operation phase.

Since recycling is more environmentally-friendly solution than disposal (landfilling), recycling of concrete in alternative case is investigated by taking 40% recycling and 60% disposal (landfilling) to demonstrate change in emissions. In this study, main focus is environmental effects of construction materials in end of life phase. For this purpose, one of the construction materials, concrete is selected to investigate change in emissions as a result of recycling. This analysis revealed that emissions of end of life in alternative case are about 92.7% less than emissions of end of life in base case. Although main reason of this result is recycling, it should be highlighted that recycling factory is closer to wind farm area compared to disposal factory which cause less distance of transportation and less emissions. Furthermore, in other phases (operation phase, maintenance phase, and construction phase) emissions of base case and alternative case are same in all impact categories (GWP, AP, EP) due to not changing parameters. It can be concluded that 40% recycling of concrete and 60% landfill of concrete reduce end of life emissions about 92.7% compared to 100% landfilling of concrete.

## 6.3 LCC of Metristepe WPP

In this study exchange rate of 20 November 2019 are used and all monetary values are given after conversion to Euro (1$ = 5.7 TL, 1 €= 6.3 TL, 1 € = 0.9$). When prices belong to past years, they are converted by using online inflation calculator (Brueau of Labor Statistics, n.d.).

LCCA studies are carried out parallel to LCA phases for 20 years lifetime. The following equation which is given as equation (8) in Chapter 5 is used to calculate total cost of systems:

$$C_{\text{Total}} = C_{\text{Initial Material}} + C_{\text{O\&M}} + C_{\text{tr}} + C_{\text{EoL}}$$

To find total cost of WPP following costs are considered: initial material cost of construction materials for foundation, cost of wind turbine equipment, cost of transportation, cost of operation and maintenance, and cost of end of life.

Calculation of cost details are summarized in the following:

1. In order to construct foundation, cost of reinforcement bars and piles are considered. In cost of piles, cost of concrete and excavation is taken into account (Planning, 2019). Cost of concrete (39.68€/$m^3$) (Küpeliler C., personal communication, November 11,2019) and reinforcement bars (469.84€/ton) (Abaklılar R., personal communication, November 11,2019) were taken from same manufacturers mentioned in Chapter 5 for Gökçekaya PSH. In addition, cost of piles is 55.6 €/m and 28 piles are used for each turbine (total 16 turbines) (Planning, 2019).

2. Cost of turbine parts such as nacelle, rotor, and tower are considered with their components. In order to find cost of turbine parts, formulas from a reference are

utilized (Chen, Wang, & Stelson, 2018). Cost of turbine parts and formulas are given in Table 6.7 where R is rotor radius (49.9 m), $P_r$ turbine rated power (2500 kW), and H is hub height (80 m).

Table 6.7 Cost of Wind Turbine Components (data are compiled from (Chen et al., 2018))

| ***Considered Parts of Wind Turbine*** | **Equation (For 1 turbine)** | **Cost (€) (for 16 Turbines)** |
|---|---|---|
| **1.Tower** | $0.59595\pi R^2 H - 2121$ | 5,337,217.00 |
| **2. Rotor Parts** | | |
| **Blade (for one blade)** | $(0.4019R^3 - 955.24 + 2.7445R^{2.5025})/0.72$ | 5,863,787.00 |
| **Hub (includes nose cone)** | $(2.0061666R^{2.53} + 24141.275) + 206.69R - 2899.185$ | 1,025,784.00 |
| **Rotor Shaft** | $0.1 \times (2R)^{2.887}$ | 850,848.75 |
| **3. Nacelle Parts** | | |
| **Bed Frame** | $11.9173875 \times (2R)^{1.953}$ | 355,577.20 |
| **Nacelle Cover** | $1.1537 \times 10^{-2} P_r + 3849.7$ | 55,851.00 |
| **Main Bearings** | $(0.64768R/75 - 0.01068672) \times (2R)^{2.5}$ | 106,440.65 |
| **Generator** | $0.065P_r$ | 2,340.00 |
| **Gearbox** | $16.45 \times (0.001P_r)^{1.249}$ | 744.00 |
| **4. Other Parts** | | |
| **Mechanical Brakes** | $1.9894 \times 10^{-3} P_r - 0.1141$ | 69.98 |
| **Pitch System** | $0.480168 \times (2R)^{2.6578}$ | 1,422,476.00 |
| **Yaw System** | $0.0678 \times (2R)^{2.964}$ | 822,271.26 |
| **Hydraulic Cooling System** | $0.012P_r$ | 432.00 |
| | **Total Cost of Turbine Parts** | **15,843,838.84** |

3. In operation, cost of start-up electricity consumption of turbine for its lifetime are taken into account. As in Chapter 5 for PSH case, electricity consumption price is taken as 56.356 €/MWh (Barbaros, 2019) and start-up electricity of wind farm for 20 years lifetime was calculated as 2093823.84 MWh.

4. Cost of transformer is taken as 44,233.68 € (Planning, 2019).

5. In cost of maintenance, replacement of turbine parts is not considered as in Chapter 5 for PSH system. Lubrication of gearbox (1995 € /barrel, (Turk Oil Market, n.d.)), hydraulic system (36.5€ /barrel, (Oil Markt, n.d.)), and yaw drive (85.8 € /barrel, (Oil Markt, n.d.)) are taken into account and costs are taken from suppliers websites.

6. To find cost of transportation, transportation of the turbine parts and construction materials (concrete, bar reinforcement, and piles) are considered. Since both landfill and recycling factories take material from the construction site and transportation cost is included in the given cost information, cost of transportation in end of life is neglected. For construction materials, transportation unit cost is taken as 0.07 €/ton-km by truck (Panesar et al., 2019). For transportation of turbine parts, National Renewable Energy Laboratory (NREL)'s cost study for onshore wind turbines are utilized and equation of transportation of turbine parts are considered. Transportation cost components are given in Table 6.8 (Chen et al., 2018).

Table 6.8 Transportation Cost Details of Metristepe WPP (Chen et al., 2018).

| | Total Amount (Ton) | Distance(km) | Unit cost (€) | Total cost (€) |
|---|---|---|---|---|
| **Concrete** | 16819.2 | 47.3 | 0.07 | 55,688.37 |
| **Reinforcement Bar** | 840 | 42.7 | 0.07 | 2,510.76 |
| **Piles** | 30863 | 253 | 0.07 | 546,583.73 |
| | **Equation (for 1 turbine)** | **Number of Turbines** | | |
| **Turbine Parts** | $1.581 \times 10^{-14} P_r^3 - 3.75 \times 10^{-8} P_r^2 + 0.0547 P_r$ | 16 | - | 1,965.83 |
| | | **Transportation Cost (Total)** | | 606,748.69 |

7. Assembly (installation) cost of wind turbine is calculated for 16 turbines (Chen et al., 2018). R is rotor radius (49.9 m) and H is hub height (80 m) in equation (14).

$$16 * 1.965 * 2HR^{1.1736} = 1{,}074{,}907.42 \text{ €} \qquad (14)$$

8. In end of life phase, disposal of concrete, reinforcement bars, and piles are considered. After private communication with factory, cost of disposal of these materials is taken as 0.4 €/ton (Anket A.Ş., personal communication, November 13,2019). In alternative case of end of life, concrete is recycled 40%, landfilled 60% and recycle of concrete cost is taken as 25.8 €/ton same as discussed in Chapter 5 ("Riverside Recycling Facility," 2018).

Total cost components of Metristepe WPP are given in Table 6.9.

Table 6.9 Cost Components of Metristepe WPP

| Components of Cost | Cost (€) |
|---|---|
| **Construction Cost of Foundation** | 892,727.84 |
| **Cost of Turbine Parts** | 15,843,838.84 |
| **Operation Cost** | 1,179,853.12 |
| **Maintenance Cost** | 541,790.94 |
| **Cost of Transformer** | 44,233.68 |
| **Transportation Cost** | 606,748.69 |
| **Assembly Cost** | 1,074,907.42 |
| **End of Life Cost** | 19,438.88 |
| **End of Life Cost (Alternative)** | 209,697.70 |
| **Total Cost** | 20,203,539.41 |
| **Total Cost (Alternative)** | 20,393,798.43 |

To calculate incomes due to generation of electricity, it is known that average electricity generation in Metristepe WPP is 104691192 kWh/year and in 20 years 2093823840 kWh electricity has been generated in average (Baskaya, 2017). Furthermore, cost of electricity generation is 56.356 €/MWh is assumed as in Chapter 5 for PSH case. In conclusion, total income of Metristepe WPP is calculated as 117,999,536.3 €.

Since same calculations are carried out as PSH case, without giving same formulations results are presented in the following.

In order to find future value of expenses and incomes, equation (11) given in Chapter 5 is used for wind turbine case.

$$Present\ Value = \frac{Future\ Value}{(1+d_{real})^n} \qquad \text{(Consulting, 2006)}$$

Where $d_{real}$ is 0.00236 as calculated before in Chapter 5 and $n$ is 20 years.

It is possible to find future value of expenses of project at the end of life time (20 years) by using equation (11):

$$20{,}203{,}539.41\ € = \frac{\text{Future Value}}{(1+0.00236)^{20}}$$

Future Value = 21,178,832.14 € (Future value of expenses)

Same formula (Equation 11 given in Chapter 5) is utilized to find future value of incomes at the end of life time (20 years) as following:

$$117{,}999{,}536.3€ \ = \frac{\text{Future Value}}{(1+0.00236)^{20}}$$

Future Value = 123,695,770.4 € (Future value of incomes)

$$\text{Future Value of Incomes} - \text{Future Value of Expenses} = 102{,}516{,}938.2\ € \quad (15)$$

As shown in Equation (15), incomes are greater than expenses which means Metristepe WPP can compensate its investments in 20 years lifetime.

Since Metristepe WPP can compensate its investments in 20 years lifetime, it might be conclude that the WPP is profitable to meet energy demand.

It is important to highlight that Metristepe WPP is a profitable and clean way of energy production.

## 6.4 Results and Discussion

LCA results of Metristepe WPP revealed that construction phase has the highest emissions followed by end of life, operation and maintenance respectively. Reasons of the highest emissions in construction phase are high amount of diesel usage in transportation of both turbine parts and construction materials, and high amount of construction material use in construction. As stated in Chapter 5, concrete is the main contributor to GWP impact category and due to having high amount of concrete construction phase has the highest emissions in GWP. Also, concrete cause $SO_2$ emissions and contribute to acidification category. Since tower is made of steel and steel contributes to three impact categories (GWP, AP, EP), contribution of steel is noticeable in construction phase. After that, in base case end of life phase has high emissions because of disposal (landfilling) of concrete, reinforcement bars, and piles. In addition to base case study, it is revealed that recycling of concrete causes less emissions than landfilling of concrete. Due to landfilling, base case has higher emissions in GWP and AP compared to alternative case. Similar to previous studies in literature given in Chapter 4, in operation phase emissions are low due to utilizing wind energy which is an environmentally-friendly energy source. Although the lowest emissions are observed in maintenance phase due to excluding replacement of pieces such as generator, gearbox, and bearings, it is known that release of lubricants to water without control cause eutrophication. Also, diesel used in engines both located in truck and in nacelle of wind turbines cause emissions in GWP category due to releasing CO gas. In addition, diesel engines cause emissions of $NO_x$ which increase emissions in AP.

To reduce emissions, increase in recycling amount can be a solution. However, it should be considered that wind turbine consists of many composite materials which cannot recycled easily. Although it is known that using today’s technology emissions of construction cannot be decreased, reduction in emissions of construction phase might be possible in the coming years due to technological developments.

As a result of economic feasibility studies of Metristepe WPP, it is found that incomes of Metristepe WPP are higher than expenses (102,516,938.2 €) and Metristepe WPP can compensate its investments in 20 years. Therefore, it can be said that Metristepe WPP is profitable and clean way to generate electricity.

# CHAPTER 7

# CONCLUSIONS

## 7.1 Conclusions

Fossil fuel reserves of Turkey are not sufficient to meet energy need of the country, therefore; Turkey imports energy such as natural gas, coal, and petroleum. This causes foreign source dependency to meet energy demand in Turkey. It should be highlighted that population increase cause rise in energy demand of the country. That means foreign source dependency will become more significant in the coming years. Also, it is known that fossil fuels are energy sources that have burdens on environment. In order to solve these problems, use of renewable energy sources should be increased in Turkey.

Hydropower is heavily used in Turkey due to having high capacity of hydropower. Since hydropower plants supply required flexibility to grid, PSH construction has not been practiced yet in Turkey despite having suitable places to construct PSH. Nevertheless, it should be reminded that Akkuyu NPP is expected to start operation until 2025 and energy storage to supply required grid flexibility might be met by PSH technology.

Another issue is that wind energy is one of the environmentally-friendly sources and Turkey has a high wind potential. Although there are many onshore WPPs in Turkey, it is necessary to increase number of WPPs in order to utilize wind power significantly. To decrease foreign source dependency and meet increasing energy demand of the country with environmentally-friendly sources, number of wind power plants should be increased. Despite being environmentally-friendly, it is known that  intermittency of wind power is one of the disadvantages of wind energy and PSH can be an efficient solution to store energy obtained from wind. A hybrid PSH-WPP system might be an efficient solution to manage intermittency of wind power and energy blackouts due to intermittency. In hybrid system, PSH provide storage of energy when electricity prices are low (at off-peak hours) and using this stored energy when wind is not available or when electricity prices are high (at peak hours). In addition to this, electricity obtained from WPPs can be used as initial energy of PSH to store water instead of electricity grid mix of the country. This will result in reducing environmental pollution when PSH operates to store water. Although these advantages of hybrid PSH-WPP system, it is known that in Turkey construction of this system has not been practiced yet. Moreover, site selection studies have not been carried out up to now. Due to unavailability of site selection, two close sites are selected to study in this thesis: Gökçekaya PSH which is not commissioned yet and Metristepe WPP which has been operated since 2011. These sites are investigated by using LCA method to find and compare their burdens on environment.

Since Gökçekaya PSH has not been carried out yet, carrying out LCA of PSH will provide opportunity to change processes that cause burdens on environment before construction of the PSH. In this thesis, LCA study of close PSH and WPP systems are investigated to understand their environmental effects and compare them before design and construction of hybrid systems. Also, to compare two systems comprehensively economic feasibility of systems are carried out by LCCA method. Construction, operation, maintenance, and end of life phases are taken into consideration in two systems to carry out LCA and the most significant three impact categories (GWP, AP, and EP) are considered to compare emissions. When LCA results of systems are compared, it is revealed that Metristepe WPP is more environmentally-friendly system due to having less emissions than Gökçekaya PSH. In addition to this, economic feasibility study is carried out to compare systems financially. It is found that while Metristepe WPP can compensate its investments, Gökçekaya PSH cannot compensate its investments in 20 years lifetime. As a result, Metristepe WPP is more economically feasible and environmentally-friendly than Gökçekaya PSH.

In conclusion, construction of WPPs should be increased and construction of PSHs should be started in Turkey to become prepared to construct hybrid system which gives opportunuity to decrease foreign source dependency. Also, in order to construct a PSH, existing dams can be utilized and in this way construction of PSH may increase significantly in Turkey. Gökçekaya PSH should be constructed due to being located on intersection of transmission lines. Moreover, studies to find suitable sites to construct hybrid systems should be carried out. It can be concluded that construction of PSH-WPP systems should be started and increased in Turkey to utilize clean source of energy.

## 7.2 Recommendations and Future Work

1. In this study lifetime is taken as 20 years and longer lifetime should be studied in future works. Since considered lifetime is 20 years, replacement of machine parts and equipment are not considered in maintenance phase. It is recommended to consider replacement of parts and machines when longer lifetime is considered.

2. When suitable site selection studies are carried out to construct hybrid PSH-WPP systems, LCA of these systems should be investigated before construction of systems.

3. From potential sites located in Turkey Gökçekaya PSH is studied in this thesis and it is recommended to study LCA of Altınkaya PSH which is the second most suitable PSH site. Also, sites that have potential to construct PSH can be designed and investigated in future studies.

4. In LCA of both PSH and WPP, system boundary might be changed in future studies. For example, recycling of all materials might be considered rather than considering only concrete and raw material extractions may be included.

4. In LCA of both PSH and WPP, system boundary might be changed in future studies. For example, recycling of all materials might be considered rather than considering only concrete and raw material extractions may be included.

5. Effects of material selection, in other words, using different materials on amount of emissions should be considered by carrying out a detailed study on type of materials.

6. In terms of cost, RETscreen which is a free software prepared by government of Canada might be used in order to take into account social impacts (i.e. environmental emissions, job opportunities) in addition to financial cost (Bali, Erbas, Akin, Akarsu, 2011). This may provide more detailed cost estimation compared to considering only financial cost.

7. It is known that German electricity mix has less emissions compared to Turkey electricity mix. In this study, due to not having electricity mix of Turkey in GaBi education database electricity mix of Germany is used. It is recommended to use electricity mix of Turkey in future studies to achieve more accurate results.

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