LIFE CYCLE ASSESSMENT OF GREENHOUSE GAS EMISSIONS, TRADITIONAL AIR POLLUTANTS, WATER DEPLETION, AND CUMULATIVE ENERGY DEMAND FROM 2-MW WIND TURBINES IN TEXAS

BY

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DISSERTATION

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1. Abstract

One renewable energy source that has witnessed a significant growth in the recent years is wind energy, with the installation of new wind farms around the globe as well as the innovations in wind power technology, which have increased the efficiency of this source. Wind power generates electrical energy from the wind's kinetic energy without causing emissions or pollution from power production; however, environmental effects are caused by the wind turbine manufacturing, transport, and other phases. Therefore, the overall goal of this study was to analyze the environmental effects associated with wind energy technology by taking into consideration the entire life cycle for wind turbines.

Specific objectives were:

1. To conduct a comprehensive life cycle assessment (LCA) for large wind turbines in Texas, including:
   - **All phases** (materials acquisition, manufacturing, transportation, installation, operation and maintenance, and end of life) and
   - **A variety of inventory emissions and resources** (greenhouse gases; traditional air pollutants SO_2, NOx, VOCs, CO and PM; water depletion; cumulative energy demand).
2. To identify a range of impacts due to uncertainty in LCA model inputs.
3. To compare impacts of wind power to literature values for coal and natural gas, as examples of fossil fuels.

The practical contribution of this study is to provide an LCA for large wind turbines in the US, which includes all life cycle phases. The study's contribution to the field of LCA is a more comprehensive LCA than has been conducted to-date for wind turbines anywhere, by including several important new elements: 1) maintenance as part of the use phase, 2) traditional air pollutants in addition to greenhouse gas emissions, 3) an energy balance to compare energy produced by the turbines over their lifetime with energy consumed to manufacture and transport them, and 4) a sensitivity analysis that examines more parameters.

The study was conducted 200 Gamesa 2-MW wind turbines G83 (100) and G87 (100) located at the Lone Star Wind Farm near Abilene, Texas. SimaPro8 was used as the modeling platform. Data were collected from different sources, including manufacturers, wind turbine farms, and the database in the software used for modeling (SimaPro8). All the data were modeled according to ISO 14040 standards. Environmental impacts (acid deposition, eutrophication, photochemical smog formation, stratospheric ozone depletion, and climate change), human health impacts (human health potential and respiratory effects), and resource consumption (fossil fuel consumption, water depletion, and cumulative energy demand) were assessed.

Manufacturing was the phase contributing the most impacts: >75% to the impact categories of respiratory effects, human health potential, and eutrophication; >50% to the categories of acidification, global warming, water depletion, and cumulative energy demand; and >25% to fossil fuel depletion, ozone smog formation, and stratospheric ozone depletion. Producing the large parts of the turbine such as the tower and the nacelle consume sizable amounts of energy and materials. Hence, to reduce adverse impacts from wind power, alternative methods of manufacturing should be explored. Impacts of the installation and transportation phases were moderate, but less than manufacturing. To reduce climate change impacts of the installation phase, use of green cement for the turbine foundation should be considered. To reduce impacts of the transportation phase, purchase of locally-manufactured turbines should be considered. Impacts of the remaining phases were very low.

Extending the turbine life span lowers impacts per kWh of electricity produced because the impacts, which are due primarily to the manufacturing phase, will be distributed over a longer period of time. For a 20-year lifetime, the turbines produce 39 times more energy than they consume. If the turbine life span is increased to 25 or 30 years, the turbines produce 45 and 50 times more energy than they consume, respectively.

The best-case wind speed recommended by the manufacturer, 8 m/s, overestimated electricity generation by a factor of 43 compared to using the wind rose at the farm site. Site-specific information should therefore be used in evaluating the potential for electricity production.

Based on a comparison with values reported in the literature, global warming potential of coal-fired and natural gas power plants with carbon capture and sequestration were still 50 times the impacts of the wind turbines. Other environmental impacts ranged from 4-8 times those of wind turbines, and human health impacts were estimated to be 370 times those of wind turbines.

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I also offer my deepest regards and gratitude to my beloved wife for her patience, support, help, and prayer. Last but not least, all love to my sons, Kareem and Amir.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AEP: Annual Energy Production

AIChE: American Institute of Chemical Engineers

AP: Acidification Potential

AWEA: American Wind Energy Association

BEES: Building for Environmental and Economic Sustainability

BOD: Biochemical Oxygen Demand

CCS: Carbon Capture and Sequestration

CED: Cumulative Energy Demand

CLR: Closed Loop Recycling

COP: Conference of Parties

COP: Conference of Parties

CTUe: Comparative Toxic Unit for Ecosystems

DCB: Dichlorobenzene

EIA: Energy Information Administration

EP: Eutrophication Potential

ETP: Ecotoxicity Potential

FGD: Flue Gas Desulfurization

GHG: Green House Gases

GRP: Glass Reinforced Plastic

GWP: Global Warming Potential

HCFCs: Hydrochloroflourocarbons

HTP: Human Toxicity Potential

HV: High Voltage

IPCC: Intergovernmental Panel on Climate Change

kW: kilowatts

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LSWF: Lone Star Wind Farm

MEA: MonoEthanolAmine

MW: Megawatts

NG: Natural Gas

NIST: National Institute of Standards and Technology

NREL: National Renewable Energy Laboratory

ODP: Ozone Depletion Potential

OLR: Open Loop Recycling

PC: Pulverized Coal

PLC: Programmable Logic Controller

PLC: Programmable Logic Controllers

POCP: Photochemical Ozone Creation Potential

SETAC: According to the Society of Environmental Toxicology and Chemistry

SMP: System Maintenance Predictive

TCoE: The Cost of Electricity

TP: Toxicity potential

TRACI: Tool for the Reduction and Assessment of Chemical and other Environmental Impacts

USEPA: United States Environmental Protection Agency

USES-LCA: The Uniform System for the Evaluation of Substances for LCA.

WC: Water Consumption

WDI: Water Depletion Index

WF: Wind Farm

CHAPTER 1

INTRODUCTION

1.1 Introduction

The availability of energy coupled with environmental threats caused by fossil fuel consumption (coal, oil, and natural gas) is an issue that is generating significant interest from researchers. In 2007, the global population stood at 6.6 billion and by 2030 is anticipated to hit 8.2 billion, indicating that energy requirements will likely increase in the future (World Nuclear Association, 2012). The generation of global electricity globally increased by 3.1% in 2011 (BP Statistical Review, 2012). Rates of usage of coal and natural gas will likely increase to meet increased demand for electricity; however, the current reserves of fossil resources are limited (coal 49,600 million tons and natural gas 29,400 billion m^3) (NREL, 2013).

Problems associated with fossil fuels include economic dependence for non-producer countries on those that produce, depletion of reserves, greenhouse gas emissions, and emissions of traditional air pollutants. In 2010, global greenhouse gas (GHG) emissions were 54 Gt CO_2-eq (Parry, 2012) and by 2050, are expected to hit 70 Gt CO_2-eq, which are potentially harmful for future human quality of life (Akashi et al., 2012). Thus, burning all remaining fossil fuel reserves is not wise policy in terms of climate change.

Increased use of renewable energy is needed to supplement limited fossil fuel supplies, and to reduce emissions of greenhouse gases. One renewable energy source that has witnessed a significant growth in recent years is wind energy, with the installation of new wind farms around the globe. In a variety of countries, government legislation currently provides support for renewable energy, and specifically wind power (Del Río et al., 2007; Jäger-Waldau, 2007; Karki, 2007; Breukers et al., 2007). Innovations in wind power technology have increased the efficiency of this resource.

The wind industry in the United States in particular has grown very fast in the last decade. Although it took around 25 years prior 2006 to reach the 10 GW in the US, the wind industry increased at a rate of 26% every year for that last 10 years (American Wind Energy Association, 2014). “As of 2016, the US had installed nearly 75 GW of wind power” (International Renewable Energy Agency, 2012).

Texas’s wind resource is ranked first in the U.S. and it is the first state to have installed more than 10,000 MW of wind energy (International Renewable Energy Agency, 2012). Texas installed power as of 2016 was 17,911 MW (American Wind Energy Association, 2016). More than 10% of the electricity used in the grid in 2014 that covered large areas of Texas was obtained from wind, and by the end of 2016 Texas may produce more than enough wind energy to meet its own needs (United States Energy Information Administration, 2015). Texas’ wind generation capacity is expected to reach 20% by 2030, and 35% by 2050 (NREL, 2013). A Texas wind power map is illustrated in Figure 1.1.

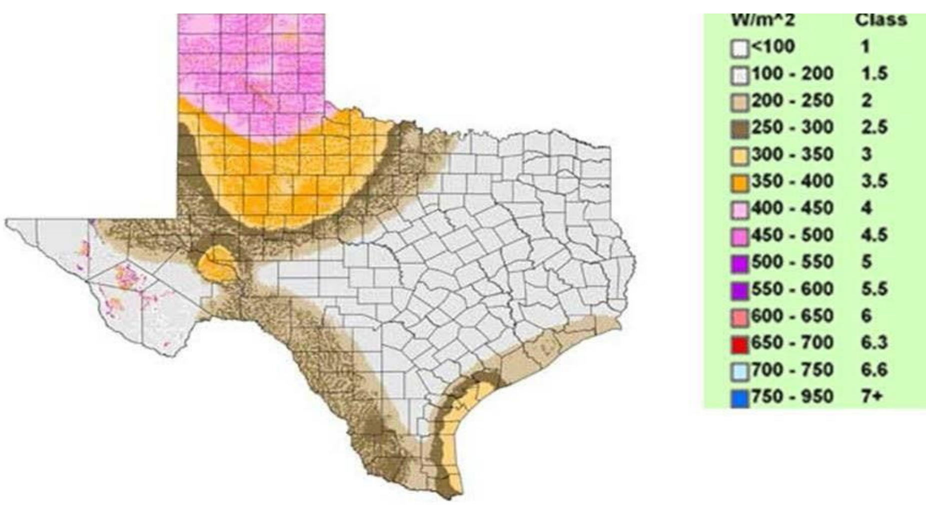

Figure 1.1- Texas Wind Power Map (NREL, 2013)

Wind power generates electrical energy from the wind's kinetic energy without causing emissions or pollution in the conversion stage; however, this does not imply that the energy source lacks greenhouse gas or traditional air pollutant emissions altogether. Notably, the wind turbine manufacturing stage and disposal stage have environmental effects. In order to compare effects of wind energy production with other energy resources, emissions and other environmental metrics of wind power must be quantified. Life Cycle Analysis (LCA) can be defined as a technique that quantifies consumption of resources and a product/system environmental impacts in its lifecycle (cradle to grave), namely materials acquisition, manufacturing/construction, transportation, use/maintenance, and end-of-life (Pehnt, 2006). LCA offers developers, designers, policymakers, and researchers' critical information regarding the environmental effects of different energy options.

1.2 Objectives

Since wind constitutes 10% of Texas' energy supply currently, and its contribution is expected to reach 35% by 2050, assessing its environmental impacts is important. This study aims to conduct a life cycle assessment of the environmental effects associated with greenhouse gas and air pollutant emissions from generating wind energy. The objectives of this study are:

1. To conduct a comprehensive life cycle assessment (LCA) for large wind turbines in Texas, including:

- ➢ All phases (materials acquisition, manufacturing, transportation, installation, operation and maintenance, and end of life) and
- ➢ A variety of inventory emissions and resources (greenhouse gases; traditional air pollutants SO2, NOx, VOCs, CO and PM; water depletion; cumulative energy demand).

2. To identify a range of impacts due to uncertainty in LCA model inputs.

3. To compare impacts of wind power to literature values for coal and natural gas, as examples of fossil fuels.

The ***practical contribution*** of this study is to provide an LCA for a large wind turbine in the US, which includes all life cycle phases; this has not been done before. The study's ***contribution to the field of LCA*** is a more comprehensive LCA than has been conducted to-date for wind turbines anywhere, by including several important new elements: 1) maintenance as part of the use phase, 2) traditional air pollutants in addition to greenhouse gas emissions, 3) an energy balance to compare energy produced by the turbines over their lifetime with energy consumed to manufacture and transport them, and 4) a sensitivity analysis that examines more parameters.

The outcomes from the current study will be beneficial to industry partners, investigators, and decision makers. This study will enable us to answer the following questions:

- What are the most important factors influencing life cycle emissions from wind energy production?
- Are emissions from maintenance of wind turbines significant in terms of the overall life cycle?
- At the end of a wind turbine's life cycle, what percent of materials are recycled back into new products?
- How sensitive is the life cycle analysis to changes in input parameters?
- What are life cycle emissions for wind energy, vs. coal and natural gas?

1.3 Dissertation Organization

Chapter 2 provides an overview of life cycle analyses, a description of parts of a wind turbine, and review previous environmental life cycle analyses of wind energy. Chapter 3 describes the data collection process and the methodology used in this research. Chapter 4 provides the results and analysis and to compares the environmental impacts of wind turbines to coal-fired and natural gas power plants. Chapter 5 summarizes the conclusions and recommendations for the future studies in this field.

CHAPTER 2

LITERATURE REVIEW

This chapter will first discuss Life Cycle Assessment. Next, background concerning wind turbines will be provided. Finally, previous LCA studies of wind power will be reviewed, and the advances of this study over previous studies will be discussed.

2.1 Introduction to Life Cycle Assessment

The environmental impacts of wind energy may be assessed and compared to those from other energy resources through life cycle analysis. The following section provides a general overview of life cycle assessment. Life cycle assessment (LCA) refers to technique of quantifying the environmental effects of a process or product in its full life (cradle to grave) (American Institute of Chemical Engineers, 2015). LCA improves decision-making processes using scientific data. LCA can help manufacturers to improve their processes to reduce the environmental impacts.

The International Organization for Standardization (ISO) 14040 standards category has set life cycle assessment examples and guidelines (ISO, 2006). Life cycle analysis is comprised of four phases, as indicated in Figure 2.1, and as described below.

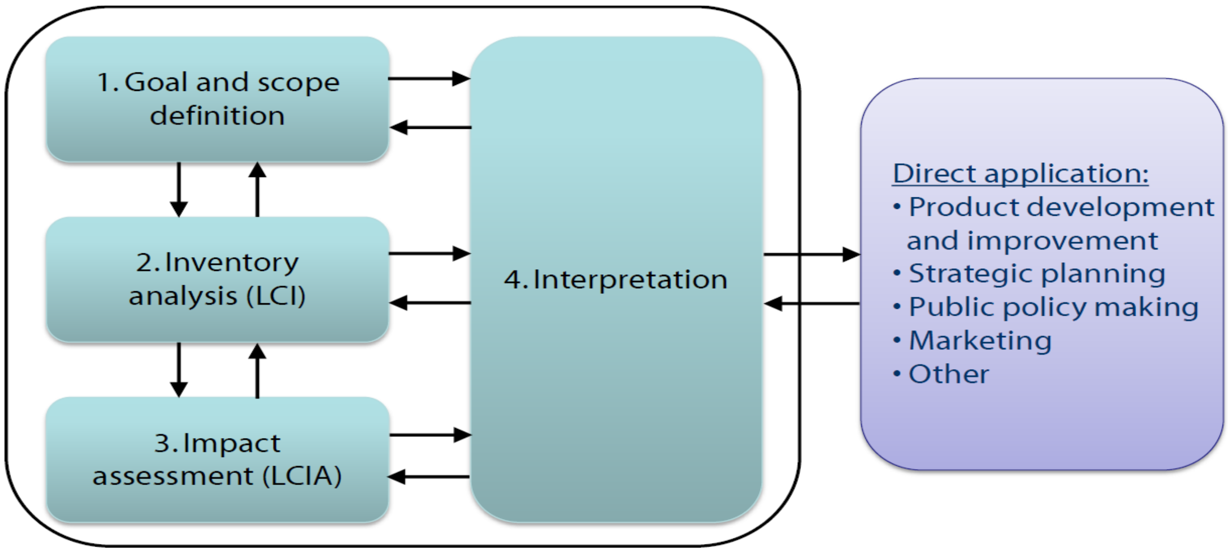

Figure 2.1: The Four Phases of Life Cycle Assessment (Guinee, 2002)

1. <u>Goal and scope definition</u>: This step offers the product system definition based on the functional unit and system boundaries. The functional unit describes what is being examined and quantifies the service provided by the product system, offering a reference for relating the outputs and inputs (for instance, duration of light offered by a light bulb). The system boundary determines processes which will be examined within the life cycle assessment. One boundary that must be defined is the geographical area, since the infrastructure and the ecosystems sensitivity to environmental impacts vary from one region to another. The time boundary must also be defined.

The LCA's goal and scope address other aspects including the targeted audience (intended users) of the study, stakeholders (interested parties), practitioner and initiator (commissioner) of the study, what type of decisions may be made after completion of the study and what the study would be utilized for, intended use (results' usage), aim of the study, reasons for undertaking the study, and limitations and assumptions.

2. Life cycle inventory (LCI): In the inventory analysis, material inputs, energy, waste outputs, and emissions for different processes that are within the system boundary are quantified. Within the life cycle inventory stage of an LCA, all appropriate data is gathered and organized. Without an LCI, a foundation for evaluating comparative environmental effects or possible environmental improvements would be impossible. The data would be collected directly from organizations, utilities, and firms or existing databases.

3. Life cycle impact assessment (LCIA): LCIA converts inventory data into information about environmental and health effects. Simultaneously, it minimizes many data items of the inventory into a small quantity of effect scores. This involves modeling the possible effects of the inventory outcomes and presenting them in form of impact scores. The life cycle impact analysis methodology may feature a weighting technique, for aggregation of LCA outcomes into common units or numbers.

4. Life cycle interpretation: According to ISO14040 (2006), the interpretation is a "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations." Life cycle assessment interpretation (improvement analysis) refers to a systematic process of evaluating, checking, qualifying, and identifying information from impact assessments and inventory analysis conclusions, and presenting them to fulfill the application requirements used for describing scope and goal of the study. Life cycle interpretation also offers recommendations and explains limitations (Goedkoop et al., 2016). Also it should describe the environmental effects of each phase of the life cycle so a relation can be drawn between the environmental impacts and the thresholds or the safety margins. The

appropriate interpretation will lead to the valid conclusions and recommendations, which will help the decision-makers to establish rules and regulations accordingly.

Concerns regarding the LCA limitations continue to emerge in present times. McManusa et al. (2015) observed that the LCA's limited scope may be insufficiently explained when utilizing the outcomes. LCA's may be redundant in terms of geographical coverage (dominated by North America and Europe) or feedstocks explored. Another issue revolves around the translation from functional unit to real-world improvements. This might be a complex issue to tackle. In the future, regional LCA databases will grow, along with new techniques and modified approaches for uncertainty analysis.

2.2 Environmental Impact Categories in SimaPro

SimaPro, the LCA software to be used in this study, expresses the results of any study using environmental impact categories, as described below.

2.2.1 Ozone Depletion Potential (ODP): The destruction of the ozone layer alludes to the thickness decrease of the stratospheric ozone layer because of the discharge of chemicals which attack and break down ozone molecules. The diminishing of the ozone layer results in an increase in the amount of UV-B radiation that reaches the earth's surface, which can cause skin tumors and immune system suppression, decreased agricultural production, degradation of plastics and damage to biological systems. The indicator to quantify these impacts is the potential for stratospheric ozone depletion. Units are measured in kg ODP of CFC-11 equivalents.

2.2.2 Global Warming Potential (GWP): Global warming typically refers to the state or condition in which there is an increase in the Earth's average surface temperature due to emissions of greenhouse gases. The energy that the earth absorbs in form of electromagnetic radiation is redistributed by the atmosphere and the oceans and is later returned to space in the form of thermal infrared radiation. Some of this radiation is absorbed by the gases in the atmosphere, causing the greenhouse effect. These gases are primarily water vapor ($H_2O_{(v)}$), carbon dioxide (CO_2) and other gases such as methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs). Human action has led to increased emissions of these gases, which leads to overheating of the planet and thus to altered conditions. This category of impact affects the areas of human, natural and human-modified environment. The indicator used to evaluate these effects is the global warming potential (GWP) created by the Intergovernmental Panel on Climate Change (IPCC). The time horizon that is used in this category is considered to be a century.

2.2.3 Photochemical Smog: Photochemical smog occurs when complex photochemical reactions between volatile organic compounds (VOC) and nitrogen oxides (NOx) forms ground level ozone smog. Typically, ozone formation results from heavy traffic, high temperatures, calm winds and sunshine.

2.2.4 Acidification Potential (AP): The emission of acidic pollutants such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) results can form sulfuric and nitric acid in precipitation. The resulting acidification can negatively impact life within ecosystems. Depending on the level of acidity human health, natural environment, human-made and natural resources are at risk from acidification. The unit for measuring acidification is kg SO_2 equivalents.

2.2.5 Eutrophication Potential (EP): This category refers to the impact on aquatic ecosystems as a result of the accumulation of nutrients both organic and mineral, usually compounds containing nitrogen, phosphorus, or both. The problem is mostly experienced in marine habitats such as lakes and usually results in algal blooms. This results in increased plant growth. When the plants die and sink to the bottom of the lake, microbes begin to degrade them. The microbes may utilize the available oxygen, leaving none for other species. The unit to measure the EP unit is kg PO_3^{-4} reciprocals.

2.2.6 Human Health: Compounds impacting human health are categorized by Simapro into carcinogens and non-carcinogens. A carcinogen is a chemical substance with radiant agent that can interfere with the genome system in the human or animal body to cause cancer. The Air Quality Guidelines do not indicate any specific levels where the problem will start, yet they ascertain the likelihood of disease at a level of 1 $\mu g/m^3$.

A non-carcinogen is a chemical that does not cause cancer, but is still considered harmful. Hydrogen peroxides are good examples of non-carcinogenic chemicals which can be found in some cosmetics products.

Table 2.1 summarizes the environmental impact categories, the used unit for each category, and the substances involved in each impact.

Table 2.1: The Environmental Impact Categories

Categories of Environmental Impacts	**Unit**	**Summary**	**Pertinent Emissions**
Ozone Depletion Potential (ODP)	kg CFC11-eq/kWh	Impact on stratospheric ozone layer owing to anthropogenic emissions, which leads to an enhanced level of UV-B radiation reaching the earth's surface.	CFCs, HCFCs, halons, methyl bromide
Global Warming Potential (GWP)	kg CO_2-eq/kWh	Impact of anthropogenic emissions augmenting the atmosphere's radiative forcing	CO_2, CH_4, N_2O, halocarbons
Photochemical Smog	kg O_3 eq/kWh	Impact of ozone on air quality	VOC, NOx
Acidification Potential (AP)	kg SO_2-eq/kWh	Impact of acidifying pollutants on soil, surface waters, groundwater, and ecosystems.	SOx, NOx, HCl, HF, NH_3
Eutrophication Potential (EP)	kg PO^{-3}_4–eq/kWh	Impact of excessive macronutrients in marine and terrestrial ecosystems	PO_4, NOx, nitrates, NH_3
Human Toxicity potential (HTP)	kg DCB-eq/kWh	Impacts of toxic substances on human health (includes carcinogenic, non-carcinogenic, and particles)	PM_{10}, $PM_{2.5}$, soot, NOx, CH_4,
Respiratory effects	kg PM2.5 eq/kWh	Impacts of pollutants caused by emissions of dust, sulfur, organic substances, and nitrogen oxides to air	PM, S, organics, and NOx
Fossil fuel depletion	kWh surplus	Amount of fossil fuel consumed through the life span of the product, which will reduce the amount of the inventory fuel.	
Water Consumption (WC)	gal H_2O/kWh	The total amount of water consumed during the life span of the product.	gal H_2O/kWh

2.3 Life Cycle Analysis Methods

Two main analysis techniques are used for LCAs studies: process analysis (PA) and input-output (I/O) analysis. The two techniques have been utilized in wind energy LCAs, as illustrated by Lenzen et al. (2004); past studies are split evenly between these two techniques. Although both techniques are valid, each is laden with drawbacks and differences, which may influence the turbine's emissions and life cycle energy balance.

PA refers to a bottom-up method of accounting for the emissions and embodied energy within materials (Lenzen et al., 2000). Through PA, each component within a turbine is traced to the process that was utilized for its manufacture. The energy input needed for producing the materials as well as the emissions emanating from production are analyzed. Finally, in the life cycle analysis, the emissions and energy consumed emanating from all materials are added up for the whole turbine system. Notably, PA constitutes a practical technique, which enables an investigator to assess a specific system, depending on the materials that are applicable to the system. However, it is characterized by drawbacks, which should be considered. PA is used for estimating the emissions and energy requirements from generation of materials; however, boundary truncation choices caused by the complex nature of the system complicates the PA technique (Lenzen et al., 2000). Boundary truncation arises when the whole life cycle is not assessed, leading to an incomplete life cycle analysis. For instance, higher-order processes that include engineering services or transportation, which support the manufacture of turbines, are not included. Because of this, values are computed with I/O analysis (Lenzen et al., 2000).

Notably, I/O analysis is different from PA in the sense that it is a top-down method. I/O analysis refers to a macro-economic technique, which evaluates the environmental emissions as well as economic inputs (Norton, 1999; Lenzen et al., 2000). National output and input tables are arranged by comparing emissions and energy use from one sector of the economy to the product's monetary value in the sector. For instance, the NOx emissions emanating from transportation of wind turbine may be located through determination of costs involved in transporting that turbine and multiplying the cost by NOx emissions per dollar (NOx/$) of the U.S. transportation economic sector. Seemingly, the I/O analysis is comprehensive compared to the PA that assesses the product's raw material inputs. I/O encompasses the effects from high-ranked operations such as construction, transportation and management. This extensive analysis results in a consistent description of a system boundary (Proops, 1996). However, the I/O analysis is characterized by numerous drawbacks, the most notable being lack of specificity and detail (Lenzen et al., 2000). Since I/O examines every economic sector holistically, it assumes every sector generates one "average" product (Treloar at al., 2000). In real sense, each sector contains numerous products, different grades of quality for all products, as well as products that are priced differently. For instance, the price variation involving two vehicles might be large (that is, Porsche and Ford Taurus); however, the emissions emanating from the manufacture of both cars might be similar. Notably, the I/O tables does not feature the wind turbine industry; thus, it is imperative to allocate different costs of generating wind turbines to other economic sectors.

Due to the inherent drawbacks of I/O and PA analysis, (Lenzen et al., 2004) suggest the application of a hybrid assessment method. A hybrid method combines both techniques by filling in the gaps within PA data using data from I/O assessment. (Treloar at al., 2000) recommend a hybrid LCA methodology in which considerable life cycle pathways are obtained from an I/O assessment and replaced with system-specific data obtained through PA. Indeed, the hybrid method represents a process assessment where estimation of higher-order process is undertaken from output/ input tables. The application of hybrid methods in wind energy analyses allows assessment of particular wind turbines while retaining an extensive system boundary. However, Weidman (2011) computed greenhouse gas emissions from wind power with two hybrid techniques and process chain analysis, and acquired significantly varying outcomes, thus indicating the results variability from single hybrid techniques.

2.4 Descriptions of Turbine Components

To conduct a full life cycle analysis for a wind turbine, all the parts of the wind turbines should be covered in the modeling, as shown in Figure 2.2. The major parts of the two turbines considered in this study, Gamesa G87 and G83-2.0 MW, are:

a) Rotor
b) Nacelle
c) Tower and foundation
d) Other parts

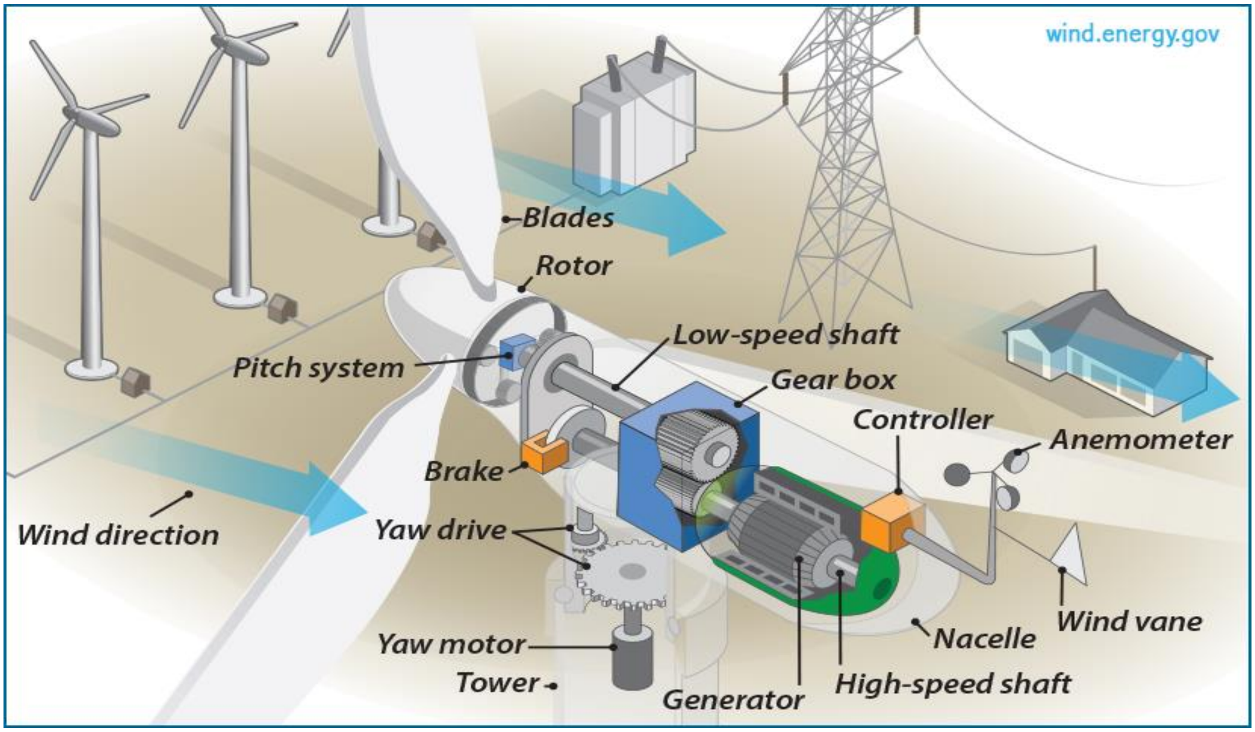

Figure 2.2: Parts in the Nacelle and the Rotor of the Turbine (U.S. Department of Energy, 2016)

2.4.1 Rotor

The rotors of the wind turbines have blades which are connected to a hub by means of blade bearings. The rotor blades are made using organic composites which have been reinforced with carbon and fiberglass. These materials allow the blade to be rigid with no effect on the weight of the blade. Some upgrades were made on the blades to reduce the production of noise and maximize load-bearing. The blades each measure 43.5 and 41.5 m for models G87 and G83, respectively. For both models, the distance from the center of the hub to the root of the blade is 1 m. Each blade has two shells which are attached to the internal stringers or structural beams. Figure 2.3 below shows the major parts of the nacelle.

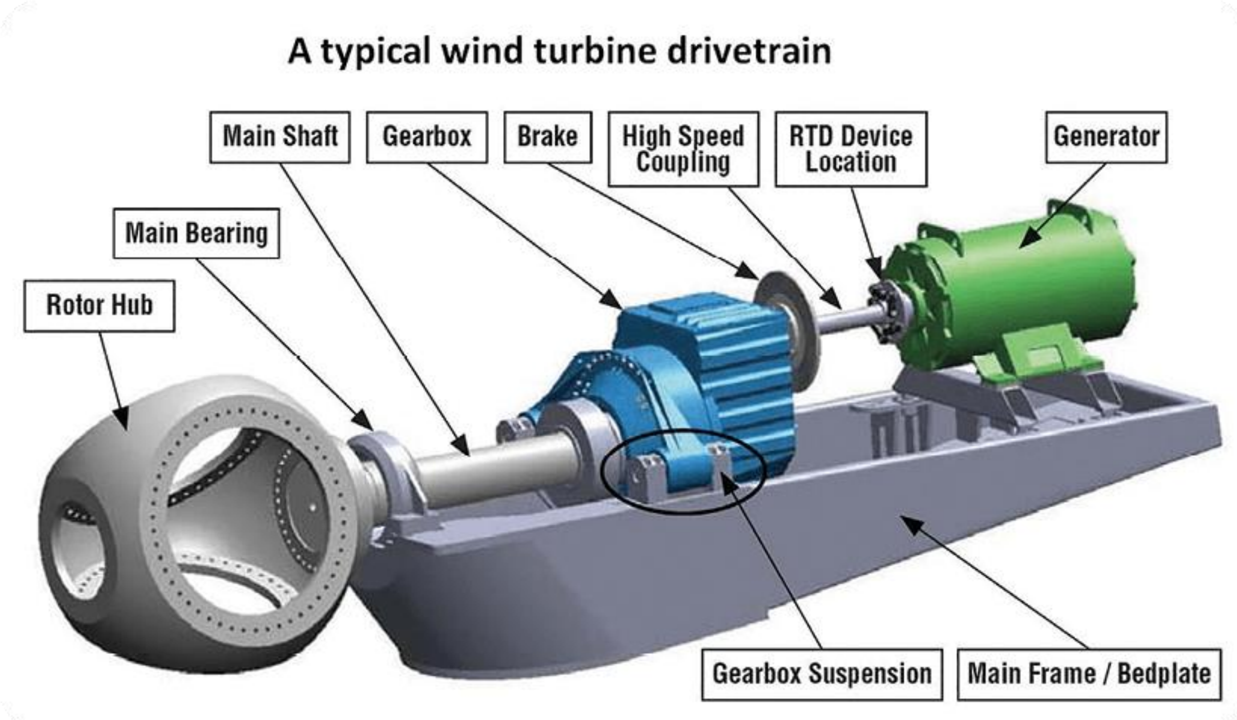

Figure 2.3: Parts Inside the Nacelle (Wind Power Engineering Development, 2016)

The design of the blade caters to aerodynamic and structural functions. The design of the blade is based on the types of materials used and the method of manufacturing to ensure safety. Additionally, the blade has a protection system-ray which is represented by a beam from the root of the blade to the receiver (see Figure 2.4 below). The beam will also keep the sides of the blades from collapsing on each other. Moreover, the blades do not retain water as their design incorporates drains; this property prevents damage as a result of water lightning or structural imbalance of the blade. The blades consist of some subparts:

a) **Blade Bearing** - Forms the interface between the blades and the hub. Allows movement during change of pitch. Bolts are used to attach the blade to the inner bearing race blade and facilitate easy inspection and disassembling.

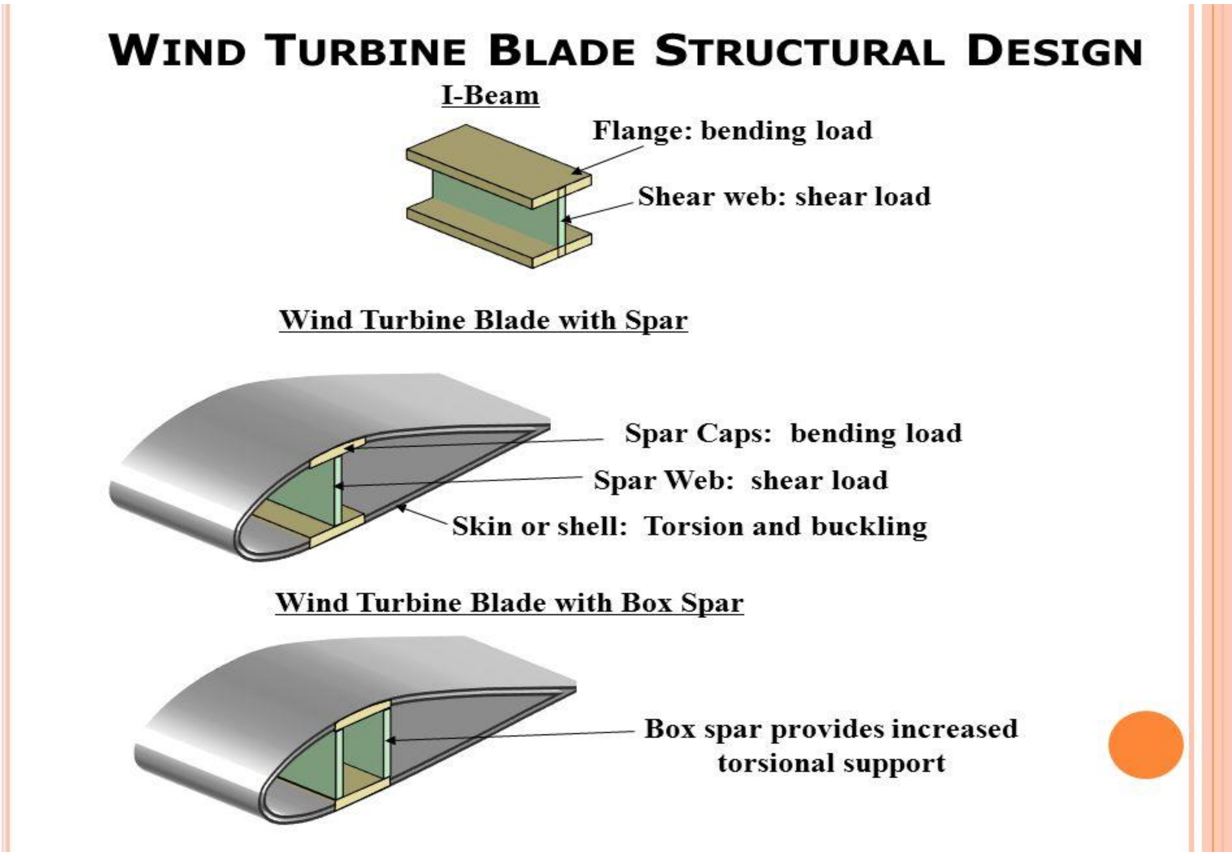

Figure 2.4: Cross Section of the Wind Turbine Blade (Johnson, 2016)

b) **Bushing**- Nodular cast iron is used in the manufacture of the bushing. Bolts bind the bushing to the main shaft and the outer surface of the three blade bearing. An opening in its front side facilitates the inspection and maintenance of the hydraulic pitch change from the inside.

c) **Cone** - The cone provides protection to the hub and reduces the temperature of the blade bearings. It is bolted to the front of the hub and its overall design facilitates maintenance by giving access to the hub.

d) **Hydraulic Pitch Change -** Has independent hydraulic actuators for each blade. Besides facilitating a rotation capability of between -5 ° and 87 °, it ensures rotation in the emergency case through an accumulator system. Various principles can guide the operation of the hydraulic pitch change system, such as: lower wind speeds than the nominal pitch angle maximize the power generated, higher wind speeds than the nominal pitch angle provide the machine with the nominal power. The activation of the brakes manages the emergency aerodynamics, which ensures safety of turbine operation. Batteries are not needed for the operation of the hydraulic systems because it has a hydraulic accumulator system, which increases system reliability in case of emergency.

2.4.2 Nacelle

The nacelle is the main body and contains most of the turbine parts. It is located at the top of the tower. Various parts of the nacelle are described in the following:

a) Housing

The housing is the cover that provides protection of the components against bad weather conditions and other unfavorable environmental conditions. This housing, which is composed of composite resin in combination with reinforced glass fiber, has space inside it to facilitate the maintenance of the turbine. Its components include three flaps. The first flap is positioned at the floor of the nacelle and provides access to the nacelle from the tower. The second flap is located at the front and forms the access door to the inner core. The third flap is located on the floor of the rear and facilitates the operation of the hatch crane.

On the roof, the housing has two skylights for letting in sunlight during the day in addition to air. It also provides access to the outside of the turbine and houses the instruments for measuring wind and the lighting rod. The rotating components inside the housing are properly protected to make sure the maintenance workers are safe. Inside the nacelle there is an 800 kg service crane.

b) Frame

The Gamesa turbines have a platform frame which is both mechanically simple and robust. These characteristics provide enough support to gondola elements and facilitate the transmission of loads to the tower through the use of a bearing system. The frame has two major parts: the front and the rear frame. The front frame is made up of the cast iron bed which provides the setting for the main shaft bearings, the torque arms in the front frame react to the yaw and the gear box. On the other hand, the rear frame is made up of mechano-welded structure, which is in turn made up of the two beams hinged at the back and front.

c) Main Shaft

The push of the wind produces the rotation of the rotor, which is transmitted to the gearbox through the main shaft. A bolted flange attaches the shaft to a hub. Two bearings contained in the supports made of cast iron support the shaft. A conical clamping collar binds the shaft to the low speed multiplier input and transmits torque by means of friction.

The shaft is produced from forged steel and has a centrally and longitudinally located bore which is used for the reception of the hydraulic hoses, in addition to controlling the pitch change system of the cables. The support of the shaft through the use the bearing has several structural benefits. For instance, it transmits every rotor effort to the front frame with the exception of torque. Torque is tapped for electricity generation. This ensures that only flexural stresses are transmitted. Another benefit is the ability to disassemble the gearbox without affecting the rotor or the main shaft, improved serviceability.

d) Gearbox

The gearbox transmits the generated power. It consists of two parallel axes and one planetary axes. The gearbox teeth have very low noise, produce minute emissions, and are very efficient. The reaction arms absorb some of the input torque due to the gear ratios. The reaction arms attach the gearbox to the frame through the use of dampers, which significantly reduces the transmission of vibrations. A flexible coupling connects the generator to the high speed shaft and has a torque limiter which prevents transmission chain overloading.

The powertrain uses a modular design. The main shaft supports the weight of the gearbox and binds the frame buffers. The shaft only reacts to the torque, restricting the gearbox rotation in addition to the absence of unwanted charges. The gearbox has a lubrication system to avoid unnecessary friction between the parts. There are also sensors that monitor the components and operating parameters of the gearbox and an extra circuit for cooling the system. During the manufacturing process, the gearbox is tested at the rated outputs so as to reduce the likelihood of their failure.

e) Brake System

The wind turbine brake system is mainly in the feathering of the blades. The system can change the pitch of each blade with triple redundancy. There is also a mechanical brake which is disc shaped and is hydraulically activated when the gearbox outputs through the high speed shaft. The mechanical brake is used for emergency purposes or as a parking brake. This system should be changed every 5 years to maintain reliability.

f) Generator

The turbine has an asynchronous generator with four poles, slip rings, and a wound rotor. The generator is fed by double lines. An air-air exchanger cools the generator, maintaining its high efficiency by controlling the rotor frequency; the control system permits working with variable speeds. The generator introduces features and functionalities like turn on and off the grid, optimal performance under varying wind speeds by varying the loads, and reduced noise; it also controls the amplitude and the phase of the rotor currents and thus facilitates controlling of both the active and reactive power.

The generator has protection for short currents and overloading. Sensors also continuously monitor the temperatures at various points including the bearing, stator points, and slip rings drawer.

g) Control System

A Programmable Logic Controller (PLC) controls the functions of the turbines in real time. Control algorithms and supervision make up the control system. The regulation system in this unit selects the best rotor speed, pitch angle, and power slogans. When the speeds of the wind change, these factors are also modified to ensure safety and reliability. This system in Gamesa wind turbines provides the following advantages:

1. Maximum production of energy.
2. Limit of mechanical loads.
3. Reduced noise from wind.
4. Production of high quality energy, which is concentrated and can do more work.

In the control system unit there are four regulations and controlling systems:

1) Step Change Regulation

The power is maintained at normal values by the control system and the pitch change system when the speeds of winds are above the nominal. When the speeds of the winds are below the nominal value, the production of energy is optimized by the control and pitch system through an optimal combination of the speed of the rotor and the pitch angle.

2) Power Regulation

The stability and the reliability of the generated power is ensured by the optimal combination of the turbine torque and its rotational speed. This combination is provided by the power control system. The regulation is achieved by the action of the control system on an electrical system set comprised of a generator, contactors, protection system, and software. In electrical terms, the converted generator set is analogous to the synchronous generator, which ensures that there is smooth connection and disconnection through optimum coupling. The generator set also has the capability to maximize the power which is produced by either high or low wind speeds. Additionally, it also manages reactive power in combination with the Gamesa Windnet system.

3) Monitoring System

The status of the internal parameters and the sensors is continuously checked by the monitoring system. These parameters include the rotational speed of the stator and the rotor and the position of step change, the conditions of the environments (speed and direction of wind and temperature), the temperature and vibration of internal components, in addition to pressure of oil and oil levels, among others, and the condition of the network, including reactive and active power generation, among others. The whole control is estimated and recommended to be changed every 10 years in the turbine.

4) Maintenance System, Gamesa SMP

Gamesa G8X turbines have a predictive maintenance system (Gamesa SMP or Gamesa System Maintenance Predictive) which was developed based on the analysis of the vibrations. The system is optimized for utilization in wind turbines and has the capability of managing and processing information and contains up to 8 accelerometers which are strategically located on the turbine, specifically on the generator, gearbox, and the main shaft. Gamesa SMP has several features which include low cost and maintenance. It processes the alarm detection system, continuously monitors critical parts of the turbine, and incorporates Gamesa Windnet system and PLCs (Programmable Logic Controllers).

The major role of the Gamesa SMP is to detect failures or deterioration in the parts of the turbines very early to prevent damage. Other benefits of the installing Gamesa predictive maintenance system can include a reduction in large corrective incidences, reduction of damage or failure in the other parts of the turbine, increased performance and the lifetime of the turbine, decreased need for maintenance resources, reduction in insurance premiums, and access to markets with very strict regulations.

In addition to the Gamesa WindNet system, there are other modules which add advanced functionality to the integrated maintenance system. These include the modules for controlling frequency, limiting active power, reducing the reactive power that is generated, generating customized reports through the use of the Gamesa Information Manager, controlling noise, controlling shadows, and controlling ice.

2.4.3 Tower and Foundation

The tower has a conical shape and is tubular; it is made up of steel and is majorly divided into several sections depending on the height of the tower. It also has stairs, platforms, and lighting system for emergency purposes. Gamesa turbines have a cable guiding elevator which facilitates easy maintenance. The height of seismic Gamesa towers is 78 m in four sections. In the top of the tower there is the active system yaw of the Gamesa turbines, which permits the nacelle to rotate around the tower axis. The active yaw system has four geared motors, which are electrically actuated to control the control system of the turbine based on the information relayed by the wind vanes and the anemometers. The direction of the rotation of the pinions orients the direction of rotation of the system motors. The teeth of the yaw bearing are at the top of the tower and produce relative rotation between the tower and the yaw.

The active yaw systems use a friction bearing having sufficient torque to control the orientation of the spin. In the hydraulic brake system there are five active jaws to provide greater torque to keep the turbine secure, and the combined actions of these systems ensure that there is no damage and fatigue to the gear orientation. The crown has six major sections, which ensures easy servicing or repairing of the teeth. Similar to the frame, the active yaw system of the Gamesa turbines is thoroughly tested during production; the test majorly simulates the durability of the steering system and thus increases the component reliability, corroborating the designs in addition to facilitating future improvements.

A reinforced concrete slab with steel is the standard foundations for turbines. These foundations are designed based on the conditions of the ground and the turbine load. They are built by considering the terrain and wind data.

2.4.4 Other Parts

2.4.4.1 Transformer

A 3-phase dry encapsulated transformer is used for this system; it has multiple outputs ranging from 6.6kV to 35kV. Additionally, it has different ranges for apparent power and was designed for electricity production using wind turbines. The transformer is placed at a separate compartment at the back of the nacelle. The compartments are made up of materials that provide thermal and electrical insulation from other nacelle parts. Its dry nature minimizes fire incidences; being wet might cause short circuits and fire. It also has other protective mechanisms such as fuses and arc detectors. The location of the transformer in the nacelle ensures the cables are shorted, thus reducing voltage losses. The transformer location also reduces visual impact.

2.4.4.2 Cabinets, Electrical Power, and Control

In this section, there are three main parts of the cabinet connected to each other: top cabinet, ground cabinet, and wardrobe hub. The top cabinet is contained in the nacelle and is further divided into the control section, frequency converter, and the section muddy and safeguards. The control section monitors the wind, changes the pitch, controls temperature, and is responsible for orientation, monitors and manages power. The power generation and all the necessary protection are found in the safeguards section.

The ground cabinet at the tower base facilitates the viewing of the ground closet parameters through the use of a touch screen. It also turns on/off the turbine and tests the various turbine sub-systems. Additionally, it provides a mechanism for connecting a laptop for viewing the parameters in the top cabinet. The wardrobe hub is situated at the rotating part of the turbine and activates the cylinders of the system for changing the pitch.

2.4.4.3 Hydraulic System

The turbine also has a hydraulic system which provides pressurized oil to the mechanical brake during high speed conditions and when the three actuators change pace. A safety system ensures that there is enough oil pressure and flow rate to change the pitch of the blades and enough oil for the brake system or disk brake.

2.4.4.4 Lightning Protection System

All the parts of the turbine are protected from lightning through a lightning protection system. The system, which runs from the receptor blades through the frame down the foundation, prevents the passage of the lightning through the sensitive parts of the turbine. Other systems for protection of the turbine include surge protectors. The electrical and the lightning protection system are designed to provide the highest levels of protection.

2.4.4.5 Sensors

Gamesa G8X wind turbines are fitted with sensors that monitor the different parameters of the turbine. Some sensors are tasked with collecting outdoor signals such as speed and direction of wind and outdoor temperatures. Others record the temperature of the various parts of the turbine, the levels of pressure, and the position or the vibration of the rotor blade. Information collected by the sensors is recorded and analyzed in real time and input into the regulatory and the supervisory parts of the control system to optimize the turbine performance.

2.4.4.6 Network Connection and Location

All the Gamesa G8X turbines can run on 50 Hz and 60 Hz frequency networks. A suitable transformer must be fit to the turbine. The low voltage network must have a provision of

± 10%, while the frequency network must give a range of 3 Hz for both the 50 Hz and 60 Hz networks. The used land system has two concentric rings with impedance levels as required by the local civil works regulations.

2.5 Wind Turbine Parameters of Importance in LCA Studies

The next sections explore different wind turbine parameters that are critical when performing life cycle assessments. Important parameters include the capacity factor, life span of the wind turbine, and power rating of the turbines (Goedkoop et al., 2016).

2.5.1 Capacity Factor

The capacity factor (the ability of a wind turbine to produce power) determines the amount of energy the turbine impact is allocated to; for instance, when a turbine having the capability of producing 250 MW in its life span had a capacity factor of 50%, the environmental impacts of the turbine's lifetime "are doubled" per MW. Rather than dividing the impacts by 250 MW, the impacts were assigned specifically to 50% of the "power rating".

2.5.2 Wind Turbine Life span

The life span of a wind turbine affects the way environmental impacts are assigned for each megawatt. When the life span of a wind turbine is 20 years, the overall impacts for processing the components are distributed across the energy produced in the 20 years. When the approximated life span of that turbine is 10 years, the same material impacts are spread over a short period resulting in low quantities of generated energy. Moreover, any environmental impacts associated with the maintenance period are considered directly proportional to the operational life span of the turbine.

Several industry estimates along with studies showed that the individual wind turbine's life span before major maintenance is conducted is 20 years (Lenzen et al., 2000; Proops et al., 1996; Schleisner, 2000; Jensen, et al., 2009). Therefore, the moving parts (generators, gearboxes, and rotors) are substituted after 20 years, while the turbines' supporting systems and wind farm were not interfered with. Industry data regarding wind turbine life spans is limited due to the short time that most farms have been in operation; therefore, the precedents created in the cited studies are adopted.

The manufacturer of the turbines evaluated in this study (Gamesa) conducted a study regarding the life span extension. They found out that increasing the life span of the wind turbines to 25 years instead of 20 years will decrease the environmental impacts by average of 20% for all categories and by 30% if it extended to be 30 years.

Most wind turbines are designed for a 20-year life. The decision to operate a turbine longer than 20 years has some advantages and disadvantages. Longer life of the turbines might be a way to increase the revenue, but it means more operation and maintenance than usual because the older the parts of the turbines mean more maintenance is needed. Also the risk of the structure failing would be greater.

DNV KEMA (2016) developed a few models to test the cost of extension of the life of wind turbines with 3 different scenarios (20 years, 22 years, and 35 years). The three models (Lidar Control, Load Reduction, and State Estimation) were compared, based on inspections, modified operations, and advanced controls. Figure 2.5 shows results of the sensitivity analysis of the models. According to Darrell Stovall, Principal Engineer at DNV KEMA, the modelling approaches considered the expenses and income over the life of the turbines, including expenses for replacement of components that wear out. Figure 2.5 shows the percent increase in internal rate of return (IRR) for various approaches to life extension over decommissioning at 20 years. An advanced controls approach can reduce turbine loads over those experienced under nominal or older control schemes. Another expense added for each turbine is control options, which is around $120,000 per year plus the annual operation and maintenance cost. All the models proved an increase of IRR compared with 20-year life span. The longer the life span of the wind turbine, the greater the financial benefits. The study thus concluded that life span extension can increase revenue, but at the same time will likely increase financial and safety risks. The results highly depend on the assumptions of the model, as well as on the farm setting and management. Hence, it is highly recommended by the experts in DNV KEMA to do an analysis on a case-by-case basis. (Wind Power Engineering, 2016,).

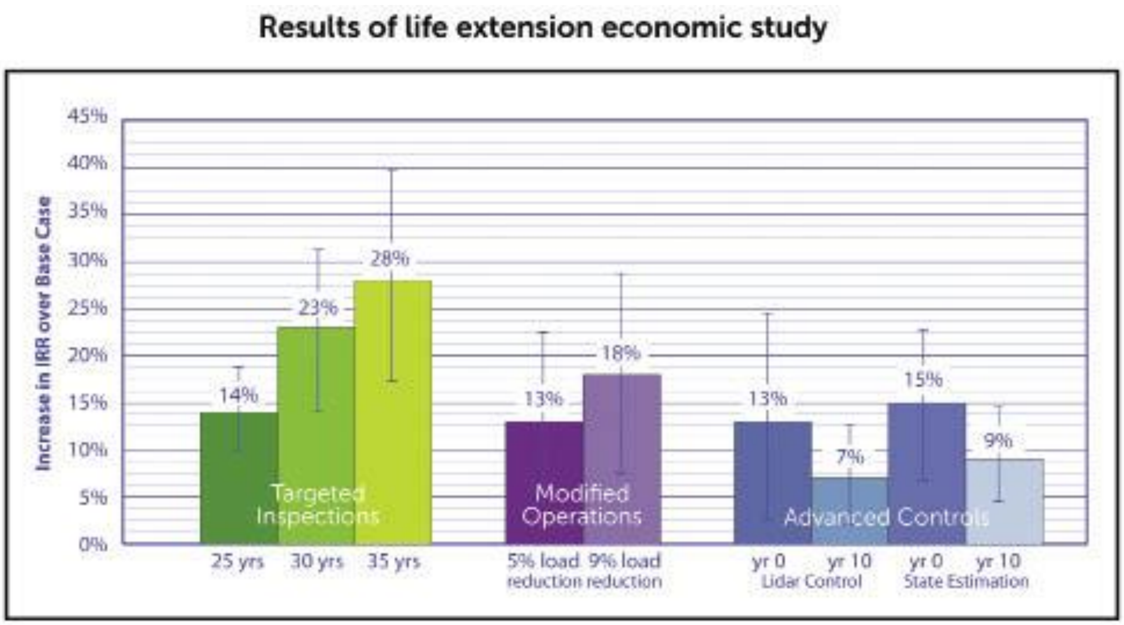

Figure 2.5: Results of DNV KEMA Wind Turbine Life Extension Models.

2.5.3 Power Rating

The power rating of the turbine is a critical system variable, as the power output of the turbine depends mainly on the size (Jensen et al., 2009). The major design criteria that determines the turbine output is the diameter of the rotor (blades length). As the rotors rotate, they form circles, which are perpendicularly aligned to the wind direction.

The created circles are called the swept area, and represent the air quantity obtained and utilized for generating electrical energy. Moreover, the larger the blade length and circle, the larger the quantity of materials required and the tower. This has a direct influence on the evaluation of environmental impacts. The power within the wind may be computed through the equation indicated below (Treloar et al., 2000):

Power (watts) = $\frac{1}{2} \rho A V^3 C_p$……………………………………………….... (Equation 1.1)

Where ρ represents the air density (kg/m^3), A represents the wind turbine rotor's swept area (m^2), v denoted the wind speed (m/s), and C_p is the wind power coefficient which is constant and equal to 0.59 according Bitz law.

2.6 Previous Studies of Wind Power

2.6.1 Non-LCA Studies

A variety of studies relate to wind power, but do not provide detailed LCAs. For example, a number of studies examine wind production potential of regions (Carolin et al., 2008; Wichser et al., 2008; Heijungs et al., 2002). Some previous LCA studies focus generally on renewable energy (Gurzenich et al., 1999; Góralczyk, 2003) but do not provide a detailed analysis of wind turbine emissions. For instance, Gurzenich et al., (1999) compared the LCA results for various renewable sources of energy without providing a detailed explanation within each case. Jackson et al. (1978) found that study participants responded negatively to transmission line images in undisturbed and natural landscapes, but not to transmission images passing through developed sites. In response, transmission line structures were modified to make them less obtrusive and narrow: tubular structures were substituted for lattice-steel structures; in addition, utilities started constructing lines within restricted corridors (Karady, 2007). He found that high voltage transmission lines produce audible broadband noise linked to corona discharge interacting with water droplets during damp weather conditions. Low noise levels can also emanate from corona discharge near conductors, as well as from the oscillatory motion created and from loose equipment (Karady, 2007) At the right-of-way edge, the level of noise ranges from 50 - 52 decibels, which is quieter than normal conversations.

2.6.2 Wind Power LCA Studies for Low Power Turbines (< 1 MW), Off-Shore Turbines, and End-of-Life Only

Some specific LCA studies of wind turbines are based on low power below 1 MW and older machines, which are not applicable to today's large wind farms in Texas. Schleiner (2000) conducted the first wind turbine LCA for a 500 kW turbine. Celik et al. (2007) focus on low-power urban installations and micro-turbines. Jungbluth et al. (2004) evaluated the applicability of the Ecoinvent database to wind power, focusing on wind turbines having power between 30 and 800 kW. They also conducted a comparison of wind turbines (< 800kW) and solar cells. Ardente et al. (2008) conducted a life cycle analysis of a wind farm with 11 turbines with rated power of 660 kW. Khan et al. (2005) created an LCA of a hybrid wind-turbine system containing fuel cells, with a wind turbine having a power rating of 500 kW. Other analyses have examined off-shore wind turbines (Tryfonidou et al., 2004; Weinzettel et al., 2009).

Krohn (2016) focused only on the end-of-life phase of wind turbines, by evaluating the quantity of energy utilized for dismantling the turbine and deducting the quantity of energy saved from recycled materials. Nalukowe et al. (2006) provide recycling options for a decommissioned wind turbine.

2.6.3 Wind Turbine LCAs for Locations outside the US

A number of studies have been conducted of large wind farms outside the US. Martinez et al. (2009) investigated the environmental effects of wind turbines in Spain using LCA; it was found that the foundation contributes significantly to environmental impacts. Oebels et al. (2013) determined that for a 141.5 MW wind farm in Brazil, over 50% of emissions emanated from tower manufacture, whereas transportation accounted for only 6%. The emission intensity of carbon dioxide was found to be 7.10 g CO_2/kWh in Brazil. Ardente et al. (2008) assessed the environmental and energy performance of a wind farm located in Italy using mean European data. They found that carbon dioxide emission intensity ranged between 8.8 and 18.5 g/kWh, whereas the energy intensity ranged between 0.04 and 0.07 kWh_{prim}/kWh_{el}; kWh_{prim} is the amount of primary electricity consumed, and the kWh_{el} is the amount of electricity produced. Additionally, the study found that the payback indexes were lower than 1 year.

2.6.4 Sensitivity of Previous LCA Studies to Assumptions

The wind turbine's indirect emissions and input energy are largely dependent on assumptions about material composition and (Lenzen et al., 2000). Lenzen et al. (2004) show that the tower, typically steel, constitutes 23.3% of the total mass of the turbine (average). The foundation, typically concrete, might account for almost thrice as much or 60.3% of the overall mass (average). Since concrete and steel account for the significant quantity of mass, choosing discrete values for emission factors and energy content may result in considerable variances within the LCA results. In addition, the input energy required for extracting and refining steel differs based on the refinement technique (that is, blast furnace or electric arc furnace), the kind of steel product (that is plate steel against galvanized or rebar coil) as well as the country where the product was manufactured. Such variability has resulted in energy input values within past studies ranging between 20.7 and 55 mega-joules for each kilogram of steel (Voorspools, et al., 2000).

Furthermore, assumptions regarding material recycling may influence LCA outcomes. Recycling may affect indirect emissions and input energy at the end of life cycle-during refining/ extraction of raw materials or in the decommission stage of the wind turbine. The application of recycled materials for manufacture of turbines leads to emissions and less input energy as the emissions and consumed energy emanating from the recycled materials do not exceed that of raw materials. Similarly, recycling materials at the end of a wind turbine's life cycle decreases the quantity of emissions and input energy emanating from the material's future use. When utilized as a credit for LCA results, this may save a significant quantity of input energy and avert associated air emissions. Given a situation where materials of the wind turbine are recycled to a maximum practical extent, recycling may lead to averting almost 20% of the wind turbine's life cycle energy input (Krohn, 2016). Moreover, Lenzen et al. (2004) cite that recycling 75-100% of wind turbine materials may lead to energy savings ranging between 12.5 and 31.9% of the total input energy required. Past studies assume different recycling levels, thus leading to variations in energy intensities. Recycling levels will be explored comprehensively in Chapters 3 and 4.

Lenzen et al. (2004) investigated 72 past CO_2 and energy analyses of small wind turbines for onshore and offshore systems globally including India, Japan, Brazil, Argentina, Belgium, Switzerland, Denmark, Germany, the UK and US. The studies differed considerably in their results. Energy intensity, described as the required energy allocated in the system to transport, manufacture, for each unit of electricity generated in its life cycle, was discovered to differ from 0.014-1kWh. The intensity of carbon dioxide, that is, CO_2 mass emitted for every unit of electricity generated in the life cycle, was discovered to range between 7.9 and 123.7 g CO_2/kWh. Differences in results could be traced to differences in boundaries and scope of the studies (for instance, including decommissioning, construction, and transportation), methodology (process assessment vs. input/output), as well as differences in assumptions about wind turbine life span, load factors, turbine power rating, capacity, rotor diameter, and on-shore vs. off-shore.

2.7 How This Study Will Advance Knowledge

Based on the previous discussion, a number of previous wind power LCA studies were for low power turbines (< 1 MW), off-shore turbines, and end-of-life only. LCAs for large wind turbines have been conducted for Spain, Brazil and Italy, but none for the US.

Earlier environmental assessment studies of the small wind power have typically addressed the production and use stage only. In the research presented in this dissertation, all life cycle phases are addressed: raw materials acquisition, manufacturing, use, transportation, and dismantling/end-of life phase. In particular, *previous studies have not included maintenance as part of the use phase*. This study includes data to evaluate environmental impacts of the maintenance phase, which is a contribution to current knowledge. Including all phases helps highlight which phases will be most effective to target to reduce environmental impacts. Also inside each phase, the sub-phases have been modelled separately, so the results give a better understanding of which sub-phase in particular is causing the environmental impacts or energy consumption.

The only study that covered all the life cycle stages was undertaken outside the USA (in Spain); the study examined Gamesa turbines with a wind speed to be 8 m/s. Conducting a similar study in US will have likely different results than the one in Spain for several reasons. For example; the wind speed in Texas is likely different from Spain, resulting in different power production. In Spain, there is no need for sea shipping since the manufacturing and all the raw materials are local. Finally, emissions from land transportation would be different due to different vehicle emission standards.

Moreover, in many previous studies, CO_2 was used as an impact metric. Even though other studies also included SO_2 and one study included energy consumption, *no study included traditional air pollutants other than SO_2 (NO_x, VOCs, PM) as impact metrics*. The research presented in this dissertation will quantify PM, VOCs, and NO_x emissions, as well as greenhouse gas emissions, energy production/consumption, and water depletion. *No previous study has provided a complete energy balance for wind turbines*, comparing the energy used to acquire the raw materials, manufacture, and transport the turbines, with the energy produced by the turbines over their lifetime. The only previous study that has examined water depletion was the one for Spain.

In summary, the *practical contribution* of this study is to provide an LCA for a large wind turbine in the US, which includes all life cycle phases; this has not been done before. The study's *contribution to the field of LCA* is a more comprehensive LCA than has been conducted to-date for wind turbines anywhere, by including several important new elements: 1) maintenance as part of the use phase, 2) traditional air pollutants in addition to greenhouse gas emissions, 3) an energy balance to compare energy produced by the turbines over their lifetime with energy consumed to manufacture and transport them, and 4) a sensitivity analysis that examines more parameters.

CHAPTER 3

METHODOLOGY

3.1 Methods to Address Objective 1: Life Cycle Environmental Analysis

This chapter will describe the used methodology to complete this study including the PRé Sustainability software (SimaPro) to model the collected data. In any life cycle assessment, there are four main steps should be followed. Figure 3.1, repeated from Chapter 2, illustrates the steps of a Life Cycle Assessment (LCA).

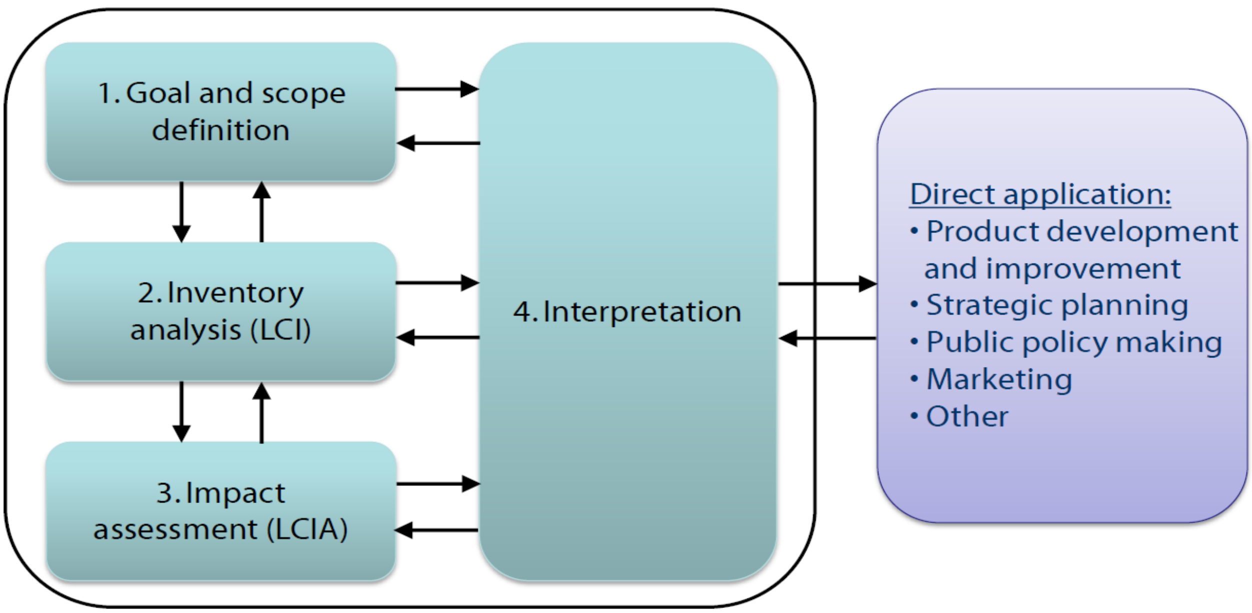

Figure 3.1 Steps of Life Cycle Assessment, (PRé Sustainability: 2015)

3.1.1 Goal and Scope Definition

3.1.1.1 Goal Definition

As mentioned in the first chapter, this study aims to conduct a life cycle analysis for greenhouse gases (CO_2 equivalents), as well as traditional air pollutants, including SO_2, NOx, VOCs, CO and PM, for wind power generation in Texas. It addresses all the phases needed to produce 1kWh.

The study covers the pollutants from cradle-to-cradle starting from the materials acquisition, construction, operation and maintenance, and end of life phase of the life cycle, along with the percentage of materials recycled back to new products. Results will be compared to literature values for emissions from coal and natural gas, as examples of non-renewable energy resources.

The results of this study will be beneficial to industry partners, investigators and researchers, and decision makers. It will answer questions like:

- What are the most important factors influencing life cycle emissions from wind energy production?
- Are emissions from maintenance of wind turbines significant in terms of the overall life cycle?
- At the end of a wind turbine's life cycle, what percent of materials are recycled back into new products?
- How sensitive is the life cycle analysis to changes in input parameters?
- What are life cycle emissions for wind energy in the US, vs. coal and natural gas?

3.1.1.2 Scope Definition

3.1.1.2.1 Wind Turbines Studied

This analysis was conducted for 200 Gamesa 2 MW wind turbines G83 (100) and G87 (100) located at the Lone Star Wind Farm near Abilene, Texas. These wind turbines were chosen because they are widely used and have publicly available data. Table 3.1 shows installed capacity of Gamesa wind turbines around the world (Gamesa Corp, 2016).

Table 3.1: Distribution of Gamesa Turbines around the World.

Country	Number of wind farms	Total capacity (MW)
China	8	494.5
India	10	1,093.3
Spain	7	31.15
Sweden	2	16
Poland	1	24
Italy	1	30
Texas	1	400

Gamesa turbines are the only brand of wind turbine used at Lone Star Wind Farm (LSWF), one of 42 wind farms in Texas, as listed in Table 3.2, in order from largest to smallest.

Table 3.2: Wind farms in Texas as of May 2016 (America Wind Energy Association, 2016)

No.	Wind farm	Installed Capacity (MW)	Turbine Manufacturer	County
1	Los Vientos Wind Farm	912		Starr, Willacy
2	Roscoe Wind Farm	781	Mitsubishi	Nolan
3	Horse Hollow Wind Energy Center	735	GE Energy/ Siemens	Taylor, Nolan
4	Capricorn Ridge Wind Farm	663	GE Energy/ Siemens	Sterling, Coke
5	Sweetwater Wind Farm	585	GE Energy/ Siemens/ Mitsubishi	Nolan
6	Buffalo Gap Wind Farm	523	Vestas	Taylor, Nolan
7	Panther Creek Wind Farm	458	GE Energy	Howard,
8	Peñascal Wind Farm	404	Mitsubishi	Kennedy
9	Panhandle Wind (I & II)	400	GE/ Siemens	Carson
10	Lone Star Wind Farm	400	Gamesa	Shackelford, Callahan
11	Papalote Creek Wind Farm	380	Siemens	San Patricio
12	Stephens Ranch Wind (I & II)	376	GE Energy	Borden, Lynn
13	Sherbino Wind Farm	300	Vestas	Pecos
14	Jumbo Road Wind	300	GE Energy	Castro
15	Green Pastures	300	Acciona	Baylor, Knox
16	Miami Wind Energy Center	289	GE Energy	Roberts, Hemphill, Gray and Wheeler
17	Gulf Wind Farm	283	Mitsubishi	Kennedy
18	King Mountain Wind Farm	279	Bonus/ GE Energy	Upton
19	Palo Duro Wind Energy Center	250	GE Energy	Hansford, Ochiltree
20	Javelina Wind Energy Center	250	GE Energy	Webb
21	Pyron Wind Farm	249	GE Energy	Scurry/ Fisher, Nolan
22	Mesquite Creek Wind	211	GE Energy	Borden, Dawson

23	Grandview Wind Farm	211	GE Energy	Carson
24	Rattlesnake Wind Energy Center	207	GE Energy	Gasscock
25	Shannon Wind	204	GE Energy	Clay
26	Magic Valley Wind Farm	203		Willacy
27	Logan's Gap Wind	200	Siemens	Comanche
28	Hereford Wind	200	GE Energy/ Vestas	Deaf Smith
29	Colbeck's Corner Wind Farm	200	GE Energy	Carson, Gray
30	Inadale Wind Farm	197	Mitsubishi	Scurry/ Nolan
31	Bull Creek Wind Farm	180	Mitsubishi	Borden
32	Turkey Track Energy Center	170		Nolan, Coke, Runnels
33	Hackberry Wind Project	165	Siemens	Shackelford
34	Wildorado Wind Ranch	161	Siemens	Oldham, Potter, Randall
35	Desert Sky Wind Farm	160	GE Energy	Pecos
36	Brazos Wind Ranch	160	Mitsubishi	Scurry, Borden
37	Woodward Mountain Wind Ranch	159	Vestas	Pecos
38	Trent Wind Farm	150	GE Energy	Taylor
39	Notrees Windpower	150		Ector, Winkler
40	McAdoo Wind Farm	150	GE Energy	Dickens
41	Langford Wind Farm	150	GE Energy	Tom Green, Schleicher, Irion
42	Goat Mountain Wind Ranch	150	Mitsubishi	Coke, Sterling

The Lone Star Wind farm is located 15 miles northeast of downtown Abilene, Texas, as shown in Figure 3.2, in the counties of Callahan and Shackelford, and has an installed capacity of 400 MW (200 turbines).

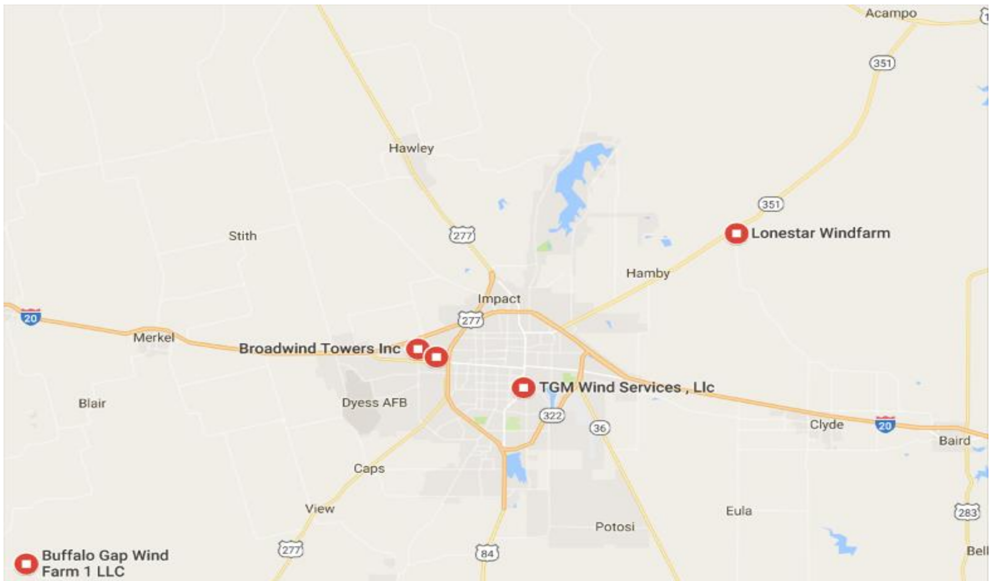

Figure 3.2 Lone Star Wind Farm near Abilene, TX (Google Maps)

The construction of the turbines at Abilene was completed in two major phases: phase one began producing power in December 2007, while phase two started in May 2008. In the Lone Star Wind Farm, there are 100 2.0 MW Gamesa G83 turbines and another 100 2.0 MW G87 turbines (http://lonestarwindfarm.com/). There are some small differences between the two models: primarily, the diameter is 83 m for the G83 and 87 m for the G87. Also, some components inside rotor of G87 are bigger than the components inside the rotor of the G83. The turbines have a life span of 20 years from their date of installation to their dismantling phase.

Consideration of how "economies of scale" might influence impacts was beyond the scope of this study. For example, for a wind farm with more 2 MW turbines (say 400 instead of 200), the transportation for the maintenance phase would be reduced per kWh: when the truck drives from the company headquarters to the wind farm, it would be servicing more turbines, so the impacts from the trip would be divided by a larger number of kWh.

3.1.1.2.2 Functional Unit

The functional unit is the unit of the service or the product that the environmental impacts will quantified according to, in this LCA research, the functional unit is defined to be *1 kWh of electricity generated*. This means that the environmental impacts will be measured per each 1 kWh generated.

3.1.1.2.3 System Boundaries

Figure 3.3 shows the steps in the life of wind turbines from the raw materials acquisition to the end of life, and Figure 3.4 shows the phases and the boundaries of this research. Six major phases characterize the life cycle of turbines:

a) Raw Materials Acquisition,

b) Manufacturing,

c) Installation,

d) Operation and Maintenance,

e) End of Life,

f) Transportation.

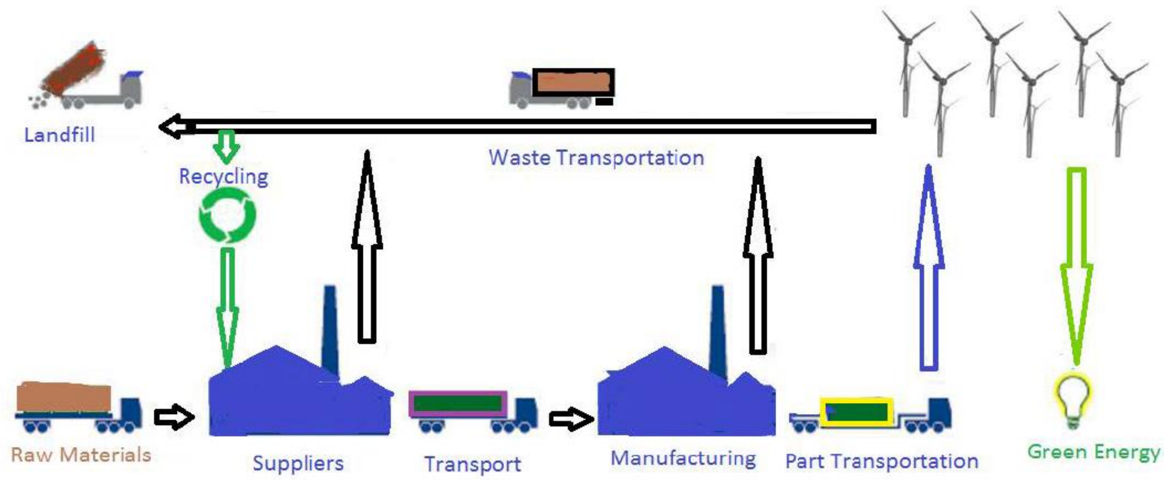

Figure 3.3: Life Cycle Steps of Wind Production

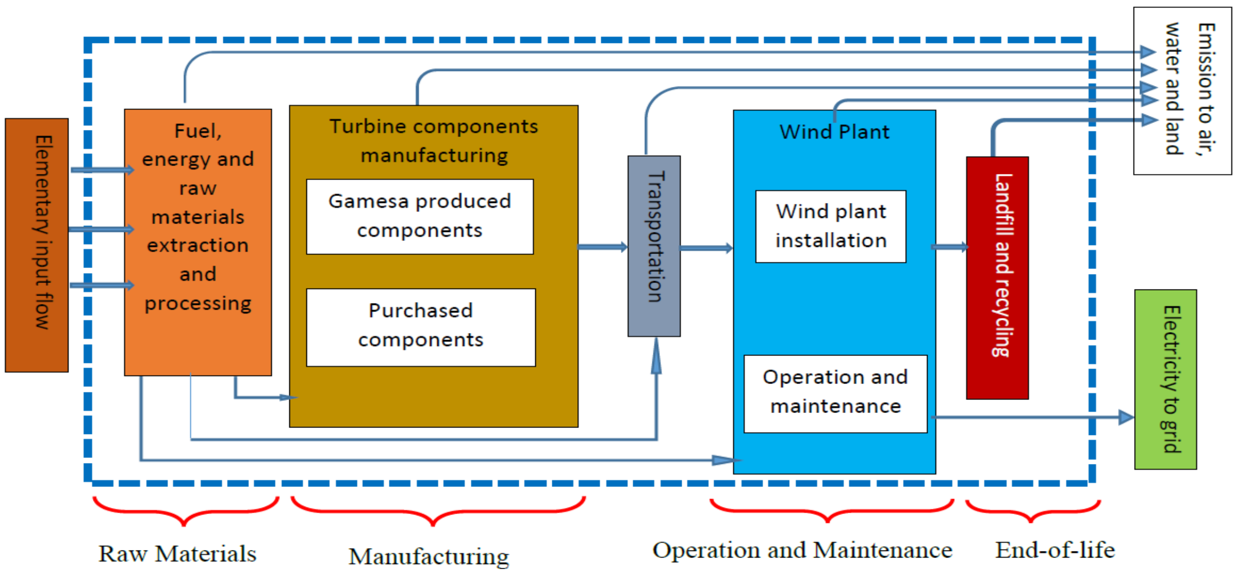

Figure 3.4: System Boundaries (D'Souza et al., 2011)

Transportation for the raw materials, parts and components, construction materials, and maintenance materials will be included in each phase. Raw materials acquisition, production, and end-of-life for materials used during the maintenance phase of the wind turbines will be included.

It should be noted that direct land/ecosystem due to placement of the turbines, such as disturbing habitat of endangered species, are beyond the scope of this study. In addition, direct impacts on wildlife during turbine operation (e.g. birds hit by the rotating turbine blades) are not considered in this study.

3.1.2 Inventory Analysis

3.1.2.1 Data Collection

The data to be utilized for life cycle inventory was gathered from a variety of sources such as the manufacturer website, data inventory in the SimaPro program (all data libraries were enabled in Simapro to ensure that all choices were presented), websites of wind turbine farms, and government agencies like US Environmental Protection Agency (EPA), Department of Energy, and the Energy Information Administration (EIA). The data collection process was guided by the quality criterion required by LCA ISOs, and that means only data from trusted primary sources was collected. Additionally, the data had high relevance regarding LCA G83 and G87 wind turbines.

The dataset presented here represents the construction of a wind turbine with a capacity of 2-MW for onshore use. The term "wind turbine" includes moving parts such as nacelle, rotor, rotor blades, and transition piece as well as fixed parts such as the tower and the foundation.

3.1.2.1.1 Data for Wind Turbine Raw Material Acquisition and Manufacturing

Table 3.3 lists the turbine components. Tables 3.4 through Table 3.9 show material quantities for particular turbine components (nacelle, rotor, wiring, tower and foundation), along with the SimaPro categories chosen for modelling that material. When a category such as steel is selected in Simapro, all processes for producing the steel, including mining of and process of raw materials, are included in the inventory numbers that accompany steel. The processes for manufacturing the materials into each turbine part were considered on an aggregated level, by considering the materials and energy used to manufacture each turbine part. Energy used for manufacturing is provided in Section 3.1.2.1.6. Detailed processes (heating a certain material to a certain temperature, then extruding it, cooling it) were not modeled individually.

Table 3.3: The Turbines Component Measurements and Weights (Gamesa, 2013)

Turbine Parameter	**Value**
Capacity of the Turbine	2000 kW
Diameter of the rotor	83m and 87m
Number of rotor blades	3
Rotor Weight	37,000 kg
Rotor Blade Weight	18,358 kg
Nacelle weight	68,266 kg
Tower type	Tubular steel tower
Tower weight	189,000 kg
Material of the tower	Steel
Tower hub height	78 m
Tower diameter	4 m
Foundation weight	1,175,000 kg
Cable for network connection (per turbine)	1000 m (6190 kg)
Lifetime of the Turbine	20 years
Operating temperature range: standard turbine	-20°C to 40°C
Operating temperature range: low temperature turbine	30°C to 40°C

Table 3.4: Nacelle Components of G83 or G87 Turbines (Gamesa, 2013)

Material	Mass (kg)	Simapro Material Category
Low alloy steel	21,805.05	Steel, low-alloyed {GLO}| market for | Alloc Def, U
High alloy steel	15,538.36	Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U
Casting	23,638.28	Cast iron {GLO}| market for Alloc Def, U
Copper	522.65	Copper {GLO}| market for | Alloc Def, U
Aluminum	1035.38	Aluminum, primary, ingot {GLO}| market for | Alloc Def, U
Brass	38.00	Brass {GLO}| market for | Alloc Def, U
Polymer	144.74	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U
Fiberglass	10.47	Glass fiber reinforced plastic, polyamide, injection molded {GLO}| market for | Alloc Def, U
GRP (Glass Reinforced Plastic)	1716.08	Glass fibre reinforced plastic, polyamide, injection molded {GLO}| market for | Alloc Def, U
Painting	73.68	Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Def, U
Components electric/electronic	905.26	Electricity, medium voltage {ES}| market for | Alloc Def, U
Lubricant	627.77	Lubricating oil {GLO}| market for | Alloc Def, U
Wires	1280.28	Copper {GLO}| market for | Alloc Def, U

Table 3.5: Rotor Components of G83 and G87 Turbines (Gamesa, 2013)

	Mass (kg)		
Material	**G83**	**G87**	**Simapro Material Category**
Low alloy steel	3,344.53	3,344.57	Steel, low-alloyed {GLO}| market for | Alloc Def, U
High alloy steel	6,817.74	6,857.63	Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U
Casting	9,445.52	9,445.52	Cast iron {GLO}| market for | Alloc Def, U
Copper	51.41	53.76	Copper {GLO}| market for | Alloc Def, U
Aluminum	50.07	50.07	Aluminum, primary, ingot {GLO}| market for | Alloc Def, U
Polymer	718.01	750.35	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U
Fiberglass	11,207.44	11,747.56	Glass fiber reinforced plastic, polyamide, injection molded {GLO}| market for | Alloc Def, U
Carbon fiber	2,755.37	2,888.16	Glass fiber reinforced plastic, polyamide, injection molded {GLO}| market for | Alloc Def, U
GRP (Glass Reinforced Plastic)	186.30	186.30	Glass fiber reinforced plastic, polyamide, injection molded {GLO}| market for | Alloc Def, U
Painting	628.86	659.17	Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Def, U
Adhesive	1,360.73	1,426.31	Adhesive mortar {GLO}| market for | Alloc Def, U

Table 3.6: Wiring of G83 and G87 Turbines (Gamesa, 2013)

Material	Mass (kg)	Simapro Material Category
Cooper	531.74	Copper {GLO}| market for | Alloc Def, U
Aluminum	2,714.24	Aluminum, primary, ingot {GLO}| market for | Alloc Def, U
Polymer	2,943.64	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U

Table 3.7: Tower Components of G83 and G87 Turbines (Gamesa, 2013)

Material	Mass (kg)	Simapro Material Category
Low alloy steel	188,179.26	Steel, low-alloyed {GLO}| market for | Alloc Def, U
Aluminum	237.00	Aluminum, primary, ingot {GLO}| market for | Alloc Def, U
Painting	580.38	Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Def, U

Table 3.8: Foundation Components of G83 and G87 Turbines (Gamesa, 2013)

Material	Mass (kg)	Simapro Material Category
Low alloy steel	14,537.00	Steel, low-alloyed {GLO}| market for | Alloc Def, U
Corrugated steel	44,000.00	Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Def, U
Concrete in mass	1,116,000.00	Concrete block {GLO}| market for | Alloc Def, U

Table 3.9: Substation Components G83 or G87 Turbines (Gamesa, 2013)

Material	Mass (kg)	SimaPro Material Category
Low alloy steel	1,833.56	Steel, low-alloyed {GLO}| market for | Alloc Def, U
Casting	37.23	Cast iron {GLO}| market for | Alloc Def, U
Copper	443.25	Copper {GLO}| market for | Alloc Def, U
Aluminum	27.36	Aluminum, primary, ingot {GLO}| market for | Alloc Def, U
Brass	1.68	Brass {GLO}| market for | Alloc Def, U
Polymers	19.68	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U
Glass fiber	18.93	Glass fiber reinforced plastic, polyamide, injection moulded {GLO}| market for | Alloc Def, U
Painting	1.56	Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Def, U
Lubricant	649.37	Lubricating oil {GLO}| market for | Alloc Def, U
Concrete	7,200.00	Concrete block {GLO}| market for | Alloc Def, U
Porcelain	52.49	Clay plaster {GLO}| market for | Alloc Def, U

In addition, it was assumed that the brake system was replaced every 5 years, according to manufacturer information, and the control system was replaced every 10 years. Hence, additional materials and energy to manufacture these parts were included as part of the manufacturing phase.

3.1.2.1.2 Data for Transportation Phase

The shipping and the transportation of the materials were done by sea shipping and land shipping by truck; both methods used diesel for their fuel resources. The transportation is grouped into seven categories, which involve the following:

1. The shipping of the raw materials and components to the Gamesa production plants from the suppliers.
2. The shipping of the parts between Gamesa production plants for assembling purposes.
3. Shipping of waste from the manufacturing plants to local recycling plants or landfills. The market option was chosen in the SimaPro modelling, so it will automatically choose the default distance from the data inventory.
4. Transportation of the final components of the turbine from the manufacturers in Spain to the closest port there in order to be shipped to the United States.
5. The shipping of the components from the port in Spain to Galveston port in the USA, a distance of 8325 km (5173 miles).
6. The shipping of the final parts of the turbine from the port of Galveston to the Lone Star wind farm.
7. The shipping of the construction wastes from the turbine construction Lone Star site in Abilene to the local recyclers. The same as above regarding the recycling plants and landfill, the market option was chosen, so the default distance is assumed by the SimaPro.

Tables 3.10 -3.12 summarize the distances and weights that were used to do the modelling in SimaPro, specifically, the distances from the manufacturing locations to the ports in Spain, then from the port in Spain to the port in USA (Galveston port), and finally from Galveston to the site of the wind farm in Abilene. Distances should be entered in ton-kilometers (tkm) to be modelled in SimaPro; one ton-kilometer means the transport of one ton over 1 kilometer, for example. For example, if 1.3 tons are transported over 100 km, then we should enter 130 tkm as quantity in SimaPro.

Table 3.10: Distances between Gamesa Manufacturing Plants

Part	**From**	**To**	**Distance (km)**	**Distance (tkm)**	**Category in SimaPro**
Nacelles	Gamesa Agreda plant	Ferrol Port	650	43,768	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U
Casting	Burgos	San Sebastian port	210	8,939	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U
Towers	Olazagutía (Navarra)	San Sebastian port	70	13,230	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U
Rotor	Medina del Campo, Valladolid	Ferrol port	380	13,895	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U

Table 3.11: Transportation Distances from Spanish Port to US Port (Galveston)

Part	**From**	**To**	**Distance (km)**	**Distance (tkm)**	**Category in SimaPro**
Nacelle	Spain Port	US port	8,325	560,572	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U
Casting	Spain Port	US port	8,325	354,370	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U
Tower	Spain Port	US port	8,325	1,573,392	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U
Rotor	Spain Port	US port	8,325	304,411	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U

Table 3.12: Transportation Distances from Galveston to Abilene

Part	From	To	Distance (km)	Distance (tkm)	Category in SimaPro
Nacelle	Galveston	Abilene	656	44,172	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U
Casting	Galveston	Abilene	656	27,924	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U
Tower	Galveston	Abilene	656	123,981	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U
Rotor	Galveston	Abilene	656	23,987	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U

3.1.2.1.3 Data for Wind Turbine Installation Phase

This phase includes the various activities performed in the putting together the various parts of the turbine, primarily the construction of the foundation of the turbine and the construction of the substation for collecting the power produced by the turbines. The other main activities in this phase include the setting up of the control building, laying underground cables for the entire project, and preparing the access roads to the project site. The foundation for the onshore turbine consists of plate foundations made with reinforced concrete. Production of the concrete was included in this phase. Typically, the foundation size is 15 × 15 meters and 2 meters deep. 17,640 gal of diesel is needed to complete each turbine construction; this amount of fuel was calculated as follows:

Each wind turbine needs around 18-21 working days to be completed, with 10 pieces of heavy equipment (2 excavators, 2 loaders, bulldozer, grader, crane, and 3 heavy trucks) involved and working at the same time for 12 hours a day. The average of diesel consumption is 7 gal/hour.

Now, 10 heavy equipment * 12 hours/ day * 21 days = 2520 hours of working

2520 hour *7 gal/hour = 17,640 gal

3.1.2.1.4 Data for Wind Turbine Operation and Maintenance Phase

The operation and maintenance phase includes corrective and preventive maintenance of the turbine. This includes change of oil, lubrication of gears and the generator, and repair of the turbines when they break down. The manufacturer recommended lubricating the turbines every other year; each turbine consumes 375 kg of lubricant oil each time it is lubricated (Konstadinos et al., 2014). Table 3.13 shows the amount of lubricant needed in 3 different life spans for all the turbines in the wind farm. The frequency of maintenance (e.g. lubricating) was assumed to remain constant over the 30-year life span. Since turbines of this model have not yet reached a 20-year life span, there no data to show that the turbines might need more maintenance after a certain year.

Table 3.13: The Amount of Lubricant Needed for the Maintenance and Operation Phase.

Life Span	Number of maintenance times	Amount of Oil Lubricant for the 200 turbine every maintenance time (kg)	Amount of Oil lubricant during the life span (kg)
20 Years	10	75,000	750,000
25 Years	12.5	75,000	937,500
30 Years	15	75,000	1,125,000

Transport of materials for maintenance and repair of the turbines is done by diesel truck. In addition, twice a year, a technician must go to the farm for carrying out surveillance of turbines and cables (Elsam Engineering, 2004). The Lone Star Wind Farm is comprised of 20,016 acres' total area, with around 100 acres per turbine (50 acres /MW) (NERL, 2009). The turbines are distributed on the two sides of the Highway 351 in Abilene, Texas. The total distance between the turbines was found to be around 100 km (using Google Earth ruler) for one way (200 km round trip). This distance covers the roads used to drive from one turbine to another and then drive back to the main office; thus the mileage will be 400 km/ year if the employees drive to the turbines twice a year for maintenance or any other purpose like regular checkup, as recommended by the manufacturer. Maintenance and surveillance are done at the same time.

3.1.2.1.5 Data for the End-of-Life Phase

Two scenarios can be considered at the end-of-life in the LCA: open loop recycling (OLR) and closed loop recycling (CLR). CLR is chosen when the product has been used for the purpose for which it was intended and is eventually recycled into the same system product. OLR is similar to CLR except that the product is recycled into a different product. The LCA using the closed loop recycling methodology and its associated positive credits are not considered in this study, because the materials comprising the components of the turbines are in most cases recycled to make other different products.

To model the end of life phase in this study, we need the recycling percentages of the parts. The percentages are assumed based common recycling percentages of the materials and upon manufacturer recommendations. Therefore, the following assumptions will be applied in this study: 98% of the metals, 90% of the plastics, 50% of the electrical and electronic components, 99% of the cables, 0% of carbon fiberglass, 0% of lubricants/grease/oils, and 0% of paints/ adhesives. Material not recycled will go to landfills by diesel trucks. Tables 3.14 to 3.21 show the amount of materials to be recycled and landfilled after applying the previous recycling percentages.

Table 3.14: The Amount of Materials to be Recycled and Landfilled from The Nacelle

Material	Total (kg)	Amount Recycled (kg)	Amount Landfilled (kg)
Low alloy steel	21,805.05	21,368.95	436.10
High alloy steel	15,538.36	15,227.59	310.77
Casting	23,638.28	23,165.51	472.77
Copper	522.65	512.20	10.45
Aluminum	1,035.38	1,014.67	20.71
Brass	38.00	37.24	0.76
Polymer	144.74	130.27	14.47
Fiberglass	10.47	0.00	10.47
GRP (Glass Reinforced Plastic)	1,716.08	1,544.47	171.61
Painting	73.68	0.00	73.68
Components electric/electronic	905.26	452.63	452.63
Lubricant	627.77	0.00	627.77
Wires	1,280.28	1,267.48	12.80
Total (kg)	67,336	64,721.01	2,614.99

Table 3.15: The Amount of Materials to be Recycled and Landfilled from the Rotor

Material	Gamesa Turbine G87			Gamesa Turbine G83		
	Total (kg)	Amount Recycled (kg)	Amount Landfilled (kg)	Total (kg)	Amount Recycled (kg)	Amount Landfilled (kg)
Low alloy steel	3,344.57	3,277.68	66.89	3,344.53	3,277.64	66.89
High alloy steel	6,857.63	6,720.48	137.15	6,817.74	6,681.39	136.35
Casting	9,445.52	9,256.61	188.91	9,445.52	9,256.61	188.91
Copper	53.76	52.69	1.08	51.41	50.38	1.03
Aluminum	50.07	49.07	1.00	50.07	49.07	1.00
Polymer	750.35	675.31	75.03	718.01	646.21	71.80
Fiberglass	11,747.56	0.00	11,747.56	11,207.44	0.00	11,207.44
Carbon fiber	2,888.16	0.00	2,888.16	2,755.37	0.00	2,755.37
GRP (Glass Reinforced Plastic)	186.30	167.67	18.63	186.30	167.67	18.63
Painting	659.17	0.00	659.17	628.86	0.00	628.86
Adhesive	1,426.31	0.00	1,426.31	1,360.73	0.00	1,360.73
Total (kg)	37,409.4	20,199.506	17,209.9	36,565.98	2,0129	16,437

Table 3.16: The Amount of Materials to be Recycled and Landfilled from the Wiring

Material	Total (kg)	Amount Recycled (kg)	Amount Landfilled (kg)
Cooper	531.74	521.11	10.63
Aluminum	2714.24	2659.96	54.28
Polymer	2943.64	2649.28	294.36
Total (kg)	6189.62	5830.34	359.28

Table 3.17: The Amount of Materials to be Recycled and Landfilled from the Tower

Material	Total (kg)	Amount Recycled (kg)	Amount Landfilled (kg)
Low alloy steel	188,179.26	184,415.67	3,763.59
Aluminum	237.00	232.26	4.74
Painting	580.38	0.00	580.38
Total (kg)	188,996.64	184,647.93	4,348.71

Table 3.18: The Amount of Materials to be Recycled and Landfilled from the Foundation:

Material	Total (kg)	Amount Recycled (kg)	Amount Landfilled (kg)
Low alloy steel	14,537.00	14,246.26	290.74
Corrugated Steel	44,000.00	43,120	880.00
Concrete	111,600,0.00	0.00	111,600,0.00
Total (kg)	117,453,7.00	57,366.26	111,717,0.74

Table 3.19: The Amount of Materials to be Recycled and Landfilled from the Substation:

Material	Total (kg)	Amount Recycled (kg)	Amount Landfilled (kg)
Low alloy steel	1,833.56	1,796.89	36.67
Casting	37.23	36.48	0.74
Copper	443.25	434.38	8.86
Aluminum	27.36	26.81	0.55
Brass	1.68	1.65	0.03
Polymers	19.68	17.72	1.97
Glass fiber	18.93	0.00	18.93
Painting	1.56	0.00	1.56
Lubricant	649.37	0.00	649.37
Concrete	7,200.00	0.00	7,200.00
Porcelain	52.49	0.00	52.49
Total (kg)	10,285.13	2,313.93	7,971.18

3.1.2.1.6 Data for Energy Consumption for All Phases

Table 3.20 provides energy consumption for each phase of the life cycle, as well as for raw materials acquisition and manufacturing the major parts of the turbine. When energy consumed was in the form of diesel fuel, it has been converted to kWh. The energy values for the parts include raw materials acquisition and manufacturing, but not transportation.

Table 3.20: Amount of Energy Consumed for all Phases

Phase/Part	**Consumed Energy (kWh)**	**Data Source**	**Category In SimaPro**
Raw Materials Acquisition	785,866	Gamesa, 2013	Electricity, medium voltage {CA-MB}| market for | Alloc Def, U
Manufacturing	3,002,503	Gamesa, 2013	
Transport	278,049	Gamesa, 2013 and calculation	
Installation	7,113,424	Calculation	
Operation and Maintenance	1,210,160	Calculation	
End of Life	367,088	Gamesa, 2013	
Nacelle	740,054	Gamesa, 2013	
Rotor	683,669	Gamesa, 2013	
Tower	1,201,706	Gamesa, 2013	

3.1.2.1.7 Conversion of LCI Data to Functional Unit

As mentioned above, the functional unit of this study is 1 kWh of the electricity that is generated and provided to the grid. The data in the LCI phase is converted into the functional unit by estimating the energy generated by the turbine over its entire life cycle.

Factors which can affect the amount of energy generated by the turbine over its life cycle include the turbine efficiency and the average wind speeds at the farm site. According to Gamesa, if the turbines are maintained regularly and according to the recommendations, then the efficiency dropping will be negligible and can be ignored. The average wind speed was calculated using the wind rose (Figure 3.5) from the area where the farm is located. The energy generated by the turbine over its life cycle depends on the cubic power of wind speed, as shown in Equation 3.1.

Wind Power (watts) = $\frac{1}{2} \rho AV^3 C_p$ …………………………………………….. (Equation 3.1)

Where:

ρ = air density = 0.91 kg/m^3 without water vaper and 0.89 kg/m^3 with water vapor

A = wind turbine rotor's swept area $(A) = \pi r^2$ (m^2),

The swept area for G83, A= $\pi 41.5^2$ =5412.8 m^2 and for G87, A= $\pi 43.5^2$ =5947 m^2

V = wind speed (m/s), and

C_p is the power coefficient = 0.59 "According to Betz Law; no wind turbine can convert more than 59.3% of the kinetic energy to a mechanical energy turning power" (Royal Academy of Engineering, 2016)

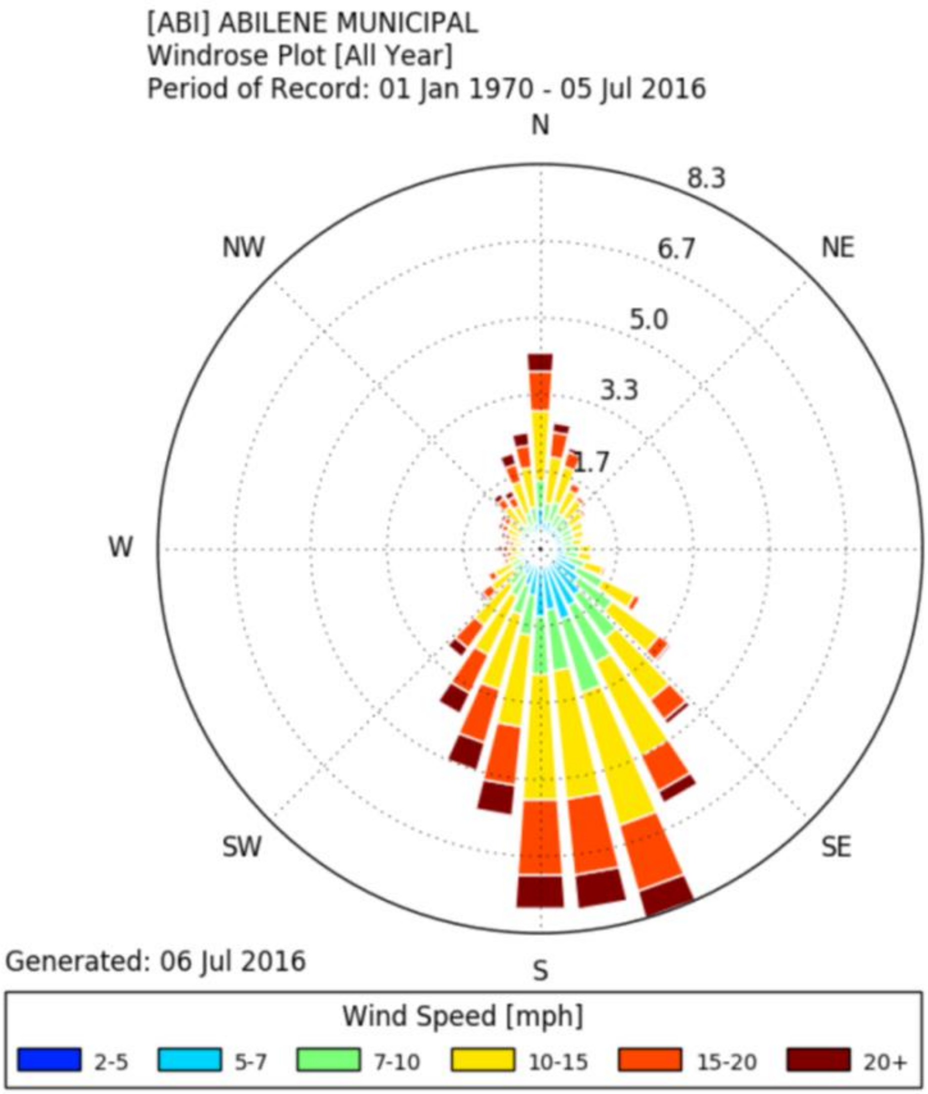

Figure 3.5: Wind Rose of Abilene Area (1970-2016) (www.tceq.state.tx.us)

From the wind rose in Figure 3.5 we can compile percent information for various wind speed categories, as shown in Table 3.21.

Table 3.21: The Percentage of Each Wind Speed Categories in Abilene, Texas.

Wind speed category (mph)	Wind speed category (m/s)	Wind speed average (m/s)	Percentage
2 to 5	0.89 - 2.24	1.56	4%
5 to 7	2.24 - 3.13	2.68	13%
7 to 10	3.13 – 4.47	3.80	21%
10 to 15	4.47 - 6.71	5.59	37%
15 to 20	6.71 - 8.94	7.82	16%
20+	8.94+	8.94	9%

Back to the equation 1, we can calculate the power to be:

For G83: Power (watts) = $\frac{1}{2} \rho A V^3 C_p$

$P = \frac{1}{2} (0.9) (5412.8) [(1.56464 \times 0.04)^3 + (2.68224 \times 0.13)^3 + (3.79984 \times 0.21)^3 + (5.588 \times 0.37)^3 + (7.8232 \times 0.16)^3 + (8.9408 \times 0.09)^3] (0.59) = 17{,}060.29$ watts

So the power of one G83 turbine is 17.06 kW; hence for 100 turbines is:

100 x 28.92 kW = 1706 kW.

For 20 years the energy will be = 1706 kW x 20 years x 365 days/year x 24 hours/day = 298,891,200 kWh

For G87: Power (watts) = $\frac{1}{2} \rho A V^3 C_p$

$P = \frac{1}{2} (0.9) (5947) [(1.56464 \times 0.04)^3 + (2.68224 \times 0.13)^3 + (3.79984 \times 0.21)^3 + (5.588 \times 0.37)^3 + (7.8232 \times 0.16)^3 + (8.9408 \times 0.09)^3] (0.59) = 18{,}744$ watts = 18.744 kW,

For the 100 turbines the power is 1874.4 kW, so for the 20 years the energy will be:

1874.4 kW x 20 years x 365 days/year x 24 hours/day = 328,394,880 kWh

Total energy of both; G83 and G87 =298,891,200 kWh+328,394,880 kWh = 627,286,080 kWh

The energy value of $6.27 * 10^8$ kWh was used to quantify the impacts in term of the functional unit (per 1 kWh generated) for Objective 1.

For the sensitivity analysis, a similar approach was used to find the energy produced by the Lone Star Wind Farm at different wind speeds and over different life spans. Table 3.22 summarizes the energy for each case.

Table 3.22: The Estimated Energy Production in Different Wind Speeds for Different Life Spans

	20 years	**25 years**	**30 years**
Wind rose averages	627,286,080 kWh	784,107,600 kWh	940,929,120 kWh
8 m/s	27,054,384,000 kWh	33,817,980,000 kWh	40,581,576,000 kWh
7 m/s	18,123,564,000 kWh	22,654,455,000 kWh	27,185,346,000 kWh

3.1.3 Impact Assessment

3.1.3.1 Impact Assessment Method and Impact Categories Using SimaPro

SimaPro uses several methods to calculate the environmental impacts of a product. Some examples of the methods in SimaPro is BEES+ (Building for Environmental and Economic Sustainability), which is a software tool developed by the National Institute of Standards and Technology (NIST). Another example is TRACI, which stands for Tool for the Reduction and Assessment of Chemical and other environmental Impacts. In this research TRACI was used to calculate the environmental impacts. TRACI is an LCA methodology that was developed by the United States Environmental Protection Agency (US EPA) using inputs variables which are in line with the various locations in the US. The methodology takes a midpoint-oriented approach and provides site specificity for many impact categories based on US locations. However, if a specific US location is not determined, an average value exists. TRACI methodology is consistent with the EPA decision of the non-aggregation between environmental impact categories and includes characterization, classification, and normalization (US Environmental

Protection Agency and PRé Sustainability, 2015). The normalization factors for the United States and Canada were calculated by Morten Rybert from the Technical University of Denmark (Bare et al., 2002; Bare et al., 2006; Frischknecht et al., 2007).

The characterization of stressors that have potential effect on the environment facilitated by TRACI method are:

a) Global warming (kg CO_2 eq)

b) Depletion of ozone (kg CFC-11 eq)

c) Eutrophication (kg N eq)

d) Human health cancer effects (Carcinogenic) (CTUh)

e) Acidification (kg SO_2 eq)

f) Tropospheric ozone (smog) formation (kg O_3 eq)

g) Fossil fuel depletion (MJ surplus)

h) Human health criteria–related effects (Non-carcinogenic) (CTUh)

i) Respiratory effects (kg $PM_{2.5}$ eq)

3.1.3.2 Allocation Procedure

Allocation is defined by ISO as: "Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO14040: 2006). The percentage of the inventory assigned to each type of turbine was based on the mass of each type; we can ignore the number of units because it is the same for both type (100 turbines of G83 and 100 turbines of G87). Regarding the mass, both brands were almost the same weight: the total weight of G83 was 1,483,937.42 kg and the total weight of the G87 was 1,484,781.48 kg. Hence if we do the percentage calculations, we will find each brand shares 50%.

3.1.4 Interpretation

In this research, the interpretation was completed for each phase as it addressed the major components of the turbine highlighting the main results of each part. That allowed us to figure out the amount of contribution from each phase or part toward the environment, so we can easily provide recommendations to the manufacturer and the operator to adjust the parts and lower the environmental impacts.

3.1.5 The Cumulative Energy Demand (CED)

The CED method allows the visualization of the ACV from an energy perspective as the product in this study is used for the generation of power. CED provides the total amount of energy that the turbine consumes in its entire life cycle. The energy consumed by the turbine includes the processes described in the life cycle phases discussed above. The total energy will be in kWh and will be grouped based on its source as listed in the following categories;

a. Non-Renewable Energy - Nuclear
b. Non-Renewable Energy - Fossil Fuels
c. Non-Renewable Energy - Biomass
d. Renewable Energy - Biomass
e. Renewable Energy – Hydro
f. Renewable Energy - Wind, solar and geothermal

The use of this methodology will also facilitated the determination of the rate of energy return in addition to providing the duration that the turbine takes to generate the amount of energy consumed in its life time.

3.2 Methods to Address Objective 2: To identify a range of impacts due to uncertainty in LCA model inputs.

As defined by ISO, uncertainty analysis is a "systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability" (ISO14040, 2006). This is performed in order to understand the impact that the uncertainties in the data may have on the modelling of the system and its effect on the LCA. Variables that should be considered in an uncertainty analysis include variables for which data input was very uncertain, and variables with a large influence on the overall LCA results.

In this work, uncertainty of 3 variables was examined:

1. Wind turbine life span,
2. Wind speed,
3. Fiberglass Vs aluminum for the blades.

3.2.1. Life of Wind Turbine (+5 / +10)

Three life spans were tested in this study (20, 25, and 30-years). Extending the life span of the turbine via maintenance is something that any wind farm owner or operator may consider in order to maximize the profits of their farm.

The life of wind turbines is estimated to be 20 years. The estimation and the extension of the life span of wind turbines is based on the experienced gained since the first wind farms were installed. As a matter of fact, studies on the modification of the life span of the wind turbines are already in progress. Two scenarios are presented to illustrate the modification of the turbine relative to their life cycles and estimate an extension of 5 to 10 years.

Several factors have been taken into consideration in modeling the longer life span of the turbines. These include additional maintenance, supplies, management of the supplies, employees, and the need to transport the supplies to the farm site. These have been considered so as to account for the likelihood that the turbines may need major corrective maintenance. In addition, additional production of energy was considered.

3.2.2 Different Wind Speeds throughout the Life Span

Three cases of the wind speed were tested. The first was using a fixed wind speed of 8 m/s. This wind speed represents the value where the turbines will perform the best (optimal performance) according to the manufacturer. In the second case, 7 m/s was chosen to test for a wind speed below the optimal performance. The third case involved using the wind rose which represents the actual wind speed in the area. The different wind speed averages were used in the equation to calculate the energy production. Changing the wind speed would also change all impacts, by changing the energy production value used to divide by to put impacts in the form of the functional unit. Since the 7 and 8 m/sec wind speeds represent optimal performance and close to optimal performance, rather than realistic performance, only energy production was calculated in this portion of the sensitivity analysis; other impacts were not revised.

3.2.3 Fiberglass vs. Aluminum for the Blades.

As explained before, one of the reasons to conduct an LCA is to test alternative materials that can serve the intended use and contribute lesser environmental impacts. Specifically, an alternative material will be evaluated for the turbine blades, since blades are one of the largest parts of the turbine and caused a substantial amount of substances to be released during the manufacturing phase. Currently the blades are made of a special type of fiberglass. In this sensitivity scenario, aluminum will be assumed to replace the fiberglass. We hypothesize that aluminum may have reduced impacts, particularly in the human health and respiratory impact categories. Glass wool fiber is considered to be a source of the carcinogenic substances and particles, which in most cases is inhalable and effects the respiratory system; it may also cause eye and skin irritation (OSHA, 2016). In addition, the processes that the aluminum requires to be cast (mostly heating and cooling) seem to be less complicated than the ones required for fiberglass, which could potentially lead to lower impacts. Aluminum is used as a blade material in some turbines; it is widely available and is also well known to resist harsh weather conditions.

Table 3.5 showed the components of the rotor which contains the blades. In those components, only the fiberglass will be replaced by aluminum; the other components will stay the same. The blades should have a specific weight regardless of the material type because the tower is designed to carry a specific weight; therefore, the aluminum is assumed to have the same weight as fiberglass. The fiberglass used in the blades was 11,207.44 kg for turbine G83 and 11,747.56 kg turbine G87; they will be replaced by aluminum with same weight.

In order for the power production to remain the same, however, the cross-sectional area of the blades needs to remain the same, since the power production is proportional to the blade cross-sectional area. Since the density of aluminum is greater than that of fiberglass, the thickness of the aluminum plates will need to be lower to maintain the same weight and cross-sectional area as the fiberglass blades. The thickness of the fiberglass blades was 2.33 inches; the thickness of the aluminum blades is 1.28 inches. The calculation is shown in Appendix A. The other parameters are assumed to stay fixed.

3.3 Methods to Address Objective 3: To compare wind power greenhouse gas and traditional air pollutant emissions to literature values for emissions from coal and natural gas, as examples of fossil fuels.

Widder et al. (2011) conducted a sustainability assessment of coal-fired power plants with carbon capture and storage. Different scenarios were considered in that study: with carbon capture and sequestration (CCS), and without CCS for both coal and the natural gas. Therefore, four scenarios are used to compare with the outcome results of the wind turbine study:

1- Pulverized Carbon (PC) without CCS
2- Pulverized Carbon (PC) with CCS
3- Pulverized Carbon (PC) with CCS and Natural Gas (NG) without CCS
4- Pulverized Carbon (PC) with CCS and Natural Gas (NG) without CCS

Pulverized carbon refers to the crushed or ground coal. The previous scenarios are very likely to be used in most of the coal and natural gas plants. Having the CCS technology installed can change the outcome gases. For instance, having CCS installed on a PC coal plant is capable of doubling the methane emissions linked with coal extraction, as a result of the augmented coal consumption, although lessening the emissions of carbon dioxide. Carbon dioxide and methane are both GHGs, but methane has a global warming potential of 25 times that of CO_2 on a weight basis over a 100-year time period (IPCC, 2007). When considering a pulverized coal (PC) station with CCS, the decrease in combustion emissions significantly offsets the increase in methane emissions, while the outcome is a considerable net reduction in global warming capacity over the PC coal plant baseline.

The greenhouse gas and traditional air pollutant emissions from the coal and natural gas plants analyzed by Widder will be compared with those from the wind turbines.

CHAPTER 4

RESULTS AND DISCUSSION

The Goal and Scope definition for this study were presented in Ch. 3. This chapter presents the other 3 steps of the LCA: Inventory Analysis, Impact Assessment, and Interpretation.

4.1 Inventory Analysis

The inventory analysis represents the summation of all substances emitted to the atmosphere from all the phases of 2-MW turbines. Table 4.1 presents the substances emitted in the greatest amounts in alphabetical order, and Table 4.2 presents the substances sorted from highest amount to lowest. In general, the manufacturing phase caused high portion in most of the pollutants, while the operation and maintenance phase caused the lowest. The raw materials acquisition phase emits particularly high levels of arsenic. Particularly noteworthy are the large quantities of the greenhouse gas carbon dioxide and methane emitted by the manufacturing phase, as well as the toxic metals arsenic, chromium, and mercury. The installation phase emits high quantities of carbon dioxide (due to fossil fuel use) and chromium as well because chromium is a naturally present in cementitious materials. Therefore, grinding and use of additives in cement or concrete production can be reasons for releasing chromium (Butera et al., 2015). As expected, the operation and maintenance phase emits negligible quantities of most pollutants. The end-of-life phase also emits negligible quantities of most pollutants. What matters in terms of health impacts, however, is the amount emitted relative to a health impacts threshold, rather than the quantity itself.

Table 4.1: Inventory Results (Alphabetical Order)

Substance	Unit	Raw Material Acquisition	Manufacturing	Installation	Operation & Maintenance	End of Life	Transportation	Total
Ammonia	kg	2.44E+00	3.87E+01	1.11E+01	1.90E-03	1.13E-07	9.83E-01	5.32E+01
Arsenic	g	1.45E+02	8.44E+02	3.28E+01	4.86E-03	4.09E-07	5.14E+01	1.07E+03
Benzene	kg	2.72E-01	3.51E+01	8.36E+00	1.35E-03	4.41E-08	4.20E+00	4.79E+01
Carbon dioxide, fossil	tn.lg= 1016.047 kg	6.94E+00	5.75E+02	2.99E+02	2.89E-01	9.38E-06	1.27E+02	1.01E+03
Carbon disulfide	kg	2.04E+00	2.11E+01	3.45E+00	2.96E-06	8.09E-11	2.86E+00	2.94E+01
Carbon monoxide	mg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E+01	1.76E+00	2.22E+01
Chlorine	kg	3.77E-02	7.62E+00	2.77E-01	7.71E-05	1.70E-09	4.11E-01	8.35E+00
Chromium	kg	1.30E-01	3.09E+01	3.52E+00	8.60E-06	5.11E-10	1.40E+00	3.59E+01
Chromium VI	g	3.20E+00	7.68E+02	8.70E+01	1.31E-04	3.46E-08	3.49E+01	8.93E+02
Copper	kg	4.05E-01	3.49E+00	1.24E+00	1.01E-03	9.43E-10	4.88E-01	5.62E+00
Dinitrogen monoxide	kg	4.70E-01	2.22E+01	5.86E+00	4.70E-03	3.14E-07	3.95E+00	3.25E+01
Ethane	kg	2.28E-01	1.48E+01	3.91E+00	1.87E-03	6.19E-07	3.00E+00	2.20E+01
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	g	5.00E-02	3.40E+00	9.71E-01	1.42E-04	4.96E-07	7.57E-01	5.17E+00
Ethene	kg	5.77E-02	1.92E+00	3.40E-01	3.12E-04	2.10E-09	4.30E-01	2.75E+00
Formaldehyde	kg	2.11E-02	1.05E+00	1.53E+00	4.24E-03	2.01E-08	2.14E-01	2.82E+00
Hydrogen chloride	kg	6.70E-01	5.98E+01	1.37E+01	1.98E-03	5.91E-07	3.77E+00	7.79E+01
Hydrogen fluoride	kg	1.73E-01	1.08E+01	1.40E+00	1.57E-04	1.73E-07	6.34E-01	1.30E+01
Hydrogen sulfide	kg	3.02E-02	3.77E+00	9.01E-01	1.22E-05	2.75E-08	3.43E-01	5.05E+00
Lead	kg	2.62E-01	2.38E+00	3.23E-01	8.13E-05	1.12E-09	6.41E-01	3.74E+00
Mercury	g	1.99E+00	2.63E+02	5.32E+01	1.12E-03	1.95E-07	7.26E+01	3.91E+02
Methane, biogenic	kg	9.65E-01	2.79E+01	6.79E+00	1.02E-03	2.77E-07	4.72E+00	4.04E+01
Methane, bromochlorodifluoro-, Halon 1211	mg	8.06E+00	5.55E+02	1.54E+02	2.15E-02	1.20E-04	6.88E+01	7.86E+02

Methane, bromotrifluoro-, Halon 1301	g	7.27E-02	1.75E+00	1.71E+00	4.87E-03	2.80E-08	2.92E-01	3.83E+00
Methane, chlorodifluoro-, HCFC-22	g	2.46E+00	1.12E+02	2.42E+01	2.38E-04	4.41E-07	1.01E+01	1.49E+02
Methane, dichlorodifluoro-, CFC-12	g	1.09E+00	5.13E+00	5.78E-02	9.50E-06	5.39E-10	5.98E-01	6.88E+00
Methane, fossil	kg	2.08E+01	1.94E+03	4.57E+02	1.77E-01	2.62E-05	2.90E+02	2.71E+03
Methane, tetrafluoro-, CFC-14	g	2.08E+00	9.58E+01	7.04E-01	8.37E-06	4.20E-09	9.56E+00	1.08E+02
Nickel	kg	2.88E-01	2.07E+00	1.68E-01	6.89E-05	3.69E-09	1.27E-01	2.65E+00
Nitrate	g	9.54E-01	4.15E+01	9.30E+01	8.09E-02	3.26E-02	8.02E+00	1.44E+02
Nitrogen	g	1.48E+01	1.02E+03	2.15E+02	1.66E-02	7.88E-06	1.20E+02	1.37E+03
Nitrogen oxides	kg	3.02E+01	1.69E+03	8.13E+02	3.23E-01	4.75E-05	2.72E+02	2.81E+03
PAH, polycyclic aromatic hydrocarbons	g	3.29E+00	2.92E+02	5.21E+01	1.70E-02	7.50E-07	4.61E+01	3.93E+02
Particulates, < 2.5 um	kg	1.01E+01	7.30E+02	1.70E+02	3.97E-02	2.32E-06	1.32E+02	1.04E+03
Particulates, > 2.5 um, and < 10um	kg	8.80E+00	7.21E+02	1.66E+02	1.80E-02	4.34E-07	1.42E+02	1.04E+03
Phosphorus	g	9.33E-01	7.46E+01	1.58E+01	2.97E-03	7.12E-07	4.65E+00	9.60E+01
Sulfur dioxide	tn.lg	1.20E-01	2.60E+00	5.83E-01	3.42E-04	5.60E-08	3.16E-01	3.62E+00
Sulfur hexafluoride	g	4.59E-01	3.18E+01	9.86E+00	1.32E-03	9.65E-08	3.06E+00	4.52E+01
Toluene	kg	4.17E-02	2.32E+00	1.00E+00	1.16E-03	3.09E-08	2.06E-01	3.57E+00
Xylene	g	3.43E+01	2.12E+03	8.25E+02	6.20E-01	5.20E-05	1.50E+02	3.13E+03
Zinc	kg	1.62E-01	7.25E+00	1.54E+00	5.27E-04	2.77E-09	3.03E-01	9.25E+00

Table 4.2: Inventory Results (Highest to Lowest)

Substance	Unit	Raw Material Acquisition	Manufac-turing	Installation	Operation and Maintenance	End of Life	Transpo-rtation	Total
Carbon dioxide, fossil	kg	7.05E+03	5.85E+05	3.03E+05	2.94E+02	9.53E-03	1.29E+05	1.02E+06
Sulfur dioxide	kg	1.22E+02	2.64E+03	5.92E+02	3.48E-01	5.69E-05	3.22E+02	3.68E+03
Nitrogen oxides	kg	3.02E+01	1.69E+03	8.13E+02	3.23E-01	4.75E-05	2.72E+02	2.81E+03
Methane, fossil	kg	2.08E+01	1.94E+03	4.57E+02	1.77E-01	2.62E-05	2.90E+02	2.71E+03
Particulates, < 2.5 um	kg	1.01E+01	7.30E+02	1.70E+02	3.97E-02	2.32E-06	1.32E+02	1.04E+03
Particulates, > 2.5 um, and < 10um	kg	8.80E+00	7.21E+02	1.66E+02	1.80E-02	4.34E-07	1.42E+02	1.04E+03
Hydrogen chloride	kg	6.70E-01	5.98E+01	1.37E+01	1.98E-03	5.91E-07	3.77E+00	7.79E+01
Ammonia	kg	2.44E+00	3.87E+01	1.11E+01	1.90E-03	1.13E-07	9.83E-01	5.32E+01
Benzene	kg	2.72E-01	3.51E+01	8.36E+00	1.35E-03	4.41E-08	4.20E+00	4.79E+01
Methane, biogenic	kg	9.65E-01	2.79E+01	6.79E+00	1.02E-03	2.77E-07	4.72E+00	4.04E+01
Chromium	kg	1.30E-01	3.09E+01	3.52E+00	8.60E-06	5.11E-10	1.40E+00	3.59E+01
Nitrous oxide	kg	4.70E-01	2.22E+01	5.86E+00	4.70E-03	3.14E-07	3.95E+00	3.25E+01
Carbon disulfide	kg	2.04E+00	2.11E+01	3.45E+00	2.96E-06	8.09E-11	2.86E+00	2.94E+01
Ethane	kg	2.28E-01	1.48E+01	3.91E+00	1.87E-03	6.19E-07	3.00E+00	2.20E+01
Hydrogen fluoride	kg	1.73E-01	1.08E+01	1.40E+00	1.57E-04	1.73E-07	6.34E-01	1.30E+01
Zinc	kg	1.62E-01	7.25E+00	1.54E+00	5.27E-04	2.77E-09	3.03E-01	9.25E+00
Chlorine	kg	3.77E-02	7.62E+00	2.77E-01	7.71E-05	1.70E-09	4.11E-01	8.35E+00
Copper	kg	4.05E-01	3.49E+00	1.24E+00	1.01E-03	9.43E-10	4.88E-01	5.62E+00
Hydrogen sulfide	kg	3.02E-02	3.77E+00	9.01E-01	1.22E-05	2.75E-08	3.43E-01	5.05E+00
Lead	kg	2.62E-01	2.38E+00	3.23E-01	8.13E-05	1.12E-09	6.41E-01	3.74E+00
Toluene	kg	4.17E-02	2.32E+00	1.00E+00	1.16E-03	3.09E-08	2.06E-01	3.57E+00
Xylene	kg	3.43E-02	2.12E+00	8.25E-01	6.20E-04	5.20E-08	1.50E-01	3.13E+00
Formaldehyde	kg	2.11E-02	1.05E+00	1.53E+00	4.24E-03	2.01E-08	2.14E-01	2.82E+00
Ethene	kg	5.77E-02	1.92E+00	3.40E-01	3.12E-04	2.10E-09	4.30E-01	2.75E+00
Nickel	kg	2.88E-01	2.07E+00	1.68E-01	6.89E-05	3.69E-09	1.27E-01	2.65E+00
Nitrogen	kg	1.48E-02	1.02E+00	2.15E-01	1.66E-05	7.88E-09	1.20E-01	1.37E+00
Arsenic	kg	1.45E-01	8.44E-01	3.28E-02	4.86E-06	4.09E-10	5.14E-02	1.07E+00
Chromium VI	kg	3.20E-03	7.68E-01	8.70E-02	1.31E-07	3.46E-11	3.49E-02	8.93E-01

PAH, polycyclic aromatic hydrocarbons	kg	3.29E-03	2.92E-01	5.21E-02	1.70E-05	7.50E-10	4.61E-02	3.93E-01
Mercury	kg	1.99E-03	2.63E-01	5.32E-02	1.12E-06	1.95E-10	7.26E-02	3.91E-01
Methane, chlorodifluoro-, HCFC-22	kg	2.46E-03	1.12E-01	2.42E-02	2.38E-07	4.41E-10	1.01E-02	1.49E-01
Nitrate	kg	9.54E-04	4.15E-02	9.30E-02	8.09E-05	3.26E-05	8.02E-03	1.44E-01
Methane, tetrafluoro-, CFC-14	kg	2.08E-03	9.58E-02	7.04E-04	8.37E-09	4.20E-12	9.56E-03	1.08E-01
Phosphorus	kg	9.33E-04	7.46E-02	1.58E-02	2.97E-06	7.12E-10	4.65E-03	9.60E-02
Sulfur hexafluoride	kg	4.59E-04	3.18E-02	9.86E-03	1.32E-06	9.65E-11	3.06E-03	4.52E-02
Methane, dichlorodifluoro-, CFC-12	kg	1.09E-03	5.13E-03	5.78E-05	9.50E-09	5.39E-13	5.98E-04	6.88E-03
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	5.00E-05	3.40E-03	9.71E-04	1.42E-07	4.96E-10	7.57E-04	5.17E-03
Methane, bromotrifluoro-, Halon 1301	kg	7.27E-05	1.75E-03	1.71E-03	4.87E-06	2.80E-11	2.92E-04	3.83E-03
Methane, bromochlorodifluoro-, Halon 1211	kg	8.06E-06	5.55E-04	1.54E-04	2.15E-08	1.20E-10	6.88E-05	7.86E-04
Carbon monoxide	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E-05	1.76E-06	2.22E-05

The top 5 substances shown in Table 4.2 are as follows:

Carbon dioxide (CO_2), fossil: very high amount of this substance released during the life cycle of the wind turbine, it was one of the highest substances to cause the global warming impact, starting from the raw materials acquisition phase, the used fossil fuel caused part of the carbon dioxide to be emitted, then the manufacturing phase which includes some heating and cooling processes to fabricate the metals and other materials. In the installation phase there were heavy processes to consume fossil fuel and release carbon dioxides beside other substances. The carbon dioxide is released in every phase or process that consume fossil fuel to be completed.

Sulfur dioxide (SO_2): Sulfur dioxide is produced whenever fossil fuel containing sulfur (coal and oil) is burned or the mineral ores are smelted. The combustion process helps the sulfur dioxide to be released.

Nitrogen oxides (NOx) contributes to the impact categories of acidification, eutrophication, respiratory effect, and ozone smog. The NOx usually is produced during the combustion at high temperature, and is thus produced during manufacture of the turbine parts.

Methane (CH_4), fossil: this substance can be released whenever fossil fuel is part of the processes just like carbon dioxide and sulfur dioxide, burning the natural gas and other kinds of fossil fuels causes the methane to be emitted. In most of the phases, burning is taking place and that is why methane is one the most pollutants caused by the wind turbine industry.

Particulates, < 2.5 µm: big amount of particles was caused by the phases and the processes of producing wind turbine parts. For example, the blades made of fiber glass, and the processes to get it completed include some sanding and grinding which caused the particles to be released.

Fossil fuel in the transportation also was a big reason to form particles during the life cycle of the wind turbine.

Table 4.3 summarizes the inventory results by impact category. In Table 4.1 and Table 4.3, even though they have the same substances, we notice that some substances concentration does not match in both tables. This is because the substances in Table 4.3 are divided into various impact categories. For example, ammonia emissions are distributed among respiratory effects, eutrophication, and acidification. Also, not all the original ammonia stays as ammonia, and some other substance gets converted to ammonia, so the substances will not necessarily balance. In addition, Table 4.3 only shows the top substances contributing to each impact category.

4.3: Inventory Substances Grouped by Environmental Impacts

	Substance	Unit	Raw Material Acquisition	Manu-facturing	Installation	Operation and Main-tenance	End of Life	Trans-portation	Total
Ozone Depletion	Total of airborne emission	kg CFC-11 eq	2.55E-03	4.77E-02	3.16E-02	7.98E-05	1.89E-09	4.48E-03	8.64E-02
	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg CFC-11 eq	5.51E-05	3.78E-03	1.08E-03	1.57E-07	5.48E-10	2.59E-04	5.17E-03
	Methane, bromochlorodifluoro-, Halon 1211	kg CFC-11 eq	5.78E-05	4.02E-03	1.11E-03	1.54E-07	8.62E-10	3.63E-04	5.58E-03
	Methane, bromotrifluoro-, Halon 1301	kg CFC-11 eq	1.19E-03	2.89E-02	2.81E-02	7.95E-05	4.57E-10	3.06E-03	6.13E-02
	Methane, chlorodifluoro-, HCFC-22	kg CFC-11 eq	1.23E-04	5.67E-03	1.22E-03	1.19E-08	2.20E-11	4.47E-04	7.46E-03
	Methane, dichlorodifluoro-, CFC-12	kg CFC-11 eq	1.12E-03	5.35E-03	6.00E-05	9.80E-09	5.56E-13	3.44E-04	6.88E-03
Global Warming	Total of airborne emission	kg CO_2 eq	7.76E+03	6.48E+05	3.18E+05	2.99E+02	1.03E-02	1.30E+05	1.10E+06
	Carbon dioxide, fossil	kg CO_2 eq	7.04E+03	5.90E+05	3.04E+05	2.93E+02	9.52E-03	1.23E+05	1.02E+06
	Methane, fossil	kg CO_2 eq	5.25E+02	4.94E+04	1.16E+04	4.46E+00	6.63E-04	6.09E+03	6.76E+04
	Dinitrogen monoxide	kg CO_2 eq	1.42E+02	6.78E+03	1.78E+03	1.42E+00	9.52E-05	9.67E+02	9.67E+03
	Sulfur hexafluoride	kg CO_2 eq	1.05E+01	7.32E+02	2.26E+02	3.00E-02	2.20E-06	6.18E+01	1.03E+03
	Methane, biogenic	kg CO_2 eq	2.34E+01	6.82E+02	1.65E+02	2.46E-02	6.72E-06	2.69E+01	8.98E+02
	Methane, tetrafluoro-, CFC-14	kg CO_2 eq	1.60E+01	7.46E+02	5.45E+00	6.45E-05	3.24E-08	3.20E+01	7.99E+02
Photochemical Smog	Total of airborne emission	kg O_3 eq	7.42E+02	4.21E+04	2.01E+04	7.98E+00	1.16E-03	6.97E+03	6.99E+04
	Nitrogen oxides	kg O_3 eq	7.40E+02	4.19E+04	2.00E+04	7.92E+00	1.16E-03	6.96E+03	6.96E+04
	Chlorine	kg O_3 eq	7.27E-01	1.49E+02	5.37E+00	1.49E-03	3.28E-08	4.79E+00	1.60E+02
	Benzene	kg O_3 eq	1.85E-01	2.41E+01	5.72E+00	9.18E-04	3.00E-08	4.49E+00	3.45E+01
	Formaldehyde	kg O_3 eq	2.06E-01	1.03E+01	1.50E+01	4.14E-02	1.96E-07	1.07E+00	2.66E+01
	Ethene	kg O_3 eq	5.73E-01	1.93E+01	3.39E+00	3.09E-03	2.09E-08	1.48E+00	2.47E+01
	Xylene	kg O_3 eq	2.69E-01	1.68E+01	6.50E+00	4.86E-03	4.08E-07	7.28E-01	2.43E+01
	Toluene	kg O_3 eq	1.69E-01	9.49E+00	4.07E+00	4.69E-03	1.25E-07	5.72E-01	1.43E+01

Acidification	Total of airborne emission	kg SO_2 eq	1.51E+02	4.10E+03	1.23E+03	5.92E-01	9.31E-05	3.65E+02	5.84E+03
	Ammonia	kg SO_2 eq	4.44E+00	7.13E+01	2.03E+01	3.47E-03	2.07E-07	4.00E+00	1.00E+02
	Hydrogen chloride	kg SO_2 eq	5.96E-01	5.37E+01	1.22E+01	1.76E-03	5.25E-07	2.06E+00	6.86E+01
	Hydrogen fluoride	kg SO_2 eq	2.83E-01	1.78E+01	2.30E+00	2.56E-04	2.82E-07	4.16E-01	2.08E+01
	Hydrogen sulfide	kg SO_2 eq	5.74E-02	7.24E+00	1.72E+00	2.32E-05	5.22E-08	4.75E-01	9.49E+00
	Nitrogen oxides	kg SO_2 eq	2.16E+01	1.22E+03	5.84E+02	2.31E-01	3.39E-05	1.38E+02	1.97E+03
	Sulfur dioxide	kg SO_2 eq	1.24E+02	2.72E+03	6.08E+02	3.55E-01	5.81E-05	2.21E+02	3.68E+03
Eutrophication	Total of airborne emission	kg N eq	1.63E+00	8.12E+01	3.79E+01	1.47E-02	3.30E-06	1.02E+01	1.31E+02
	Ammonia	kg N eq	2.80E-01	4.50E+00	1.28E+00	2.19E-04	1.30E-08	2.52E-01	6.31E+00
	Nitrate	kg N eq	3.40E-05	1.49E-03	3.33E-03	2.88E-06	1.16E-06	3.10E-04	5.17E-03
	Nitrogen	kg N eq	2.29E-03	1.60E-01	3.35E-02	2.58E-06	1.22E-09	1.03E-02	2.06E-01
	Nitrogen oxides	kg N eq	1.35E+00	7.65E+01	3.66E+01	1.45E-02	2.12E-06	9.95E+00	1.24E+02
	Phosphorus	kg N eq	1.08E-03	8.70E-02	1.83E-02	3.43E-06	8.22E-10	1.07E-03	1.07E-01
Human Health	Total of airborne emissions	CTUh	1.07E-02	4.77E-01	8.63E-02	1.01E-05	2.52E-10	4.33E-02	6.17E-01
	Mercury	CTUh	1.87E-03	2.48E-01	5.00E-02	1.05E-06	1.86E-10	2.97E-02	3.29E-01
	Zinc	CTUh	2.52E-03	1.13E-01	2.37E-02	7.79E-06	4.24E-11	6.77E-03	1.46E-01
	Lead	CTUh	3.51E-03	3.25E-02	4.19E-03	1.10E-06	1.55E-11	3.42E-03	4.36E-02
	Arsenic	CTUh	2.40E-03	1.42E-02	5.50E-04	8.40E-08	6.85E-12	8.91E-04	1.80E-02
	Carbon disulfide	CTUh	9.66E-05	1.00E-03	1.64E-04	1.40E-10	3.82E-15	1.07E-04	1.37E-03
	Copper	CTUh	5.81E-06	5.03E-05	1.76E-05	1.42E-08	1.33E-14	2.38E-06	7.61E-05
	Benzene	CTUh	1.06E-08	1.22E-06	3.09E-07	1.53E-10	2.37E-15	1.67E-07	1.71E-06
	Chromium	CTUh	2.86E-04	6.88E-02	7.80E-03	2.07E-08	1.25E-12	2.44E-03	7.93E-02
	Nickel	CTUh	1.31E-05	9.66E-05	8.18E-06	3.58E-09	1.93E-13	1.02E-05	1.28E-04
	PAH, polycyclic aromatic hydrocarbons	CTUh	2.46E-08	2.10E-06	3.57E-07	1.35E-10	5.75E-15	2.46E-07	2.73E-06
Respiratory Effects	Total of airborne emission	kg $PM_{2.5}$ eq	7.22E+03	3.17E+05	1.51E+05	3.58E+02	8.89E-03	5.15E+05	9.91E+05
	Ammonia	kg $PM_{2.5}$ eq	1.57E-01	2.53E+00	7.19E-01	1.23E-04	7.33E-09	1.42E-01	3.55E+00
	Carbon monoxide	kg $PM_{2.5}$ eq	1.73E-02	1.95E+00	5.13E-01	6.08E-05	8.50E-09	2.45E-01	2.72E+00
	Nitrogen oxides	kg $PM_{2.5}$ eq	2.20E-01	1.25E+01	5.96E+00	2.36E-03	3.46E-07	1.62E+00	2.03E+01
	Particulates, < 2.5 um	kg $PM_{2.5}$ eq	1.01E+01	7.37E+02	1.71E+02	3.97E-02	2.31E-06	1.25E+02	1.04E+03
	Particulates, > 2.5 um, and < 10um	kg $PM_{2.5}$ eq	2.03E+00	1.68E+02	3.85E+01	4.13E-03	9.99E-08	2.84E+01	2.37E+02

	Sulfur dioxide	kg $PM_{2.5}$ eq	7.35E+00	1.61E+02	3.59E+01	2.10E-02	3.44E-06	2.02E+01	2.25E+02
Fossil Fuel Depletion		MJ surplus	7.20E+03	3.16E+05	1.51E+05	3.58E+02	8.88E-03	5.14E+05	9.89E+05

4.2 Impact Assessment: 20-Year Turbine Life Span

4.2.1 Impact Assessment of the Complete Turbine

Table 4.4 and Figure 4.1 show the contribution of all phases of the wind turbine to the environmental impacts categories. As was explained in Chapter 3, the wind turbine has six main phases throughout its life cycle: raw materials acquisition, manufacturing, installation, operation and maintenance, and end-of-life, which includes the disassembling the turbine, and then recycling or landfilling the materials. The sixth phase, transportation, addresses the transportation activities between all the previous phases. The study addressed 8 environmental impact categories shown in Table 4.4, plus the water depletion and an energy balance throughout the life span of the wind turbine. The water depletion index and cumulative energy demand, used in the energy balance, are computed using a separate command in Simapro, and thus are discussed separately.

Table 4.4: The Environmental Impacts of Generation of 1 kWh Electricity During 20-Year Life Span

Impact category (unit) \ Part	Raw Materials Acquisition	Manufacturing	Installation	Operation & Maintenance	End of Life	Transportation	Total
Ozone depletion (kg CFC-11 eq)	1.77E-07	3.37E-06	2.15E-06	4.84E-07	8.36E-10	1.09E-06	7.26E-06
	2.4%	46.4%	29.6%	6.7%	0.0%	14.9%	100.0%
Global warming (kg CO_2 eq)	2.81E-05	2.34E-03	1.15E-03	2.09E-04	6.04E-07	2.24E-04	3.96E-03
	0.7%	59.2%	29.1%	5.3%	0.0%	5.7%	100.0%
Photochemical Smog (kg O_3 eq)	2.63E-05	1.49E-03	7.11E-04	1.56E-04	3.32E-07	2.24E-03	4.63E-03
	0.6%	32.3%	15.4%	3.4%	0.0%	48.4%	100.0%
Acidification (kg SO_2 eq)	5.13E-05	1.39E-03	4.18E-04	1.19E-04	3.51E-07	1.21E-04	2.10E-03
	2.4%	66.2%	19.9%	5.7%	0.0%	5.8%	100.0%
Eutrophication (kg N eq)	9.57E-05	1.65E-03	3.18E-04	6.81E-05	2.94E-07	1.34E-05	2.15E-03
	4.5%	76.9%	14.8%	3.2%	0.0%	0.6%	100.0%
Human Health Potential (CTUh)	4.98E-06	1.15E-04	1.99E-05	2.85E-07	6.48E-09	7.49E-07	1.41E-04
	3.5%	81.7%	14.1%	0.2%	0.0%	0.5%	100.0%
Respiratory effects (kg $PM_{2.5}$ eq)	7.11E-06	3.90E-04	9.10E-05	8.43E-06	6.48E-08	1.31E-05	5.10E-04
	1.4%	76.5%	17.8%	1.7%	0.0%	2.6%	100.0%
Fossil fuel depletion (kWh surplus)	1.33E-04	5.83E-03	2.79E-03	6.16E-04	1.34E-06	1.34E-02	2.27E-02
	0.6%	25.6%	12.3%	2.7%	0.0%	58.8%	100.0%

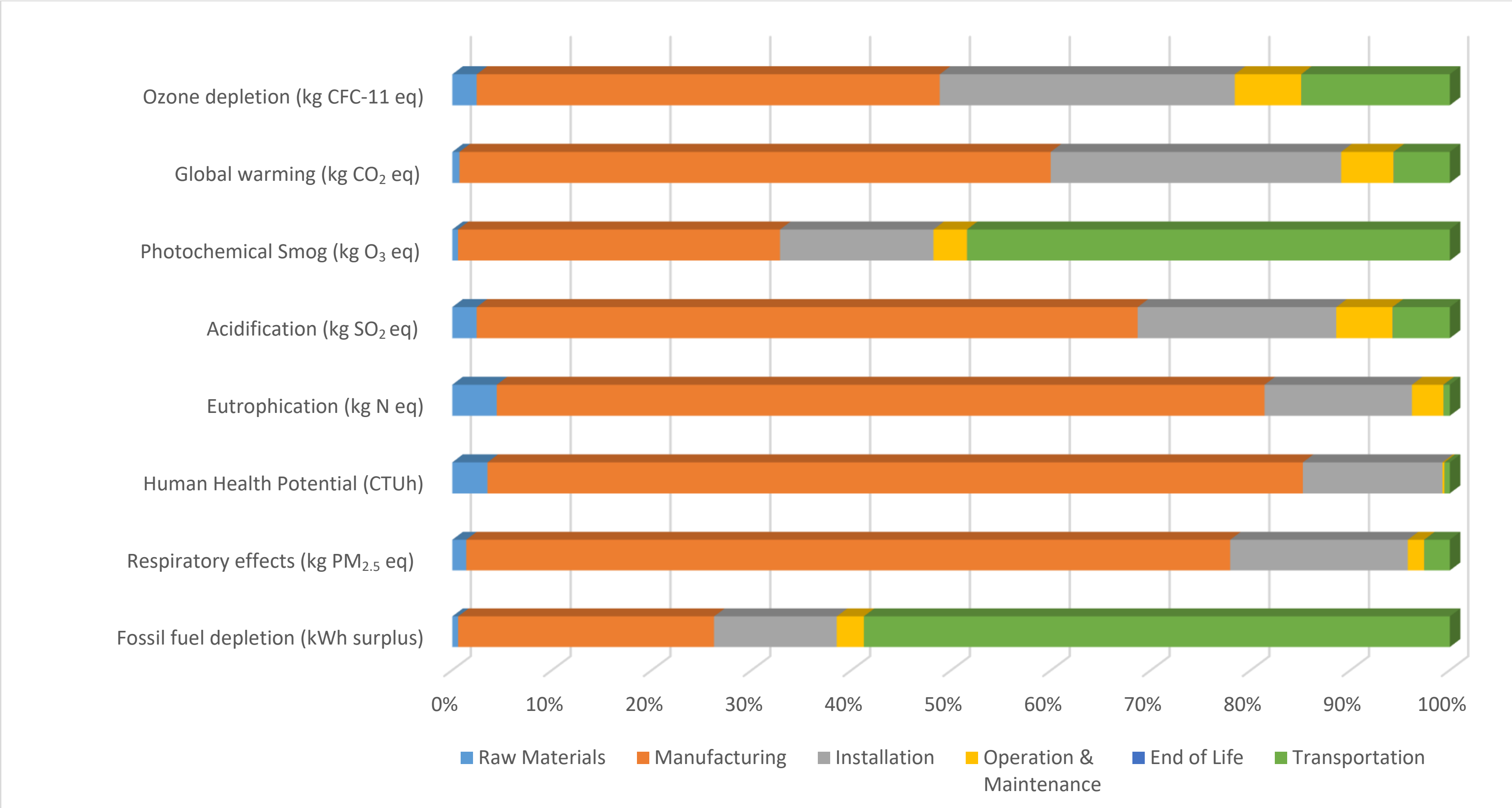

Figure 4.1: Environmental Impacts / 1kWh Generated, 20-Year Turbine Life Span

As shown in Fig. 4.1, the **manufacturing** phase is the main phase that influences the results in this study. Specifically, the manufacturing phase contributes >75% to the impact categories of respiratory effects, human health potential, and eutrophication; >50% to the categories of acidification and global warming; and >25% to fossil fuel depletion, ozone smog formation, and stratospheric ozone depletion. The manufacturing phase consists of complicated processes and many activities. For example, manufacturing the <u>*blades*</u> starts with lay-up of a wet fiber made of fabric, which is placed in a tool and resin by hand. Then it will be laminated to uniformly distribute the resin; this lamination causes pollutants to be released, especially particles because this process requires some grinding and sanding. After the resin is cured, it will be covered with the prepreg lay-up (the prepreg is a term for fabric reinforcement that has been pre-impregnated with a resin). The next step is to heat it with high pressure at the same time so it can take the desired shape; the heating requires some fuel to be completed and that will cause some pollutants to be released like the carbon dioxide. Finally, it gets skinned and sealed. The sealant contains high concentrations of chemicals such polycyclicaromatic hydrocarbons (PAHs) and acids. The <u>*tower*</u> is the largest part of the turbine and completely made of steel covered with zinc. It is very difficult to manufacture the tower as one piece because the size; also its diameter decreases as it goes from bottom to the top. Therefore, it is divided into several parts. Each part has a specific mold where the steel is heated to a very high temperature (2500°F) and fixed in the mold to cast the required shape. The higher the required temperature, the greater the consumption of fossil fuels, which causes several pollutants to be emitted. After all pieces are cast, they are welded together and then covered by zinc for protection. Welding process causes various pollutants to be released, including components of particulates like lead, nickel, zinc, iron oxide, copper, cadmium, fluorides, manganese, and chromium, and gases like carbon monoxide and oxides of nitrogen (Golbabaei et al., 2015). The last part is the *nacelle* which contains the engine and all other devices to control the engine and the blades. As was explained in Chapter 3, most of the nacelle parts are manufactured in different plants and then assembled in one place. The transportation of the parts generates emissions like the NO_x and PM because the used fuel for the transportation purposes mainly is diesel (The National Academic Press, 2016)

Electricity used for manufacturing contributes most of the inventory emissions and impacts. Burning of coal for power production generates sulfur dioxides, fine particulates, and mercury, which according to Table 4.3 are the primary contributors to acidification, respiratory effects and non-carcinogenic health impacts from the manufacturing phase, respectively. Burning coal or natural gas for electricity production generates nitrogen oxides, which according to Table 4.3 are the main contributor to eutrophication and ozone smog formation from the manufacturing phase, as well as a secondary contributor to acidification. The global warming impact derives primarily from fossil fuel consumed during the manufacturing of the different types of steel for the tower and the nacelle, and fiberglass for the rotor blades.

The **transportation** phase contributes around 50% to the impact categories of ozone smog formation and fossil fuel depletion, due to consumption of diesel fuel. Vehicles burning diesel fuel generate large amounts of nitrogen oxides, which contribute to smog formation and transportation the largest contributor to ozone smog formation. Unlike electric power plants, which remove NOx using selective catalytic reduction or non-selective catalytic reduction controls, diesel vehicles typically do not have any NOx controls. The large contribution to fossil fuel depletion (higher than transportation's impact on other categories) may be due to the low efficiency of diesel engines (30-35%) compared to the efficiency of steam turbines (40-45%) used at power plants producing electricity. The transportation phase also contributes 15% to ozone layer depletion, perhaps due to CFC emissions from vehicle air conditioners. Although transportation contributes 59% to fossil fuel consumption, transportation contributes only 5.7% to climate change. This may be due to the fact that coal produces more CO_2 per unit of power generated when burned than diesel. Also, methane has a global warming potential 25 times that of CO_2 on a per mass basis, and electricity generation would have more leakage of methane due to natural gas consumption than transportation. The contribution from the transportation phase toward the impacts can be significantly decreased if the turbine parts manufactured locally (in the US).

The **installation** phase contributes almost 30% to the climate change and ozone depletion impact categories, and between 12 and 20% to the remaining impact categories. The installation phase includes production of cement for the concrete foundation; cement production is very energy-intensive, and thus contributes substantial greenhouse gas emissions. The energy is used for operating heavy equipment to do the installation, as well as welding, also contribute to fossil fuel consumption which generates emissions of carbon dioxide in the climate change category.

As shown in Table 4.4 and Fig. 4.1, the remaining three phases have small impacts compared to the manufacturing, transportation, and installation phases. The **raw material acquisition phase** is comprised of the preparation of the steel, copper, aluminum, fiber glass to go to manufacturing phase. The contribution from this phase is ≤4.5% for all impact categories. The **operation and maintenance** phase includes the driving between the turbines twice a year to lubricate and inspect them, as was explained in Chapter 3; hence, its impacts are ≤6.7% for all categories. Finally, the **end-of-life** phase contributed around 0% for all impact categories. The reason for that is the amount of materials that will go to the landfill at the end-of-life is very small; a large portion of the turbine materials will be reused. Fiberglass of the blades usually goes to the landfill as a bulk waste, and lubricants, plastic, and adhesive will be totally landfilled. However, most of the steel, aluminum, and copper will be recycled and reused; 98% of it, as was assumed in Chapter 3. The impacts from the recycling were not included in the end-of-life phase, because the recycled materials are used to make a different product; the emissions are thus appropriately counted with the new product.

4.2.2 Environmental Impacts of the Turbine Parts

This section is to address the environmental impacts of the turbine components. As mentioned in the previous section, the manufacturing of the turbine is the most important phase for the environmental impacts. The turbine main parts (tower, nacelle, and the rotor) are very large parts of the turbine; they require many processes and consume large amounts of energy to be manufactured. Table 4.5 and Figure 4.2 below shows the environmental impact of each major part of the turbine.

Table 4.5: The Contribution of the Wind Turbine Parts to the Environmental Impacts Categories During 20-Years Life Span

Part / Impact Category (unit)	Nacelle	Rotor	Tower
Ozone Depletion (kg CFC-11 eq)	1.44E-06	4.87E-07	1.44E-06
Global Warming (kg CO_2 eq)	7.18E-04	5.26E-04	1.10E-03
Photochemical Smog (kg O_3 eq)	5.43E-04	2.96E-04	6.54E-04
Acidification (kg SO_2 eq)	6.04E-04	2.58E-04	5.30E-04
Eutrophication (kg N eq)	8.01E-04	1.41E-04	7.09E-04
Human Health Potential (CTUh)	5.01E-05	8.46E-06	5.68E-05
Respiratory effects (kg $PM_{2.5}$ eq)	1.46E-04	5.62E-05	1.88E-04
Fossil fuel depletion (kWh surplus)	1.77E-03	2.13E-03	1.93E-03

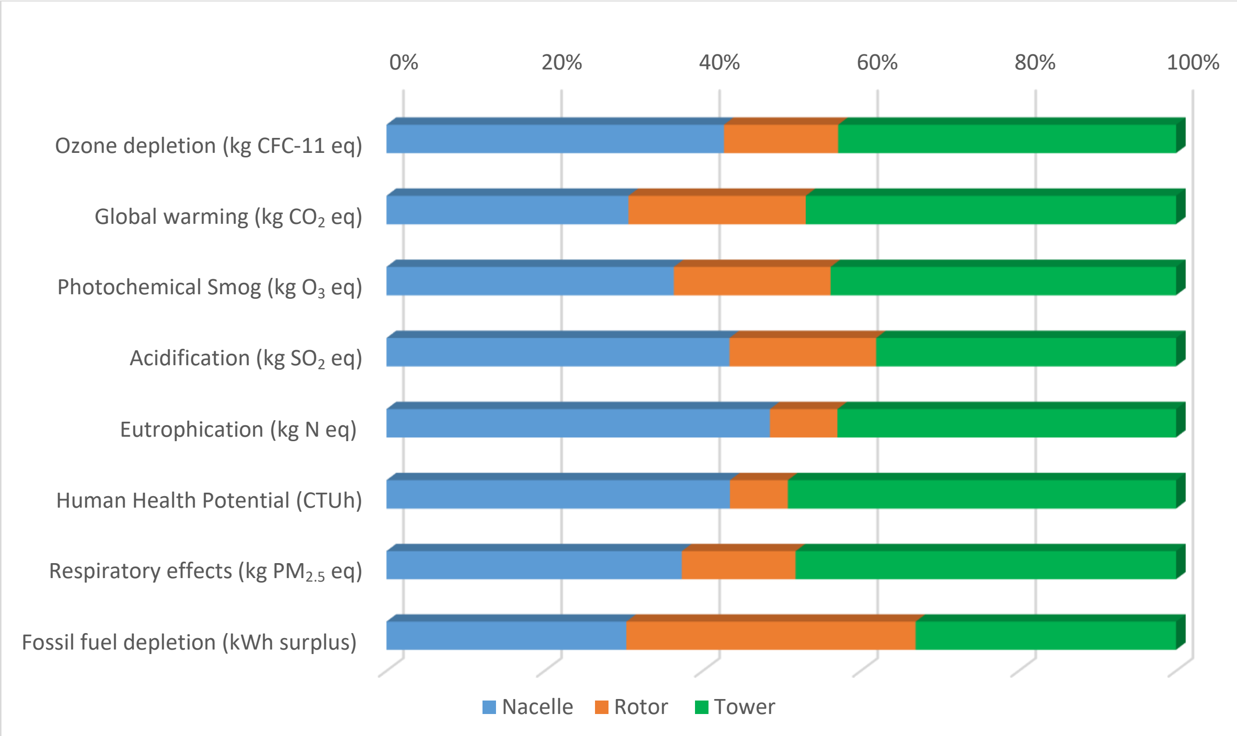

Figure 4.2: Environmental Impacts of the Turbine Parts

Manufacturing the turbine parts is the most complicated phase; it consumes intensive amount of fuel energy plus large amounts of metals (steel, copper, and aluminum) for the nacelle and tower, and large amounts of fiberglass for the tower. The higher the amount of metal is used, the higher the amount of energy is needed to process it and cast it to the designed shape. For example, steel starts melting at 2500ºF, aluminum at 1218 ºF, and copper at 1981ºF (American Elements, 2016); a very high melting temperature leads to emitting more CO_2 if the energy comes from fossil fuels. Other hazardous materials and particles are produced from the metal processing and casting. For example, the used resin in the blades is a mix of chemicals including acids and when applied to the fiber of the blades, it requires some sanding and washing which causes some particles and chemicals to be released to the air and to the water. Fiberglass, which is the main component of the blades, causes higher Global Warming Potential (GWP) than metal, mainly because it consumes a high amount energy to be cast and compressed. This requires a large amount of fossil fuels, leading to more fossil fuel depletion and releasing more carbon dioxide into the air.

Figure 4.3 below shows the contribution from the tower to the global warming potential. 95% of the global warming pollutants when manufacturing the tower comes from processing the steel, while the rest is from transportation of the tower and electricity needed to process the tower. If there is a plan to lessen the global warming from the tower, then the steel processing is the first thing we should consider because it contributes the highest amount to global warming. Either an alternative material can be considered to do the same job of the steel with reduced global warming impacts, or different steel processes can be used to lower the same impact. Similar charts can be prepared for every part of the turbine to determine which component or process contributes the most toward the environmental impacts. The chart below was prepared with activating cut-off criteria in the model to be 5%; therefore, the processes with less than 5% contribution will not be seen in that chart. For example, the transportation of the tower contributed 3.4% of the global warming from the tower, so it is not shown in the chart.

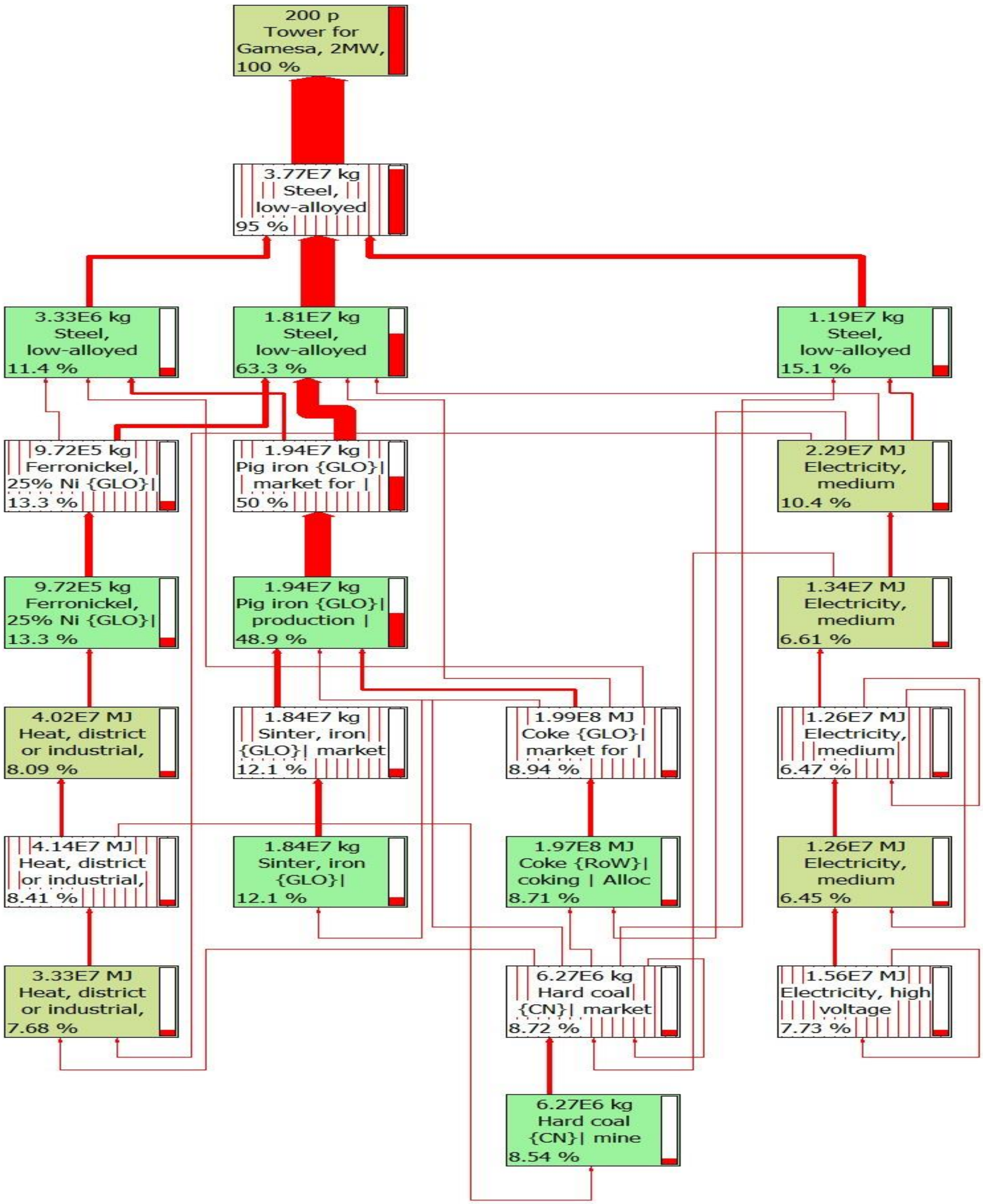

Figure 4.3: The Effect of the Tower Manufacturing on Global Warming.

4.2.3 Water Depletion Index (WDI)

Water Depletion Index is the amount of water consumed which can lead to depletion of freshwater resources throughout the life span of the turbine; m^3 is the unit used to address this impact. Table 4.6 and Figure 4.4 show the total water consumed by each phase of the Lone Star Wind Farm during the 20 years' life span per turbine every year. Manufacturing was the most water consuming phase, accounting for around two thirds of the depleted water. The fabrication of the parts is highly water consuming because of the heating and cooling processes involved, especially when casting the big parts of the turbine. In the second place for water consumption is the installation phase; the processes of the construction and installation consume a large amount of water to prepare the concrete mix for foundation and installing the towers. The raw materials acquisition, operation and maintenance, transportation, and end-of-life phases consumed little amount of water, less than 8% for all of them together.

Table 4.6: Total Water Depleted in Every Phase of the Wind Turbine

Phase	**Water Depletion Index (m^3)**	**Percentage**
Raw Materials Acquisition	3.45	0.9%
Manufacturing	258.25	66.6%
Installation	99.25	25.6%
Operation and Maintenance	5.05	1.3%
End of Life	14.4	3.7%
Transportation	7.3	1.9%
Total (m^3)	387.7	100.0%

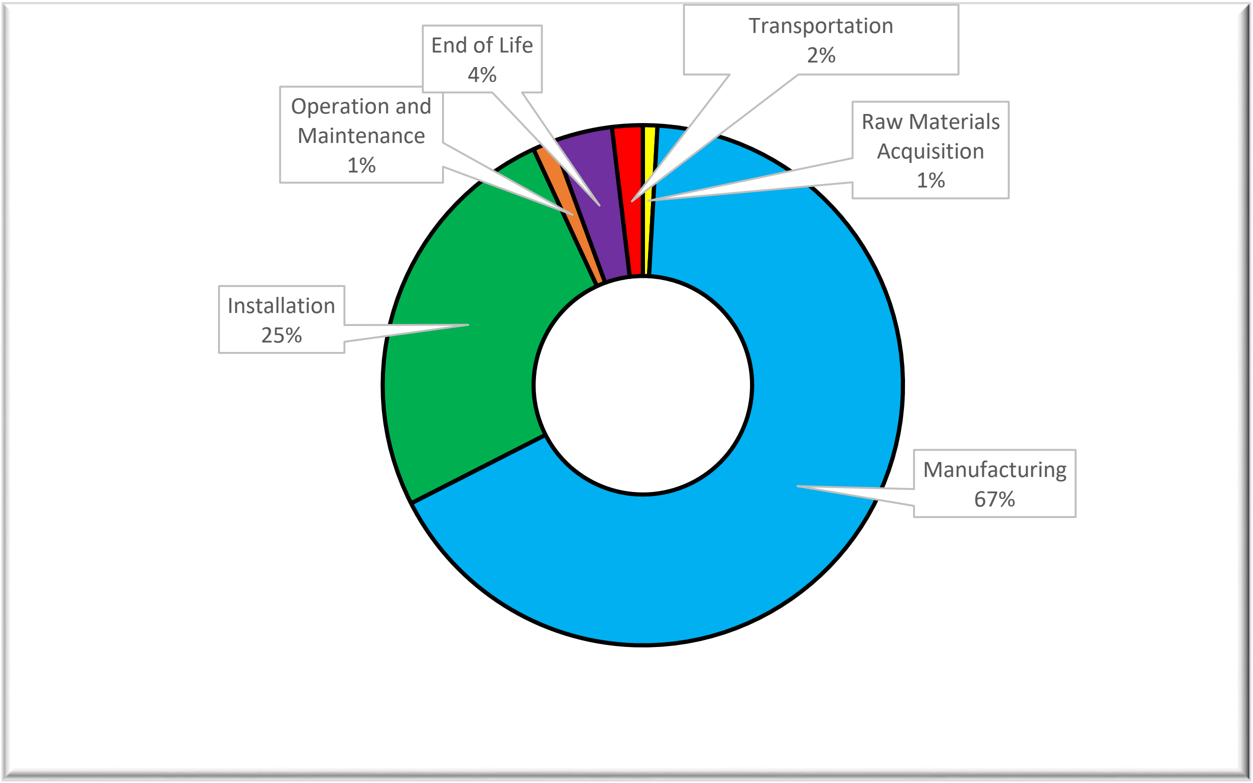

Figure 4.4: Water Index for Wind Turbines with 20-Year Life Span

4.2.4 Energy Balance

One of the most helpful assessments in any life cycle analysis is the product's energy balance. It is the net sum of the **cumulative energy demand (CED)** (negative) and **energy production** (positive) throughout the lifetime of the product. This method allows us to estimate how long it takes the turbine to generate the amount of energy consumed during its entire life cycle and the number of times it is amortized in terms of energy.

Table 4.7 and Figure 4.5 show in details of the cumulative energy demand from each phase of the turbines' life cycle. All the phases used the most energy (> 90%) from nonrenewable sources (fossil fuel and nuclear). Most large industries in the US still rely on the fossil fuel as an energy resource. Manufacturing the turbine components was responsible for 64% of the total energy consumption.

Figure 4.6 shows the contribution to CED from each major turbine part. The tower is the biggest part in the turbine and is made of steel; casting the tower and assembling its parts require high energy. The rotor consumes the lowest energy compared to the other parts; the rotor blades are made of fiber glass, which is lighter and easier to cast than steel.

Table 4.7: The Cumulative Energy Demand of Each Phase for Each Type of Energy for 20-Years Life Span

Type of Energy		Raw Materials Acquisition	Manufacturing	Installation	Operation and Maintenance	End of Life	Transportation	Total
Non-renewable (kWh)	Fossil fuel	39.17	2,087.40	812.88	287.78	103.06	160.69	3,490.97
	Nuclear	2.50	173.70	37.99	7.33	5.25	9.13	235.90
	Biomass	0.00	0.11	0.04	0.01	0.01	0.00	0.17
Renewable (kWh)	Biomass	0.98	42.79	20.02	3.19	1.01	2.86	70.84
	Geo-thermal	0.19	8.66	2.50	0.56	0.25	0.41	12.58
	Water	1.67	152.20	27.74	13.62	4.79	8.05	208.08
Total		44.51 (1.11%)	2,464.85 (61.34%)	901.18 (22.43%)	312.48 (7.78%)	114.37 (2.85%)	181.13 (4.51%)	4,018.53

We notice in the previous that the biomass energy can be either renewable or non-renewable. Renewable biomass, such as the wood, is derived from living, or recently living organisms like the plants or plant-based materials that are not used for food or feed. Non-renewable biomass comes from plants or living materials that are not going to be replanted.

Energy production for the 200 turbines at the Lone Star Wind Farm over the 20-year life span was estimated in Chapter 3 to be 627 million kWh or 156,822 kWh/turbine every year. As shown in Table 4.7, the CED per turbine is 4,018.53 kWh. That means the turbines can produce 156,822 kWh/4,018.53 kWh = 39 times more energy than they consume over their life cycle. In other words, it will only take 0.51 year (around six months) to produce or return the energy consumed during the whole life span of the turbine.

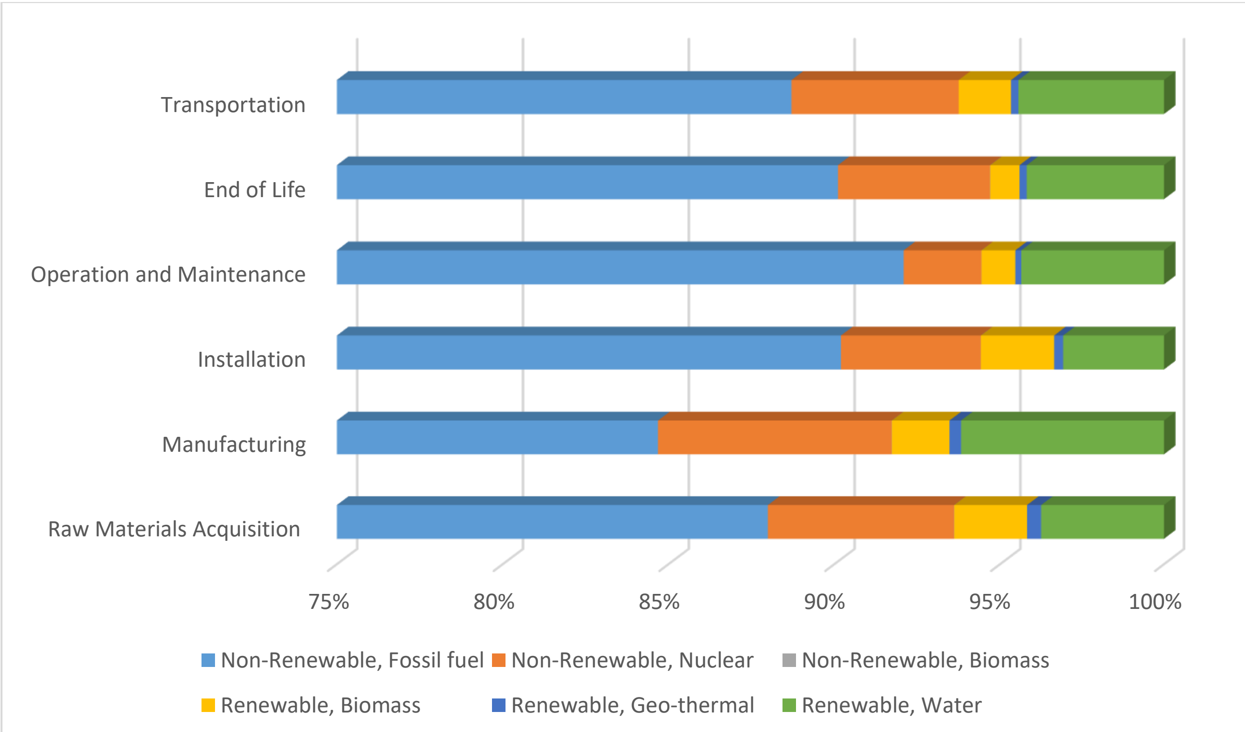

Figure 4.5: Cumulative Energy Demand (kWh) of Each Phase of the Turbine's 20-Year Life Span

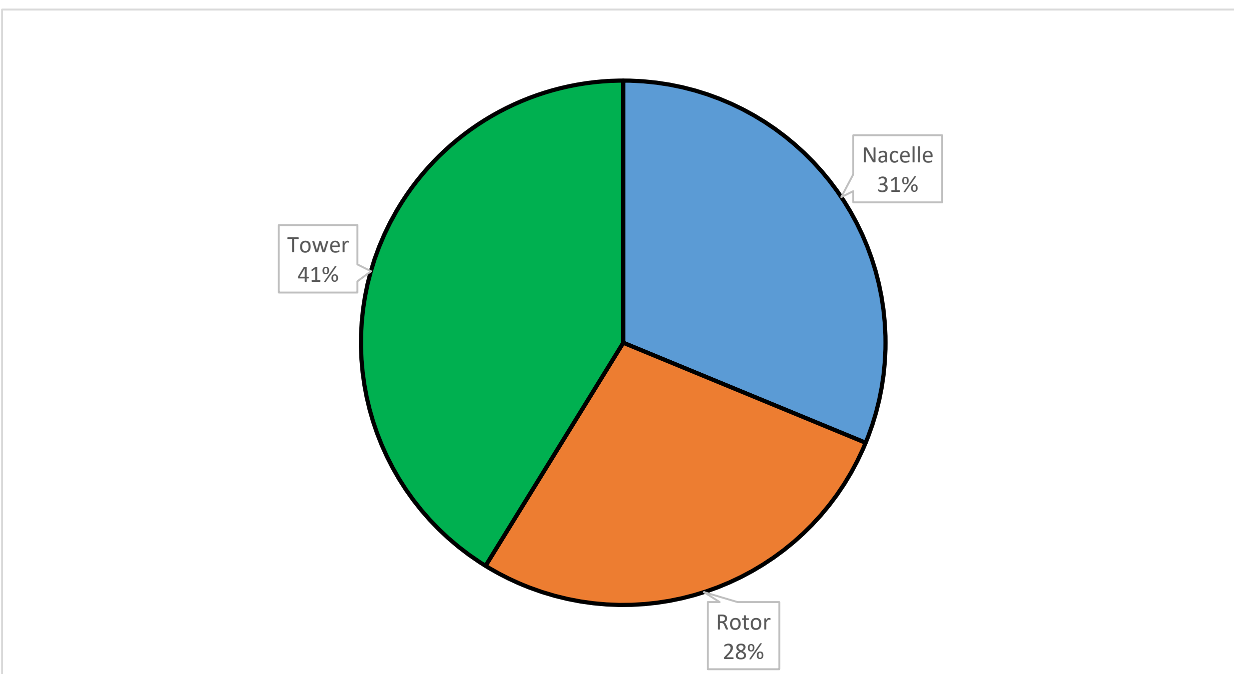

Figure 4.6: CED of the Turbine Parts for 20-Years Life Span

4.3 Objective 2: Sensitivity Analysis

This section addresses Objective 2: To identify a range of impacts due to uncertainty in LCA model inputs. Identification of impacts of uncertainty is part of the 4^{th} step of the LCA

4.3.1 Sensitivity Analysis for Parameter 1: Extension of the Turbine Life Span

4.3.1.1 Eight Impact Categories from Simapro for 25- and 30-year life spans

Tables 4.8 and 4.9 and Figures 4.7 and 4.8 represent the environmental impacts for the turbines if the life span is extended to 25 or 30 years. Figures 4.7 and 4.8 are similar, because both life spans influenced with environmental impacts similarly. Tables 4.10 and 4.11 show the percent decreases in impacts when the life span is extended from 20 to 25 and 30 years, respectively. The environmental impacts decrease for all phases except transportation and operation and maintenance. The decreases would be expected because most of the impacts are due to the manufacturing phase, and with a longer life span, the pollutants from manufacturing are distributed over more years. In the case of the transportation and operation and maintenance phases, they increased because during the additional 5 to 10 years of life span, supplies are needed to maintain the turbine every 6 months, and this work includes traveling to and from the turbines. However, the total of impact of all phases per kWh generated decreases for both the 25- and 30-year life spans.

Table 4.8: Environmental impacts for a 25-year turbine life span, per kWh of power generated

Environmental Impacts for 25-Years Life Span.	Raw Material Acquisition	Manu-facturing	Installation	Operation & Maintenance	End of Life	Trans-portation	Total
Ozone depletion (kg CFC-11 eq)	1.56E-07	2.92E-06	1.88E-06	5.13E-07	7.63E-10	1.13E-06	6.61E-06
Global warming (kg CO_2 eq)	2.45E-05	2.01E-03	9.98E-04	2.23E-04	5.66E-07	2.35E-04	3.49E-03
Smog (kg O_3 eq)	2.25E-05	1.26E-03	6.07E-04	1.65E-04	3.06E-07	2.33E-03	4.38E-03
Acidification (kg SO_2 eq)	4.44E-05	1.17E-03	3.53E-04	1.26E-04	3.22E-07	1.26E-04	1.82E-03
Eutrophication (kg N eq)	8.20E-05	1.38E-03	2.72E-04	7.10E-05	2.68E-07	1.40E-05	1.82E-03
Human Health Potential (CTUh)	4.31E-06	9.73E-05	1.70E-05	2.94E-07	5.94E-09	7.78E-07	1.20E-04
Respiratory effects (kg $PM_{2.5}$ eq)	6.19E-06	3.29E-04	7.86E-05	8.75E-06	5.89E-08	1.36E-05	4.36E-04
Fossil fuel depletion (kWh surplus)	1.15E-04	5.15E-03	2.42E-03	6.46E-04	1.24E-06	1.40E-02	2.23E-02

Table 4.9: Environmental impacts for a 30-year turbine life span, per kWh of power generated

Environmental Impacts for 30-Years Life Span.	Raw Material Acquisition	Manu-facturing	Installation	Operation & Maintenance	End of Life	Trans-portation	Total
Ozone depletion (kg CFC-11 eq)	1.43E-07	2.66E-06	1.88E-06	5.28E-07	7.32E-10	1.17E-06	6.38E-06
Global warming (kg CO_2 eq)	2.27E-05	1.87E-03	9.98E-04	2.29E-04	5.23E-07	2.43E-04	3.36E-03
Smog (kg O_3 eq)	2.15E-05	1.16E-03	6.07E-04	1.69E-04	2.84E-07	2.39E-03	4.36E-03
Acidification (kg SO_2 eq)	4.13E-05	1.10E-03	3.53E-04	1.29E-04	2.96E-07	1.29E-04	1.76E-03
Eutrophication (kg N eq)	7.68E-05	1.30E-03	2.72E-04	7.37E-05	2.51E-07	1.43E-05	1.74E-03
Human Health Potential (CTUh)	4.07E-06	9.12E-05	1.70E-05	3.08E-07	5.54E-09	7.99E-07	1.13E-04
Respiratory effects (kg $PM_{2.5}$ eq)	5.76E-06	3.09E-04	7.86E-05	9.12E-06	5.60E-08	1.39E-05	4.17E-04
Fossil fuel depletion (kWh surplus)	1.09E-04	4.69E-03	2.36E-03	6.69E-04	1.16E-06	1.44E-02	2.22E-02

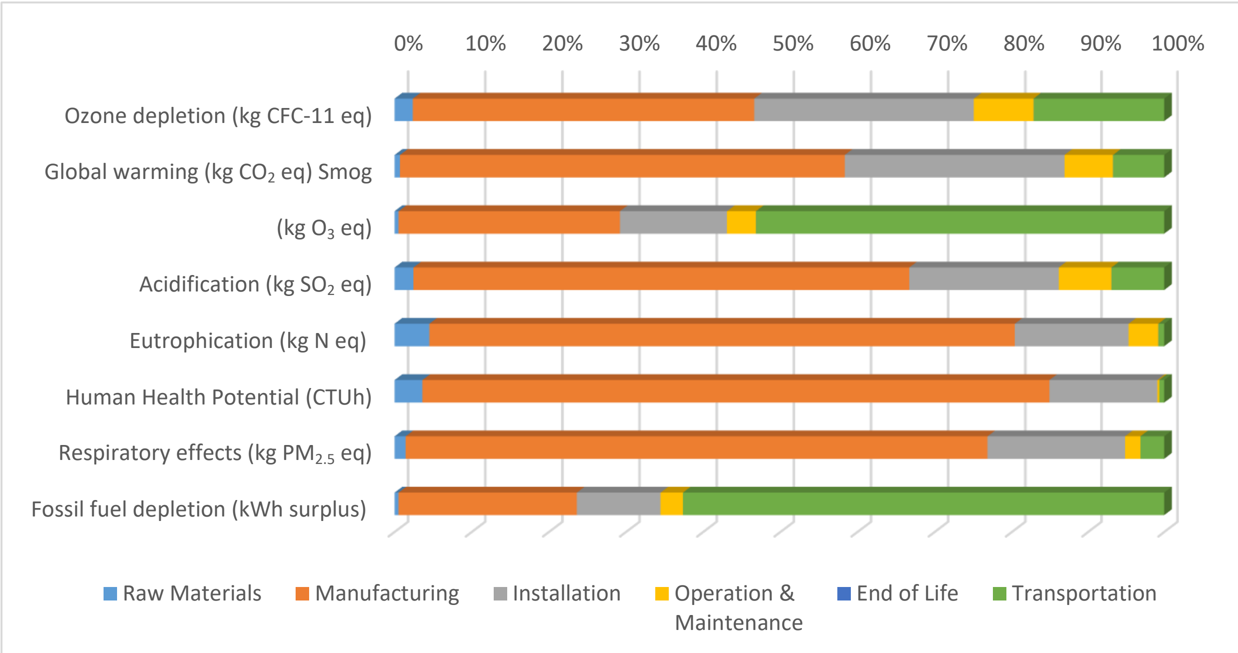

Figure 4.7: Environmental Impacts/ 1kWh Generated for 25-Year Turbine Life Span

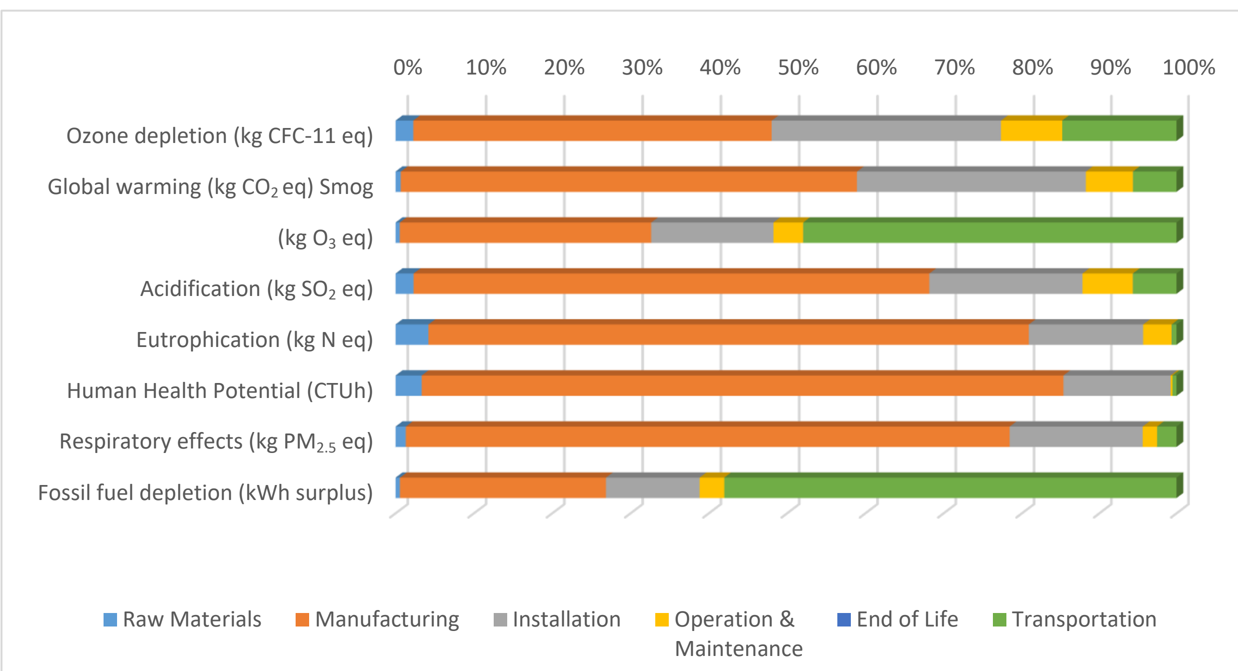

Figure 4.8: Environmental Impacts/ 1kWh Generated for 30-Year Turbine Life Span

Table 4.10: Percentage Changes in Impacts When the Turbine Life Span Is Extended from 20-Years to 25-Years:

Environmental Impacts	Raw Materials	Manufacturing	Installation	Operation & Maintenance	End of Life	Transportation	Total
Ozone depletion	-13.64%	-15.21%	-14.18%	5.66%	-9.56%	4.26%	-9.92%
Global warming	-14.94%	-16.41%	-15.49%	6.28%	-6.77%	4.60%	-13.28%
Smog	-16.73%	-18.75%	-17.07%	5.39%	-8.75%	3.79%	-5.62%
Acidification	-15.65%	-19.26%	-18.50%	5.06%	-8.92%	3.81%	-15.75%
Eutrophication	-16.71%	-19.55%	-17.14%	4.15%	-9.78%	4.02%	-17.96%
Human Health Potential	-15.52%	-18.59%	-17.05%	3.15%	-9.07%	3.73%	-18.06%
Respiratory effects	-14.78%	-18.55%	-15.69%	3.70%	-10.02%	3.78%	-16.84%
Fossil fuel depletion	-15.69%	-13.17%	-15.56%	4.57%	-8.36%	4.30%	-1.99%

Table 4.11: Percentage Changes in Impacts When the Turbine Life Span Is Extended from 20-Years to 30-Years:

Environmental Impacts	Raw Materials	Manufacturing	Installation	Operation & Maintenance	End of Life	Transportation	Total
Ozone depletion	-23.64%	-26.90%	-14.18%	8.34%	-14.18%	7.56%	-13.82%
Global warming	-23.77%	-25.47%	-15.49%	8.93%	-15.49%	8.04%	-17.72%
Smog	-22.26%	-28.21%	-17.07%	7.66%	-17.07%	6.43%	-6.20%
Acidification	-24.41%	-26.12%	-18.50%	7.73%	-18.50%	6.42%	-19.66%
Eutrophication	-24.60%	-27.15%	-17.14%	7.65%	-17.14%	6.09%	-23.72%
Human Health Potential	-22.26%	-26.44%	-17.05%	7.56%	-17.05%	6.27%	-24.56%
Respiratory effects	-23.49%	-26.12%	-15.69%	7.64%	-15.69%	5.92%	-22.31%
Fossil fuel depletion	-21.68%	-24.21%	-18.29%	7.95%	-15.56%	7.01%	-2.39%

4.3.1.2 Water Depletion Index for 25- and 30-year Life Spans

Table 4.12 and Figure 4.9 show the WDI comparison between the different life spans. Table 4.13 shows the percentage change in WDI when the life span is extended to 25 and 30 years. Like the 8 Simapro environmental impact categories, the overall WDI decreased with the longer turbine life spans. The WDI decreased for all phases, with the exception of the operation and maintenance phase. In every extra year there are 2 more trips to the turbines to conduct the maintenance service; therefore, more supplies including water are needed. For example, the air exchanger and cooler in the engine requires water constantly. In fact, the older the turbine, the more maintenance is needed and that means more water will be consumed.

Table 4.12: Water Depletion Index (m^3) for 20-, 25-, and 30-Year Turbine Life Spans

Phase	**20-Years Life Span**	**25-Years Life Span**	**30-Years Life Span**
Raw Materials Acquisition	3.45	3.17	3.03
Manufacturing	258.25	229.56	221.11
Installation	99.25	89.43	86.04
Operation and Maintenance	5.05	5.14	5.20
End of Life	14.4	13.64	13.18
Transportation	7.3	7.20	7.18
Total (m^3)	387.7	348.15	335.75

Table 4.13: Percentage Changes in Water Depletion Index When the Turbine Life Span Is Extended from 20-Years to 25- and 30-Years:

	Percentage Change in WDI	
Phase	**20 to 25 years**	**20 to 30 years**
Raw Materials Acquisition	-8.11%	-12.04%
Manufacturing	-11.11%	-14.38%
Installation	-9.89%	-13.31%
Operation	1.86%	2.91%
End of Life	-5.26%	-8.50%
Transportation	-1.34%	-1.58%
Total (m^3)	-10.20%	-13.40%

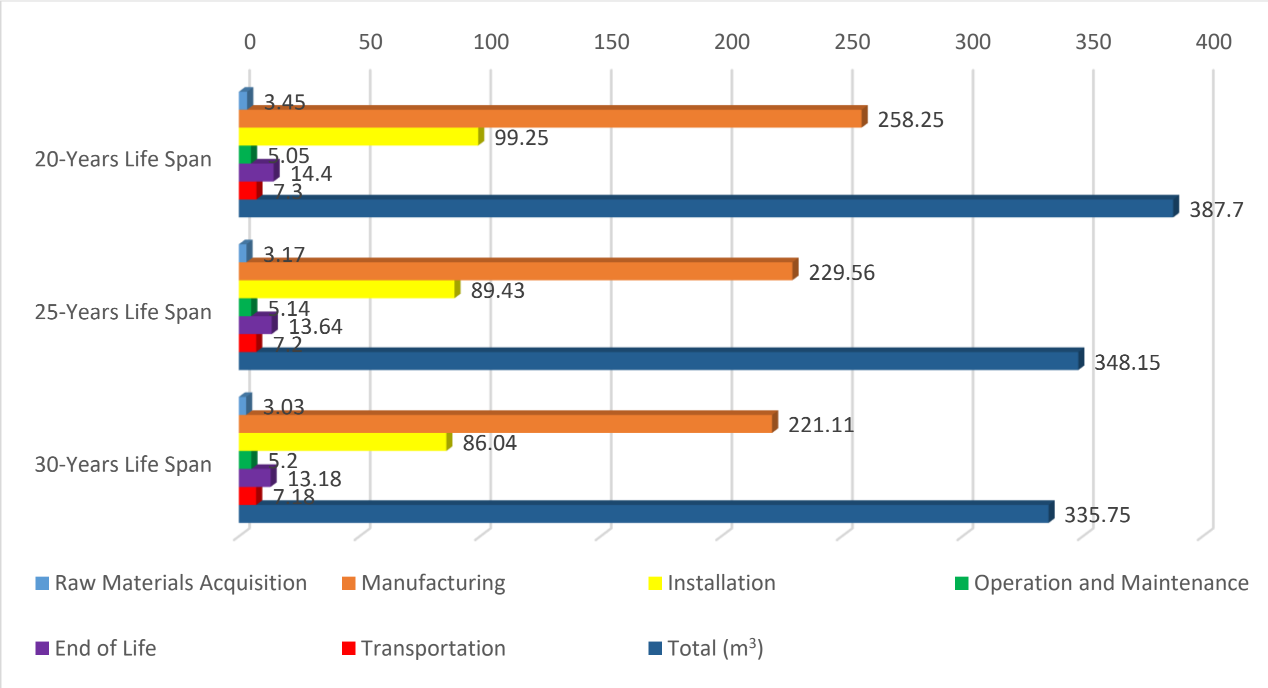

Figure 4.9: WDI (m^3) of Every Phase for the 3 Different Life Spans

4.3.1.3 Energy Balance for 25- and 30-year Life Spans

Tables 4.14 and 4.15 show the CED if life span extended to 25 or 30 years. Table 4.16 compares the cumulative energy demand for the 20, 25, and 30-year life spans. Extending the life span means that more energy will be generated with the same devices. Energy consumption associated with manufacturing will be distributed over a longer life span.

Table 4.14: The Cumulative Energy Demand of Each Phase for Each Type of Energy for 25-Years Life Span

Type of Energy		Raw Materials Acquisition	Manufacturing	Installation	Operation and Maintenance	End of Life	Transportation	Total
Non-renewable (kWh)	Fossil fuel	32.46	1,814.90	609.59	231.53	79.61	287.70	3,055.79
	Nuclear	1.90	128.99	28.17	5.94	4.09	19.89	188.98
	Biomass	0.00	0.09	0.03	0.01	0.01	0.01	0.15
Renewable (kWh)	Biomass	0.74	31.74	14.97	2.58	0.78	5.83	56.65
	Geo-thermal	0.14	6.56	1.85	0.46	0.20	0.93	10.14
	Water	1.29	112.61	20.55	11.05	3.71	17.48	166.69
Total		36.53	2,094.88	675.17	251.57	88.40	331.84	3,478.39

Table 4.15: The Cumulative Energy Demand of Each Phase for Each Type of Energy for 30-Year Life Span

Type of Energy		Raw Materials Acquisition	Manufacturing	Installation	Operation and Maintenance	End of Life	Transportation	Total
Non-renewable (kWh)	Fossil fuel	26.03	1,564.51	498.95	190.72	61.80	367.93	2,709.94
	Nuclear	1.49	115.56	22.16	4.83	3.16	29.68	176.88
	Biomass	0.00	0.06	0.03	0.01	0.00	0.07	0.17
Renewable (kWh)	Biomass	0.59	24.56	11.74	2.14	0.61	8.31	47.96
	Geo-thermal	0.12	4.93	1.47	0.38	0.15	1.22	8.27
	Water	1.01	108.73	16.25	9.01	2.90	27.68	165.57
Total		29.24	1,818.35	550.59	207.08	68.62	434.89	3,108.78

Table 4.16: Energy Balance for Different Life Spans

Life Span / Energy (kWh)	20 years	25 years	30 years
Total Cumulative Energy Demand (CED)/Year	4,019	3,478	3,109
Total Energy Produced/Year	156,822	156,822	156,822
Net Energy/Year	152,803	153,343	153,713
Ratio of Produced Energy to CED	39 Times	45 Times	50 Times

4.3.2 Sensitivity Analysis for Parameter 2: Assumed Wind Speed

Table 4.17 shows the net energy balance per turbine for different wind speed scenarios (assuming 8 m/sec fixed wind speed as a best-case scenario recommended by the manufacturer; assuming a 7 m/sec fixed wind speed; and using the annual wind rose at the wind farm site). Obviously, increasing the wind speed for the farm will increase the energy production. However, assuming that the wind speed is fixed for the whole life span and assuming that the turbines are operating 24/7 during its life span is far from reality. There are some times when the turbines are not operating for different reasons such as the maintenance or malfunction in the system, or even no wind at all to push the blades. In addition, the wind speed continually fluctuates. Assuming constant high wind speed represents a best-case scenario. The most realistic way is to use the wind rose for the area where the farm is operating. Table 4.18 shows the return energy period in every life span with different wind speeds.

Table 4.17: Energy Balance for Different Wind Speeds, over Different Life Spans per Turbine Every Year

		20-Years	25-Years	30-Years
	Total CED (kWh)	4,019	3,478	3,109
Wind Rose Average	Produced Energy (kWh)	156,822	156,822	156,822
	Net Energy (MJ)	152,803	153,343	153,713
	Ratio of Produced to CED Energy	39 Times	45 Times	50 Times
Wind Speed is 8 m/s	Produced Energy (kWh)	6,763,596	6,763,596	6,763,596
	Net Energy (kWh)	6,759,577	6,760,118	6,760,487
	Ratio of Produced to CED Energy	1,683 Times	1,944 Times	2,176 Times
Wind Speed is 7 m/s	Produced Energy (kWh)	4,530,891	4,530,891	4,530,891
	Net Energy (kWh)	4,526,872	4,527,413	4,527,782
	Ratio of Produced to CED Energy	1,127 Times	1,303 Times	1,457 Times

Table 4.18: The Return Energy Period in Every Life Span with Different Wind Speeds

	20 Years	25 Years	30 Years
Wind Rose Averages	187.07 days	202.39 days	217.08 days
8 m/s	4.34 days	4.69 days	5.03 days
7 m/s	6.47 days	7.01 days	7.51 days

In the study completed in Spain on the same turbine, the energy payback time was estimated to be 9 months of the operating in case of 8 m/s and in 11 months in case of 7 m/s for each turbine. In this study it is six months because the estimate was for the whole farm and not only one turbine and there are some processes that are combined. Therefore, it will save some of the consumed energy.

4.3.3 Sensitivity Analysis for Parameter 3: Aluminum VS Fiberglass for the Blades

Table 4.19 shows environmental, health, and resource depletion impacts for aluminum blades and a 20-year life span. Tables 4.20 - 4.22 compare the impacts of the aluminum blades with the fiberglass blades.

Table 4.19: The Environmental Impacts of Generation of 1 kWh Electricity During 20-Year Life Span for the Whole Turbine with Aluminum Blades

Impact category (unit) \ Part	Raw Materials Acquisition	Manufacturing	Installation	Operation & Maintenance	End of Life	Transportation	Total
Ozone depletion (kg CFC-11 eq)	1.99E-07	3.79E-06	2.15E-06	4.84E-07	4.48E-10	1.09E-06	7.71E-06
	2.59%	49.18%	27.87%	6.28%	0.01%	14.09%	100.00%
Global warming (kg CO_2 eq)	3.22E-05	2.68E-03	1.15E-03	2.09E-04	3.68E-07	2.24E-04	4.30E-03
	0.75%	62.37%	26.80%	4.86%	0.01%	5.21%	100.00%
Photochemical Smog (kg O_3 eq)	3.02E-05	1.71E-03	7.11E-04	1.56E-04	1.90E-07	2.24E-03	4.85E-03
	0.62%	35.32%	14.66%	3.21%	0.00%	46.18%	100.00%
Acidification (kg SO_2 eq)	6.23E-05	1.69E-03	4.18E-04	1.19E-04	1.63E-07	1.21E-04	2.41E-03
	2.58%	70.09%	17.35%	4.95%	0.01%	5.02%	100.00%
Eutrophication (kg N eq)	9.95E-05	1.67E-03	3.18E-04	6.81E-05	1.53E-07	1.34E-05	2.17E-03
	4.60%	76.93%	14.70%	3.14%	0.01%	0.62%	100.00%
Human Health Potential (CTUh)	5.12E-06	1.19E-04	1.99E-05	2.85E-07	4.61E-09	7.49E-07	1.45E-04
	3.54%	82.03%	13.71%	0.20%	0.00%	0.52%	100.00%
Respiratory effects (kg $PM_{2.5}$ eq)	8.48E-06	4.65E-04	9.10E-05	8.43E-06	2.77E-08	1.31E-05	5.86E-04
	1.45%	79.37%	15.51%	1.44%	0.00%	2.23%	100.00%
Fossil fuel depletion (kWh surplus)	1.41E-04	6.21E-03	2.79E-03	6.16E-04	1.14E-06	1.34E-02	2.31E-02
	0.61%	26.87%	12.08%	2.67%	0.00%	57.77%	100.00%

Table 4.20: Impacts Comparison Between Fiberglass vs Aluminum For the Blades Only

Environmental Impacts	Impacts from Blades Only			Impacts from the Entire Turbine		
	Fiberglass Blades	Aluminum Blades	Percent Change	Fiberglass Blades	Aluminum Blades	Percent Change
Ozone Depletion (kg CFC-11 eq)	4.87E-07	9.09E-07	+87%	7.26E-06	7.71E-06	+6%
Global Warming (kg CO_2 eq)	5.26E-04	8.63E-04	+64%	3.96E-03	4.30E-03	+9%
Photochemical Smog (kg O_3 eq)	2.96E-04	5.17E-04	+75%	4.63E-03	4.85E-03	+5%
Acidification (kg SO_2 eq)	2.58E-04	5.56E-04	+116%	2.10E-03	2.41E-03	+15%
Eutrophication (kg N eq)	1.41E-04	1.56E-04	+11%	2.15E-03	2.17E-03	+1%
Human Health Potential (CTUh)	8.46E-06	1.19E-05	+41%	1.41E-04	1.45E-04	+3%
Respiratory effects (kg $PM_{2.5}$ eq)	5.62E-05	1.31E-04	+133%	5.10E-04	5.86E-04	+15%
Fossil fuel depletion (kWh surplus)	2.13E-03	2.51E-03	+18%	2.27E-02	2.31E-02	+2%

Table 4.21: The CED Change Between Fiberglass and Aluminum for the Blades Only.

Impact category (Unit)	Fiberglass Blades	Aluminum Blades	Percent Change
Non-renewable, fossil (MJ)	2,157,909	2,518,970	+17%
Non-renewable, nuclear (MJ)	226,516	245,562	+8%
Non-renewable, biomass (MJ)	97	101	+4%
Renewable, biomass (MJ)	44,993	47,445	+5%
Renewable, wind, solar, geothermal (MJ)	5881	6051	+3%
Renewable, water (MJ)	96,089	96,697	+1%
Total	2,531,485	2,914,826	+15%

Table 4.22: The WDI Change Between Fiberglass and Aluminum for the Blades Only.

Phase	Fiberglass Blades	Aluminum Blades	Percent Change
Raw Materials Acquisition	69	74	+7%
Manufacturing	5165	5372	+4%
Installation	1985	1985	0%
Operation and Maintenance	101	101	0%
End of Life	288	156	-46%
Transportation	146	146	0%
Total (m^3)	7754	7834	+1%

Replacing the fiberglass blades with aluminum ones increased all impacts. Even though the fiber glass requires at least 1555 ^oF to start softening while the aluminum start melting at 1220 ^oF (Engineering Tool Box, 2016), fabricating blades from aluminum still requires more energy due to the need for multiple heating and cooling processes during manufacturing. Despite the fact that OSHA considers fiberglass contain carcinogenic substances, and to be an eye and skin irritant, the fact aluminum required greater energy consumption caused it to have greater impacts on human health potential and respiratory effects, as well as in the other categories. This is because most energy is produced from burning fossil fuels, which releases pollutants. When looking specifically at the end-of-life phase, however, all impacts decreased because 98% of the aluminum was assumed to be recycled. The installation phase did not change because the type of blades is not a factor of the installation process. Similarly, operation and maintenance stayed the same because the assumption is that the blades will survive the whole life span of the turbine and will not need to be replaced. The transportation phase did not change also because transportation fuel consumption was based on the weight of the components, which did not change. In conclusion, replacing the fiberglass blades by aluminum blades is not good idea in terms of environmental, health, or resource depletion impacts.

4.4 Life Cycle Assessment of Coal-Fired Power Plant Vs. Wind Turbines.

The goal of this part is to answer the question; what are life cycle emissions for wind energy in the US, vs. coal and natural gas?

Coal and natural gas represent the main nonrenewable energy resources that have been widely used in US. According to the US Energy Information Administration, coal contributed 32% and natural gas contributed 33% of the energy used in 2016 (US EIA, 2016). This section will compare the life-cycle impacts of a coal-fired plant with and without carbon capture and sequestration (CCS), and with and without natural gas.

CCS is capable of drastically minimizing the emissions of CO_2 from power generation. A wide range of studies have confirmed 70%-80% minimization in carbon dioxide emissions on a life-cycle basis, irrespective of the technology (Widder et al., 2011). However, the execution of CCS schemes will exhibit manifold other economic, social and environmental impacts past controlling GHG emissions, which should be considered to attain sustainable energy production. For instance, SO_2, NOx, and PM emissions are also environmental concerns for coal-fired power plants. Any increase of air pollutants' emissions by a carbon-capture plant's parasitic energy intake ought to be taken into consideration while assessing the general sustainability or ecological impact of the technology.

Widder et al. (2011) conducted an LCA of coal-fired and natural gas power plants in the US (US Energy Information Administration, 2016). They addressed social, economic, and environmental impacts, as well as the relationship between carbon capture and sequestration (CCS) and CO_2 reduction. GHG and other emissions (NOx, SO_2, and PM) were addressed, since they are important issues with coal-fired plants. There were several reasons behind choosing this study for the comparison with our wind turbine study. First, the Widder study was comprehensive (covered all phases of the plant) and covered two non-renewable energy resources, coal and natural gas. Secondly, two options were addressed in the study: with carbon capture and without carbon capture. Finally, the methods and modelling tools (TRACI and SimaPro software) were the same we used in our study, so environmental impact categories were the same. The same functional unit used for comparison was 1kWh of power generated.

The life-cycle phases in Widder's study were coal mining and transportation, natural gas production and transportation, MEA production and disposal, operation of other emissions control technologies, power production, and sequestration (CO_2 transportation and storage). The coal plant was 500 MW burning lignite, with an amine-stripping system. A key aspect of the Widder's study was the use of the MonoEthanolAmine (MEA) scrubbing method for carbon dioxide removal, with 90% efficiency. The greater the percent carbon capture desired, the greater the required use of MEA, which increases environmental impacts like eutrophication and acidification due to ammonia. Table 4.23 and Figure 4.10 compare the impacts of the coal/natural gas plants with the wind turbines.

Table 4.23: The Environmental Impacts of Coal-Fired Power Plant and Natural Gas Vs the Wind Turbines

Environmental Impacts	PC with-out CCS	PC with CCS	PC with CCS & NG without CCS	PC with CCS & NG with CCS	Wind Turbine
Water Depletion Index (gal/MWh)	796.00	1122.00	790.00	905.00	267.00
Human Health (kg DCB-eq/MWh)	33.00	73.00	52.00	52.00	0.14
Eutrophication Potential (kg PO_3^{-4}-eq/MWh)	7.50	14.10	14.50	17.80	2.15
Acidification Potential (kg SO_2-eq/MWh)	9.00	10.85	8.10	8.70	2.10
Ozone Layer Depletion (kg CFC11-eq/MWh)	0.039	0.059	0.040	0.040	0.007
Global Warming Potential (kg-CO_2-eq/MWh)	838.00	220.00	265.00	200.00	3.96

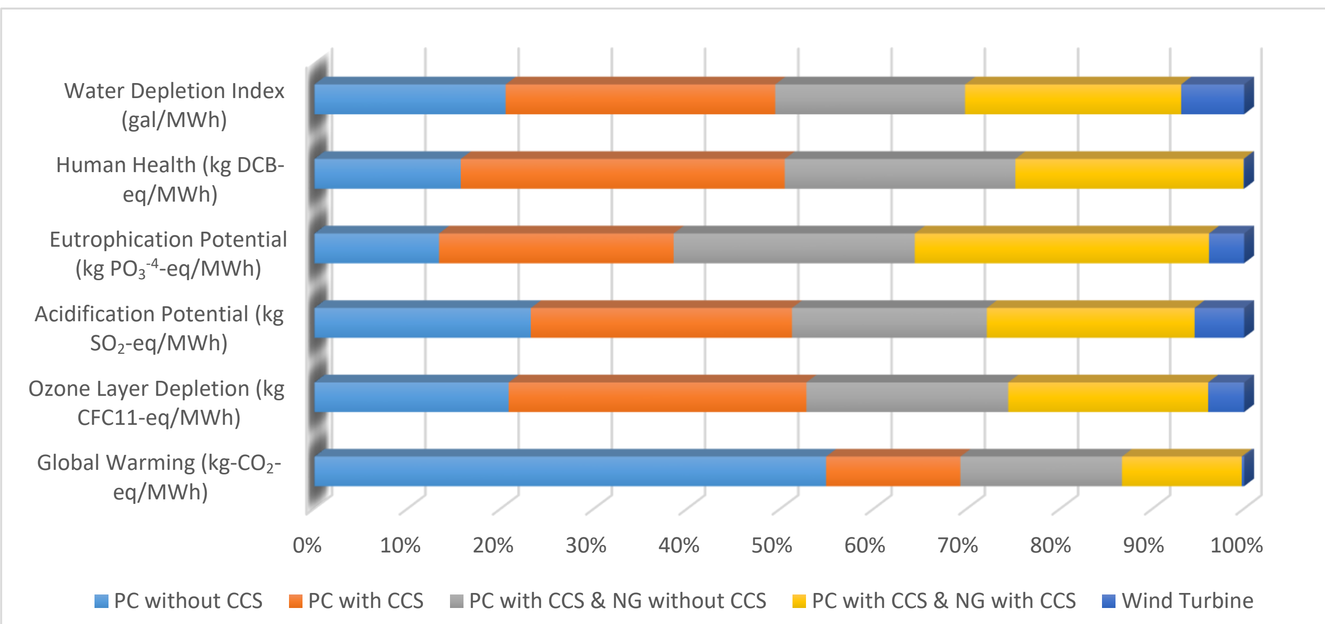

Figure 4.10: The Environmental Impacts of Coal-Fired Power Plant Vs the Wind Turbines

For all cases, the coal-fired power plant causes substantially more environmental impacts than the wind turbines for the same amount of power produced. Water depletion index results in

Table 4.21 indicate that PC/NG plants consume at least 3 times more water than the wind turbines. In PC/NG plants, water is continuously used for the purposes of systems cooling, while in the case of wind turbine, water is not continuously needed; it is only used during the manufacturing phase. Human health impacts caused by PC/NG plants are particularly large because of the ethylene oxide emissions from MEA, ranging from 236 to 521 times those caused by the wind turbines. Producing energy from coal it causes between 3.5 to 8.3 times the eutrophication caused by the wind turbines, due to NOx emissions. The use of the CCS technology lowers the global warming contribution of the PC & NG plant. when using this technology in both PC and NG, it lowered the global warming from 265 to 200 kg-CO_2-eq/MWh; yet, this is still >50 times that of the wind turbine.

4.5 Questions to be Answered by the Dissertation

- **What are the most important factors influencing life cycle emissions from wind energy product?**

  Manufacturing the parts was the most critical phase; it caused the most of the environmental impacts during the life cycle of the wind turbine. The wind turbine parts are very large and required great amounts of energy from fossil fuels to manufacture, which caused sizable environmental impacts. For example, the tower caused 47% of the global warming from the manufacturing phase and 28% of the global warming overall. Altogether, the parts manufacturing phase was responsible for 59% of the global warming, and was also the largest contributor to the other impacts.

- **Are emissions from maintenance of wind turbines significant in terms of the overall life cycle?**

  Maintenance was not very significant compared to the other phases. Among the 8 main impact categories in Simapro, the highest contribution from the maintenance phase was 6.7% to ozone depletion, as shown in Table 4.1. In term of the water consumption, the impact was very small (1%). Even when the life span increased by 5 years, the WDI was still less than 2%. The CED for maintenance was 8.1% of the total.

- **At the end of a wind turbine's life cycle, what percent of materials are recycled back into new products?** Table 4.24 shows recycling percentages, according to information from the manufacturer.

Table 4.24: Materials Recycling Percentages

Material Type	Percentage Recycled
Metals (Steel, Copper, Aluminum)	98%
Plastic	90%
Electrical and Electronic Components	50%
Cables	99%
Carbon Fiberglass	0%
Lubricant/Grease/Oil	0%
Paints/Adhesive	0%

- **How sensitive is the life cycle analysis to changes in input parameters?**

Turbine life span: Total environmental impacts per kWh decreased when the life span increased. Impacts decreased in all phases except maintenance and transportation. For example, the total WDI decreased by 10.3 % when the life span increased from 20 to 25 years and decreased by 13.6% when the life span increased from 20 to 30 years. As another example, global warming potential was 0.00396 kg CO_2 eq/kWh generated for a 20-year life span; it dropped to 0.00349 kg CO_2 eq/kWh generated (around 13% difference) when the life span increased to 25 years. Finally, the produced energy increased from 627,286,080 kWh to 784,107,600 kWh when the life span increased from 20 to 25 years (25 % difference).

Wind speed: The higher the wind speed, the more energy can be produced up to certain limits; there is a brake system in the turbine to cap the blade rotation if the wind speed become very strong (safety purposes). When the wind speed was 7 m/s, then the energy production was 18,123,564,000 kWh over 20 years and it increased to 27,054,384,000 kWh when the wind speed assumed to be 8 m/s (around 50% increase). In reality, it is impossible to maintain the wind speed constant during the life span of the turbine. The production using the wind rose average was only 2.32 percent of the best-case using 8 m/sec constant wind speed.

- **What are life cycle emissions for wind energy, vs. coal and natural gas?**

For all cases, the coal-fired power plant causes substantially more environmental impacts than the wind turbines for the same amount of power produced. Water depletion index results indicate that PC/NG plants consume at least 3 times more water the wind turbines. In PC/NG plants, water is continuously used for the purposes of systems cooling, while in the case of wind turbine, water is not continuously needed; it is only used during the manufacturing phase. Human health impacts caused by PC/NG plants are particularly large because of the ethylene oxide emissions from MEA, ranging from 236 to 521 times those caused by the wind turbines. Producing energy from coal it causes between 3.5 to 8.3 times the eutrophication caused by the wind turbines, due to NOx emissions. The use of the CCS technology lowers the global warming contribution of the PC & NG plant. when using this technology in both PC and NG, it lowered the global warming from 265 to 200 kg-CO2-eq/MWh; yet, this is still >50 times that of the wind turbine.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH.

5.1 Conclusions

This life cycle assessment study addressed the impacts (environmental, health, and resource consumption) of a 300 2-MW turbines installed in Abilene, Texas. The study covered all the phases that the turbines went through from cradle to cradle: raw acquisition materials, manufacturing, installation, operation and maintenance, and recycling into new products at the end-of-life phase.

- The manufacturing phase produced the largest impacts: 46% of ozone depletion, 59% of global warming, 77% of eutrophication, 81% of human health impacts, 67% of water depletion index, and 64% of the cumulative energy demand. The tower is the largest part of the turbine, so it was responsible for higher percentages of the impacts caused by the manufacturing phase than the other parts. Hence, to reduce environmental impacts, health impacts, and resource consumption from wind power, alternative methods of tower manufacturing should be explored.
- The transportation phase contributed around 50% to the impact categories of fossil fuel depletion and ozone smog formation, due to consumption of diesel fuel.
- The installation phase contributed around 30% of the ozone depletion and global warming impacts, due to fossil fuel consumption.
- The raw material acquisition, operation and maintenance, and end-of-life phases contributed small impacts.
- Assuming a 20-year lifetime, the turbines produce 39 times more energy than is consumed for manufacturing, transporting, and disposing of them. If the turbine life span is increased to 25 years, then they produce 55 time more energy than they consume. For a life span of 30 years, they produce 71 times more energy than they consume.

- Carbon dioxide, sulfur dioxide, nitrogen oxides, methane, and particles were the air pollutants released in the largest quantities due to fossil fuel consumption.
- Extending the turbine life span lowers impacts per kWh of electricity produced because the environmental, health, and resource consumption impacts, which are due primarily to the manufacturing phase, will be distributed over a longer period of time. For example, global warming potential for a 20-years life span was 0.00396 kg CO_2 eq/ kWh generated, but in 25 years it went down to 0.00349 kg CO_2 eq/ kWh generated, and to 0.00336 when the life span extended to 30 years.
- The best-case wind speed recommended by the manufacturer, 8 m/s, overestimated electricity generation by a factor of 43 compared to using the wind rose at the farm site.
- The third parameter is test different materials for the blades in the turbine's rotor.
- Based on a comparison with values reported in the literature, global warming potential of coal-fired and natural gas power plants with carbon capture and sequestration were still 3 50 times the impacts of the wind turbines. Other environmental impacts ranged from 4-8 times those of wind turbines, and human health impacts were estimated to be 370 times those of wind turbines.

5.2 Future Study Recommendations

1- In this study, electricity transmission was not included due to lack of available data. Future work should include collaborations with power companies to determine impacts of wind power delivered with power from other sources. Since wind power production in Texas tends to be long distances from major population centers, transmission losses are greater than for other sources of power.

2- This study addressed 2 MW turbines. Larger capacity turbines should be analyzed for comparison. In addition, the impact of producing the same amount of power from different size turbines should be compared.

3- Methods of reducing energy consumption and other impacts from manufacturing turbine parts should be investigated, since the manufacturing phase generated the greatest impacts. For example, replacing the steel in the tower with fiberglass or green cement could be evaluated.

4- Green cement should be considered in order to reduce the climate change impacts of the installation phase, which includes cement used for the wind turbine foundation.

5- Methods of lengthening the life span of turbines via additional maintenance should be investigated, because this reduces the turbine impacts per kWh of power produced.

6- Compare the results of this study to impacts for the following:

- a similar turbine manufactured in the US instead of Spain.
- a turbine with a permanent magnet generator rather than an induction generation because permanent magnet generation produces power with higher efficiency and less maintenance, so it might reduce the impacts.
- a turbine designed to have a longer lifetime, to determine whether the increased lifetime makes up for the potential increase in manufacturing emissions, in terms of overall impacts per kWh.

5.3 Recommendations for Policy Makers

To reduce the impacts of wind turbines in terms of the environment, human health, and resource consumptions, policy makers can consider a number of options, as determined by this study:

- Policies/incentives should be directing wind turbine investors to use local turbine manufacturers. Transport of turbines from Spain to Texas caused substantial impacts in this study, particularly in terms of photochemical ozone smog formation and fossil fuel depletion Encouraging wind farm owners to use local manufacturers will avoid the unnecessary transportation and reduce the impacts.
- Policies should encourage wind turbine manufacturers to conduct full life cycle assessment studies for their turbines, to aid in selecting turbine materials and manufacturing processes which cause lesser impacts. In particular, manufacturers should look for ways to reduce the impacts of manufacturing the tower, since it had the largest contribution in this study. In addition, turbine manufacturers should investigate ways to increase the life span of their turbines, because this would reduce the overall impacts
- Use of green cement in turbine foundations should be encouraged to reduce impacts of the installation phase.
- Given the substantially reduced life cycle impacts of wind turbines over coal and natural gas, loans and tax credits to wind turbine investors should be considered to encourage investors toward this industry.

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Appendix A

The used fiberglass in the blades was 11,207.44 kg for turbine G83 and 11,747.56 kg turbine G87, they will be replaced by aluminum with same weight. Aluminum and fiberglass have different densities, therefore to maintain the shape and the weight, the thickness need to be adjusted as in the following calculations:

The density of the fiberglass is 0.055 lb/in3 and for the aluminum is 0.10 lb/in3

The mass of the blade is 11,207.44 kg = 24,708.18 lbs

The volume can be found from the dimension of the blade whcih is 134 ft x 10 ft (5x2 layers; top and bottom) x thickness

The fiberglass thickness will be:

24,708.18/0.055 = (134 ft *12 in/ft) * (10 ft *12 in/ft) * Thickness

Thickness of fiberglass = 2.33 in

The Aluminum thickness will be:

24,708.18/0.10 = (134 ft *12 in/ft) * (10 ft *12 in/ft) * Thickness

Thickness of aluminum = 1.28 in