LIFE CYCLE ASSESSMENT OF WIND POWER FOR ELECTRICITY GENERATION IN PAKISTAN

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LIFE CYCLE ASSESSMENT OF WIND POWER FOR ELECTRICITY GENERATION IN PAKISTAN

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ABSTRACT

LIFE CYCLE ASSESSMENT OF WIND POWER FOR ELECTRICITY GENERATION IN PAKISTAN

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Pakistan is a developing country and energy crisis has always emerged as the key hindrance in economic development. Besides the increasing demand and supply gap, it is alarming fact that the current energy mix is mainly dependent on fossil fuels which results in environmental and energy security issues. As part of efforts for transition towards clean and renewable technologies for electricity generation, the assessments carried out by Pakistan Meteorological Department and Ministry of Energy in collaboration with National Renewable Energy Laboratory, USA revealed the huge potential of utilizing wind energy and solar power for the generation of electricity. The Alternative Energy Development Board under its Renewable Energy Policy, 2006 invites independent power producers for investing in the technologies employing renewable energy resources. There has been miscellaneous views of the practitioners and policy makers towards utilizing wind power. Wind power projects appears as a clean source of energy however life cycle assessment enables the resources to be studied in a wider perspective incorporating impacts arising from all stages involved in a project life cycle. This study involves assessment of wind power project for electricity generation in Pakistan with a life cycle perspective using GaBi Education 6.0 as life cycle assessment tool. The impact assessment has been performed by adopting CML problem-oriented approach and 10 environmental indicators have been assessed that incorporated life cycle stages from raw material extraction to operation phase, hence it is a cradle-to-gate study. It has been found that the manufacturing and transportation phase mainly contributes towards environmental impact while the share of construction and operation phase is negligible.

Keywords: Life cycle, wind power, environmental impact, renewable, electricity

ÖZ

PAKİSTAN'DA ELEKTRİK ÜRETİMİ İÇİN RÜZGAR GÜCÜ YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

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Pakistan gelişmekte olan bir ülke ve enerji krizi her zaman ekonomik kalkınmanın önündeki en büyük engel olarak ortaya çıkmıştır. Artan talep ve arz farkının yanı sıra, mevcut enerji karışımının temel olarak çevre ve enerji güvenliği sorunlarına neden olan fosil yakıtlara bağlı olması endişe vericidir. Elektrik üretimi için temiz ve yenilenebilir teknolojilere geçiş çabalarının bir parçası olarak, Ulusal Yenilenebilir Enerji Laboratuvarı, ABD, Pakistan Meteoroloji Bölümü ve Enerji Bakanlığı tarafından yapılan değerlendirmeler, rüzgar ve güneş enerjisini elektrik üretimi kaynağı olarak kullanma potansiyelini ortaya koydu . Yenilenebilir Enerji Politikasına Göre Alternatif Enerji Geliştirme Kurulu, 2006, yenilenebilir enerji teknolojilerine yatırım yapmak için bağımsız güç üreticilerini davet etmektedir. Uygulayıcıların ve politika yapıcıların rüzgar enerjisinden faydalanma konusunda çeşitli görüşleri olmuştur. Rüzgar enerjisi projeleri temiz bir enerji kaynağı olarak görünmekle birlikte, yaşam döngüsü değerlendirmesi, kaynakların bir proje yaşam döngüsünde yer alan tüm aşamalardan kaynaklanan etkileri içeren daha geniş bir perspektifte çalışılmasını sağlar. Bu çalışma, Pakistan'da elektrik üretimi için rüzgar enerjisi projesinin, yaşam döngüsü değerlendirme aracı olarak GaBi Education 6.0 kullanılarak yaşam döngüsü perspektifiyle değerlendirilmesini içermektedir. Etki değerlendirmesi, CML probleme yönelik yaklaşım kullanılarak gerçekleştirildi ve hammadde ekstraksiyonundan operasyon aşamasına kadar yaşam döngüsü aşamalarını kapsayan 10 çevresel gösterge değerlendirildi, bu nedenle beşikten kapıya bir çalışma. İnşaat ve işletme aşamasının payı ihmal edilebilir düzeyde iken imalat ve nakliye safhasının çevresel etkiye esas olarak katkıda bulunduğu tespit edilmiştir.

Anahtar Kelimeler: yaşam döngüsü, rüzgar gücü, çevresel etki, yenilenebilir, electrik

I dedicate my work to my parents and my siblings whose love, affection, trust and prayers have made me who I am. “It is all because of them, and it is all for them.”

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CHAPTER 1

INTRODUCTION

1.1. Rationale

The Islamic Republic of Pakistan is the second biggest country in the region of South Asia and thirty seventh in the world according to the area (CIA n.d.). Pakistan is the fifth most populous nation of the world with more than 200 million inhabitants (PBS 2017) with an annual population growth rate of 2% (World Development Indicators Database 2017). Until 2018, it was the second fastest growing economy among ten most populous countries of the world that ranked as 24th largest country in terms of purchasing power (IMF) and 41st largest in absolute terms (World Development Indicators Database 2017). The economic growth in Pakistan reached its 11-year high value of 5.8 percent during the fiscal year 2018, however it started to decline afterwards. Due to the lack of adjustment policies, the economic crisis is continuously deepening with an increasing account deficit and shrinking foreign reserves. As estimated by IMF, the growth is further expected to decline as low as 1.5 percent by the end of 2019.

Pakistan is one of countries with highest growth rates in the world. The Labour Force Survey 2017-18 conducted by (Pakistan Bureau of Statistics 2018) indicated that workforce comprises of 31.7% of total population of Pakistan which is approximately 65.6 million people. The unemployment rate stood around 5.8% of the workforce. This is approximately 3.8 million people which raises concerns as the Poverty Estimation Committee of Planning Commission of Pakistan estimated that almost 24.3% of population of Pakistan was living under national poverty line in 2015. Ministry of Planning predicted that creation of jobs for the unemployed workforce requires market creation and expansion i.e., attaining annual economic growth of at least 7% which is dependent on growth in power sector (Kafait Ullah 2013).

The economic prosperity and sustainable growth of a country is critically dependent on availability of affordable, reliable and cleaner energy (Qudrat-Ullah 2015). The persisting energy deficit in Pakistan has resulted in severe electricity crisis which raises alarms for projected economic growth and endangers the efforts being made to reduce energy intensification. The electricity crisis in the past decade already contracted the annual growth rate between 3-4% which affected industrial sector and increased unemployment and poverty during that period (Aized et al. 2018; Ishaque 2017; Kafait Ullah 2013; Khan et al. 2015).

With the emerging concept of sustainability, it has been realized that nations must adopt sustainable means of electricity production that ensure development in all the spheres i.e., economy, environment and society (Maxim 2014) with a holistic approach. Many nations are now considering harnessing renewable energy resources as reliable environmental-friendly source of energy. Pakistan due to its geographical location has great potential for utilizing renewable resources for energy production. The availability of almost 800,000 square kilometers of land with a plenty of sunshine, enormous wind and water promises that renewable resources offer long term solution to ongoing energy crisis of Pakistan (Shakeel, Takala, and Shakeel 2016). Government of Pakistan is also determined to increase investment in renewable sector, reduce reliance on imported fuels (NEPRA 2017) and meet national targets set up by (Planning Commission 2018) to achieve Sustainable Development Goals. Of these SDGs, SDG7 refers to “ensuring access to affordable, reliable, sustainable and modern energy to all” which has been classified as Category-I goal which require immediate strategic policy interventions so anticipated outcomes can be shortly realized.

The Federal Government has assigned Alternative Energy Development Board (AEDB), the task for utilizing renewable energy technologies for power generation. For improving energy sector of Pakistan, the primary concern is to meet the national priority SDG indicators developed for SDG7. The targets are planned to be achieved tentatively by 2030 (Planning Commission 2018).

Achievement of the targets planned in national agenda require review of existing energy mix and analyze renewable energy resources with a lifecycle perspective which has never been carried out for Pakistan. The only results are available from (Akber, Thaheem, and Arshad 2017) for sustainability assessment of electricity generation mix of Pakistan during 2015 with a life cycle perspective. Wind sector was quite immature at that time and most of the wind power projects were in planning stage. LCOE determined at that time was 12.71 PKR/kWh which made the authors conclude it as worst option for investment of capital in Pakistan. Recent developments in wind power sector over last four years have completely changed the scenario and require wind sector to be reconsidered with a life cycle perspective as it appears to be a promising solution for ongoing electricity crisis. AEDB is making efforts for the sector to progress and most of the relevant data sets have been made available publicly now.

1.2. Research objectives

In light of the rationale, this research work is aimed at:

i. Conducting LCA of wind power for electricity generation using GaBi Education 6.0
ii. Analyze environmental issues related to resource use and emissions during manufacturing, construction and use phase.
iii. Compare results to available information for other currently utilized power generation sources and propose policy reforms accordingly in the light of results.

1.3. Document structure

This structure of this thesis is as follows:

Chapter 1 (this chapter) is Introduction to the research work conducted including rationale and objectives. The literature review extends over chapter 2 to 4. Chapter 2 provides a brief description of life cycle assessment, chapter 3 discusses evolution of wind power for electricity generation, current status of wind power in the world and components of a wind farm while chapter 4 describes the power generation framework and potential of wind energy for electricity generation in Pakistan. Chapter 5 briefly defines the methodology adopted for this study. Chapter 6 and 7 discusses the goal and scope definition and inventory analysis for this study respectively. Results of impact assessment are provided in chapter 8 while interpretation of results is given in chapter 9. Chapter 10 includes conclusions, policy recommendations and areas of further work.

CHAPTER 2

LIFE CYCLE ASSESSMENT

2.1. Introduction

Life cycle assessment is one of the techniques used to address the environmental aspects and potential environmental impacts throughout a product lifecycle (ISO 2006a). It is also termed as cradle to grave analysis, life cycle analysis, life cycle approach or Eco-balance

Society of Environmental Toxicology and Chemistry (SETAC) defines life cycle assessment as "an objective process to evaluate the environmental burdens associated with a product process or activity by recognizing and quantifying energy and material uses and releases to environment". It helps to evaluate and implement opportunities for environmental improvement hence provide an opportunity for product stewardship at all levels.

There is a consecutive order of stages in the life span of a certain product and distinctively they are divided into three stages: production or manufacturing, use/ operation and disposal/ end-of-life. Manufacturing phase includes raw material extraction and its acquisition for production including handling and processing. The use phase includes operation or utilization of product or product system based on its intended use. The end of life phase may include final disposal or recycling of the product (Menoufi 2011). Each phase utilizes certain amount of materials, resources and energy and creates an impact on natural environment (ecosystem), human health and natural resources in form of emissions and releases.

2.2. ISO standard for Life Cycle Assessment (LCA)

The International Organization for Standardization (ISO) have developed (ISO 2006a; 2006b) standards for practitioners of life cycle assessment that guide through the whole process of life cycle assessment.

These ISO standards only address the environmental aspects and impacts of a product system. Economic and social aspects are typically not included in the scope of LCA. To conduct such extensive assessments, other tools like input-output analysis combined with LCA are used.

2.3. Historical evolution

The first use of life cycle assessment as a method for examining the environmental impacts dates back to late sixties. The first studies conducted using LCA were focused on energy and material use while quantifying emissions and wastes from the product during different life cycle phases (EEA 1997). In 1969, Coca Cola took the initiative to examine the resource consumption and releases to environment from production of beverage containers with a life cycle perspective (CCC 2012). In early seventies, inventory approaches started to develop simultaneously in US and Europe and were called "Resource and Environmental Profile Analysis (REPA)" (Hunt and Franklin 1996) and "Eco-balance" respectively (EEA 1997).

Initially energy use was given more priority than wastes and output. (Boustead and Hancock 1979) published the "Handbook of Industrial Energy Analysis". It was the consolidated manuscript of methodology Ian Boustead adopted in 1972 to calculate total energy utilization for manufacturing various types of beverage containers including steel, glass, plastic and aluminum. LCA studies were extended during 70s, when US and Europe were investigating alternative options to overcome oil crisis.

Until 1980s, the inventory development and interpretation of total associated impacts was not clearly distinct. Until 1988, the oil crisis subsided when solid waste was recognized as a global matter of concern, LCA studies were extended to focus on environmental issues and creating an inventory for inputs of materials and resources. SETAC for the first time redefined LCA by take it to the level of impact assessment, a step ahead to establishing inventory analysis (SETAC n.d.). In early 1990s, LCA had been recognized as an effective tool and there was a growing pressure from environmental practitioners and organizations to devise a standardized framework for conducting life cycle assessment. ISO in collaboration with International Electrotechnical Commission (IEC) and technical bodies worked on the subject and laid forward first set of international standards during 1997 to 2000 which were later repealed in 2006.

In 2002, United Nations Environment Program (UNEP) and SETAC collaborated for a life cycle initiative program. It was an international collaboration launched with the objective to consider practical approaches of life cycle thinking and refining the supporting tools (Curran 2006). Many other similar projects were initiated at the same time. The development led ISO to revise the standard and ISO 14040/44 were published which replaced the previous versions.

Currently, LCA has been widely used as decision support tool in various industrial sectors around the globe. Besides its use for product development and improvement, it is also used for marketing purposes. Schemes like Eco-labelling and Environmental Product Declaration (EPD) is a great tool for marketing product as environmentally safe and friendly.

2.4. General framework

The general framework is illustrated in Figure 2.1 and discussed step-wise in chapter 5. According to ISO 14040/44, there are four steps of conducting a life cycle assessment.

i. Goal and scope definition
ii. Inventory analysis
iii. Impact Assessment
iv. Interpretation

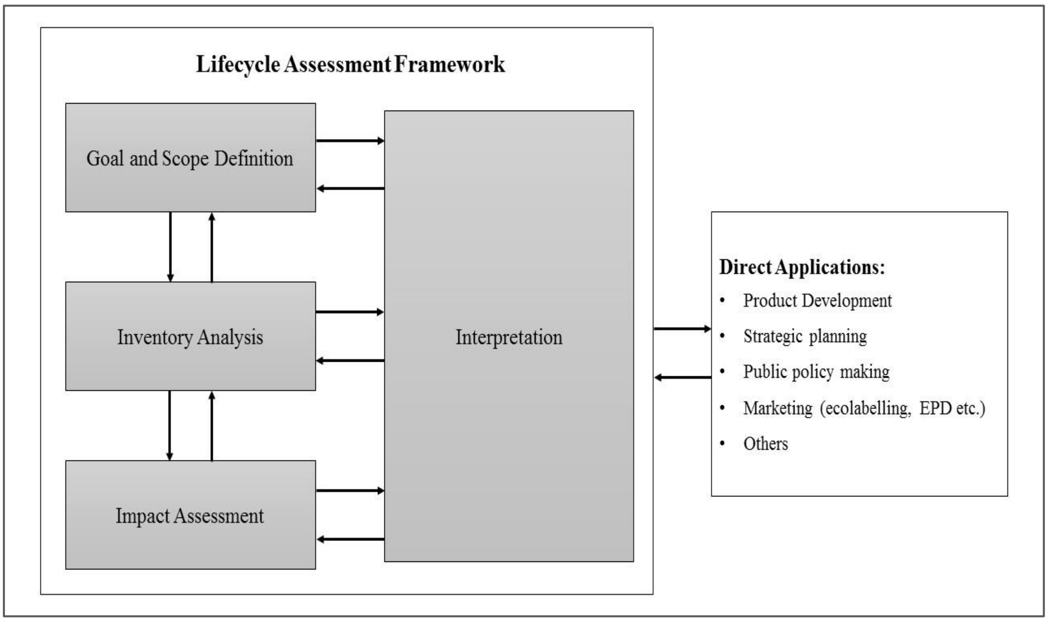

Figure 2.1. LCA framework according to ISO 14040 standard

2.5. Life cycle impact assessment methodologies

The impact assessment phase in life cycle assessment in the most data intensive and critical step. A rigorous amount of data is presented in inventory results which are converted to comprehensible impact indicators within the selected impact categories. Complex environmental models are used for characterization of impact indicators to different impact categories and normalization of impacts. Political, social and ethical factors are considered for weighting (Menoufi 2011).

Two type of main approaches are used for characterization of impacts that form the two school of methodologies:

i. Mid-point approach (Problem oriented methods)
ii. End-point approach (Damage oriented methods)

2.5.1. Mid-point approach (Problem oriented methods)

The cause-effect chain initiate with a specific activity or a process in the mid-point approach. The activity lead to emissions that consequently result in primary changes in environment that could be physical or chemical in nature and often occur early in the chain. The problem-oriented methods employ midpoint approach. They limit the quantitative modelling to the initial stages in the chain and group the results accordingly (Menoufi 2011). Classical example of methods based on this approach include CML 2001, EDIP, TRACI.

2.5.2. End-point approach (Damage oriented methods)

In this approach the cause-effect chain is modelled to the endpoint/ point of damage related to different areas of environmental pollution concerned. Methods based on damage-oriented approach are Eco-indicator 99; EPS; Eco-scarcity (or eco-points) or JEPIX.

The example provided in Figure 2.2 (Jolliet et al. 2003) illustrates the difference between midpoint and endpoint approach.

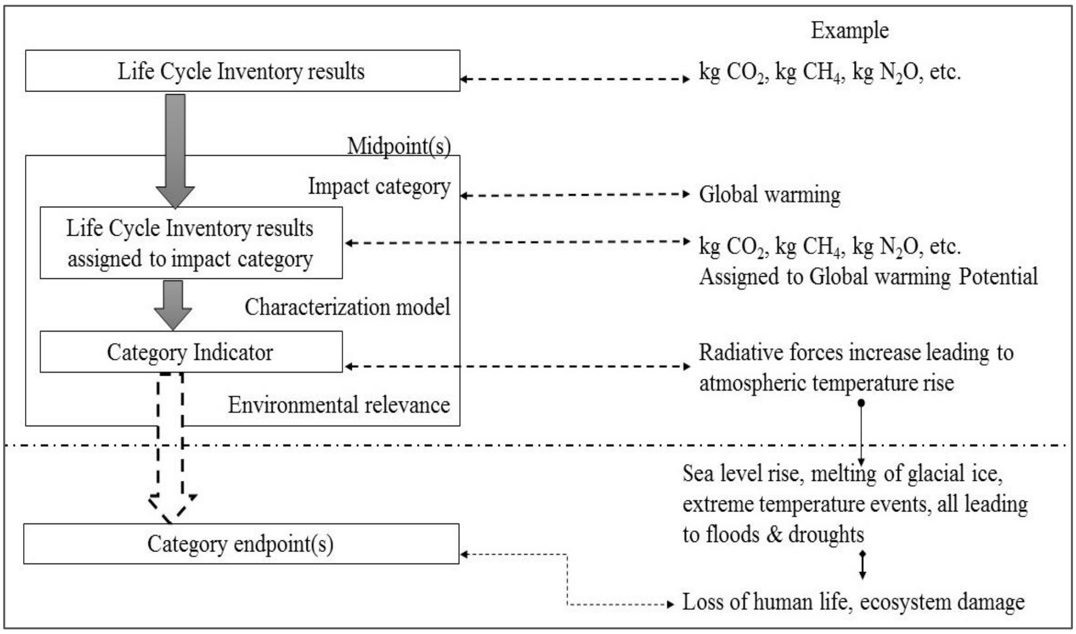

Figure 2.2. Example for difference between midpoint and endpoint approach

2.5.3. Combined midpoint and endpoint approach

Some life cycle impact assessment methods make combined use of midpoint and endpoint approach. These include ReCiPe, LIME, Impact 2002+, LUCAS etc.

2.5.4. Other methodologies

Some of the impact assessment methods are used to assess specific environmental areas or impact categories. *Table 2.1* provides an example of some of these methods.

2.6. Life cycle assessment software tools

There are specific software tools being developed too deal with the LCIA methods. These include but are not limited to Sima Pro by PRé Sustainability, GaBi by Thinkstep, BEES (Building for Environmental and Economic Sustainability) by National Institute of Standards and Technology (NIST), GEMIS by Institute of Applied Ecology. These tools enable the practitioners to conduct LCA effectively and efficiently.

Table 2.1. *Overview of other LCA based methodologies*

Methodology	Impact categories
Method for Evaluation of Energy using products (MEEup)	Energy consumption, water consumption, materials in use, waste and to incinerator), hazardous waste generation, emissions to air
Building for Environmental & Economic Sustainability (BEES)	Global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, smog, ecotoxicity, ozone depletion, and human health.
Ecological footprints	Direct and indirect land occupation; Direct land occupation: cropland, pasture, forest, built-up area and hydropower; Indirect land occupation: nuclear energy, fossil fuels
USEtox	Ecotoxicity
Ecosystem Design Potential (EDP)	Land transformation, land occupation, biodiversity
Intergovernmental Panel on Climate Change (IPCC)	Climate Change

Cumulative Energy Demand (CED)/ Cumulative Exergy Consumption (CExC	Fossil based resources (hard coal, lignite, peat, natural gas, and crude oil), nuclear, renewable resources (biomass, water, wind, solar energy)
Cumulative Exergy Demand (CExD)	Fossil based resources (hard coal, lignite, peat, natural gas, and crude oil), nuclear, renewable resources (biomass, water, wind, solar energy), non-energetic resources (water, wind, solar energy)
Cumulative Exergy Extraction from Natural Environment (CEENE)	Fossil based resources (hard coal, lignite, peat, natural gas, and crude oil), nuclear, renewable resources (biomass, water, wind, solar energy), non-energetic resources (water, wind, solar energy), land use

CHAPTER 3

WIND POWER FOR ELECTRICITY GENERATION

3.1. Evolution

The wind-driven wheels were being used for various purposes like pumping water or grinding flour since first century A.D. The first known use of wind turbine for electricity generation dates back to 1887 in Scotland. The first wind turbine used for electricity generation was invented by Professor James Blyth of Anderson’s College, Glasgow (Sustainnovate 2014). The process of evolution, improvement and perfection continued, and different prototypes were introduced. Most notable contribution came from Professor Charles Brush of Ohio, US and Paul la Cour, a Danish scientist. The contribution of P. Cour are notable in the wind energy sector and he established Society of Wind Electricians in 1903 (Staff 2008; Sustainnovate 2014).

During the last stages of first world war, 25 kW wind turbine generators were widely used in Denmark and the market flourished in Europe after second world war. The Arab Oil Embargo in decade of 1970 proved to be a milestone in terms of wind power when US government started research and development for utilizing wind as energy source. The era between 1980 and 1990 witnessed the first large scale wind energy outbreak in California (Kaldellis and Zafirakis 2011) and over 16,000 turbines of cumulative power (~1.7GW) ranging from 20 to 350 kW were installed . The wind farm installation steadily increased in Europe and market expanded through 80s and 90s and Vestas (a Danish wind turbine manufacturer) sold its 1000th turbine (Sustainnovate 2014). In last twenty years, the development in wind sector have greatly increased and most of the key players are continuous engaged in improving the technology while reducing initial capital cost.

3.2. Current status in the world

A relatively stable renewable energy market was evidenced in the year 2018 with addition of 181GW in installed capacity growing global renewable power capacity to about 2,378GW. This was the fourth consecutive year of addition to global renewable energy installations that surpassed combined addition in fossil fuel and nuclear power installations (REN21 2019).

3.2.1. Market and industry trends in wind power

The wind market experience stability in 2018 with an increase of 51GW from 2017 boosting cumulative wind capacity to 591GW (Figure 3.1). During 2017, there was a record increase in installed capacity of wind power in Europe and India which declined in 2018. There was however a notable increase in several other regions and countries and Asia turned out be largest regional market with addition of 52% in installed capacity.

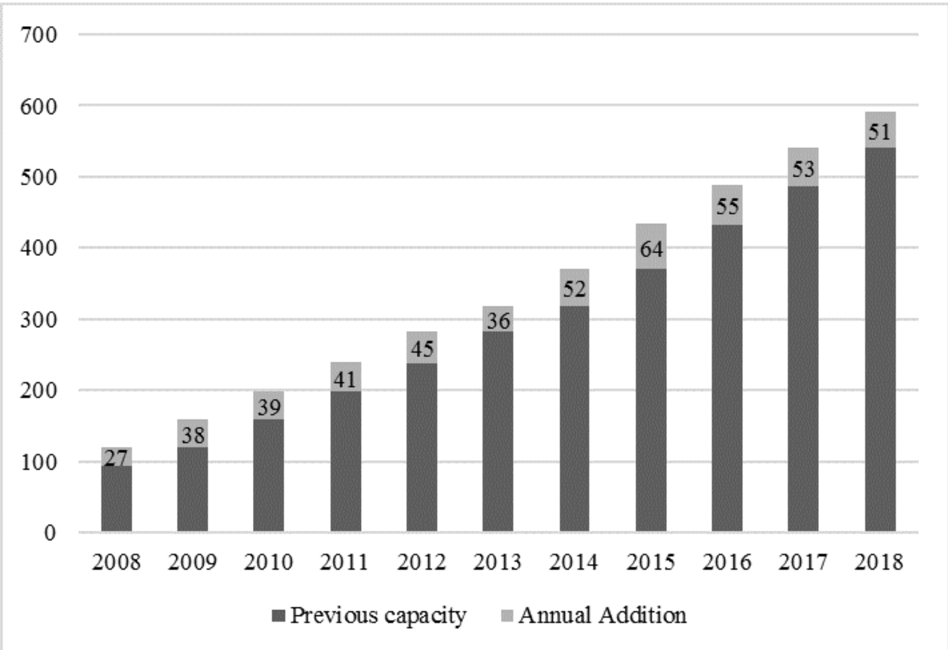

Figure 3.1. Wind power global capacity and annual additions, 2008-2018

China is the leading country with total capacity exceeding 200GW for wind power capacity in 2018. The regime is followed by United States, Germany, India and Brazil.

Other countries in top ten for wind power capacity addition are France, Mexico, Sweden and Canada as shown in while represents the top ten countries by total installed capacity.

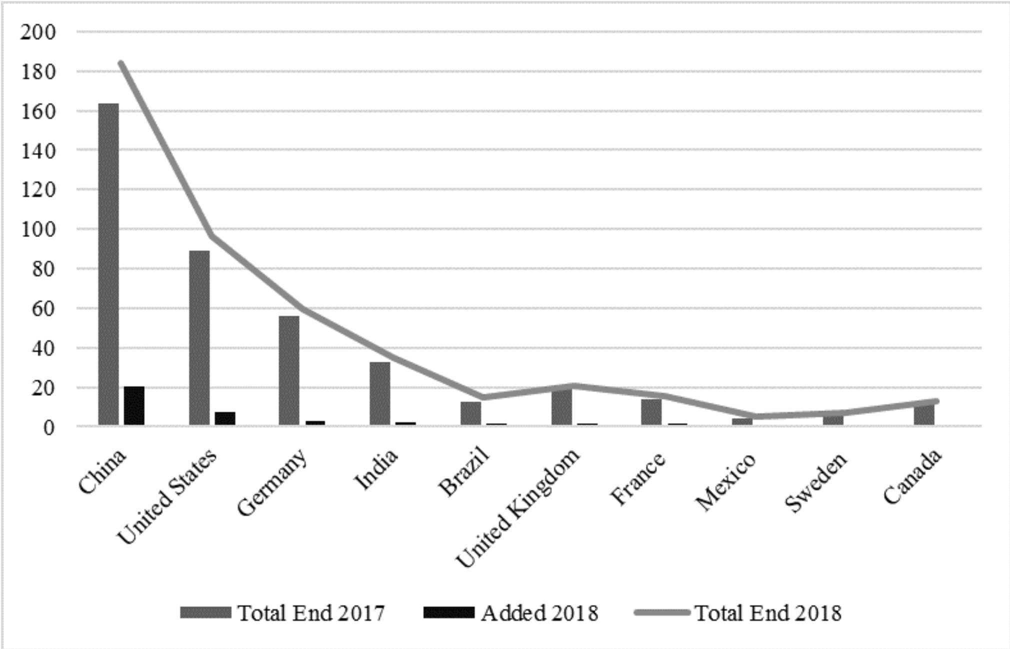

Figure 3.2. Top ten countries of the world by capacity addition in wind power (2017-18)

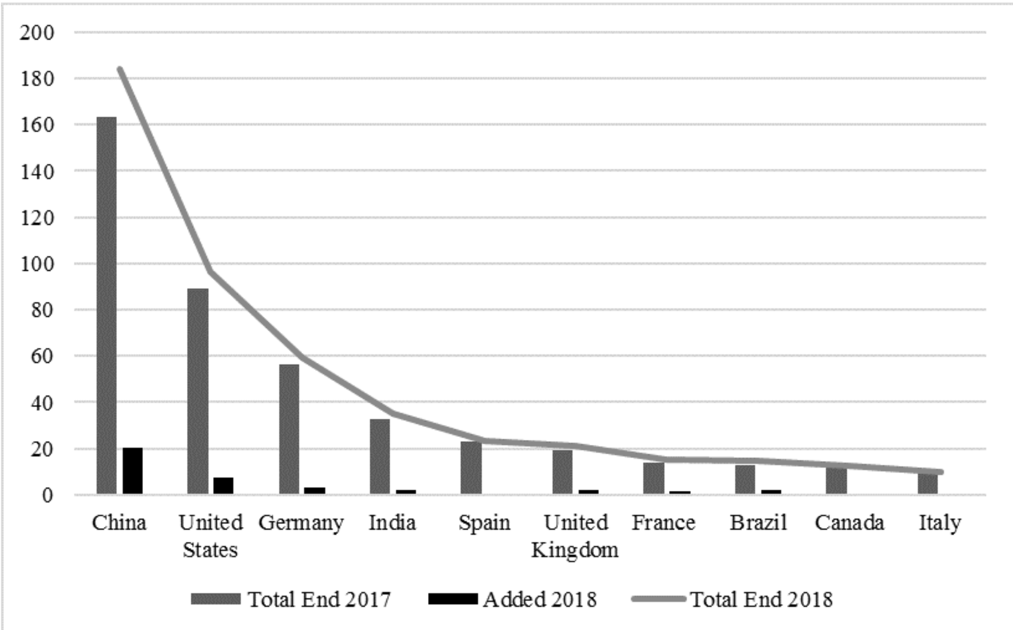

Figure 3.3. Top ten countries of the world by total installed capacity of wind power

This increase in sales is mainly driven by falling prices and global transition from feed-in tariff to more competitive mechanisms like competitive bidding and tenders. This intense price competition squeezes the entire value chain creating challenge for wind turbine manufacturers and developers. To cater these challenges, industry is adopting advanced technology including increase in energy production per turbine, plant efficiency and overall output while reducing levelized cost of electricity from wind energy (REN21 2019). Another driver for increasing investment in wind sector is national targets for reduction in greenhouse gases.

3.2.2. Leading wind turbine manufacturers

There are around thirty-seven (37) manufacturers that delivered turbines to global market during 2018 however top ten manufacturers capture 85 percent of the market share. Of these, two-third turbines are being manufactured and supplied by top-five of these including Vestas (Denmark) contributes one-fifth (20.3%) to the global market. Other top manufacturers are China based Gold wind (13.8%), Siemens Gamesa (Spain) (12.3%), United States based GE Renewable Energy (10%) and China based Envision Energy (8.4%) which is gradually replacing Germany based Enercon (5.5%). (REN21 2019)

Most of these manufacturers are based in China while for others not originating from China have their global production facilities to serve the region by being in the region.

3.3. Components of a wind farm

A typical wind farm comprises of on-site and off-site structures. On-site structures include technical components i.e., wind turbine generators and substation and nontechnical components include site and auxiliary structure (store, security cabins, living quarters). The offsite structures may include access road. This section discusses the technical components of the wind farm.

3.3.1. Wind turbine generator

A typical wind turbine generator is generally composed of 25,000 or more components (Vestas 2015) which are grouped into the main system. These include nacelle, turbine tower, rotor comprising of hub and blade and the internal wiring of the turbine (Gamesa 2013). This section mainly provides information from Gamesa G90-2MW which is considered as base model for this study.

3.3.1.1. Nacelle

Nacelle is the most complicated part of wind turbine which have all of its electrical and mechanical components. These mainly include generator, gear box, shafts, frame, crane system and control system. Many components are not manufactured at Gamesa site instead they are individually purchased from different approved suppliers. For procured parts, final finishing activities are however held at Gamesa site (Gamesa 2013). Major component used in manufacture of nacelle parts is steel, cast iron and copper. The main components of nacelle for Gamesa G90-2MW turbines is illustrated in Figure 3.4.

The housing of the nacelle is made of reinforced fiberglass that protects it from weather effects and extreme environmental conditions. Transformer is mainly composed of steel and aluminum alloys. The gearbox is three-staged with one planetary and two parallel axes and mainly consist of cast iron and steel. Generator is doubly fed asynchronous 4-pole generator and made of steel, cast iron and copper as main components. The generator is highly efficient and is cooled by an air-air exchanger.

3.3.1.2. Rotor

The rotor comprises of three blades attached to the hub through blade bearings as illustrated in Figure 3.5. The blades are made of composite material reinforced with fiberglass and carbon. It provides necessary rigidity without penalizing the weight of the blade. The hub is made of cast iron and steel.

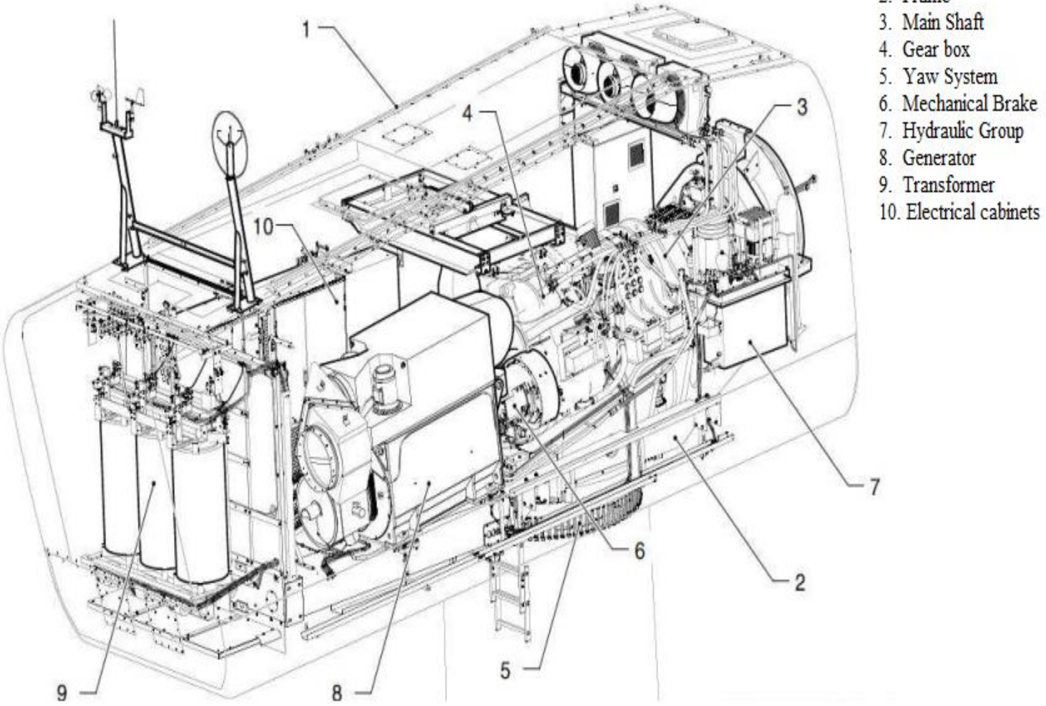

Figure 3.4. Components of nacelle in a wind turbine of Gamesa G90-2MW

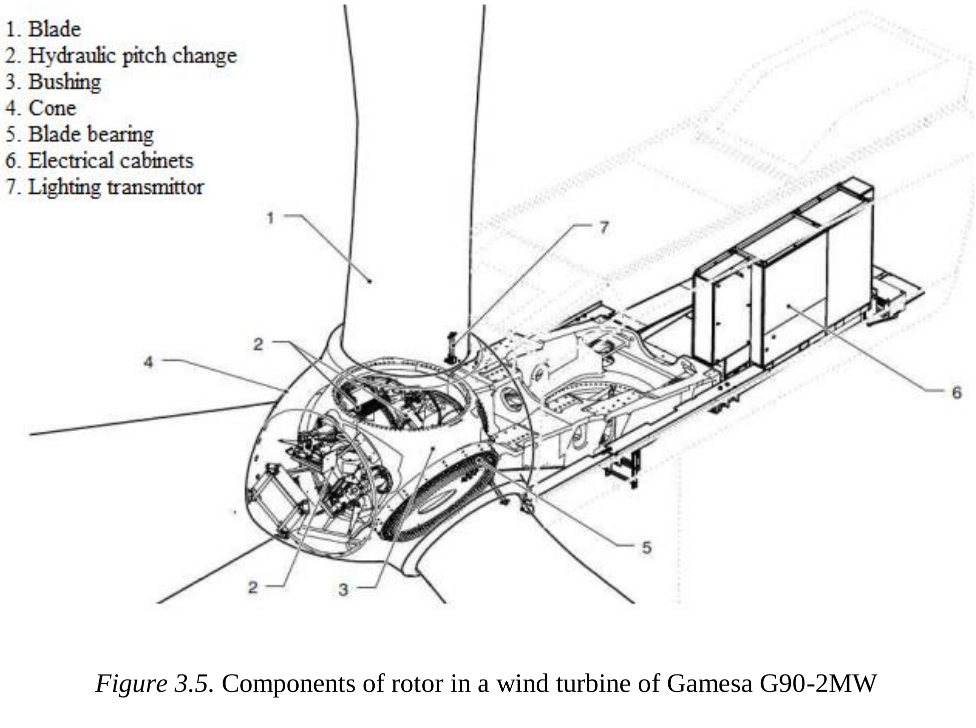

Figure 3.5. Components of rotor in a wind turbine of Gamesa G90-2MW

3.3.1.3. Turbine Tower

The turbine tower forms the major proportion of entire turbine by mass and by size. The conical tubular tower is made of steel and divided into three, four or five sections depending on height of tower. After completing the surface treatment of turbine towers, the internal parts i.e., platforms and ladders are fixed and fixtures for cables are fitted.

3.3.2. Foundation

The standard foundation is made of reinforced concrete slabs with steel. The compositions depend on the size, load and weight of the turbine to be mounted and ground stability conditions as well as depth of the water table. Usually, geological site survey is conducted along with wind data assessment for a site to select the most appropriate foundation.

3.3.3. Cables and wiring

The cables are mainly composed of aluminum alloys, copper and polymers

3.3.4. Access road

An access road is required to provide access between the turbines mostly in remote areas. Depending on the plant location, an access road can be a combination of tarred and dirt track.

CHAPTER 4

ELECTRICITY GENERATION IN PAKISTAN AND POTENTIAL OF WIND POWER SECTOR

4.1. Power generation framework in Pakistan

Following the independence of Pakistan in 1947, the power generation sector was one of the major value chain sectors that required effective management. The only power generation setup existing at that time was Karachi Electric Supply Corporation (KESC) that was established in 1913 during the British Rule. In 1958, major value chains of the country were concentrated into a single public entity called Water and Power Development Authority (WAPDA) which was responsible for generation, transmission and distribution of power in addition to drainage, irrigation and flood control. For next three decades, WAPDA and KESC served as two vertically integrated public entities for power generation where WAPDA covered whole Pakistan except Karachi that was served by KESC. The decade of 60s marked construction of major dams in Pakistan and 65% of power generation was covered by hydel energy until the last decade of the century. Pakistan Atomic Energy Commission (PAEC) entered the market as another key player in 1970s with the commissioning of first set up called Karachi Nuclear Power Plant (KANUPP) in Karachi in 1971 (World Nuclear Association n.d.).

The decade of 1990 evidenced major restructuring in the electricity sector when WAPDA was unwinded by separating fundamentally monopolistic segments from controllable market competitive segments. The dissociation of WAPDA resulted in formation of four generation companies (GENCOs), nine distribution companies (DISCOs) and one transmission company however the whole infrastructure remained heavily under public monopoly. Another agency, Pakistan Electric Power Company

(PEPCO) was formed to maintain effective coordination mechanisms between these unwinded entities and strengthen the overall organizational set up. PEPCO is regulated by National Electric Power Regulatory Authority (NEPRA) established under (*Regulation of Generation Transmission and Distribution of Electric Power Act* 1997). Through the powers conferred under this regulation and its further amendments, NEPRA issues the licenses for electricity generation and determines tariffs for different licensees. Electricity generation was opened for market competition however other sectors i.e., distribution and transmission continued to be under monopoly however separated from WAPDA as independent publicly owned companies. KESC was transferred to private sector without any disaggregation and now known as K-Electric (KEL) responsible for generation, transmission and distribution of electricity for Karachi, the economic hub and largest city of Pakistan. Private Power Infrastructure Board (PPIB) oversees matters related to private sector.

Under this restructuring, private sector poured into generation sector (M. Baloch et al. 2017) however, they were mainly attracted towards thermal sources based on imported fuels. Hydel power projects were also opened for investment by private Independent Power Producers (IPPs), but they did not gain much attention despite lucrative incentives being offered and therefore the sector remained dependent on public finances. Thermal power has now surpassed production from other sources in current energy mix because of the independent power producers. The ratio of hydel to thermal electricity generation that was originally 67% to 33% back in 1985 has become 30% to 65% in last two decades. This scenario has not only resulted in increasing account deficit (NEPRA 2017) but with the increasing demand and supply gap due to continuous population growth and industrialization (Asif 2009). Pakistan is also subject to circular debts due to increased use of imported fuels, system losses and seasonal reduction in generation from hydropower. Even though, currently maximum installed capacity in Pakistan is greater than peak demand but it is still insufficient due to unreliability of supply structure. Transmission and distribution losses further worsen the situation specially during hot climates.

4.2. Status of electricity production in Pakistan

The current electricity generation in Pakistan is a mix of thermal, hydro, nuclear and renewable energy, almost two-third of which relies on fossil fuels. The State of Industry reports (NEPRA 2017) indicated that total generation of electricity in Pakistan was 120,621 GWh as of June 30, 2017 of which 65.34% i.e., 78,818 GWh was produced by thermal power plants. Electricity generation from different energy sources in Pakistan during the year 2017 is illustrated in Figure 4.1. It depicts that besides thermal sources, 30,279 GWh was produced by hydel power and 6,278 GWh was produced by nuclear power plants. The contribution of renewables including wind, solar and bagasse was limited to 2.45% i.e., only 2,950 GWh was produced by harnessing freely available renewable resources while a very small proportion 496 GWh was imported from Iran. It is interesting to note that since year 2016, maximum installed capacity has surpassed maximum (peak) demand in June 2016. The maximum installed capacity for electricity generation in Pakistan was 25,421 MW while peak demand was recorded at 23, 286 MW reported on June 30, 2016. although there was a surplus of 2,135 MW, the demand and supply gap could not be reduced specially in summers when demand increased due to soaring temperatures. This resulted in power outages of six to eight hours and longer power cuts in low-recovery and high-loss areas. A major reason of this shortfall are the losses during transmission and distribution of electricity. Unfortunately, there was no improvement recorded in terms of T&D losses as they remained fluctuating between 17% to 19% over 2015 to 2017. The increasing shortfall existed in 2017 despite an increase of 2,978 MW in fiscal years (FY) 2016-17. The total installed capacity of Pakistan was recorded 28,339 MW on June 30, 2017 against the 25,421 MW recorded in 2016. Source wise installed generation capacity during 2017 is illustrated in Figure 4.2. Table *4.1* presents a comparison of source wise installed generation capacity (MW) and generation (GWh) of electricity by type during FY 2015-16 and 2016-17.

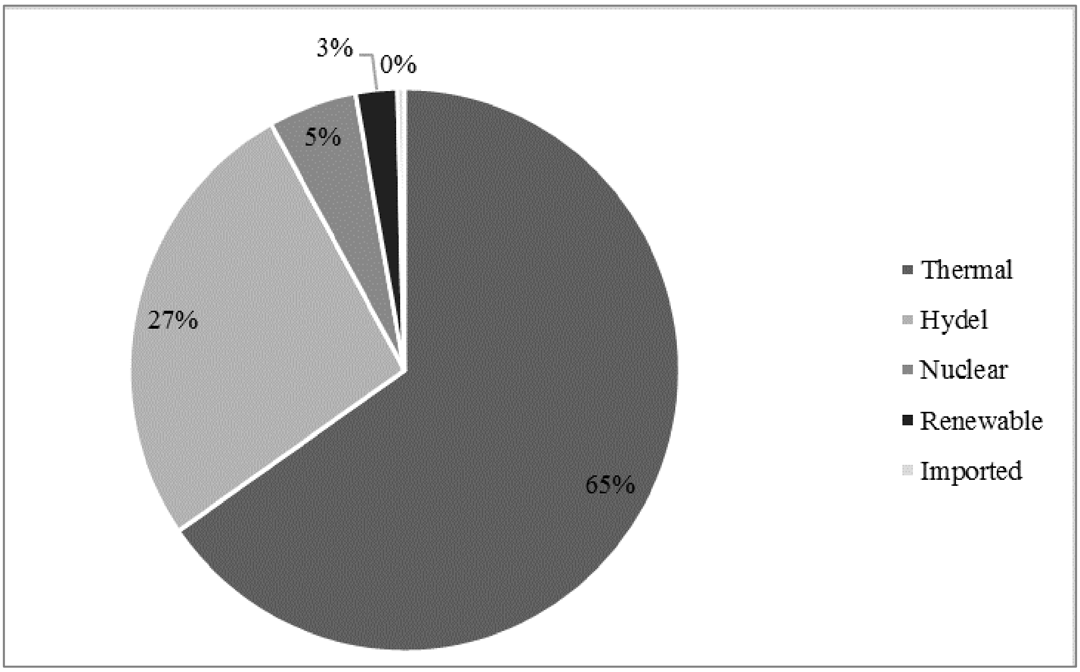

Figure 4.1. Total electricity generation mix in Pakistan during 2017

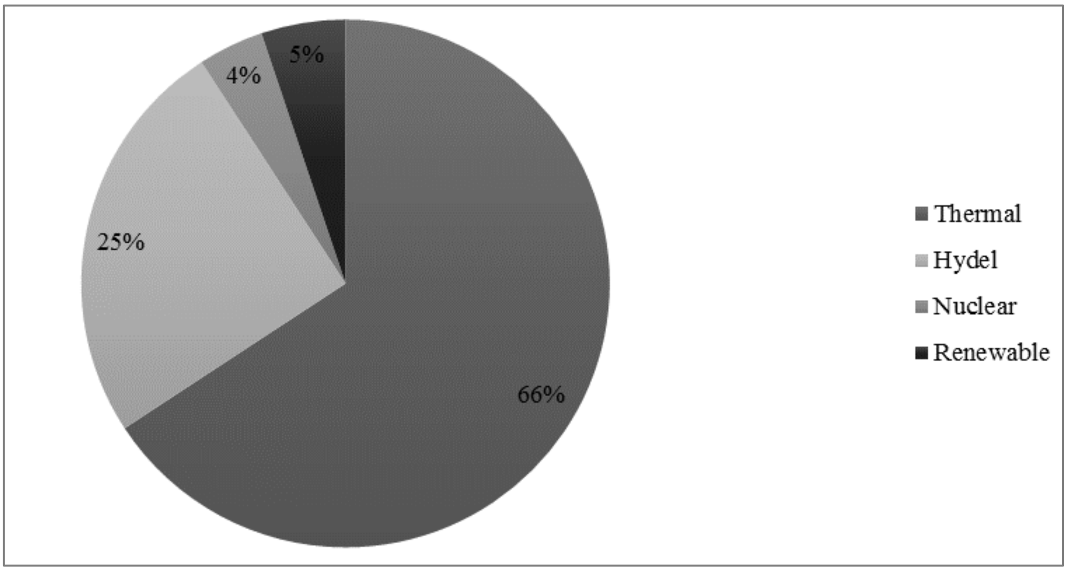

Figure 4.2. Proportion of source-wise installed electricity generation capacity in Pakistan for FY2016-17

Table 4.1. *Source wise installed capacity and electricity generation by during FY2015-16 and FY2017-18 in Pakistan*[1]

Fiscal year closing June 30	*Installed capacity by type (MW)*				*Generation by Type (MW)*			
	2016	2017	Variation Cap.	Variation %	2016	2017	Variation Cap.	Variation %
Hydel								
-*WAPDA*	6902	6902	-	-	33,433	31,091	(2,342)[2]	(7)
-*IPPs*	214	214	-	-	1,121	988	(133)	(11.86)
Thermal[3]								
-*PEPCO*								
◆GENCOs	5,897	5,897	-	-	16,392	18,710	2,318	14.14
◆IPPs	8,643	10,566	1,923	22.25	45,146	47,972	2,826	6.26
◆CPPs/SPPs[4]	-	-	-	-	251	271	20	7.97
-*KEL*								
◆KEL own	1,874	1,874	-	-	10,323	10,147	(176)	(1.7)
◆IPPs	252	252	-	-	1,421	1,531	110	7.74
◆CPPs/SPPs	35	87	52	148.6	139	187	48	34.53
Nuclear								
-*CHASNUPP (I, II & III)*[5]	615	1,005	390	63.41	3,854	5,868	2,014	52.26
-*KANUPP*	137	137	-	-	362	410	48	13.26
Renewables	852	1,465	613	71.94	1,187	2,950	1,763	148.53
Import from Iran	-	-	-	-	463	496	33	7.13
Total	25,421	28,399	2,978	11.71	114,093	120,621	6,528	5.72

[1] Data Sources: Official reports of National Transmission and Dispatch Center (NTDC) and K-Electric Limited (KEL)
[2] () = Decrease in generation during FY 2017 as compared to FY2016
[3] PEPCO and KEL are vertically integrated electric supply companies
[4] CPP-Captive Power Plant; SPP-Small Power Producer
[5] Chashma Nuclear Power Complex (CHASNUPP) is group of four operating (Chashma-I, II, III, IV) power plants while Chashma-V is under construction. Chashma-IV with an installed capacity of 340 MW started operating in June 2017 so data for its electricity generation is currently not available publicly.

The ongoing energy crisis have urged scientists and economists towards exploring indigenous alternative resources for electricity generation and renewable resources have gained increasing attention as a resolve to global warming and climate change issues. One of these resources include wind energy which is environmentally responsible during operations and do not release any direct emission while utilizing little energy. Majority of the environmental impacts of wind power plant result from manufacture, transportation and construction processes (Haapala and Prempreeda 2014). Following the establishment of AEDB in 2003, National Renewable Energy Laboratory (NREL), World Bank, United States Agency for Industrial Development (USAID) and Pakistan Meteorological Department (PMD) have collaborated to identify wind and solar resource potential for Pakistan and developed wind atlas and wind classification map of Pakistan. The analysis of satellite data collected over a period of ten (10) years from 2000 to 2010 and ground conditions indicated good wind regime in the country (Ministry of Energy n.d.).

4.3. Alternative Energy Development Board (AEDB)

Alternative Energy Development Board (AEDB) was established in May 2003 by the federal government for alternative energy development. The mission of AEDB was to "Introduce Alternative and Renewable Energies (AREs) at an accelerated rate" and it had the objective to "facilitate, promote and encourage development of Renewable Energy in Pakistan." In 2006, Ministry of Water and Power took over the administrative control of AEDB (Ministry of Energy n.d.).

The Government of Pakistan has assigned AEDB the responsibility to take following measures in the field of Alternative and Renewable Energies (AREs):

- Implement policies, programs and projects through private sector;
- Achieve sustainable economic growth through assistance and facilitate development and generation of ARE;
- Encourage transfer of technology and develop indigenous manufacturing base;

- Promote provision of ARE based energy services; and
- Undertake ARE projects on commercial scale (Government of Pakistan 2010)

4.4. Renewable energy policy

The Policy for Development of Renewable Energy for Power Generation (Government of Pakistan 2006) was the first policy developed by the Ministry of Water and Power to promote renewable energy projects in Pakistan. The policy envisaged in 2006 comprised of three phases: short, medium and long term. The short-term policy comprised of the period up to June 2008 proposed very liberal and attractive incentives to attract investors to put Pakistan on the renewable energy map of the world. It was considered that policy measures for the next phases would be consolidated based on experiences gained in the short-term. Elements of competition were also anticipated to be introduced. The policy objectives included:

- increasing the deployment of renewable energy technologies;
- promote private sector investment in RETs through incentives;
- introduction of finance mobilization measures;
- facilitate the development of a domestic RET manufacturing industry;
- increase per capita energy consumption and social welfare, especially in remote and rural areas; and
- promote environmental protection and awareness.

The key features of the policy included:

- Under this policy, private investors were invited to submit proposals in the following categories:
    - for selling power to the grid exclusively (IPP projects)
    - for self-use and sale to the utility, if desired (captive power projects)
    - for small-scale standalone projects (isolated grid power projects)

- Letters of Intent (LOI), Letters of Support (LOS) and Implementation Agreements (IA) with the government are not required for all non-IPP projects;
- Surplus electricity can be sold to the grid and electricity can be drawn as required (known as net metering and billing);
- Producers can inject electricity at one point on the grid and receive an equivalent amount at another location upon paying a wheeling charge (accounting for transmission charges).
- There are no customs or sales taxes on equipment.
- There are no income taxes.
- IPP projects may obtain carbon credits.
- IPPs are protected against resource variability (e.g. variable wind speeds or water flows); this risk is borne by the power purchaser.
- It is mandatory for power distribution utilities to purchase all power offered by renewable energy projects.

This policy provided a base for Independent Power Producers (IPP) interested in investing in wind sector to attain licenses for power generation from NEPRA.

4.4.1. Methods for determination of tariff

To encourage participation of IPPs in renewable energy, government signs the Energy Purchase Agreement (EPA) and Implementation Agreement (IA) with the IPP that defines direct contractual obligations between the government and IPP including the guarantee for power purchase (Ministry of Energy n.d.). there are three modes of tariff determination for renewable energy projects owned by IPPs:

i. Upfront tariff where government determines and announces the tariff based on its assessments and proponent may accept it based on their viability. It does not necessarily cover the whole project cost.
ii. Cost plus tariff where IPP is paid the actual project cost plus an agreed profit;

iii. Competitive bidding (this has not initiated in Pakistan yet)

Earlier the upfront tariff regime was practiced however to attract investors and increase generation by wind energy, government has moved the tariff regime to cost-plus while offering lucrative incentives to the investors.

4.5. Wind power potential in Pakistan

Pakistan has massive potential for utilizing wind energy as a clean and renewable energy supply source. A survey was conducted by PMD and Ministry of Science and Technology, Pakistan in 2002 to assess the wind power potential along coastal belt of Pakistan. It reported that potential exists along the coastal areas in Sindh and Baluchistan (Hashmi, Malik, and Yousuf 2007) with good to excellent wind resource at 50 m height (Elliott 2011). The wind speed along costal belt of Sindh varies between 5-12 m/s and a generation output of up to 20GW.

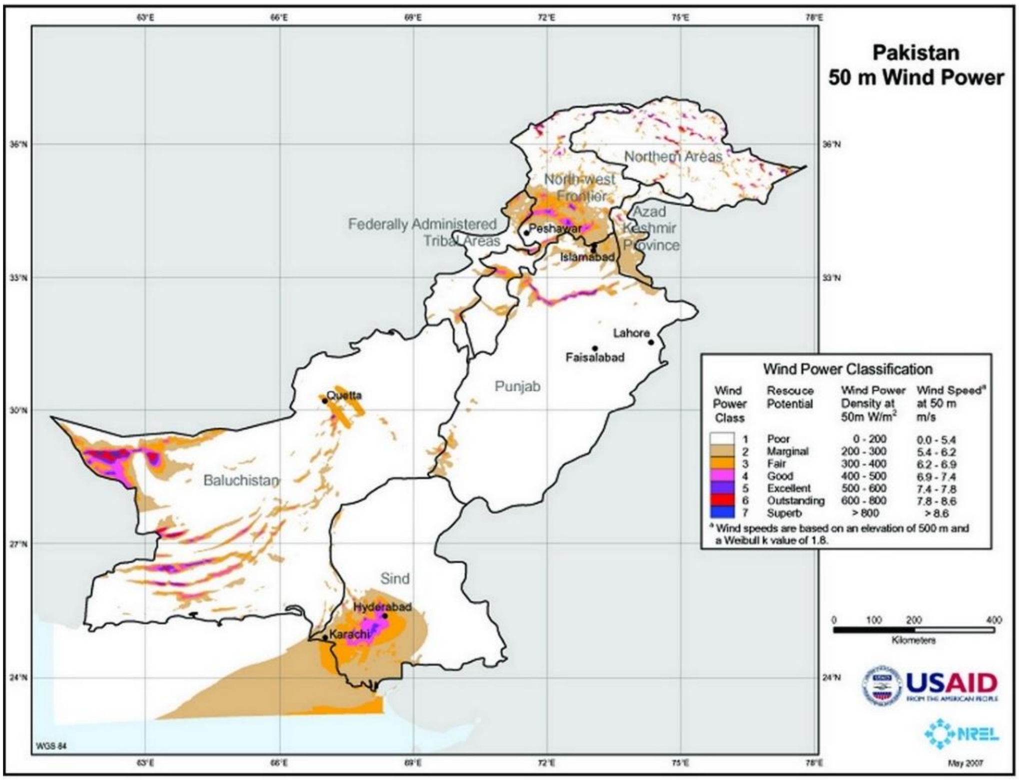

Figure 4.3. Wind Classification Map of Pakistan (Source: AEDB)

The report published by National Renewable Energy Laboratory, USA published the wind classification map of Pakistan and mentioned that Pakistan has the generation potential of around 346GW by utilizing wind energy.

4.6. Current status of wind power

The Alternative Energy Development Board has identified a number of sites in Pakistan however Gharo-Jhimpir-Keti Bandar area located along the Sindh shore received widespread attention (M. H. Baloch, Kaloi, and Memon 2016; M. Baloch et al. 2017; Siddique and Wazir 2016). Licenses have been issued to independent power producers and as many as twenty-six (26) projects with a cumulative installed capacity of 1335 MW are operational in Gharo and Jhimpir region. Moreover, seventeen (17) projects with a total capacity of 824 MW are in different stages of development and will start operation between 2020 to 2022 (Ministry of Energy n.d.; NEPRA 2017). The wind power projects are mainly installed in two clusters in this corridor i.e., Jhimpir cluster and Gharo-Bhambore cluster. There are five projects in Gharo-Bhambore cluster (Figure 4.4) and all of them are in operational stage. For Jhimpir cluster Figure 4.5, currently there are twenty-one projects in operational stage while fifteen of them are in LOI or construction stage. The project information for projects in Gharo cluster is provided in *Table 4.2*. The information of projects that have achieved COD and are operational in Jhimpir is provided in *Table 4.3*while of projects in LOI stage or under construction is given in *Table 4.4*. Besides Gahro and Jhimpir cluster, it is under consideration to expand wind power projects to Gujjo and Son Walhar sub-districts.

The key players in wind energy sector in Pakistan are Gold Wind (USA), GE (China) and Gamesa. Other manufacturers supplying wind turbines in Pakistan include Vestas, Nordex, Aviconna and Ming Yang. The market competition is enhancing as the proponents prefer supplier with effective price, high generation and capacity factor for the wind class.

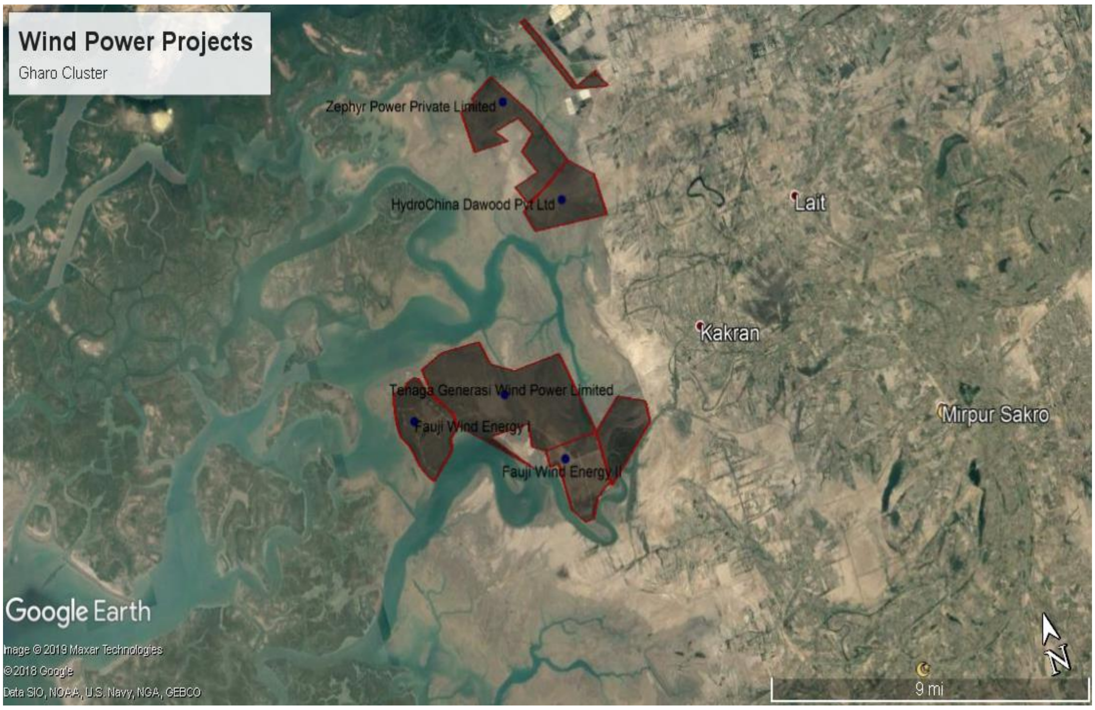

Figure 4.4. Wind Power Projects in Gharo-Bhambore cluster

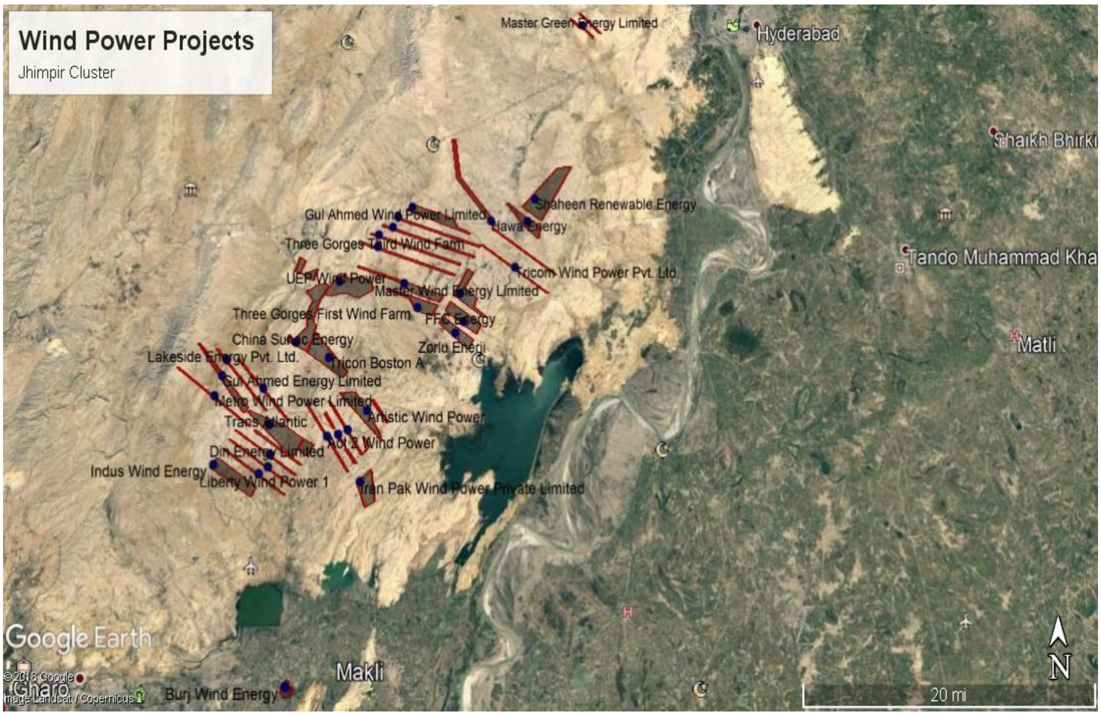

Figure 4.5. Wind Power projects in Jhimpir cluster

Table 4.2. *Projects operating in Gharo cluster, Sindh, Pakistan*

Name of Project	Capacity (MW)	Tariff type	Turbine manufacturer	Total WTGs	COD
Foundation Wind Energy-I Limited	50	Cost plus	Nordex N-100/2.5	20	April 11, 2015
Foundation Wind Energy-II (Pvt.) Limited	50	Cost plus	Nordex N-100/2.5	20	December 10, 2014
Tenaga Generasi Wind Power Limited	49.5	Upfront	GE 82.5/1.6	31	October 11, 2016
HydroChina Dawood Private Limited	49.5	Upfront	Type-3 Ming Yang 82/1.5	33	April 4, 2017
Zephyr Power (Pvt.) Limited	50	Upfront	Siemens Gamesa G114/2.0	25	May 10, 2017

Table 4.3. *Projects operating in Jhimpir cluster, Sindh, Pakistan*[6]

Name of Project	Capacity	Tariff type	Turbine manufacturer	Total WTGs	COD
FFC Energy Limited	49.5	Cost plus	Nordex S77/1.5	33	May 16, 2013
Zorlu Enerji Pakistan (Pvt.) Limited	56.4	Cost plus	Vestas V90/1.8 & Vensys 62/1.2	28+5	July 26, 2013
Three Gorges Pakistan First Wind Farm (Pvt.) Limited	49.5	Cost plus	Gold wind GW-77/1.5	33	November 25, 2014
Sapphire Wind Power Company Limited	52.8	Upfront	GE-82.5/1.6	33	November 22, 2015
Metro Power Company Limited	50	Cost plus	Nordex N-100/2.5	20	September 16, 2016
Younus Energy Limited	50	Upfront	Nordex N-100/2.5	20	September 16, 2016
Master Wind Energy Pvt. Limited	52.8	Upfront	GE-82.5/1.6xle	33	October 14, 2016
Act Wind (Pvt.) Ltd.	30	Upfront	Gold wind GW-82/2.5	12	October 8, 2016
Gul Ahmed Wind Power Ltd	50	Upfront	Nordex N-100/2.5	20	October 18, 2016
Sachal Energy Development Pvt. Limited	49.5	Cost plus	Gold wind GW-77/1.5	33	April 11, 2017
UEP Wind Power Pvt. Limited	99	Upfront	Gold wind GW-82/1.5	66	June 16, 2017
Jhimpir Wind Power Limited	46.735	Upfront	GE 103/1.715	29	March 16, 2018
Hawa Energy Pvt. Limited	46.735	Upfront	GE 103/1.715	29	March 15, 2018
Hartford Alternative Energy Pvt. Limited	46.735	Upfront	GE 103/1.715	29	March 16, 2018
Three Gorges Pakistan Second Wind Farm Pakistan Limited	49.5	Upfront	Gold wind GW-77/1.5	33	June 20, 2018

[6] Data Source: AEDB, NEPRA

Table 4.3. (continued)

Three Gorges Pakistan Third Wind Farm Pakistan (Pvt.) Limited	49.5	Upfront	Gold wind GW-82/1.5	33	June 9, 2018
Tricon Boston Consulting Corporation Pvt. Limited – A	46.735	Upfront	GE 103/1.715	29	August 16, 2018
Tricon Boston Consulting Corporation Pvt. Limited – B	46.735	Upfront	GE 103/1.715	29	September 14, 2018
Tricon Boston Consulting Corporation Pvt. Limited – C	46.735	Upfront	GE 103/1.715	29	September 11, 2018
Artistic Wind Power Private Limited	49.3	Cost plus	GE 103/1.7	29	May 2018

Table 4.4. *Projects in LOI/construction stage in Jhimpir cluster, Sindh, Pakistan*

Name of Project	Capacity	Tariff type	Turbine manufacturer	Total WTGs	Expected COD
Act2 Wind (Pvt.) Ltd.	50	Cost plus	Gold Wind GW-121/2.5	20	December 31, 2019
Western Energy Pvt. Ltd	50	Cost plus	N/A	N/A	N/A
Trans-Atlantic Energy Pvt. Ltd	50	Cost plus	Vestas V-126/3.45	14	July 31, 2019
Shaheen Renewable Energy - 1 Pvt. Ltd	51	Cost plus	Acciona AW 123/3	17	September 30, 2020
China Sunec Energy (Pvt.) Ltd.	49.5	N/A	Gold wind GW-77/1.5	33	N/A
Master Green Energy Limited	50	Cost plus	Gamesa G114/2.0	25	September 30, 2019
Din Energy Limited	50	Cost plus	Gamesa G114/2.0	25	October 31, 2019
Gul Ahmed Electric Ltd	50	Cost plus	Gold Wind GW-121/2.5	20	December 31, 2019
Indus Wind Energy Limited	50	N/A	Gamesa G114/2.0	25	October 31, 2019
Lakeside Energy (Pvt.) Ltd.	50	Cost plus	Gamesa G114/2.0	25	March 31, 2020
Nasda Green Energy (Pvt.) Ltd.	50	Cost plus	Gamesa G114/2.0	25	October 31, 2019
Liberty Wind Power 2 (Pvt.) Ltd.	50	Cost plus	Gamesa G114/2.0	25	July 31, 2019
Metro Wind Power Limited	60	Cost plus	Gamesa G114/2.0	25	January 3, 2020
Norinco International Thatta Power (Pvt.) Limited	50	N/A	Gold Wind GW-121/2.5	20	December 31, 2019
Tricom Wind Power (Pvt.) Limited	50	Cost plus	Gamesa G114/2.0	25	June 30, 2020
Liberty Wind Power 1 (Pvt.) Ltd.	50	Cost plus	Gamesa G114/2.0	25	October 31, 2019
Iran-Pak Wind Power Private Limited	50	N/A	Gamesa G114/2.0	25	December 31, 2021

CHAPTER 5

METHODOLOGY

5.1. Introduction

This study has been conducted according to methodology prescribed for life cycle assessment in (ISO 2006a; 2006b) illustrated in Figure 5.1 using GaBi Sustainability Software (Education license).

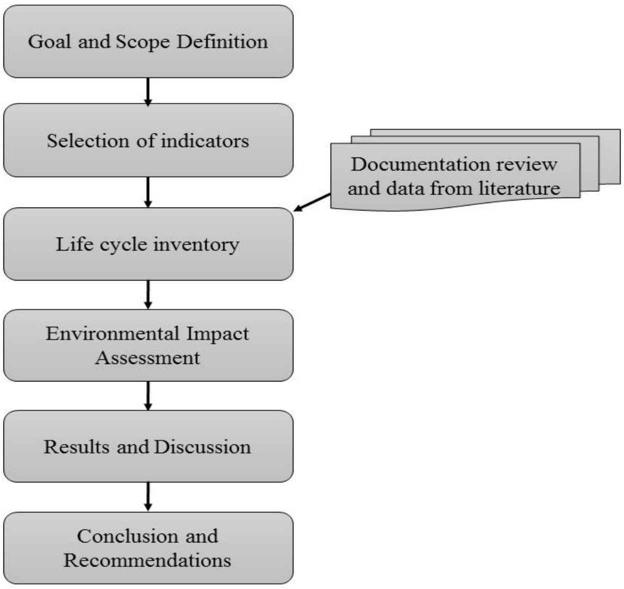

Figure 5.1. Research methodology adopted for the study

5.2. Goal and scope definition

5.2.1. Goal definition

This includes a statement of purpose and intended application of the study including intended audience. It is also defined in goal definition if the results are intended to be used for comparative analysis.

5.2.2. Scope definition

Following items are considered and described in the scope definition:

- Function of the product or the demand product/ system under study have to fulfill;
- Functional unit i.e., quantified definition of the function of the product;
- Reference flow, the measure of product components and materials needed to fulfill the function;
- System boundaries by defining if the assessment is cradle to grave, cradle to gate, gate to gate or gate to grave;
- Cut-off criteria defining materials included and excluded from the system;
- Allocation procedures if more than one product is produced from the system;
- Data assumptions where real time data is not available;
- Limitations of the study;
- Data quality requirements to assess documentation and assessment quality;
- Impact categories and the impact assessment methods used for the study;
- Interpretation of the results of the study;
- Peer review (if applicable)

5.3. Inventory analysis

In this phase, inputs and outputs for a single process or a product system are quantified and compiled for all life cycle phases. Data is collected and compiled in form of Life Cycle Inventory (LCI) tables. This step is the most work intensive, data intensive and time consuming among all phases of LCIA.

The LCI is calculated by using GaBi software for this study as GaBi automatically generates the LCI of the system once system of processes is developed (PE, 2013). The basic processes have been adopted from processes already adopted in the database.

5.4. Life cycle assessment

This step involved identification and evaluation of potential environmental impacts arising from the LCA. Different methods for life cycle assessment are discussed in section 2.5. The methodology adopted for this study is CML 2001 developed by Centre for Environmental Studies, University of Leiden. This method deals with identification of various environmental impact categories expressed in terms of emissions/ releases to the environment. The choice of these impact assessment methods depends on the goal of the study. It is followed by classification and characterization of impact as mandatory steps and normalization, grouping and weighing as optional steps.

5.4.1. Classification

The results of life cycle inventory analysis include different emissions. Following the selection of relevant impact categories, the LCI results are assigned to one or more impact categories. When a substance contributes to more than one impact category, it is classified to all relevant categories. For example: both carbon dioxide and methane are greenhouse gases and are assigned the category of global warming potential, similarly nitrogen oxides contribute both to acidification and eutrophication hence assigned to both the categories.

5.4.2. Characterization

This step is performed to describe and quantify the environmental impacts of the study. The characterization is conducted to convert the results of life cycle inventory into reference units using the characterization factors which are included in the selected impact assessment methods i.e., CML for this study.

For example, SO_2 is the reference substance for impact category acidification potential and the reference unit is kg SO_2-equivalent. All emissions that contribute to acidification potential are kg SO_2-equivalent by multiplying with the characterization factor of the emission.

5.5. Interpretation

In this phase, results are evaluated to check their consistency with the goal and scope defined and completion of the study. This step is an iterative procedure and it includes identification of significant issues and evaluation of the data quality and results. The significant issues can be expressed in terms of:

- Inventory results like major flows of material and energy, wastes and emissions etc.
- Impact category indicators of special interest; and
- Contribution of individual processes to overall impact.

5.6. Conclusion and recommendation

The objective of interpretation phase is to draw conclusions, identify limitations and provide recommendations based on:

- Identified significant issues;
- Evaluation of methodology and results for consistency and completeness;
- Primary conclusions and their consistency with goal and scope definition.

CHAPTER 6

GOAL AND SCOPE DEFINITION

6.1. Goal definition

The goal of this life cycle assessment is to analyze the environmental impacts associated with production of electricity from a 50MW onshore wind power project in Gharo-Jhimpir Wind Corridor of Pakistan. The assessment considers manufacturing of components, transportation, construction and use phase for the wind farm comprised of 25 Wind Turbine Generators (WTGs). The 50MW plant represents the typical size of wind farms installed in Pakistan. Gamesa, Gold Wind and General Electric are the three top wind turbine suppliers operating in Pakistan. Based on the data available for wind farms installed in Pakistan, Gamesa G90-2MW WTGs are considered for this study. This study does not intend to make any comparative assessments between the turbines or various methods of electricity generation. the intended audience for this study includes general population of Pakistan (particularly grid connected consumers), policy makers, institutional and non-institutional stakeholders associated with electricity generation sector.

6.2. Scope definition

This is a cradle to gate assessment assessing material and energy flows and probable environmental impacts resulting from generation of electricity from a 50MW onshore wind power plant that comprises of twenty-five (25) Gamesa G90-2.0MW wind turbines. The operational life for the project is taken as twenty (20) years. The study only considers raw material extraction, manufacturing of components, construction and operation phase.

6.2.1. Function

The function of the wind power plant is to generate electricity that can be transmitted to national grid for supplying to general consumers.

The wind turbines selection for baseline scenario has been done based on the wind class in Gharo-Jhimpir Wind Corridor in Sindh Province of Pakistan.

6.2.2. Functional unit

The functional unit for this LCA study is 1kWh of electricity delivered to the grid by a 50MW wind power plant. The functional unit could also be selected based on total generation from the power plant throughout its lifecycle however selecting the unit based on “unit of electricity delivery” basis ensures accuracy and keeps it comparable enough to be used as reference.

The functional unit defined above reflects the electricity delivered to the grid. It does not shows electricity received by the consumer as the transmission and distribution of electricity is beyond the scope of this study therefore grid distribution losses are not considered.

The operational life for this study is considered twenty (20) years for this study however some of the current installations in Pakistan also have an operational life of twenty-five (25) years however life cycle inventory data is not publicly available for any of them.

6.2.3. Reference flow

The total electricity production from 50MW wind power plant is 2717.46 GWh while considering a capacity factor of 31% (average capacity factor for similar turbine size) over a lifetime of 20 years. This results in a reference flow of 3.6799×10^{-10} power plants per 1 kWh of electricity delivered.

6.2.4. System boundary

The system boundary for this LCA starts at raw material extraction and include manufacturing of components, transport of components to plant site, construction and operation. It does not include connection to grid and the decommissioning phase. The system boundary is illustrated in Figure 6.1.

The processes incorporated in the study include:

- Raw material extraction for manufacturing of all parts of the wind power plant. The list of components is discussed in inventory analysis. These include parts manufactured at Gamesa' factories. The information has been obtained from (Gamesa 2013) and it covers over 99% of the turbine mass.
- Transport of turbine components from manufacturing facilities to wind farm site which include both maritime and road transport from each region.
- Installation and erection of wind power plant components
- Use phase electricity production

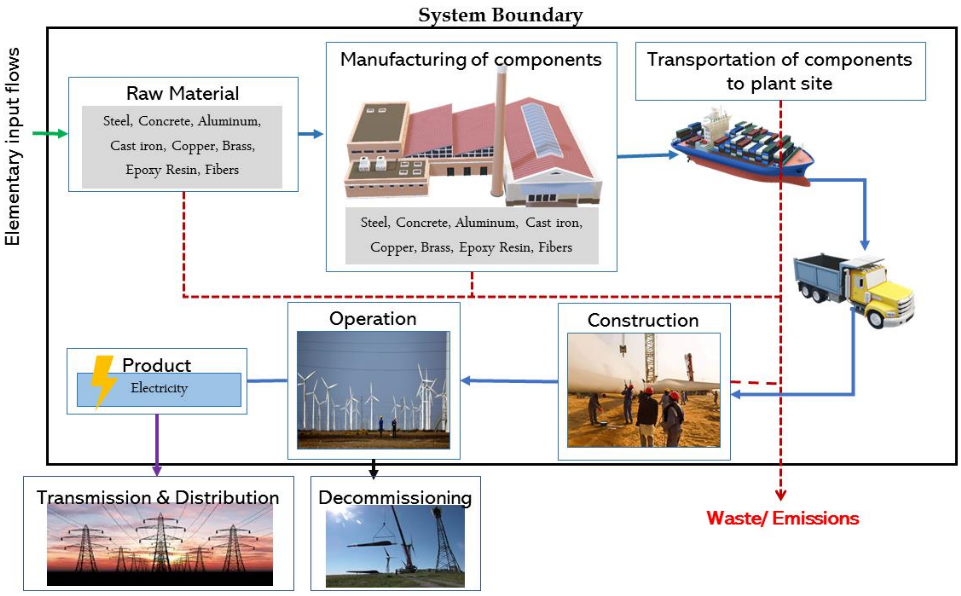

Figure 6.1. System boundary defining scope of the study

6.2.4.1. Geographical boundary

The geographical boundary for this LCA study is Gharo - Jhimpir Wind Corridor in Sindh province of Pakistan. All the components for construction of wind farms are imported from global facilities of the suppliers. Although most of the suppliers are establishing their regional production facilities to cater the region. Parts of turbines are imported from nearest possible production facility.

Gamesa formed a consortium with Siemens and currently they have production facilities in USA, Europe, Brazil, China and India. Based on the components manufactured in each region, components and their region of production is as follows:

- China: Nacelle, cables, substation
- Europe: Rotor
- Brazil: Turbine Towers

6.2.4.2. Temporal coverage

The life cycle inventory data for turbine components have been drawn from (Gamesa 2013) however reference year for this study has been selected as 2018 as it is the most representative year for recent developments in wind sector in Pakistan. A period of 20 years has been considered as operational life of the wind power plant.

6.2.5. Cut-off criteria

Following components have not been incorporated into this LCA:

- Transport of raw materials from extraction site to manufacturing facilities and from the facilities to respective ports has not been included due to lack of data;
- Manufacturing of components within the turbine itself have not been included because of unavailability of data;
- Replacements and repair of components and transportation associated with these processes throughout operational life have not included in the study;

- Construction of access road for transportation of turbine components is not included because Jhimpir wind corridor opens to Nooribad access point on Super Highway and Gharo wind corridor can be easily accessed by Sindh Coastal Highway and most of the internal roads have already been constructed. Construction of any further access road would only require levelling of existing dirt tracks and the impact would not be greater than 1% of the total impact from the project.
- Impacts from construction of temporary labor camp for the erection and installation period has not been included;
- Impacts from domestic activities in labor camp and office activities during operational life are not considered.
- Decommissioning phase of the project has not been included in this study because the regime of using wind power for electricity generation in Pakistan started in 2012 and no country-specific relevant information is available regarding end-of-life phase of wind power project.

6.2.6. Allocation

There were no allocation problems associated with this study. Inputs and outputs were simple and could be easily incorporated to procedure therefore no allocation procedure was required at any step.

6.2.7. Assumptions

The model contains following non-representative assumptions:

- Life cycle inventory data obtained from (Gamesa 2013) is represented for global supply chain and it fulfills defined spatial, temporal and technological scope;
- Data has been used in GaBi Education Database 6.0 and production of raw materials have been adapted from GaBi database available for the most suitable regions;

- No waste, emissions or effluents are produced during operational phase of the wind farm;
- The environmental impacts are similar for establishment of wind power projects in Gharo and Jhimpir.

6.2.8. Limitations

Results of this LCA must be considered with following limitations:

- Turbine model Gamesa G90-2.0MW used for this study is suitable for installation in region with medium wind speed (>8m/s) i.e., suitable for Pakistan however currently installed wind turbines of 2.0MW platform have rotor diameters more than 90 meters that increase the swept area and result in more generation, but inventory data is not available for any of them;
- GaBi Education database have limited material input options therefore high alloyed steel, low alloyed steel and cast iron are simplified to one class of steel;
- There were no related input objects for some materials including unspecified lubricant, paints, wires and adhesives. The inventory data available for Gamesa was estimated at 99.7% complete however with this limitation, system completeness is reduced to 99.24%.

6.2.9. Impact categories and impact assessment method

This LCA was performed by using GaBi LCA modeling software using CML 2001 method developed by Center of Environmental Science, Leiden University. CML is an impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. The method uses classification and characterization and group the results in midpoint categories according to common mechanisms (e.g. the emissions of CO_2, CH_4, N_2O impart to climate change, so they are collectively classified under Global Warming Potential (GWP) and characterized based on the impact nature) or commonly accepted groupings (e.g. ecotoxicity). Ozone depletion potential has not been included from the selected impact categories as it is no longer a significant issue after introduction of Montreal protocol (1987). The protocol has drastically consumed the use and release of ozone depleting substances (UNEP, 2007). CML does not go as far as to assess damage resulting from impacts like damage to human health, loss of biodiversity etc. Non-impact indicators assessed are not based on CML.

CML 2001-Jan 2016 was used in the study to evaluate following impact categories.

i. Global Warming Potential (100 years)
ii. Acidification potential
iii. Eutrophication potential
iv. Abiotic depletion (elements)
v. Abiotic depletion (fossils)
vi. Fresh water ecotoxicity potential
vii. Marine water ecotoxicity potential
viii. Human toxicity potential
ix. Terrestrial ecotoxicity potential
x. Photochemical ozone creation potential

Non-impact indicators considered for this study include:

i. Primary energy from renewable raw material (net calorific value)
ii. Primary energy from resources (net calorific value)
iii. Water consumption

Generally, a life cycle assessment does not address some other environmental impacts that are mostly localized. These may include potential impacts of land use at the site, local impacts on flora and fauna, noise etc. Such parameters require a risk assessment or environmental impact assessment to be conducted prior initiation of a project. As part of Sindh Environmental Protection Act 2014, all wind farms installed in Gharo-Jhimpir wind corridor have submitted their Initial Environmental Examination/ Environmental Impact Assessment Reports to acquire NOC from Sindh Environmental Protection Agency.

6.3. Interpretation

The interpretation of results have been conducted according to the approach defined in (ISO 2006a; 2006b) for life cycle assessment. It included establishing the life cycle inventory for the wind power plant to assess significant environmental flows and environmental impacts associated with them.

The datasets and assumptions are also qualitatively evaluated to ensure completeness and consistency. The data quality assessment has been carried out based on the data acquisition and its temporal and geographical coverage, precision, completeness, representativeness and consistency. Any kind of sensitivity analysis have not been performed in this study.

CHAPTER 7

INVENTORY ANALYSIS

7.1. Introduction

To conduct LCA of wind power plants in Pakistan, inventory data has been taken from LCA report (Gamesa 2013) of a similarly sized wind turbine Gamesa G90-2MW which is suitable for installation in Pakistan based on its wind class. The turbine characteristics are summarized in *Table 7.1*. The hub height and rated power of Gamesa G90 is same as majority of wind turbines installed in Pakistan however there are variations in diameter of rotor. The hub height and rotor together form major mass of the turbine. Additionally, the LCA for Gamesa G90 is peer reviewed therefore results deemed reliable.

Table 7.1. *Characteristics of Gamesa G90-2MW turbine*

Turbine Model	Gamesa G90-2.0MW
Number of turbines for 50MW project	25
Rotor diameter (m)	90
Swept area (m^2)	6362
Blade length (m)	44
Blade weight (kg)	5800
Gear box	Three staged, one planetary and two parallel shift gears
Generator	Doubly fed asynchronous generator
Hub height (m)	80

7.2. Materials

The entire power plant with its components i.e., Turbine tower, nacelle, rotor, cables, foundations and substation have been considered for the life cycle inventory except for replacement parts. Figure 7.1 illustrate the material breakdown of wind turbine by percentage mass of each material and Figure 7.2 illustrates the breakdown of material used in complete wind power plant by mass.

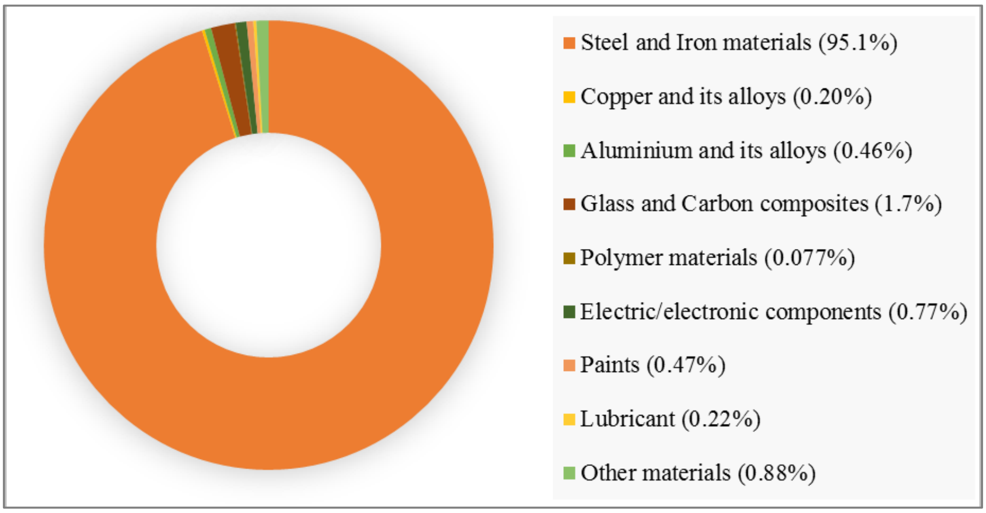

Figure 7.1. Breakdown of materials used in Gamesa G90-2 MW Turbine only (% mass)

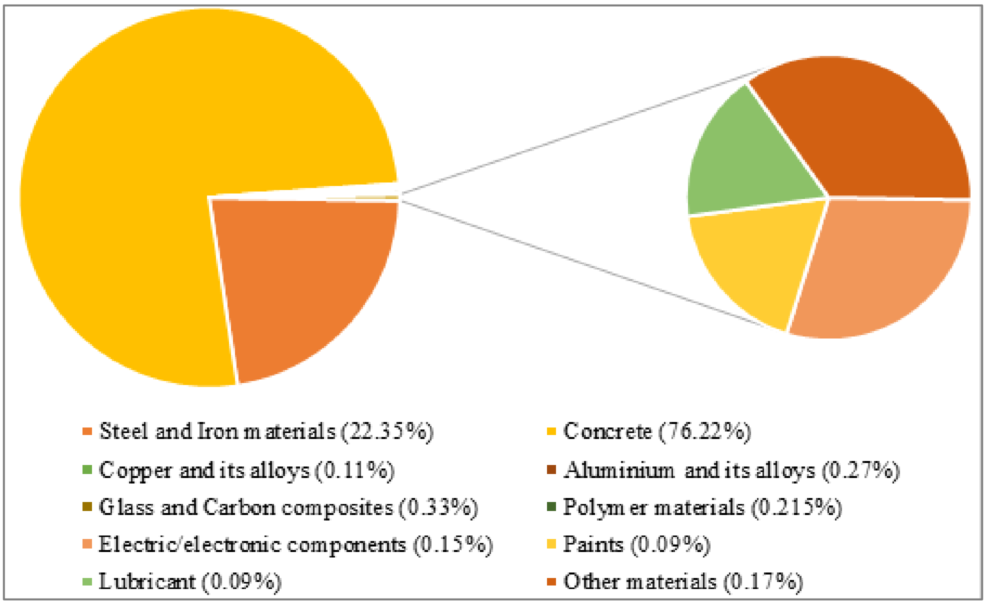

Figure 7.2. Breakdown of materials used in 50MW wind power plant of Gamesa G90-2MW (% mass)

Table 7.2 to 7.10 represent the inventory summary of the materials that assemble the turbines. The data provided is for one turbine of G90-2.0MW and material breakdown represents the mass of an erected turbine. It does not include wastes generated during production or parts for servicing. The complete life cycle inventory results are provided in Appendix A.

Table 7.2. *Mass of materials used in parts of Rotor for each G90-2MW turbine*

Materials (kg)	**Blades**	**Pitch system**	**Hub**	**Rotor (Others)**	**Sub total**
Steel and iron materials	898.45	1548.72	8360	8870.5	19677.67
◆ *Low alloy steel*	*1.08*	*409.29*	*0*	*2934.24*	*3344.61*
◆ *High alloy steel*	*897.37*	*281.91*	*0*	*5708.26*	*6887.54*
◆ *Cast iron*	*0*	*857.52*	*8360*	*228*	*9445.52*
Copper and its alloys	52.98	2.55	0	0	55.53
Aluminum and its alloys	0	34.79	0	15.28	50.07
Polymer materials	727.64	20.46	0	26.5	774.6
Glass and Carbon Composites	15140.4	0	0	186.3	15326.7
◆ *Fiberglass*	*12152.65*	*0*	*0*	*0*	*12152.65*
◆ *Carbon fiber*	*2987.75*	*0*	*0*	*0*	*2987.75*
◆ *GRP (Glass Reinforced Plastic)*	*0*	*0*	*0*	*186.3*	*186.3*
Painting	681.9	0	0	0	681.9
Adhesive	1475.49	0	0	0	1475.49
Other materials	14.46	7.17	6.56	0	28.19
Total (kg)	19889.77	3162.41	16726.56	17969.08	57747.82

Table 7.3. *Mass of materials used in parts of Turbine Towers for each G90-2MW turbine*

Material (kg)	**Tower sections**	**Flanges**	**Fastener kits**	**Others**	**Sub-total**
Low alloy steel	166237.82	15962.95	3434	2544.5	188179.27
Aluminum and its alloys	0	0	0	237	237
Paint	0	0	0	580.38	580.38
Total (kg)	166237.82	15962.95	3434	3361.88	188996.65

Table 7.4. *Mass of materials used in foundation of wind turbine (proportional to one turbine installed)*

Material (kg)	Welded section	Footing	Total
Low alloy steel	14537	0	14537
Steel rebar	0	44000	44000
Concrete C30-37	0	1116000	1116000
◆ *Concrete for cleaning*	*0*	*60000*	*60000*
◆ *Concrete in mass*	*0*	*1056000*	*1056000*
Total	14537	1160000	1174537

Table 7.5. *Mass of materials used in internal wiring of wind farm (data extrapolated for each G90-2MW turbine installed)*

Material (kg)	Mass used
Copper and its alloys	531.74
Aluminum and its alloys	2714.24
Polymer materials	2943.64
Total	6189.62

Table 7.6. *Mass of materials used in parts of Nacelle for each G90-2MW turbine (Part A)*

Material (kg)	**Gearbox**	**Generator**	**Transformer**	**Shaft (low speed)**
Steel and iron materials	16167.66	5578.66	3225.06	11475.29
◆ *Low alloy steel*	*1913.43*	*5408.71*	*3225.06*	*615.79*
◆ *High alloy steel*	*6246.01*	*46.85*	*0*	*7724.9*
◆ *Cast iron*	*8008.22*	*123.1*	*0*	*3134.6*
Copper and its alloys	0	352.37	0	0
Aluminum and its alloys	2.56	24	675.02	3.79
Brass	2.75	0	0	0
Polymer materials	9.87	14	22.49	0
Glass and carbon composites	2.7	13.94	7.7	0
◆ *Fiberglass*	*0*	*10.47*	*0*	*0*
◆ *GRP (Glass Reinforced Plastic)*	*2.7*	*3.47*	*7.7*	*0*
Painting	37.7	35.48	0	0
Electrical components	191.82	126	0	0
◆ *Electric/electronic component*	*191.82*	*126*	*0*	*0*
◆ *Wires*	*0*	*0*	*0*	*0*
Lubricant	0	0	0	0
Other materials	10.21	109.58	344.99	28.8
Total (kg)	16425.26	6254.02	4275.26	11507.88

Table 7.7. *Mass of materials used in parts of Nacelle for each G90-2MW turbine (Part B)*

Material (kg)	**Yaw system**	**Electric cabinets/ converter**	**Nacelle structure**	**Shaft (high speed)**	**Frame**
Steel and iron materials	4311.72	1551.78	775.44	788.57	13865.32
◆ *Low alloy steel*	1636.66	1551.78	757.65	662.28	2963.42
◆ *High alloy steel*	1445.66	0	17.79	0.03	2
◆ *Cast iron*	1229.4	0	0	126.26	10899.9
Copper and its alloys	0	155.28	0	0	0
Aluminum and its alloys	240	0	11.37	0	53.63
Brass	35.1	0	0.15	0	0
Polymer materials	22.91	22.17	35.72	2.6	7.68
Glass and carbon composites	0	0	1702.22	0	0
◆ *Fiber glass*	*0*	*0*	*0*	*0*	*0*
◆ *GRP (Glass Reinforced Plastic)*	*0*	*0*	*1702.22*	*0*	*0*
Painting	0	0	0	0	0.5
Electrical components	144	487.56	0	0	0
◆ *Electric/electronic component*	144	443.44	0	0	0
◆ *Wires*	0	44.12	0	0	0
Lubricant	0	0	0	0	0
Other materials	3.5	0	3.64	0.87	409.7
Total (kg)	4757.23	2216.79	2528.54	792.04	14336.83

Table 7.8. *Mass of materials used in parts of Nacelle for each G90-2MW turbine (Part C)*

Material (kg)	**Crane system**	**Hydraulic group**	**Other nacelle parts**	**Sub-total**
Steel and iron materials	2444.65	500	297.54	60981.69
◆ *Low alloy steel*	2307.85	499.94	262.47	21805.04
◆ *High alloy steel*	20	0.06	35.07	15538.37
◆ *Cast iron*	116.8	0	0	23638.28
Copper and its alloys	0	15	0	522.65
Aluminum and its alloys	0	25	0	1035.37
Brass	0	0	0	38
Polymer materials	0	6	1.32	144.76
Glass and carbon composites	0	0	0	1726.56
◆ *Fiber glass*	0	0	0	10.47
◆ *GRP (Glass Reinforced Plastic)*	0	0	0	1716.09
Painting	0	0	0	73.68
Electrical components	0	0	0	2185.54
◆ *Electric/electronic component*	0	0	0	905.26
◆ *Wires*	0	0	1236.16	1280.28
Lubricant	0	0	627.77	627.77
Other materials	0.36	0	19.07	930.72
Total (kg)	2445.01	546	2181.86	68266.72

Table 7.9. *Mass of materials used in parts of Substation (Part A-data extrapolated for each G90-2MW turbine installed)*

Material (kg)	**Power transformer**	**Auxiliary system transformer**	**Concrete/ elements**	**Metallic structure**
Steel and iron materials	1471.42	35.76	0	325.72
◆ *Low alloy steel*	*1471.42*	*35.76*	*0*	*288.49*
◆ *Cast iron*	*0*	*0*	*0*	*37.23*
Copper and its alloys	370.07	0	0	0
Aluminum and its alloys	3.81	8.34	0	0
Brass	1.68	0	0	0
Polymer materials	0	2.5	0	0
Glass fiber	18.93	0	0	0
Painting	1.56	0	0	0
Lubricant	635.15	14.19	0	0
Concrete	0	0	7200	0
Porcelain	6.47	0.46	0	0
Other materials	63.39	0	0	0
Total	2572.48	61.25	7200	325.72

Table 7.10. *Mass of materials used in parts of Substation (Part B-data extrapolated for each G90-2MW turbine installed)*

Material (kg)	Busbar	Equipment electrical	Grounding systems	Sub total
Steel and iron materials	0	37.88	0	1870.78
◆ *Low alloy steel*	0	*37.88*	*0*	*1833.55*
◆ *Cast iron*	0	*0*	*0*	*37.23*
Copper and its alloys	64.78	3.64	4.76	443.25
Aluminum and its alloys	3.65	11.55	0	27.35
Brass	0	0	0	1.68
Polymer materials	16.19	0.78	0.22	19.69
Glass fiber	0	0	0	18.93
Painting	0	0	0	1.56
Lubricant	0	0.03	0	649.37
Concrete	0	0	0	7200
Porcelain	0	45.55	0	52.48
Other materials	0	6.64	0	70.03
Total (kg)	84.62	106.07	4.98	10355.12

7.3. Transportation

Data for transportation has been derived mainly from maps.google.com and sea-distances.com for road transport and maritime shipping respectively. Distance values have been incorporated in GaBi software while other free parameters were kept at default.

Based on data available for Gamesa Supply chain, it is assumed that cargo is shipped from respective ports. All the materials are received at Port Qasim, Karachi and transported to plant sites through trucks.

Table 7.11. *Distances between the ports*

Port of departure	Port of arrival	Distance (nautical miles)	Distance (kilometers)
Port Beigang, China	Port Qasim, Karachi	5350	9908.2
Port Sao Sebastiao, Brazil	Port Qasim, Karachi	7995	14806.74
Hamburg, Germany	Port Qasim, Karachi	6386	11826.87

The distance between Port Qasim to Gharo Wind Farm area is 60 kilometers when accessed through Sindh Coastal Highway while Jhimpir wind farm area is accessed through Nooriabad via National Highway N-5 and Super Highway M-9. The distance between Port Qasim and Nooriabad when accessed by N-5 is 165 kilometers and 180 kilometers for M-9. Extrapolating the average values for reaching wind farms, the road transport distance is kept at 200 kilometers.

7.4. GaBi process flow

The real time process flow for LCA of wind power project generated in GaBi is illustrated in Figure 7.3.

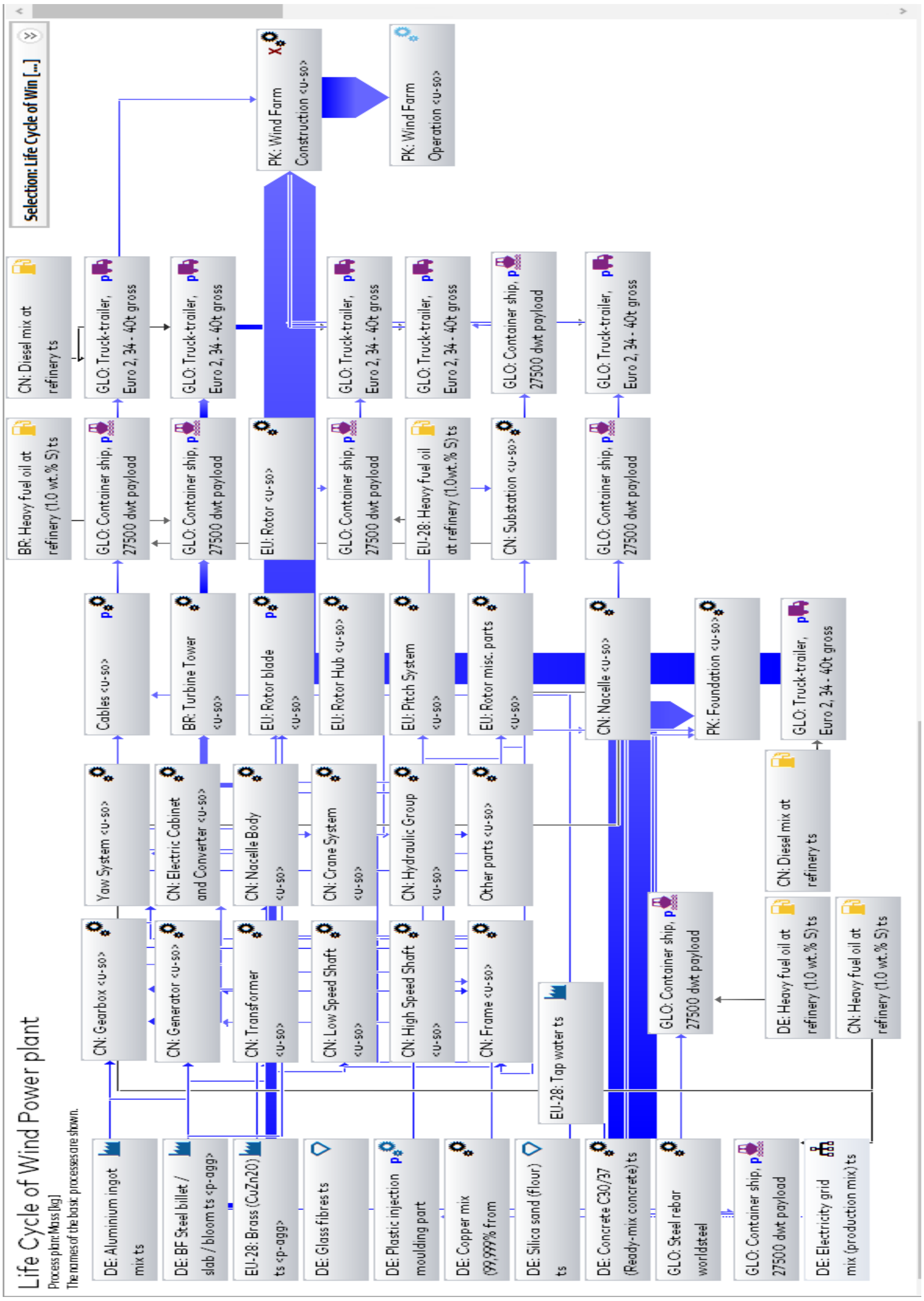

Figure 7.3. Process flow of Wind Power Project developed in GaBi Education 6.0

CHAPTER 8

IMPACT ASSESSMENT

8.1. Summary of results

The total potential environmental impacts associated with an onshore 50 MW wind power plant is summarized in Table *8.1*. Additional breakdown of the results providing an assessment of each impact category is provided in section 8.2.

Table 8.1. *Whole life environmental impacts for 50MW wind power project (per kWh)*

Environmental Impact categories	Units	Quantity
Abiotic resource depletion (elements)	µg Sb eq./kWh	2.83
Abiotic resource depletion (fossils)	MJ/kWh	0.00297
Global warming potential	g CO2 eq./kWh	0.345
Acidification potential	mg SO2 eq./kWh	1.6
Eutrophication potential	mg PO4 eq./kWh	0.158
Freshwater ecotoxicity	mg DCB eq./kWh	1.08
Human toxicity	mg DCB eq./kWh	229
Marine water ecotoxicity	g DCB eq./kWh	43.1
Terrestrial ecotoxicity	mg DCB eq./kWh	0.391
Photochemical oxidation potential	mg C2H4 eq./kWh	0.11
Non-impact indicators		
Primary energy demand from renewable and non-renewable resources	MJ[7]/kWh	0.00328
Primary energy from non-renewable resources	MJ/kWh	0.00327
Primary energy from renewable resources	MJ/kWh	0.000217
Water use	g/kWh	207

Figure 8.1 presents potential environmental impacts for manufacturing of turbine components, transportation to plant site and installation of wind turbines. The impacts

[7] Net calorific value

from transportation are disintegrated into maritime and road transport. There are no environmental impacts identified during operation stage as it does not involve extraction activity, use of fuel or release of emissions. Other receptor based localized impacts like shadow flicker, noise level or bird mortality are studied as part of environmental impact assessment study or additional studies based on plant site location, presence of receptors and potential identified impacts.

The results show that the turbine components including nacelle, turbine tower and rotor collectively contribute most significantly to all impact categories. This is followed by foundation with most significant contribution to human toxicity potential. Cables and substation contribute the least to impact categories. The installation phase has very contribution while among transportation, maritime transportation contributes the most towards acidification potential, eutrophication potential, fresh water ecotoxicity potential and photochemical ozone creation potential. Road transport has the most minimal contribution to the impact categories.

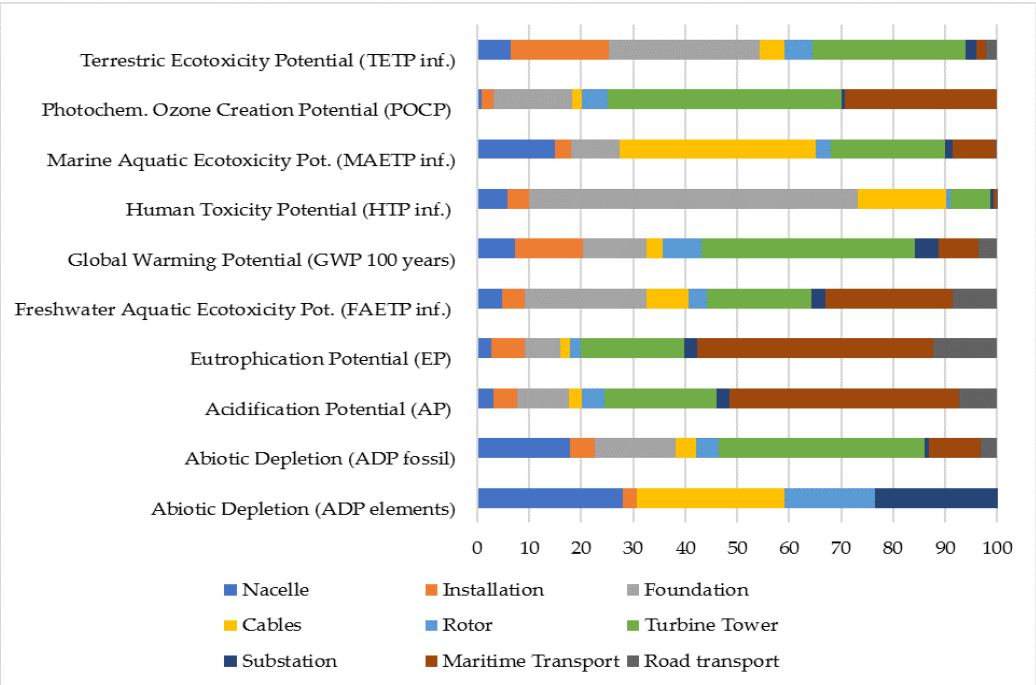

Figure 8.1. Production and installation phase environmental impacts

8.2. Analysis of results: impact categories

This section elaborates results for each impact category. The impacts have been analyzed from the perspective of its main components manufacturing (including raw material extraction and production in factory), transportation to wind farm site by maritime shipping from country of manufacturing to Port Qasim, Karachi, Pakistan and then to wind farm site and the installation phase. *Table 8.2* shows component wise result for each impact category. The impacts of wind power on different environmental matrices is provided in Appendix B for key processes.

Table 8.2. *Environmental impacts for component-wise manufacturing, transportation and istallation of wind turbines*

Impact categories	Units (per kWh)	Nacelle	Rotor	Tower	Foundation
Abiotic resource depletion (elements)	µg Sb eq.	0.7934	0.4912	0.002	-0.0048
Abiotic resource depletion (fossils)	MJ	4.53E-5	1.28E-4	1.18E-3	4.62E-4
Global warming potential	g CO_2 eq.	0.054	0.035	0.142	0.042
Acidification potential	mg SO_2 eq.	0.238	0.047	0.344	0.1613
Eutrophication potential	mg PO_4 eq.	0.0221	0.0134	0.0224	0.0108
Freshwater ecotoxicity	mg DCB eq.	0.0152	0.127	0.117	0.053
Human toxicity	mg DCB eq.	27.19	14.226	57.57	40.75
Marine water ecotoxicity	g DCB eq.	6.43	5.724	9.51	4.045
Terrestrial ecotoxicity	mg DCB eq.	0.109	0.077	0.045	0.0332
Photochemical oxidation potential	mg C_2H_4 eq.	0.021	0.0122	0.0295	0.0145
Impact categories	**Units (per kWh)**	**Cables**	**Sub-station**	**Transport**	**Installation**
Abiotic resource depletion (elements)	µg Sb eq.	0.804	0.668	0.0009	0.076
Abiotic resource depletion (fossils)	MJ	1.16E-4	2E-5	3.9E-4	6.25E-4
Global warming potential	g CO_2 eq.	0.0108	0.0124	0.0298	0.019
Acidification potential	mg SO_2 eq.	0.039	0.0085	0.757	0.0136
Eutrophication potential	mg PO_4 eq.	0.0107	0.00065	0.0747	0.0029
Freshwater ecotoxicity	mg DCB eq.	0.388	0.029	0.192	0.213
Human toxicity	mg DCB eq.	73.56	4.094	7.68	2.929
Marine water ecotoxicity	g DCB eq.	8.276	0.609	8.017	0.25
Terrestrial ecotoxicity	mg DCB eq.	0.019	0.0148	0.0753	0.03
Photochemical oxidation potential	mg C_2H_4 eq.	0.0022	0.0007	0.0238	0.0051

8.2.1. Abiotic depletion (elements)

Abiotic depletion of elements refers to depletion of non-energetic natural resources found in elemental form in the earth crust. It accounts for extraction of minerals based on remaining geographical reserves and their rate of depletion. Mass of Antimony is used as reference comparison case and this category is reported in mass of antimony equivalent (Sb eq.).

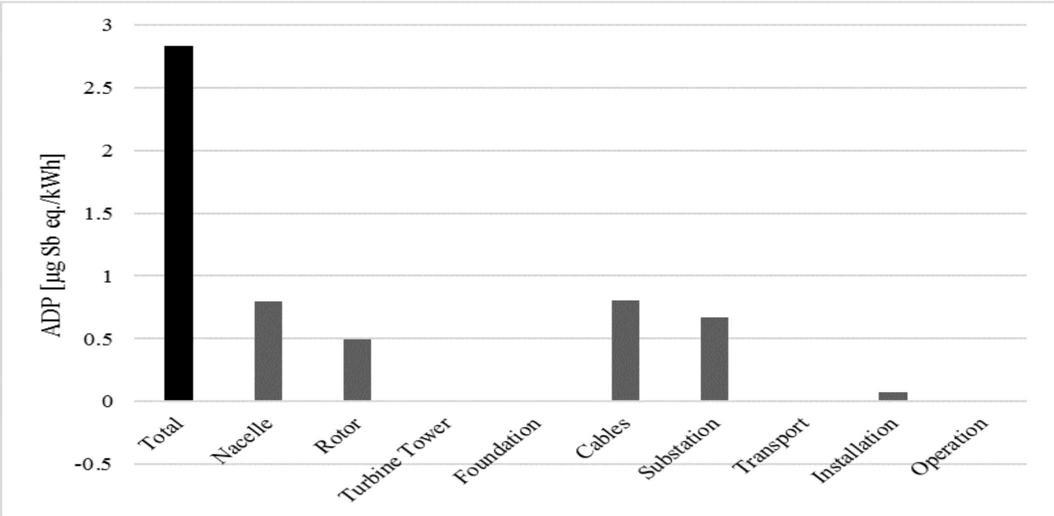

Figure 8.2. Contribution to abiotic depletion (elements) per kWh of electricity produced by 50 MW wind farm

Figure 8.2 illustrates the potential impacts of abiotic depletion (elements) from manufacturing of wind farm components, transportation, installation and operation per kWh of electricity produced from the wind farm. The total depletion of elements is 2.83 µg Sb equivalent per kWh and the most significant contribution is from raw material extraction and manufacturing of cables (28.4%) followed by nacelle (28%) and substation (23%). It is evident that manufacturing stage dominates the impact and it is primarily driven by use of metals including lead, copper, chromium, silver and zinc in nacelle and substation while colemanite ore is used in manufacturing blades of the turbine. Impact was minimal for installation phase (~3%) while negligible (<1%) for turbine tower, foundation and transportation of turbine components to plant site.

The depletion of abiotic elements during the operation phase is only associated with repair, servicing and maintenance of turbines which is not covered in this assessment.

8.2.2. Abiotic depletion (fossils)

This category indicates potential depletion of energetic non-renewable resources measured in terms of energetic value (MJ).

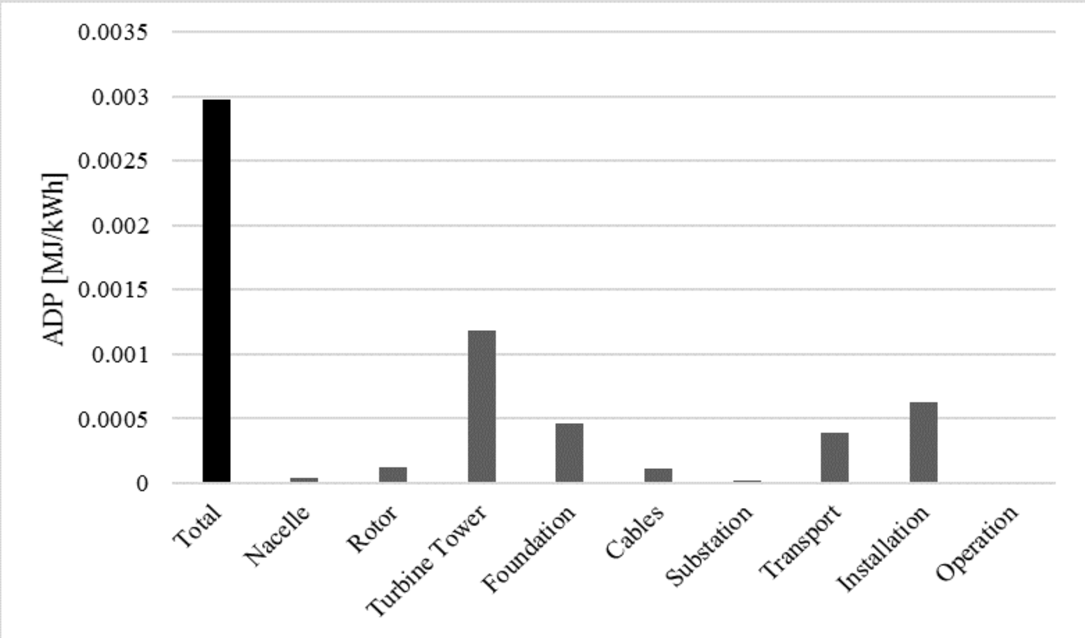

Figure 8.3. Contribution to abiotic depletion (fossils) per kWh of electricity produced by 50 MW wind farm

Figure 8.3 shows the potential impacts of abiotic depletion (fossils) for lifecycle of wind farm including manufacturing of wind farm components, transportation, installation and operation per kWh of electricity produced from the wind farm. The total impact for this category is 2.97E-3 MJ/kWh. The manufacturing of turbine components has significant contribution (>65%) for depletion of fossils which is driven by manufacturing of turbine towers (40%) which utilizes maximum amounts of low alloy steel and aluminum. This is followed by foundation (15%) which utilizes concrete and steel as main components. Transportation and installation phase also contribute to this impact. Overall the impact is driven by use of oil, natural gas for production of metals and polymers and utilized as fuel for transportation.

8.2.3. Global warming potential

Greenhouse effect results from absorption and re-radiation of incoming infrared radiation by greenhouse gases (e.g. carbon dioxide, methane, chlorofluorocarbons etc.) in the troposphere. Although greenhouse effect is a natural phenomenon to keep earth warm, anthropogenic activities particularly burning of fossil fuels have enhanced the greenhouse effect leading to global warming. The global warming potential is calculated in mass of carbon dioxide equivalent (CO_2 eq.). The residence time of gases in the atmosphere is incorporated while calculating global warming potential therefore a time range for assessment is specified. The customary 100 years period has been considered for this study.

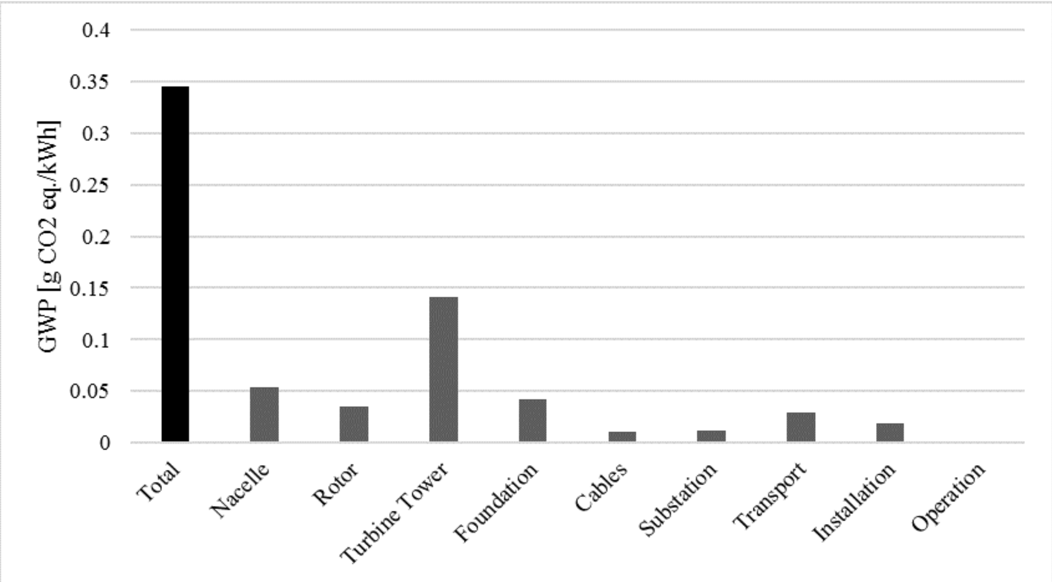

Figure 8.4. Contribution to global warming potential (100 years) per kWh of electricity produced by 50 MW wind farm

Figure 8.4 shows the potential impacts of global warming from 50MW wind power project per kWh of electricity produced. Total global warming potential per kWh of electricity produced is 0.345 g CO_2 equivalent. Like other impact categories, manufacturing of turbine components is the dominant category for global warming potential. The most significant category is manufacturing of turbine towers (41%) followed by nacelle (~16%), foundation (12%) and rotor (10%). Transportation of turbines components has 8% contribution for global warming potential. The major contributors for global warming potential are emissions of greenhouse gases during different phases. Carbon dioxide is the major contributor and produced due to combustion of fuels for production of raw materials for manufacturing of turbines. The second important contributor is methane produced during manufacture of steel and glass fiber for rotor blades.

8.2.4. Acidification potential

Acidification potential is the measure of decrease in pH-value of precipitation (including rain water and fog) to 4 and below. It leads to deleterious ecosystem impacts like washing out of soil nutrients and increased solubility of metals in soil. The main contributors towards this impact are oxides of Sulphur and nitrogen and their respective acids. Although acidification potential is global issue, regional impacts may vary. The impact category is measured in mass of Sulphur dioxide equivalent (SO_2 eq.).

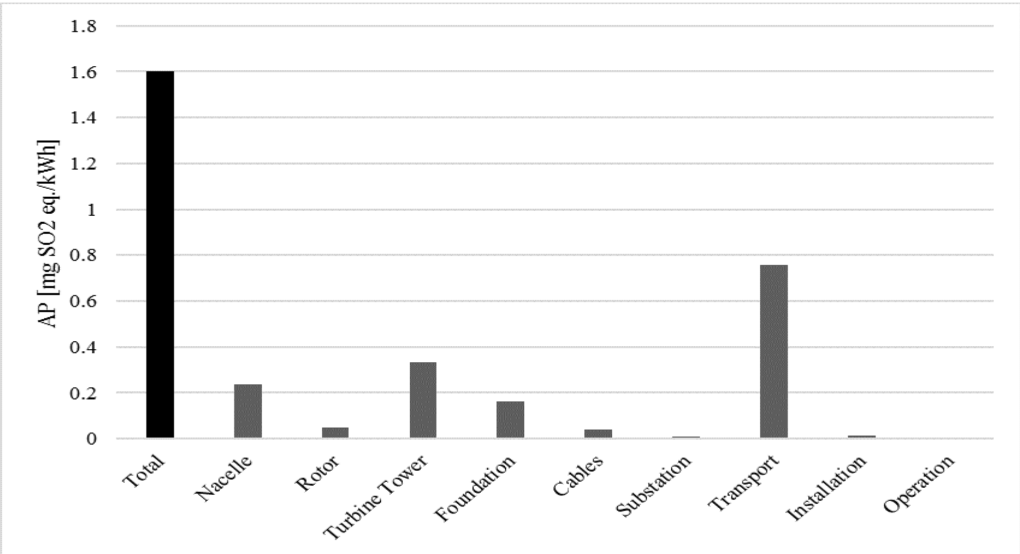

Figure 8.5. Contribution to acidification potential per kWh of electricity produced by 50 MW wind farm

Figure 8.5 represents the potential impacts of acidification from 50MW wind power project per kWh of electricity produced. The total potential for acidification is found to be 1.6 mg SO2 eq./kWh. Manufacturing process of powerplant also dominates the potential of acidification and significant contribution is from production of towers (21%), nacelle (15%), foundation (10%), rotor (3%) and cables (2%). This impact arises from emission of Sulphur dioxide (SO_2) and Nitrogen oxides (NO_x) during iron and steel production. Transportation process contributes significantly to acidification potential i.e., around 47% which is mainly associated with maritime shipping of heavy turbine components from Gamesa global facilities to Pakistan. The contribution of installation process is insignificant (<1%).

8.2.5. Eutrophication potential

This impact indicates increased nutrient content mainly nitrates and phosphates in terrestrial or aquatic environment. The over-enrichment of nutrients produces ecosystem damages like formation of algal blooms, hypoxic conditions, death of aquatic ecosystem, degradation of plant stability in terrestrial environments and increased susceptibility of plants to diseases and pests. Like acidification, eutrophication impacts also vary regionally. The impact category is measured in mass of phosphate equivalent (PO_4 eq.).

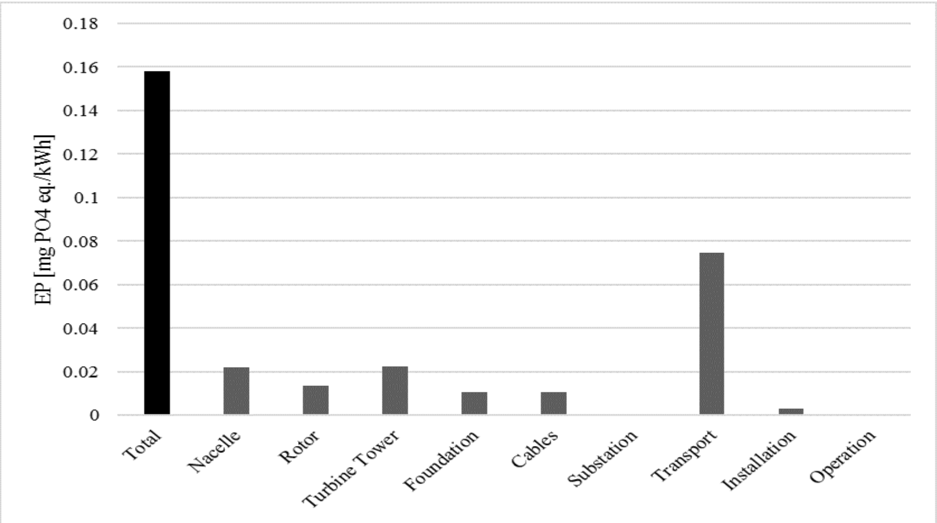

Figure 8.6. Contribution to eutrophication per kWh of electricity produced by 50 MW wind farm

Figure 8.6 shows the potential impacts of eutrophication from 50MW wind power project per kWh of electricity produced. The total eutrophication potential was found to be 0.158mg PO_4 eq./kWh. The manufacturing process has major contribution in eutrophication too where manufacturing of towers and nacelle contribute for 14% each. Other components include rotor (8%), cables and foundation 6% each. Emissions of nitrogen oxides, nitrous oxides and inorganic emissions too fresh water are primary substances that contribute towards eutrophication. Transportation process is also a significant contributor (47%) to eutrophication potential. Impact from installation and operation is insignificant.

8.2.6. Fresh water ecotoxicity potential

Emissions of toxic substances to air, water and soil induce toxicity in all ecosystems. This impact category indicates impacts on fresh water ecosystem from these emissions and measured in mass of 1,4-dichlorobenzene equivalents (DCB eq.)

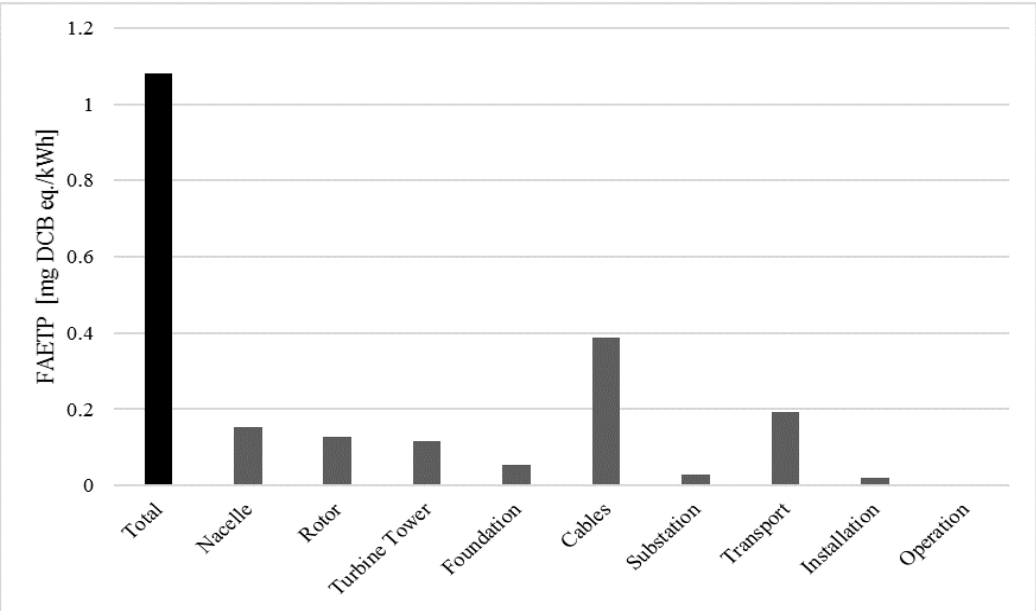

Figure 8.7. Contribution to freshwater ecotoxicity potential per kWh of electricity produced by 50 MW wind farm

Figure 8.7 illustrates the fresh water ecotoxicity potential during life cycle of 50MW wind power project per kWh of electricity produced. The total potential for fresh water ecotoxicity is 1.08 mg DCB eq./kWh. Similar to other impacts, manufacturing process is the major contributor with maximum contribution from manufacturing of cables (36%) due to use of polymer materials that result in emission of polychlorinated dibenzo-p-dioxins in water. The contribution of other components i.e., nacelle (14%), rotor (11%), towers (10%) and foundation (5%) is related to release of heavy metals e.g., nickel and barium to air and water during production processes of metals. Transportation process also contribute (~18%) to fresh water ecotoxicity due to release of metals from refinery operations that produce fuel as output for use in shipping operations.

8.2.7. Human toxicity potential

Human toxicity potential indicates impacts on human health produced by emissions of toxic substances to air, water and soil. The impact is measured in mass of 1,4-dichlorobenzene equivalents (DCB eq.).

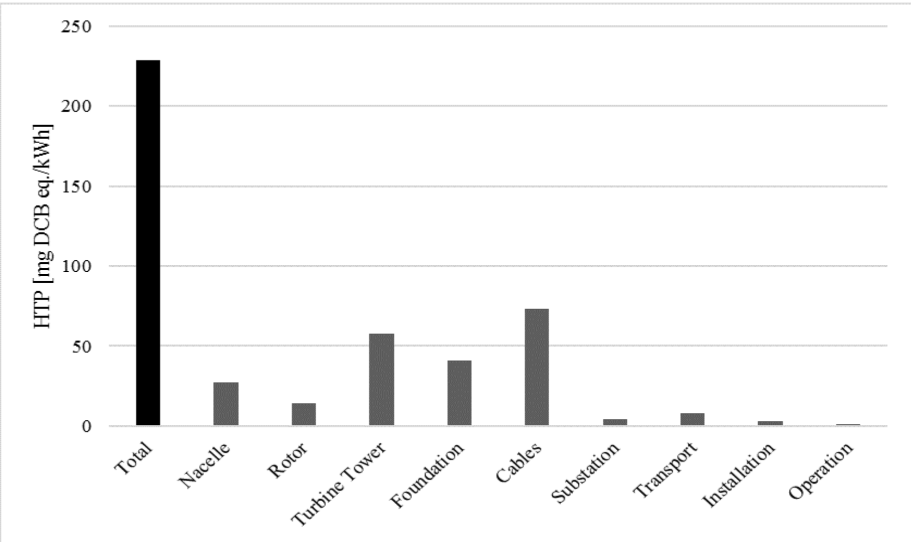

Figure 8.8. Contribution to human toxicity potential per kWh of electricity produced by 50 MW wind farm

Figure 8.8 represents the human toxicity potential during life cycle of 50MW wind power project per kWh of electricity produced. The total potential for human toxicity is 229mg DCB eq./kWh. As with the other impact categories, the manufacturing processes are dominant where production of cables have the most significant share (32%) followed by towers (~28%), foundation (~18%) and nacelle (~12%).

Main contributors to human toxicity potential are emission of heavy metals to air including nickel and arsenic. Non-methane volatile organic compounds are also released from manufacture of aluminum for cables. Negligible impacts have been identified for transportation, installation and operation.

8.2.8. Marine water ecotoxicity potential

This impact category indicates impacts on marine water ecosystem from emissions of toxic substances to air, water and soil measured in mass of 1,4-dichlorobenzene equivalents (DCB eq.).

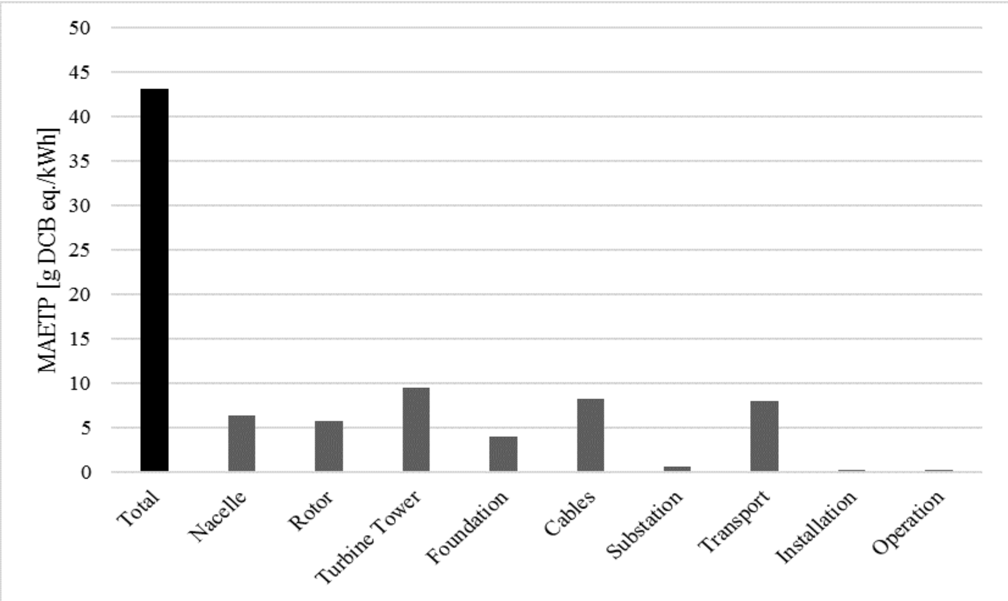

Figure 8.9. Contribution to marine water ecotoxicity potential per kWh of electricity produced by 50 MW wind farm

Figure 8.9 illustrates the marine water ecotoxicity potential during life cycle of 50MW wind power project per kWh of electricity produced. The total impact for this category was found to be 43.1 g DCB eq./kWh. Manufacturing stage dominates the life cycle impacts and major impact comes from production of turbine towers (22%), cables (19%), nacelle (15%) and rotor (13%). Transportation of wind turbine components to plant site also contribute (18%) to marine water ecotoxicity. Major impact arise from aluminum and steel production for manufacturing turbine components and primarily result from emissions of toxic substances to air, fresh water and sea-water.

8.2.9. Terrestrial ecotoxicity potential

This impact category indicates impacts on terrestrial ecosystem from emissions of toxic substances to air, water and soil measured in mass of 1,4-dichlorobenzene equivalents (DCB eq.).

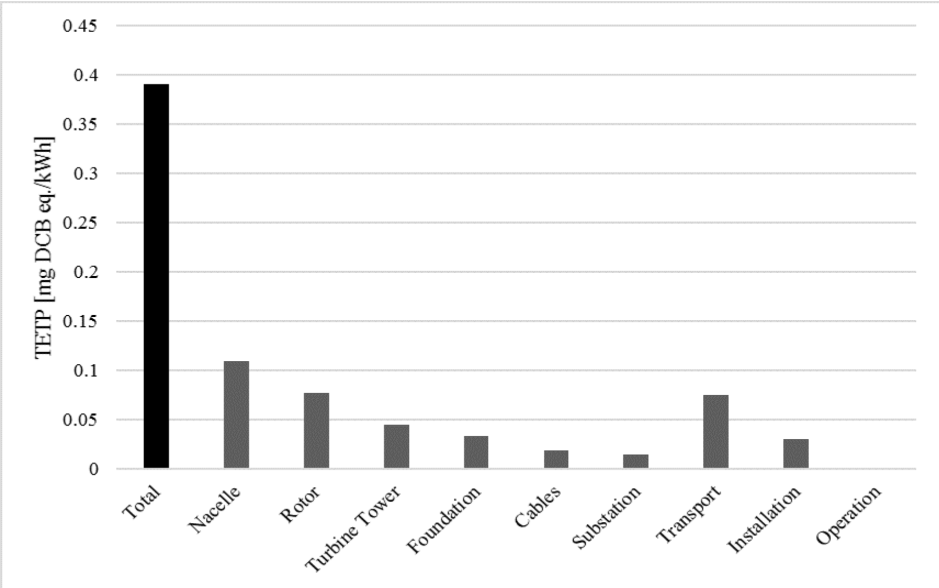

Figure 8.10. Contribution to terrestrial ecotoxicity potential per kWh of electricity produced by 50 MW wind farm

Figure 8.10 represents the terrestrial ecotoxicity potential during life cycle of 50MW wind power project per kWh of electricity produced. The total potential for terrestrial ecotoxicity was found to be 0.391 mg DCB eq./kWh. The manufacturing of turbine components is the dominant contributor to terrestrial ecotoxicity with major share from nacelle (28%) and rotor (20%) followed by turbine towers (11%) and foundation (8%). Transportation process also contributes (~20%) towards terrestrial ecotoxicity. The impact is driven by emission of heavy metals during production of metals for manufacturing of steel and iron materials used in turbine.

8.2.10. Photochemical oxidant formation potential

Photochemical oxidation potential is a potential indication of formation of low-level oxidants from oxides of nitrogen and volatile organic compounds in presence of light. This is also referred as summer smog. It damages vegetation and induce toxicity in humans when formed in high concentrations. The category is measured in mass of ethene equivalent (C_2H_4 eq.).

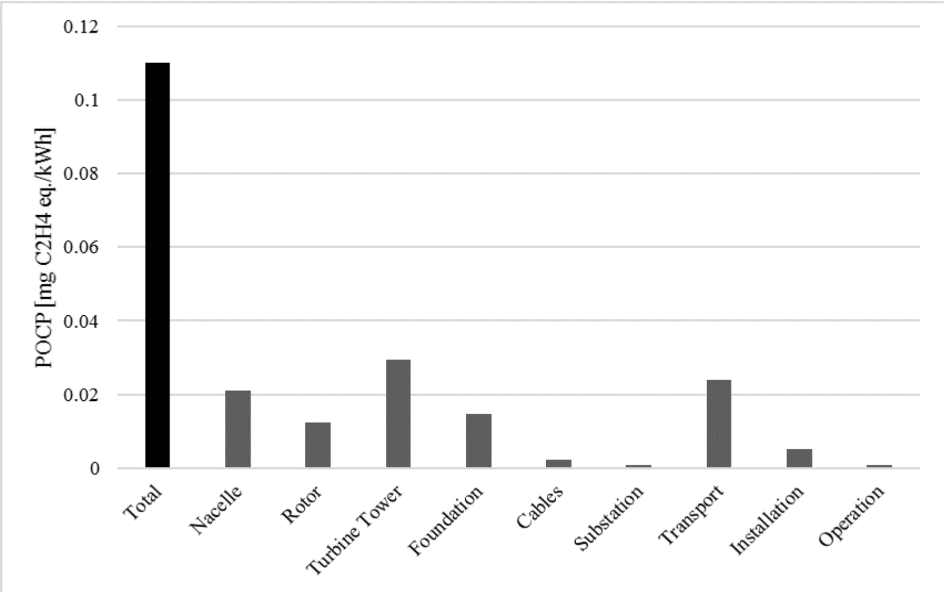

Figure 8.11. Contribution to photochemical oxidant potential per kWh of electricity produced by 50 MW wind farm

Figure 8.11 shows the potential for formation of photochemical oxidant per kWh of electricity produced. The total photochemical oxidant potential for the wind farm is 0.11 mg C_2H_4 eq./kWh. As other impact categories, manufacturing process is the most significant contributor with maximum share comes from manufacture of turbines (27%) followed by nacelle (19%), foundation (13%) and rotor (11%). Main contributing substances are carbon monoxide, nitrogen oxides, Sulphur dioxide, non-methane volatile organic compounds and other VOCs from manufacturing processes of steel, aluminum, copper and glass fiber production process. Transportation also contribute 22% to potential of photochemical oxidant formation primarily due to shipping operation.

8.3. Summary of results: non-impact categories

This section provides the analysis of non-impact indicators considered during the study. summarizes the component wise results for non-impact indicators considered for this study. *Table 8.3* summarizes the component wise results for non-impact indicators considered for this study.

Table 8.3. *Summary of non-impact indicators for component-wise manufacturing, transportation and installation of wind turbines*

Non-impact categories	Units (per kWh)	Nacelle	Rotor	Tower	Foundation
Primary energy demand from resources	MJ	7.14E-5	1.4E-4	1.26E-3	4.83E-4
Primary energy from non-renewable resources	MJ	5.55E-5	1.32E-4	1.2E-3	4.66E-4
Primary energy from renewable resources	MJ	1.59E-5	8.03E-6	5.33E-5	1.73E-5
Water use	g	34.178	14.89	31.87	22.698
Non-impact categories	**Units (per kWh)**	**Cables**	**Sub-station**	**Transport**	**Installation**
Primary energy demand from resources	MJ	1.91E-4	2.37E-5	3.93E-4	7.22E-4
Primary energy from non-renewable resources	MJ	1.45E-4	2.14E-5	3.92E-4	6.56E-4
Primary energy from renewable resources	MJ	4.61E-5	2.33E-6	1.27E-6	6.97E-5
Water use	g	70.72	1.807	2.492	28.339

8.3.1. Water consumption

The water use indicates the net balance of water inputs and outputs of freshwater throughout various stages of the product life cycle. The indicator is measured in grams per kWh of electricity produced.

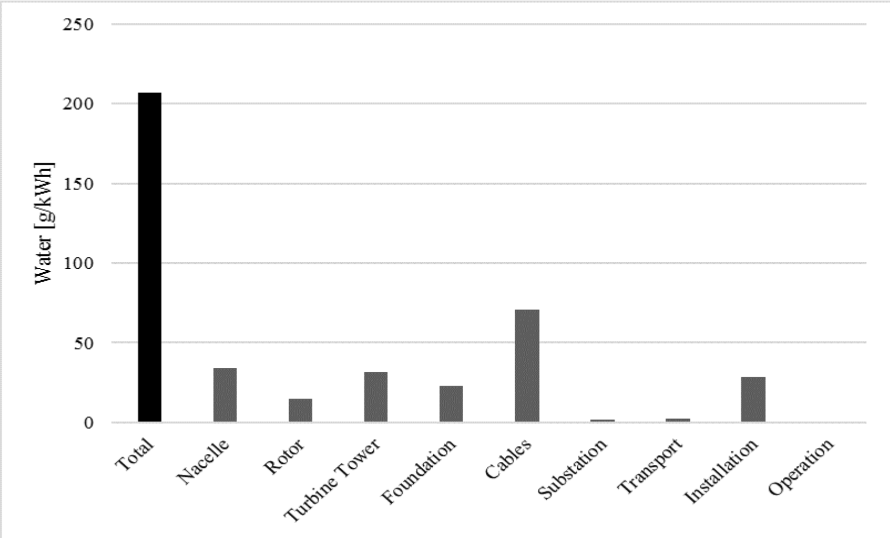

Figure 8.12. Water consumption per kWh for 50MW Wind power project

Figure 8.12 represents the water use per kWh of electricity produced by 50 wind power plant which is primarily related to manufacturing phase. The production of turbine components contributes significantly for water consumption including cables (34%), nacelle (17%), tower (15%), foundation (11%) and rotor (7%). The manufacturing phase water consumption is mainly driven by production of iron, steel, aluminum used in the wind turbine. Installation phase also utilizes freshwater for strengthening of concrete foundations and contributes 14% of total water use per kWh.

8.3.2. Primary energy demand

Primary energy demand is the amount of energy withdrawn from any renewable or non-renewable energy resource without any anthropogenic change and measured in MJ/kWh.

8.3.2.1. Primary energy from non-renewable resources

This is a measure of consumption of non-renewable energy (e.g., energy from coal, gas, oil, nuclear energy) over the life cycle of the wind power project. The net calorific value is expressed in MJ/kWh.

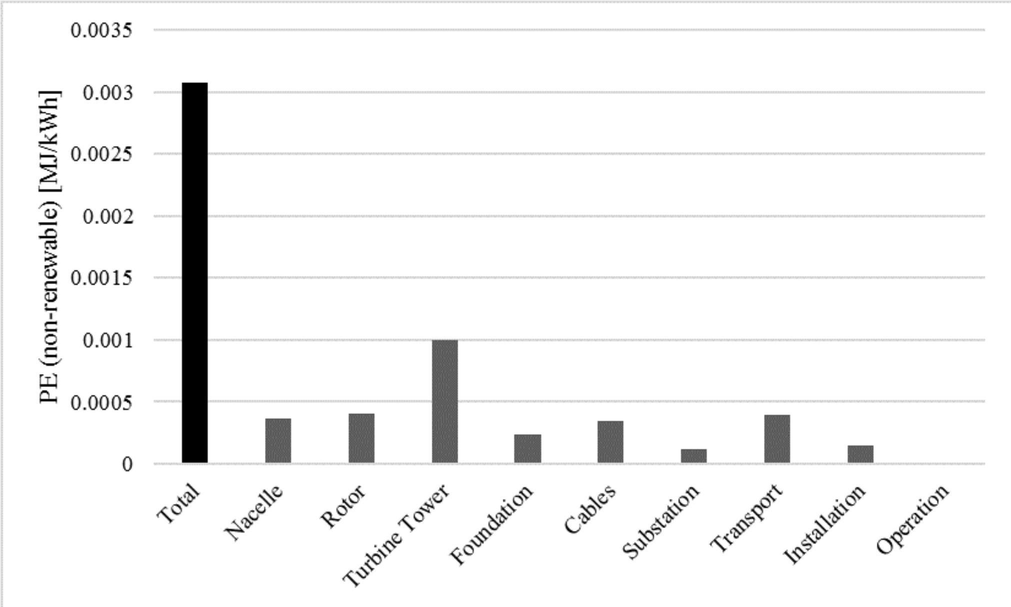

Figure 8.13. Primary energy from nonrenewable resources per kWh of electricity produced from 50MW Wind power plant

Figure 8.13 illustrates consumption of primary energy from non-renewable resources per kWh of electricity produced from the wind farm and total primary energy demand is 0.00307 MJ/kWh. Manufacturing processes utilizes the maximum primary energy with significant contributors are production of turbine towers (33%), rotor (13%), nacelle (12%), cables (11%) and foundation (8%). Contribution to this indicator arises from use of coal, oil and natural gas in manufacturing processes. Transportation process also contribute around 13% to this indicator and driving factor is use of fuel for shipping and transportation of turbine components to plant site.

8.3.2.2. Primary energy from renewable resources

This is the amount of energy consumed from renewable energy resources including hydropower, wind power, solar energy and biomass during life cycle of the project and expressed in MJ/kWh.

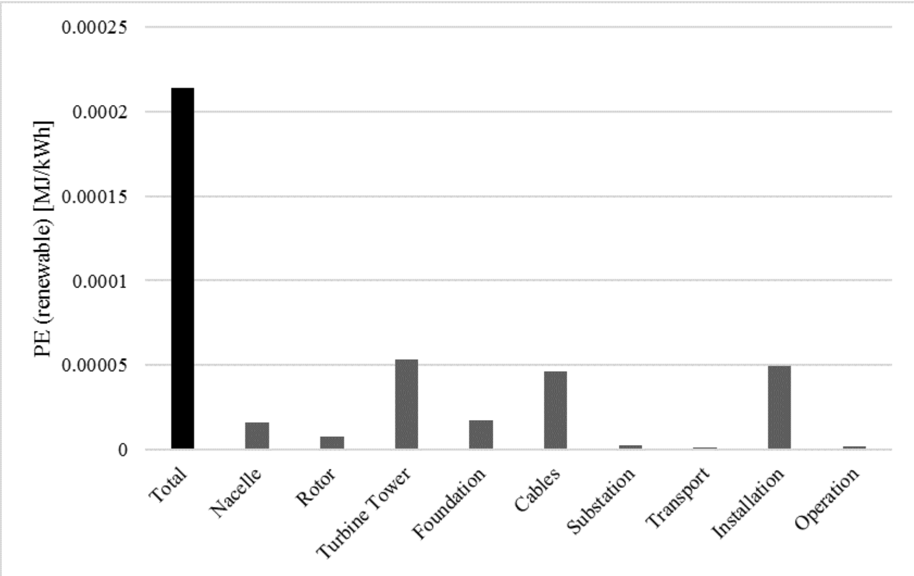

Figure 8.14. Primary energy from renewable resources per kWh of electricity produced from 50MW Wind power plant

Figure 8.14 shows consumption of primary energy from renewable resources (net calorific value) per kWh of electricity and total consumption is found to be 0.000214MJ/kWh. The manufacturing stage dominates life cycle for this indicator too and most significant contribution is from production of turbine towers (25%), cables (21%), foundation (8%) and nacelle (7%). The plant set-up stage also contributes around 23% and all the contribution to this indicator arise from utilization of primary energy from solar energy, wind energy and hydropower.

8.4. Return on energy

This section discusses the environmental performance of the wind power plant under consideration in terms of return-on-energy. This indicates the energy balance of power plant indicating relationship between energy requirement for manufacturing, construction and operation of the plant versus electricity output from the plant. Payback period as measured, is the duration in months when energy requirement for setting up a wind power plant equals the electricity produced. The payback period can be estimated by multiple approaches using net energy payback or primary energy payback. For the purpose of this study, net energy payback approach is used. Net energy is the product energy requirement for wind plant throughout its life cycle and power plant lifetime in months divided by electrical energy output of the plant. It is given as:

$$\text{Net energy payback (months)} = \frac{\text{life cycle energy requirement of WPP (MJ)}}{\text{electrical energy output from WPP (MJ)}} \text{ x lifetime of WPP (months)}$$

This lifecycle assessment does not include end-of-life phase for wind farm which according to studies (Gamesa 2013; Gard et al., n.d.; Vestas 2015) provides energy credit. With this limitation, life cycle energy requirement for wind power project is estimated 238,000,000 MJ while the energy generation in MJ is 9,782,856,000 over a period of 20 years lifetime. Following the net energy payback approach therefore, the breakeven time for the power plant is six (6) months for medium wind by Gamesa G90-2MW turbines. With more advanced turbines like using 3MW platform with higher capacity factors and installing a smaller number of turbines for same 50MW wind power plant, the payback time decreases further. The net return on energy approach however do not incorporate any relative conversions and provides an absolute indication of performance and used as preferred indicator for energy-investment.

CHAPTER 9

INTERPRETATION OF RESULTS

9.1. Significant issues

The results of this study represent environmental profile for production of electricity from a wind power plant comprised of 25 Gamesa 90-2.0 MW turbines. They were selected as base scenario based on its similarity to already installed wind turbines in Pakistan and availability of life cycle inventory data that could be incorporated in GaBi Education 6.0 software.

The life cycle assessment is a comprehensive study and to conduct it with robustness and accuracy, cut off criteria is applied as discussed in section 6.2.5. The LCA considered 99.24% of entire mass of the entire plant. The missing mass relates either to the unidentified materials or to materials with no related input objects due to limitation of GaBi education 6.0 software.

The life cycle inventory data (provided in section 7.2) and life cycle impact assessment (section 8.2 and 8.3) clearly reflects that manufacturing process dominates all potential impacts and inventory flows. Installation i.e., construction and operation phase show much less significant to negligible impact. In general, the part of turbine contributing most significantly to life cycle impact assessment are largest metal parts i.e., steel and iron materials. They form the major mass of nacelle, rotor and turbine towers. Besides iron and steel, aluminum and concrete were also among primary contributors to almost elemental flows to and from the environment.

The impacts from transportation of turbine components from Gamesa sites to wind power plant site in Gharo Jhimpir wind corridor also reflected significantly impacts (varying between 1% to 48%) for individual impact categories. The transportation involved maritime shipping from different Gamesa sites to Port Qasim in Karachi, Pakistan and then to wind farm site by heavy haul trucks. The factors affecting impacts from transportation process include type and quantity of fuel used, distance travelled and vehicle utilization data.

The results of the LCIA also shows the importance of wind plant siting and wind conditions that determine the type of turbine to be installed. The impacts from the whole wind farm have been referenced to 1kWh of electricity delivered to the grid and therefore the type of turbine, its suitability with the wind class of geographical area selected and capacity factor may greatly influence the impacts. These kinds of variations can be studied by conducting a sensitivity analysis however, no such analysis is conducted for this study.

Another dominating factor is lifetime of wind power project while determining impacts of electricity production per kWh from the wind power project. This LCA assumed the standard lifetime of 20 years however it is assumed that they could be operated for a period longer than standard lifetime. Global data for some turbine manufacturers is available where turbines with 20 years of lifetime have been disposed of after an operational life of 30 years but no such example is available for Pakistan. The wind energy utilization in Pakistan is still immature and first project of Zorlu Energy Pakistan (Pvt.) Limited started operating in 2012.

The current assessment does not involve calculation of localized impacts like land use change or clearance of vegetation for erection of turbines or levelling or roads and dirt tracks. In general, there is no significant vegetation present in Jhimpir wind corridor however some species of mangroves are present in creek area of Gharo wind corridor. These aspects are taken into consideration while conducting Initial Environmental Examination (IEE) or Environmental Impact Assessment (EIA) at proposed project site to fulfill regulatory and financer’s requirements.

Overall, when comparing the scale of environmental impacts per 1kWh for 50MW wind power project of Gamesa G90-2MW in Pakistan, the results are found similar to (Gamesa 2013) and (Vestas 2015) which are peer reviewed assessments so the results are considered reliable. The study thus can be considered aligned with global LCAs for wind power projects, however there is no benchmark data available for Pakistan. (Akber, Thaheem, and Arshad 2017) conducted the life cycle assessment of electricity generation in Pakistan using 2015 as base year. Based on the information available for wind power sector and levelized cost of generating electricity, wind was concluded as worst option for capital investment in Pakistan however the duration between 2015 to 2018 evidenced major transformations in wind power sector that further attracted financers to invest in this sector as independent power producer.

9.2. Data Quality

It has been indicated previously that there are certain stages in life cycle where environmental impacts of the wind power plant are dominated by assumptions and inventory datasets. While conducting this LCIA, data have been complied and structured according to the objective and scope defined and cut-off criteria provided in section 6.2.5. In general, the accuracy of important data is complete, consistent and representative of system being assessed. Following are the important areas that have been checked for data quality.

9.2.1. Material composition

The data on material compositions have been taken from (Gamesa 2013). Production LCI data sets for iron, steel components, aluminum, concrete, copper, silica flour, brass and polymers have been obtained from Thinkstep (2017) generated datasets. In general, these datasets can be considered of good to high quality.

9.2.2. Transport

The transportation includes specific fuel use based on type of carriage (ship/ truck) and distance measurements for transportation of specific turbine components. To estimate transport distances, locations of manufacture of components have been assumed with reasonable certainty. The shipping distances from Brazil (for turbine towers), Spain (rotors) and China (all other parts including nacelle, substation, cables, materials for foundation) and truck distances with Pakistan from Port Qasim, Karachi to wind farm sites are assessed accurately because locations were known. The details related to transportation between raw material processing and manufacturing locations and from there to respective sea ports are unknown, hence neglected. The fuel and truck category used for transportation in Pakistan is based on selection of most suitable GaBi dataset available that is comparable to case of Pakistan in terms of Euro standard for truck (Euro II truck is used) and Sulphur content for fuel type.

9.2.3. Use of energy

The inputs and outputs into construction and operation stage have limited information on GaBi and it reduces quality of contribution analysis. An analysis with complete bill of materials (BOM) or Ecoinvent life cycle inventory is required to determine realistic contributions from each life cycle stage.

CHAPTER 10

CONCLUSION, RECOMMENDATIONS AND FURTHER WORK

10.1. Conclusion

The life cycle assessment of 50MW wind power project in Gharo-Jhimpir Wind Corridor has been carried out using GaBi Education 6.0. The purpose of this assessment was to identify environmental issues related to resource use and emissions during manufacturing, construction and use (electricity generation) phase of the project. Results reveal that although the manufacturing of raw materials and transportation activities contribute significantly to the impact categories, none of these impacts pose any significant environmental consequence. An additional feature associated with wind power projects is they do not require fuel during operation hence all material flows, and emissions are generated only during manufacturing and construction stage which can be controlled/ treated appropriately. Wind power projects can therefore be considered as safe or low-impact source for electricity generation.

Despite huge potential and low environmental impacts, wind energy sector in Pakistan is under-developed. Out of 2.5% share of renewable in electricity generation mix of Pakistan, the contribution of wind power sector is hardly 1% (Mohsin et al. 2019) while having a potential of 132,000 MW (Siddique and Wazir 2016). Another resource that can be coupled with wind power projects is Solar energy as Pakistan has huge potential to utilize both these resources for electricity generation. This enables the IPPs to get maximum benefit from the land allocated for the projects and generate more electricity. Currently, sufficient data for solar power is not available to conduct its life cycle assessment and compare the results for both the resources.

Besides these sources, all other fossil fuel based, and large hydropower projects require a longer construction period and involve various environmental and/or social impacts. Power plants based on coal, oil, natural gas (even with or without carbon capturing and storage mechanism) are known to have high potential for environmental impacts due to emission of greenhouse gases and criteria air pollutants. Hydropower projects although do not create much environmental impacts but their social impacts including physical/ economic displacement, loss of agricultural land, potential danger of desertification to low lying areas reduce its feasibility. Nuclear power plants require an extensive environmental impact assessment and have a longer construction period. Also, nuclear waste disposal requires special considerations.

While considering economic aspect, wind power is one of the two cheapest sources of electricity generation in Pakistan, coal being the other however it is known to have adverse impacts to environment and human health (Aized et al. 2018). Until 2016, wind power sector has been widely criticized by policy makers and institutional stakeholders for huge capital investment and levelized cost (PKR/kWh) as compared to hydropower or other conventional power plants however, technological advancement in turbine design, individual capacity and enhanced capacity factor along with government policies and incentives attracted the independent power producers. The optimization in capital investment i.e., from 12,000 million PKR in 2015 to 8000-9000 million PKR in 2018 while decreasing average levelized tariff from PKR 16 (2015) to PKR 8 (2018) have encouraged more investors towards wind power sector. NEPRA issues licenses only if capacity factor is above 25%. The capacity factor of all currently installed wind power projects varies between 31 to 44 percent.

The modification in tariff regime from upfront to cost-plus has become an additional incentive. For upfront tariff, prices have been determined and announced by the regulator based on its own scrutiny and calculations along with certain terms and conditions while projects sponsors were bound to accept of back-off from the tariff based on whether or not they found it viable for their project. The cost-plus tariff is the one where IPP receives it actual cost plus an agreed profit, along with certain incentives for establishing renewable energy-based power project (Ministry of Energy n.d.). This has invited foreign investment to generate tax income as well as increase employment hence positively contributing in maintaining sustainability.

Wind power projects are also viable from creating positive social impact. The Gharo Jhimpir Wind Corridor was a completely barren land with no resources of income and even basic amenities of life. With the installation of wind power projects, it provided a source of employment for unskilled and skilled labor. (Akber, Thaheem, and Arshad 2017) estimated direct and total (including direct and indirect) employment for wind power and found them to be 411 job-years/TWh and 815 job-years/TWh respectively which is higher than employment rate for hydropower.

NEPRA issues generation licenses to investors only when they are funded by International Finance Institutions. IPPs are bound to comply to all requirements of DFIDs and conducting Corporate Social Responsibility (CSR) activities to strengthen local community is a key requirement of all finance institutions. In this way, this tends to improve the quality of life for local communities.

There are some localized impacts associated with wind power generation like noise, shadow flicker, bird mortality etc. which are assessed and mitigated individually for the projects. Until first quarter of 2019, there is no incident data available for bird mortality due to turbines.

Considering the three aspects of sustainability with a life cycle perspective, wind power is a suitable option for electricity generation in Pakistan.

10.2. Recommendations

The Renewable Energy Policy announced in 2006 provided multiple incentives to independent power producers however it failed to achieve all desirable results due to lack of an action plan that could complement the policy framework. The new government formed in August 2018 is enthusiastic towards utilizing renewable energy resources for electricity generation hence meeting targets set in national development agenda, Nationally Determined Contributions (NDCs) and Vision 2025. The new target established is to increase the share of renewable up to 30% in total power generation by 2030.

To combat climate change and global warming challenges, Pakistan has ratified the Paris Agreement and devised its Intended Nationally Determined Targets (INDCs) and policy reforms have been introduced through Climate Change Policy, 2012. These INDCs provide a roadmap to Pakistan for eliminating the current gap in electricity demand and supply and also aims to optimize the energy mix of Pakistan. Pakistan ranks 135th in per capita carbon emissions emitter however it is among top seven countries of the word with maximum casualties and losses due to climate change. Despite its low contribution, combating global warming and climate change issues a challenge and shift in energy generation regime has a key contribution towards it. Wind power is therefore, a recommendable resource for electricity generation to meet INDCs and climate change initiatives planned under the policy.

The Renewable Energy Policy 2019 is in process of development which will harness the objectives established by Government of Pakistan to achieve sustainability and address the dimensions of economic benefits, energy security, social equity and environmental protection.

Life cycle assessment can enable policy makers to identify potential environmental impacts arising from a variety of scenarios. However, it is a comprehensive process and require a lot of data. It is recommended to:

- conduct life cycle assessment of current and suggested energy mix
- ensure related technical data is publicly available and accessible for comparison
- utilize the information to identify the mix where maximum economic and social benefits are guaranteed without harming the environment.

Besides holding life cycle assessment, it is necessary to consider following aspects in policy making:

- The process of establishing renewable energy projects is very lengthy and takes 9 months for solicited projects to 24 months for unsolicited proposals of wind power projects for issuance of Letter of Support (LoS). Future policy can introduce mechanisms to reduce this time by using fast-tracking mechanisms for renewable energy projects;
- The proponent is responsible for holding all technical and feasibility studies for the site themselves. The policy should have recommendations or subsidies that could save the costs associated with these activities.
- There is lack of suitable infrastructure for commissioning wind power projects. The IPP is not only responsible for constructing access roads to the plant sites but also handle the social issues arising from these activities, like, right-of-way or disturbance of environment for local communities residing nearby. At minimum, government should provide a support mechanism to handle social issues.
- There is a huge capital costs associated wind power project and one of the reasons for this is absence of local production facilities. All the components including turbine tower, nacelle, rotor and steel for foundations is imported from different countries. This do not increase the capital cost only but also increase impacts by involving maritime transportation across countries/ continents.

The incentives provided by government to subsidize crude oil prices attract IPPs for investment in thermal power projects however renewable energy technologies face a setback due to already high capital costs. The cost of externalities (both negative and positive) is not considered however. To support renewable energy technologies, policy framework should consider integration of cost of negative and positive externalities into project cost and determined levelized tariff based on social marginal costs.

10.3. Further work

This life cycle assessment study for electricity generation through wind power has been done by applying a certain cut-off criterion due to software and data limitations and resource constraints. For future, it is recommended to conduct a life cycle assessment for all the various turbine models installed in the corridor and compare the results to determine the potential impacts for various suppliers. It is suggested to use advanced GaBi Dfx software along with the globally accepted data inventory that could provide complete bill of materials to determine real-time impacts associated with each phase. Additionally, the results could be compared by conducting LCA using other software or methodologies.

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APPENDICES

A. Material and Energy flow for key processes

Mass (g)	Total	DE: Electricity grid mix (production mix) ts <LC>	Total heavy fuel use (maritime shipping)	Total fuel use (Road Transport)	DE: Aluminum ingot mix ts	DE: BF Steel billet / slab / bloom ts <p-agg>
Resources	**211.228739**	**3.42023937**	**0.36374366**	**0.14380023**	**131.196853**	**38.1735053**
Energy resources	**0.10716836**	**0.00088349**	**0.00711518**	**0.00216452**	**0.00429109**	**0.07018998**
Non-renewable energy resources	***0.10716836***	***0.00088349***	***0.00711518***	***0.00216452***	***0.00429109***	***0.07018998***
Crude oil (resource)	0.01780049	1.48E-05	6.64E-03	0.00198713	0.00096632	0.00557795
Hard coal (resource)	0.07669312	0.00021759	5.1039E-05	4.98E-05	0.002071621	0.06393643
Lignite (resource)	0.00916929	0.00059232	7.3091E-06	8.19E-07	0.000203483	0.00326845
Natural gas (resource)	0.00350362	5.87E-05	4.18E-04	0.00012676	0.00104817	-0.0025939
Material resources	**211.1215713**	**3.419355873**	**0.356628482**	**0.141635708**	**131.1925626**	**38.10331531**
Non-renewable elements	***0.10807427***	***-7.22E-08***	***5.30E-06***	***2.02E-06***	***2.32E-05***	***0.09409031***
Chromium	4.90E-06	1.09E-08	2.41E-09	7.39E-10	2.33E-07	1.28E-07
Cobalt	2.89E-11	3.78E-13	1.66E-14	8.28E-15	6.01E-13	1.75E-12
Copper	0.00083559	1.85E-07	1.61E-08	5.69E-09	8.22E-07	1.03E-06
Gold	2.99E-09	2.64E-12	3.98E-14	1.89E-14	9.06E-13	9.30E-12
Iron	0.10601389	-9.11E-07	5.08E-06	1.94E-06	2.18E-05	0.09332162
Lead	4.27E-05	3.43E-08	7.71E-08	2.74E-08	8.70E-08	2.27E-07
Manganese	0.00093076	4.05E-08	5.24E-08	2.07E-08	2.86E-07	0.00076469
Nickel	3.81E-07	2.49E-09	2.25E-12	2.59E-11	-8.33E-09	5.17E-09
Phosphorus	1.11E-06	8.67E-09	1.54E-08	4.09E-09	2.30E-08	5.07E-07
Silicon	4.11E-07	1.96E-08	-7.46E-10	3.92E-12	-1.49E-07	9.92E-09
Silver	5.36E-07	2.21E-10	8.40E-11	3.00E-11	1.64E-10	8.67E-10
Sulphur	3.75E-06	3.74E-07	8.03E-09	1.39E-09	1.16E-07	1.50E-06
Zinc	0.00024671	1.44E-07	5.12E-08	1.83E-08	1.02E-07	5.62E-07

Non-renewable resources	***1.81854389***	***0.01002236***	***0.00043093***	***0.00020249***	***0.02567091***	***0.94572089***
Bauxite	0.00852457	7.98E-07	4.51E-08	1.78E-08	0.00823597	-5.62E-06
Bentonite	0.00010567	1.14E-07	7.84E-06	2.78E-06	2.37E-06	-3.56E-06
Clay	0.00309496	7.03E-07	4.08E-07	1.65E-07	0.00013579	-0.0002356
Colemanite ore	0.00059088	8.19E-09	3.12E-10	1.52E-10	4.38E-09	4.85E-08
Dolomite	0.00140117	8.88E-07	3.02E-08	8.34E-09	6.57E-07	2.86E-06
Fluorspar (calcium fluoride; fluorite)	9.64E-05	2.36E-08	1.89E-09	8.04E-10	4.18E-05	1.56E-07
Gypsum (natural gypsum)	0.00172376	7.50E-08	2.81E-07	1.08E-07	1.03E-06	-0.0002748
Ilmenite (titanium ore)	2.27E-06	2.60E-10	3.21E-10	1.23E-10	8.56E-09	1.50E-07
Inert rock	1.31979045	0.00993004	0.00039464	0.00018607	0.01546009	0.95975341
Kaolin ore	4.10E-06	5.08E-10	2.11E-10	7.28E-11	4.89E-09	-1.41E-08
Limestone (calcium carbonate)	0.10853351	3.61E-05	1.60E-05	7.21E-06	0.00038446	0.02091174
Magnesite (Magnesium carbonate)	3.57E-06	4.84E-08	2.02E-08	6.80E-09	6.43E-08	1.55E-06
Magnesium chloride leach (40%)	2.03E-05	1.31E-06	1.55E-08	7.93E-09	5.70E-07	1.05E-05
Natural Aggregate	0.30296111	1.07E-05	3.21E-06	2.24E-06	0.00052689	-0.0318509
Natural pumice	5.64E-05	2.35E-09	4.47E-10	1.65E-10	3.51E-08	1.70E-08
Potash-salt, crude (hard salt, 10% K2O)	0.00013175	1.25E-05	8.24E-07	2.52E-07	4.06E-06	5.83E-06
Pyrite	2.88E-06	-1.40E-10	1.16E-09	4.15E-10	-1.38E-09	5.53E-09
Quartz sand (silica sand; silicon dioxide)	0.00440882	1.46E-06	2.39E-07	9.97E-08	9.49E-05	0.00166096
Shale	0.00047783	1.56E-08	2.62E-09	1.02E-09	1.86E-07	7.20E-08
Sodium chloride (rock salt)	0.00022597	5.81E-07	3.01E-08	1.10E-08	0.00016911	2.07E-05

Soil	0.06648249	1.78E-05	7.14E-06	3.48E-06	0.0006064	-0.0041371
Stone from mountains	8.14E-06	2.09E-08	1.08E-09	3.95E-10	6.09E-06	7.46E-07
Renewable resources	***209.194953***	***3.40933359***	***0.35619225***	***0.14143119***	***131.166868***	***37.0635041***
Water	208.715785	3.39922048	0.35472378	0.14058983	131.115607	36.7887936
Air	0.47085659	0.00975640	0.00145044	0.00082392	0.05111607	0.27280964
Carbon dioxide	0.00815024	0.00035631	1.7961E-05	1.74E-05	0.00014335	0.00176805
Oxygen	0.00016174	3.99E-07	6.96E-08	2.50E-08	2.43E-06	0.00013282

Mass (g)	**DE: BF Steel billet / slab / bloom ts <p-agg>**	**DE: Concrete C30/37 (Ready-mix concrete) ts**	**DE: Copper mix (99,999% from electrolysis) ts**	**DE: Glass fibres ts**	**DE: Silica sand (flour) ts**
Resources	**38.1735053**	**13.76312767**	**2.190062214**	**9.148594511**	**2.08E-05**
Energy resources	**0.070189989**	**0.006392498**	**0.000741838**	**0.003340735**	**4.95E-09**
Non-renewable energy resources	*0.070189989*	*0.006392498*	*0.000741838*	*0.003340735*	*4.95E-09*
Crude oil (resource)	0.005577946	0.001120222	0.000405485	9.06E-05	1.20E-10
Hard coal (resource)	0.063936434	0.001444481	0.000175297	0.000463011	1.03E-09
Lignite (resource)	0.003268448	0.003484214	4.87E-05	0.001243329	2.82E-09
Natural gas (resource)	-0.002593979	0.000343376	0.000112213	0.001543732	9.88E-10
Material resources	**38.10331531**	**13.75673517**	**2.189320375**	**9.145253776**	**2.07E-05**
Non-renewable elements	***0.09409031***	***0.000469945***	***0.001118952***	***1.04E-05***	***5.65E-12***
Chromium	1.28E-07	3.62E-08	9.86E-09	3.30E-08	5.97E-14
Cobalt	1.75E-12	1.14E-12	7.68E-14	8.14E-13	1.80E-18
Copper	1.03E-06	5.65E-07	0.000831005	6.54E-07	8.82E-13
Gold	9.30E-12	7.92E-12	2.95E-09	8.13E-12	1.24E-17
Iron	0.093321618	0.000466879	2.14E-06	8.06E-06	1.54E-12
Lead	2.27E-07	1.17E-07	4.17E-05	1.16E-07	1.72E-13
Manganese	0.000764699	1.71E-07	2.56E-08	1.90E-07	2.54E-13
Nickel	5.17E-09	7.37E-09	1.44E-11	5.48E-09	1.17E-14
Phosphorus	5.07E-07	2.52E-07	7.25E-08	2.19E-08	5.53E-14
Silicon	9.92E-09	5.68E-08	-3.08E-09	3.98E-08	8.99E-14
Silver	8.67E-10	6.84E-10	5.50E-07	9.35E-10	1.05E-15
Sulphur	1.50E-06	1.36E-06	5.18E-08	7.80E-07	1.81E-12
Zinc	5.62E-07	4.41E-07	0.000243428	4.89E-07	6.79E-13

Non-renewable resources	***0.945720895***	***0.554227281***	***0.17899466***	***0.031301967***	***9.96E-08***
Bauxite	-5.62E-06	0.000206127	1.89E-07	1.80E-06	3.80E-12
Bentonite	-3.56E-06	8.93E-05	8.55E-07	2.52E-06	1.72E-12
Clay	-0.000235607	0.003085253	5.05E-05	3.86E-05	6.53E-11
Colemanite ore	4.85E-08	2.46E-08	2.08E-09	0.000590779	3.86E-14
Dolomite	2.86E-06	3.42E-06	1.70E-07	0.000387551	4.51E-12
Fluorspar (calcium fluoride; fluorite)	1.56E-07	1.45E-07	8.49E-09	5.38E-05	1.24E-13
Gypsum (natural gypsum)	-0.000274793	0.002096449	9.45E-08	3.27E-07	4.64E-13
Ilmenite (titanium ore)	1.50E-07	2.08E-06	2.31E-09	8.57E-10	1.33E-15
Inert rock	0.959753409	0.058971483	0.178557765	0.024552766	4.88E-08
Kaolin ore	-1.41E-08	2.11E-09	5.27E-10	8.09E-09	5.91E-15
Limestone (calcium carbonate)	0.02091174	0.085444602	7.87E-05	0.001851778	1.79E-10
Magnesite (Magnesium carbonate)	1.55E-06	1.45E-06	1.28E-07	1.15E-07	2.97E-13
Magnesium chloride leach (40%)	1.05E-05	4.24E-06	1.51E-07	3.28E-06	6.15E-12
Natural Aggregate	-0.031850972	0.335524719	6.09E-05	7.31E-05	1.20E-10
Natural pumice	1.70E-08	5.64E-05	1.85E-09	8.45E-09	1.37E-14
Potash-salt, crude (hard salt, 10% K2O)	5.83E-06	7.44E-05	3.83E-06	2.29E-05	6.24E-11
Pyrite	5.53E-09	5.62E-08	7.61E-11	-5.25E-10	-8.00E-16
Quartz sand (silica sand; silicon dioxide)	0.001660958	0.000399273	0.000151141	0.001824805	3.86E-08
Shale	7.20E-08	0.000478419	1.07E-08	6.18E-08	9.36E-14
Sodium chloride (rock salt)	2.07E-05	7.55E-06	6.89E-06	1.08E-05	3.31E-12
Soil	-0.004137104	0.067751544	8.30E-05	0.001877511	1.16E-08
Stone from mountains	7.46E-07	2.72E-07	2.48E-07	3.89E-07	1.19E-13
Renewable resources	***37.06350411***	***13.20203794***	***2.009206763***	***9.113941372***	***2.06E-05***

Water	36.78879361	13.16224841	1.996931966	9.082340871	2.06E-05
Air	0.272809638	0.035431505	0.012176958	0.030826752	5.86E-08
Carbon dioxide	0.001768045	0.004350705	9.74E-05	0.000767294	1.70E-09
Oxygen	0.000132815	7.32E-06	4.65E-07	6.45E-06	1.88E-12
Mass (g)	**EU-28: Brass (CuZn20) ts <p-agg>**	**EU-28: Heavy fuel oil at refinery (1.0wt.% S) ts**	**EU-28: Tap water ts**	**Total Maritime transport**	**GLO: Steel rebar world steel**
Resources	**0.011225262**	**0.057179383**	**0.000823402**	**12.81674352**	**12.8167435 2**
Energy resources	**2.94E-06**	**0.000486075**	**9.67E-08**	**0.012045952**	**0.01204595 2**
Non-renewable energy resources	***2.94E-06***	***0.000486075***	***9.67E-08***	***0.012045952***	***0.01204595 2***
Crude oil (resource)	1.40E-06	0.000451548	3.46E-08	0.000998043	0.00099804 3
Hard coal (resource)	6.43E-07	1.68E-06	2.30E-08	0.008283177	0.00828317 7
Lignite (resource)	2.97E-07	2.06E-06	1.74E-08	0.000320342	0.00032034 2
Natural gas (resource)	5.85E-07	3.08E-05	2.18E-08	0.002445739	0.00244573 9
Material resources	0.011222321	0.056693307	0.000823305	12.80469756	12.8046975 6
Non-renewable elements	***2.71E-06***	***3.54E-07***	***1.00E-08***	***0.012351453***	***0.01235145 3***
Chromium	3.94E-11	1.67E-10	5.28E-13	4.44291E-06	4.44E-06
Cobalt	4.75E-16	1.86E-15	1.10E-17	2.40952E-11	2.41E-11
Copper	1.84E-06	1.24E-09	5.19E-12	-5.31083E-07	-5.31E-07
Gold	6.48E-12	8.00E-15	6.59E-17	3.58512E-12	3.59E-12
Iron	6.55E-09	3.39E-07	9.91E-09	0.012187252	0.01218725 2
Lead	2.35E-07	4.90E-09	1.53E-12	6.31095E-08	6.31E-08
Manganese	1.06E-10	3.64E-09	9.59E-11	0.000165275	0.00016527 5
Nickel	1.60E-12	9.36E-12	6.91E-14	3.6848E-07	3.68E-07
Phosphorus	1.71E-10	2.58E-10	7.56E-13	2.04379E-07	2.04E-07
Silicon	2.03E-12	3.01E-11	4.68E-13	4.36893E-07	4.37E-07
Silver	1.36E-09	5.73E-12	6.21E-15	-1.82113E-08	-1.82E-08
Sulphur	2.41E-10	1.13E-09	9.28E-12	-4.35433E-07	-4.35E-07
Zinc	6.27E-07	3.50E-09	3.96E-12	8.45199E-07	8.45E-07
Non-renewable resources	***0.000402501***	***6.72E-05***	***7.97E-07***	***0.07156899***	***0.07156899***

Bauxite	3.10E-09	4.84E-09	1.24E-08	8.52341E-05	8.52E-05
Bentonite	2.85E-09	4.90E-07	1.02E-10	3.49368E-06	3.49E-06
Clay	1.13E-07	2.72E-08	5.49E-09	1.90375E-05	1.90E-05
Colemanite ore	1.09E-11	7.97E-11	2.28E-13	1.68556E-08	1.69E-08
Dolomite	7.83E-10	5.61E-09	2.86E-11	0.001005585	0.001005585
Fluorspar (calcium fluoride; fluorite)	5.41E-11	2.26E-10	9.44E-13	4.485E-07	4.48E-07
Gypsum (natural gypsum)	3.41E-10	1.74E-08	6.39E-10	-9.98127E-05	-9.98E-05
Ilmenite (titanium ore)	8.37E-12	2.00E-11	1.74E-12	3.20106E-08	3.20E-08
Inert rock	0.000400536	6.50E-05	4.94E-07	0.071583102	0.071583102
Kaolin ore	4.14E-12	5.27E-11	1.13E-13	4.09644E-06	4.10E-06
Limestone (calcium carbonate)	8.24E-07	9.90E-07	6.55E-08	-0.00019793	-0.00019793
Magnesite (Magnesium carbonate)	3.24E-10	3.67E-09	3.37E-12	1.81359E-07	1.81E-07
Magnesium chloride leach (40%)	9.43E-10	2.95E-09	2.06E-09	2.06694E-07	2.07E-07
Natural Aggregate	1.59E-07	2.21E-07	8.59E-09	-0.00138991	-0.00138991
Natural pumice	7.57E-12	4.29E-11	1.28E-13	6.13135E-09	6.13E-09
Potash-salt, crude (hard salt, 10% K2O)	1.10E-08	6.18E-08	-3.67E-09	7.16253E-06	7.16E-06
Pyrite	1.43E-13	7.02E-11	4.54E-14	2.82134E-06	2.82E-06
Quartz sand (silica sand; silicon dioxide)	3.34E-07	1.89E-08	1.64E-07	0.000275383	0.00027538
Shale	4.42E-11	3.03E-10	8.97E-13	-9.4020E-07	-9.40E-07
Sodium chloride (rock salt)	2.45E-07	5.69E-09	6.45E-09	1.00276E-05	1.00E-05
Soil	2.62E-07	3.30E-07	5.69E-08	0.000272293	0.00027229
Stone from mountains	8.83E-09	2.05E-10	2.32E-10	3.66977E-07	3.67E-07
Renewable resources	***0.010817114***	***0.056625781***	***0.000822498***	***12.72077712***	***12.7207771***
Water	0.010765507	0.056530661	0.00080718	12.66373578	12.6637358

Air	5.10E-05	9.36E-05	1.53E-05	0.056398504	0.05639850
Carbon dioxide	4.37E-07	1.56E-06	1.10E-08	0.000631346	0.00063135
Oxygen	1.35E-07	3.03E-09	3.85E-11	1.16297E-05	1.16E-05

B. Emissions to air, water and soil from key processes

Mass (g)	Total	DE: Electricity grid mix (production mix) ts <LC>	Total heavy fuel use (maritime shipping)	Total fuel use (Road Transport)	DE: Aluminium ingot mix ts
Deposited goods	**1.369038106**	**0.009860054**	**0.000309844**	**1.58E-04**	**0.017761897**
Radioactive waste	**3.96E-05**	**1.78E-06**	**7.02E-08**	**2.26E-08**	**1.50E-05**
Stockpile goods	**1.368998552**	**0.009858271**	**0.000309774**	**1.58E-04**	**0.017746891**
Hazardous waste (deposited)	3.17E-08	1.63E-11	3.28E-11	1.24E-11	1.18E-10
Overburden (deposited)	1.166491465	0.009806276	0.000279633	1.47E-04	0.013860286
Slag (deposited)	1.56E-12	1.60E-13	1.65E-15	7.16E-16	4.62E-14
Spoil (deposited)	0.054067907	1.86E-05	1.96E-05	7.96E-06	0.000570252
Tailings (deposited)	0.123910639	1.15E-05	9.50E-06	1.84E-06	9.13E-05
Waste (deposited)	0.02452851	2.18E-05	1.09E-06	6.39E-07	0.00322504
Emissions to air	**1.660287351**	**0.050745016**	**0.010417232**	**0.003366693**	**0.191454721**
Heavy metals to air	**4.98E-06**	**1.69E-09**	**1.09E-08**	**8.10E-09**	**1.40E-08**
Inorganic emissions to air	**1.386686652**	**0.039302048**	**0.009490274**	**0.002742728**	**0.149776528**
Carbon dioxide	0.334805717	0.001573495	0.00186391	0.000629393	0.011965178
Carbon dioxide (biotic)	0.0086212	0.00035359	1.5692E-05	3.08E-06	0.000159954
Carbon dioxide (land use change)	0.000111433	3.85E-06	1.26E-06	3.18E-07	3.29E-06
Carbon monoxide	0.00220924	8.14E-07	2.35E-06	8.63E-07	4.64E-06
Chloride (unspecified)	2.52E-07	8.53E-11	1.24E-08	3.33E-09	3.04E-09
Fluoride	3.11E-06	5.13E-10	2.11E-11	6.39E-12	3.61E-07
Hydrogen	6.73E-07	7.28E-10	6.94E-10	2.45E-10	5.56E-08
Hydrogen chloride	5.25E-06	7.56E-08	2.35E-08	4.55E-09	3.74E-07
Hydrogen fluoride	9.52E-07	4.45E-09	5.80E-10	3.53E-10	5.73E-07
Hydrogen sulphide	3.14E-06	1.50E-07	2.38E-08	7.67E-09	6.88E-08
Nitrogen (atmospheric nitrogen)	5.66E-05	1.30E-07	2.41E-07	8.02E-08	1.08E-06
Nitrogen dioxide	1.91E-05	1.39E-09	7.35E-11	3.09E-11	6.05E-09
Nitrogen monoxide	7.25E-05	1.90E-08	8.71E-10	2.38E-10	2.57E-08
Nitrogen oxides	0.001029984	1.72E-06	5.77E-06	2.50E-06	2.18E-05
Nitrogen, total	3.63E-12	3.64E-13	4.12E-15	1.90E-15	1.06E-13
Nitrous oxide (laughing gas)	3.96E-06	7.31E-08	3.67E-08	1.13E-08	2.18E-07

Oxygen	0.000680442	2.71E-05	3.66E-07	7.31E-08	1.46E-05
Sulphur dioxide	0.000841787	1.00E-06	7.78E-06	3.01E-06	3.09E-05
Water (evapotranspiration)	0.562656162	0.030963709	0.003620159	0.000922372	0.013189933
Water vapour	0.475562895	0.006376241	0.00397263	0.001181002	0.124383393
Organic emissions to air (group VOC)	**0.000340295**	**2.34E-06**	**2.67E-05**	**8.96E-06**	**2.80E-05**
Group NMVOC to air	***5.32E-05***	***1.18E-07***	***5.45E-06***	***1.79E-06***	***2.29E-06***
Methane	0.000275867	1.88E-06	2.12E-05	7.16E-06	2.56E-05
Other emissions to air	***0.27304242***	***0.011440307***	***0.000899548***	***0.000614489***	***0.041644398***
Clean gas	9.74E-05	7.76E-08	3.49E-08	1.40E-08	9.76E-06
Exhaust	0.18271671	0.007871981	0.000851881	0.000592846	0.040098785
Unused primary energy from solar energy	0.036285074	0.003520608	4.33331E-05	2.00E-05	0.001120857
Used air	***0.053943274***	***4.76E-05***	***4.30E-06***	***1.61E-06***	***0.000414992***
Particles to air	***0.000213002***	***3.24E-07***	***6.86E-07***	***5.11E-07***	***5.75E-06***
Emissions to fresh water	**208.6046335**	**3.484151921**	**0.351637322**	**0.139661109**	**131.9354075**
Analytical measures to fresh water	**5.21E-05**	**2.26E-06**	**2.19E-06**	**6.48E-07**	**4.78E-06**
Biological oxygen demand (BOD)	1.68E-06	5.47E-09	2.61E-08	9.68E-09	2.80E-08
Chemical oxygen demand (COD)	5.17E-05	2.25E-06	2.09E-06	6.16E-07	4.67E-06
Heavy metals to fresh water	**3.19E-05**	**1.17E-06**	**2.22E-07**	**4.47E-08**	**4.49E-07**
Inorganic emissions to fresh water	**0.003783403**	**1.73E-05**	**1.64E-03**	**0.000421841**	**0.000145561**
Calcium	1.55E-05	7.85E-07	5.38E-08	5.24E-08	4.64E-06
Carbonate	3.79E-05	2.21E-08	2.03E-05	5.21E-06	1.23E-06
Chloride	0.003529127	9.12E-06	1.61E-03	0.000412916	0.000127961
Chlorine (dissolved)	1.80E-07	7.97E-09	4.15E-10	1.37E-10	6.74E-08
Fluoride	2.06E-05	1.66E-06	1.54E-08	1.76E-09	1.37E-06
Hydrogen peroxide	3.55E-08	3.43E-09	5.90E-11	3.07E-11	1.06E-09
Sodium	3.10E-05	1.17E-06	4.46E-07	1.88E-07	2.37E-06
Sodium chloride (rock salt)	1.16E-08	1.19E-09	2.92E-11	1.13E-11	7.26E-10
Sodium hypochlorite	6.49E-07	2.02E-09	6.19E-11	1.78E-11	7.86E-09
Sodium sulphate	8.67E-07	8.20E-08	1.44E-09	7.45E-10	2.53E-08
Sulfate	0.000123303	3.83E-06	9.23E-06	2.39E-06	5.49E-06

Sulphide	6.94E-06	3.87E-09	3.70E-06	9.50E-07	2.23E-07
Organic emissions to fresh water	**3.99E-05**	**1.09E-06**	**1.14E-06**	**2.81E-07**	**1.93E-06**
Other emissions to fresh water	**205.7097163**	**3.360025601**	**0.345092348**	**0.137528238**	**130.8234311**
Pesticides to fresh water	5.78E-10	5.63E-11	8.29E-13	4.28E-14	1.63E-11
Collected rainwater to river	0.018524932	1.05E-05	7.44E-07	4.40E-07	0.00240235
Cooling water to river	0.042276986	2.30E-05	8.08E-04	0.000373389	0.001133047
Processed water to groundwater	0.000366535	2.22E-05	1.61E-06	1.60E-06	6.50E-05
Processed water to river	0.455944308	0.000664407	0.007166225	0.001817281	0.012839073
Turbined water to river	18.79515678	0.002113415	0.014943277	0.001586266	16.37898305
Particles to fresh water	**0.00028005**	**1.08E-05**	**1.73E-05**	**6.82E-06**	**1.44E-05**
Soil loss by erosion into water	0.000187199	1.05E-05	8.65E-07	1.97E-07	4.54E-06
Solids (suspended)	9.29E-05	3.32E-07	1.64E-05	6.63E-06	9.81E-06
Radioactive emissions to fresh water	**2.890729761**	**0.124093642**	**0.004884699**	**0.001703233**	**1.111809415**
Radium (Ra226)	2.890729761	0.124093642	0.004884699	0.001703233	1.111809415
Emissions to sea water	**0.653739092**	**0.003083838**	**0.002361084**	**0.001023364**	**0.158664872**
Analytical measures to sea water	**6.23E-07**	**1.06E-09**	**2.97E-07**	**3.78E-08**	**4.11E-08**
Heavy metals to sea water	**4.98E-08**	**4.61E-11**	**2.52E-08**	**3.42E-09**	**3.09E-09**
Inorganic emissions to sea water	**0.000544612**	**4.46E-07**	**2.68E-04**	**3.66091E-05**	**3.30E-05**
Chloride	0.000532955	4.36E-07	2.63E-04	3.5868E-05	3.18E-05
Organic emissions to sea water	**3.26E-07**	**2.67E-10**	**1.59E-07**	**2.17E-08**	**1.93E-08**
Other emissions to sea water	**0.65318738**	**0.003083349**	**0.002089572**	**0.000986495**	**0.158631202**
Particles to sea water	**6.10E-06**	**4.21E-08**	**2.78E-06**	**1.97E-07**	**6.53E-07**
Emissions to industrial soil	**6.26E-07**	**1.09E-08**	**2.36E-10**	**4.63E-11**	**1.71E-08**

Mass (g)	DE: BF Steel billet / slab / bloom ts <p-agg>	DE: Concrete C30/37 (Ready-mix concrete) ts	DE: Copper mix (99,999% from electrolysis) ts	DE: Glass fibres ts
Deposited goods	**0.989426061**	**0.147628683**	**0.176968395**	**0.023802001**
Radioactive waste	**1.15E-05**	**6.38E-06**	**3.81E-07**	**4.41E-06**
Stockpile goods	**0.989414576**	**0.1476223**	**0.176968014**	**0.023797589**
Hazardous waste (deposited)	1.27E-09	4.57E-09	1.58E-10	7.97E-11
Overburden (deposited)	0.932155285	0.073616349	0.113762667	0.022536221
Slag (deposited)	5.39E-13	4.74E-13	1.47E-14	3.29E-13
Spoil (deposited)	-0.007122743	0.060460656	3.37E-05	5.77E-05
Tailings (deposited)	0.061380585	4.25E-05	0.061964587	0.00027132
Waste (deposited)	0.003001448	0.01350275	0.0012071	0.000932302
Emissions to air	**0.734749725**	**0.26377272**	**0.060294788**	**0.127785939**
Heavy metals to air	**4.31E-06**	**3.61E-08**	**3.42E-07**	**4.74E-09**
Inorganic emissions to air	**0.625955295**	**0.226105373**	**0.051743637**	**0.102361593**
Carbon dioxide	0.208720833	0.045349407	0.001988981	0.007305107
Carbon dioxide (biotic)	0.002125257	0.00430509	9.09E-05	0.000789959
Carbon dioxide (land use change)	5.00E-05	2.60E-05	6.44E-06	8.39E-06
Carbon monoxide	0.001757759	0.000155671	1.53E-06	2.53E-06
Chloride (unspecified)	4.10E-09	1.66E-09	5.33E-10	2.24E-07
Fluoride	2.85E-09	1.81E-09	1.14E-10	2.74E-06
Hydrogen	1.38E-07	2.39E-07	2.10E-08	1.49E-07
Hydrogen chloride	3.22E-06	6.31E-07	2.56E-07	1.63E-07
Hydrogen fluoride	2.64E-07	2.38E-08	2.34E-08	9.59E-09
Hydrogen sulphide	2.04E-06	4.50E-07	1.14E-08	3.14E-07
Nitrogen (atmospheric nitrogen)	4.43E-05	3.82E-06	1.27E-07	8.30E-07
Nitrogen dioxide	-2.41E-08	1.13E-06	3.59E-10	1.36E-05
Nitrogen monoxide	4.41E-08	1.33E-05	5.61E-09	4.25E-08
Nitrogen oxides	0.000331089	5.10E-05	4.78E-06	4.89E-06
Nitrogen, total	1.24E-12	1.08E-12	3.48E-14	7.50E-13
Nitrous oxide (laughing gas)	2.08E-06	3.83E-07	1.84E-07	1.69E-07
Oxygen	0.000401989	9.24E-05	4.10E-06	7.40E-05
Sulphur dioxide	0.000287453	2.94E-05	1.00E-05	3.54E-05
Water (evapotranspiration)	0.23377786	0.151566213	0.017892939	0.065135302
Water vapour	0.178449969	0.024509763	0.031743261	0.028987538
Organic emissions to air (group VOC)	**0.000152807**	**2.21E-05**	**3.35E-06**	**1.58E-05**
Group NMVOC to air	***1.41E-05***	***5.49E-06***	***4.11E-07***	***2.29E-06***

Methane	0.000130486	1.53E-05	2.50E-06	1.28E-05
Other emissions to air	***0.108508226***	***0.037598243***	***0.008546669***	***0.025406235***
Clean gas	1.18E-05	5.75E-05	3.76E-06	5.22E-06
Exhaust	0.045010648	0.026798548	0.006958629	0.017812726
Unused primary energy from solar energy	0.012473482	0.010484659	0.000410702	0.007278769
Used air	***0.05101234***	***0.000257529***	***0.001173574***	***0.000309518***
Particles to air	***0.000129091***	***4.70E-05***	***7.89E-07***	***2.34E-06***
Emissions to fresh water	**37.24991666**	**13.37235691**	**1.972663679**	**9.289137436**
Analytical measures to fresh water	**2.41E-05**	**7.26E-06**	**2.96E-06**	**4.96E-06**
Biological oxygen demand (BOD)	1.34E-06	5.15E-08	1.25E-08	9.02E-08
Chemical oxygen demand (COD)	2.13E-05	7.18E-06	2.94E-06	4.86E-06
Heavy metals to fresh water	**1.68E-05**	**6.94E-06**	**4.35E-07**	**2.46E-06**
Inorganic emissions to fresh water	**0.001053837**	**0.000194799**	**8.27E-05**	**4.54E-05**
Calcium	5.23E-06	2.51E-06	1.98E-07	1.85E-06
Carbonate	7.56E-06	1.56E-06	8.54E-07	1.38E-07
Chloride	0.000951672	0.000155903	6.89E-05	2.72E-05
Chlorine (dissolved)	5.15E-08	2.86E-08	1.72E-09	1.98E-08
Fluoride	8.18E-06	5.15E-06	9.31E-08	3.49E-06
Hydrogen peroxide	1.25E-08	1.02E-08	3.83E-10	7.08E-09
Sodium	1.34E-05	6.70E-06	2.40E-07	2.68E-06
Sodium chloride (rock salt)	2.67E-09	3.59E-09	1.44E-10	3.07E-09
Sodium hypochlorite	5.44E-07	1.78E-08	3.84E-09	3.27E-08
Sodium sulphate	2.99E-07	2.46E-07	9.15E-09	1.69E-07
Sulfate	5.69E-05	1.98E-05	1.18E-05	8.17E-06
Sulphide	1.37E-06	2.79E-07	1.55E-07	2.49E-08
Organic emissions to fresh water	**2.49E-05**	**5.43E-06**	**1.41E-06**	**2.37E-06**
Other emissions to fresh water	**36.42026345**	**12.92446288**	**1.943783983**	**8.97959932**
Pesticides to fresh water	2.00E-10	1.68E-10	6.03E-12	1.17E-10
Collected rainwater to river	0.002166078	0.009973683	0.000892559	0.000675595
Cooling water to river	0.000599471	0.007195721	0.000249629	0.0006169
Processed water to groundwater	0.000146713	6.69E-05	1.56E-06	4.64E-05
Processed water to river	0.32069477	0.007196683	0.010586648	0.02498558
Turbined water to river	0.318655788	0.015309527	0.002643159	0.008664288

Particles to fresh water	**0.000115381**	**5.61E-05**	**7.30E-06**	**2.76E-05**
Soil loss by erosion into water	8.17E-05	5.14E-05	4.71E-06	2.22E-05
Solids (suspended)	3.37E-05	4.61E-06	2.59E-06	5.32E-06
Radioactive emissions to fresh water	**0.828418138**	**0.447623542**	**0.028784896**	**0.309455379**
Radium (Ra226)	0.828418138	0.447623542	0.028784896	0.309455379
Emissions to sea water	**0.050014197**	**0.016086776**	**0.003989094**	**0.010943203**
Analytical measures to sea water	**1.27E-07**	**4.04E-08**	**1.56E-08**	**1.90E-08**
Heavy metals to sea water	**1.21E-08**	**3.17E-09**	**1.29E-09**	**3.94E-10**
Inorganic emissions to sea water	**0.000129969**	**3.35E-05**	**1.37E-05**	**2.95E-06**
Chloride	0.000127347	3.28E-05	1.34E-05	2.86E-06
Organic emissions to sea water	**7.70E-08**	**1.99E-08**	**8.12E-09**	**1.77E-09**
Other emissions to sea water	**0.049883805**	**0.016052679**	**0.003975212**	**0.010939158**
Particles to sea water	**2.06E-07**	**5.65E-07**	**1.71E-07**	**1.07E-06**
Emissions to industrial soil	**4.32E-07**	**4.35E-08**	**4.33E-09**	**4.41E-08**

Mass (g)	DE: Plastic injection moulding part (unspecific) ts <u-so>	DE: Silica sand (flour) ts	EU-28: Brass (CuZn20) ts <p-agg>	EU-28: Heavy fuel oil at refinery (1.0wt.% S) ts
Deposited goods	**0**	**5.97E-08**	**0.000396262**	**4.61E-05**
Radioactive waste	**0**	**9.98E-12**	**4.03E-09**	**2.44E-08**
Stockpile goods	**0**	**5.97E-08**	**0.000396258**	**4.61E-05**
Hazardous waste (deposited)	0	2.16E-16	3.82E-13	2.33E-12
Overburden (deposited)	0	5.80E-08	0.000256774	3.98E-05
Slag (deposited)	0	7.47E-19	9.15E-17	4.35E-16
Spoil (deposited)	0	1.13E-10	1.06E-07	1.10E-06
Tailings (deposited)	0	5.66E-11	0.000136671	5.03E-06
Waste (deposited)	0	1.58E-09	2.71E-06	1.25E-07
Emissions to air	**0.000629092**	**2.60E-07**	**0.00018649**	**0.000477909**
Heavy metals to air	**0**	**8.26E-15**	**8.76E-10**	**4.01E-10**
Inorganic emissions to air	**0.000629092**	**1.96E-07**	**0.00014989**	**0.000401783**
Carbon dioxide	0	9.39E-09	7.74E-06	0.000146772
Carbon dioxide (biotic)	0	1.68E-09	4.36E-07	1.39E-06
Carbon dioxide (land use change)	0	1.92E-11	1.57E-08	5.44E-08
Carbon monoxide	0	5.53E-12	6.43E-09	1.69E-07
Chloride (unspecified)	0	4.67E-16	2.41E-12	1.08E-09
Fluoride	0	2.69E-15	1.00E-12	4.63E-12
Hydrogen	0	2.85E-14	1.15E-09	4.36E-11
Hydrogen chloride	0	3.67E-13	6.61E-10	1.03E-09
Hydrogen fluoride	0	2.11E-14	5.53E-11	6.46E-11
Hydrogen sulphide	0	7.04E-13	1.28E-10	2.83E-09
Nitrogen (atmospheric nitrogen)	0	8.73E-13	2.80E-06	2.24E-08
Nitrogen dioxide	0	7.02E-15	1.19E-11	1.10E-11
Nitrogen monoxide	0	9.30E-14	2.13E-11	8.35E-11
Nitrogen oxides	0	1.20E-11	1.79E-08	3.75E-07
Nitrogen, total	0	1.70E-18	2.19E-16	1.02E-15
Nitrous oxide (laughing gas)	0	3.84E-13	4.58E-10	5.58E-09
Oxygen	0	1.33E-10	4.15E-08	1.67E-07
Sulphur dioxide	0	5.32E-12	4.10E-08	4.62E-07
Water (evapotranspiration)	0	1.51E-07	5.09E-05	0.00012748
Water vapour	0.000629092	3.38E-08	8.79E-05	0.000124876
Organic emissions to air (group VOC)	**0**	**1.66E-11**	**1.43E-08**	**2.39E-06**

Group NMVOC to air	***0***	***1.12E-12***	***1.97E-09***	***4.86E-07***
Methane	0	1.39E-11	1.11E-08	1.88E-06
Other emissions to air	***0***	***6.38E-08***	***3.66E-05***	***7.37E-05***
Clean gas	0	5.37E-12	9.35E-09	2.74E-09
Exhaust	0	4.71E-08	2.16E-05	6.11E-05
Unused primary energy from solar energy	0	1.65E-08	2.76E-06	1.18E-05
Used air	***0***	***2.42E-10***	***1.22E-05***	***7.76E-07***
Particles to air	***0***	***5.85E-12***	***2.20E-09***	***2.67E-08***
Emissions to fresh water	**0**	**2.11E-05**	**0.010914539**	**0.057894269**
Analytical measures to fresh water	**0**	**1.06E-11**	**7.88E-09**	**8.76E-08**
Biological oxygen demand (BOD)	0	3.20E-14	7.08E-11	2.02E-09
Chemical oxygen demand (COD)	0	1.05E-11	7.77E-09	7.75E-08
Heavy metals to fresh water	**0**	**5.58E-12**	**1.48E-09**	**9.81E-09**
Inorganic emissions to fresh water	**0**	**8.88E-11**	**3.84E-07**	**4.65E-05**
Calcium	0	3.74E-12	3.55E-08	3.02E-09
Carbonate	0	1.80E-13	2.52E-09	5.71E-07
Chloride	0	4.93E-11	2.94E-07	4.55E-05
Chlorine (dissolved)	0	4.47E-14	2.06E-10	1.16E-10
Fluoride	0	7.90E-12	7.73E-10	5.54E-09
Hydrogen peroxide	0	1.61E-14	2.51E-12	1.08E-11
Sodium	0	5.64E-12	1.74E-08	3.21E-08
Sodium chloride (rock salt)	0	5.89E-15	8.95E-13	7.26E-12
Sodium hypochlorite	0	1.08E-14	2.40E-11	8.42E-12
Sodium sulphate	0	3.84E-13	6.00E-11	2.61E-10
Sulfate	0	1.84E-11	3.16E-08	3.28E-07
Sulphide	0	3.18E-14	4.58E-10	1.04E-07
Organic emissions to fresh water	**0**	**5.38E-12**	**3.86E-09**	**8.36E-08**
Other emissions to fresh water	**0**	**2.04E-05**	**0.010601398**	**0.056048285**
Pesticides to fresh water	0	2.65E-16	3.17E-14	1.42E-13
Collected rainwater to river	0	1.15E-09	2.00E-06	8.00E-08
Cooling water to river	0	2.82E-10	9.55E-07	0.000203933
Processed water to groundwater	0	1.05E-10	1.36E-08	8.50E-08
Processed water to river	0	3.33E-07	3.17E-05	0.000844523

Turbined water to river	0	1.49E-08	0.000127095	0.002106816
Particles to fresh water	**0**	**5.58E-11**	**3.23E-08**	**1.14E-06**
Soil loss by erosion into water	0	5.18E-11	1.51E-08	5.56E-08
Solids (suspended)	0	3.94E-12	1.72E-08	1.08E-06
Radioactive emissions to fresh water	**0**	**7.00E-07**	**0.000312711**	**0.001798149**
Radium (Ra226)	0	7.00E-07	0.000312711	0.001798149
Emissions to sea water	**0**	**2.45E-08**	**2.97E-05**	**0.000250538**
Analytical measures to sea water	**0**	**1.41E-14**	**5.40E-11**	**1.59E-08**
Heavy metals to sea water	**0**	**4.23E-16**	**4.40E-12**	**1.40E-09**
Inorganic emissions to sea water	**0**	**3.72E-12**	**4.66E-08**	**1.49E-05**
Chloride	0	3.62E-12	4.57E-08	1.46E-05
Organic emissions to sea water	**0**	**2.22E-15**	**2.76E-11**	**8.85E-09**
Other emissions to sea water	**0**	**2.45E-08**	**2.97E-05**	**0.00023547**
Particles to sea water	**0**	**6.98E-13**	**6.31E-10**	**1.12E-07**
Emissions to industrial soil	**0**	**5.43E-14**	**3.60E-11**	**1.03E-10**

Mass	EU-28: Tap water ts	GLO: Steel rebar worldsteel	Total Maritime transport	Total Truck-Trailer Transport
Deposited goods	**6.21E-07**	**0.002726636**	**0.002726636**	**0**
Radioactive waste	**8.75E-11**	**7.49E-09**	**7.48997E-09**	**0**
Stockpile goods	**6.20E-07**	**0.002726629**	**0.002726629**	**0**
Hazardous waste (deposited)	4.48E-15	2.54E-08	2.53865E-08	0
Overburden (deposited)	4.89E-07	7.03E-05	7.0297E-05	0
Slag (deposited)	3.89E-18	2.42E-16	2.41948E-16	0
Spoil (deposited)	2.73E-09	2.21E-05	2.20862E-05	0
Tailings (deposited)	6.73E-09	7.32E-07	7.32067E-07	0
Waste (deposited)	1.22E-07	0.002633488	0.002633488	0
Emissions to air	**5.07E-06**	**0.189471372**	**0.210991262**	**0.005888341**
Heavy metals to air	**6.92E-13**	**2.58E-07**	**2.5779E-07**	**0**
Inorganic emissions to air	**3.14E-06**	**0.151051105**	**0.172541796**	**0.00588506**
Carbon dioxide	1.95E-07	0.029342997	0.049879348	0.005522116
Carbon dioxide (biotic)	1.48E-07	0.00048647	0.00048647	0.000290638
Carbon dioxide (land use change)	1.35E-10	1.18E-05	1.18373E-05	0
Carbon monoxide	3.42E-10	0.000216011	2.74E-04	8.67003E-06
Chloride (unspecified)	3.33E-13	2.42E-09	2.42372E-09	0
Fluoride	1.97E-14	7.97E-09	7.97321E-09	0
Hydrogen	7.77E-11	6.71E-08	6.71394E-08	0
Hydrogen chloride	7.89E-12	4.98E-07	4.97656E-07	0
Hydrogen fluoride	7.80E-13	5.24E-08	5.23843E-08	0
Hydrogen sulphide	5.05E-12	7.24E-08	7.2353E-08	0
Nitrogen (atmospheric nitrogen)	5.57E-10	3.27E-06	3.27494E-06	0
Nitrogen dioxide	1.51E-12	2.05E-09	2.04677E-09	4.45E-06
Nitrogen monoxide	7.79E-12	2.69E-08	2.68912E-08	5.91E-05
Nitrogen oxides	3.72E-10	6.14E-05	6.06E-04	0
Nitrogen, total	8.93E-18	5.19E-14	5.1922E-14	0
Nitrous oxide (laughing gas)	1.19E-11	2.12E-07	7.31E-07	7.32E-08
Oxygen	9.91E-10	6.59E-05	6.58538E-05	0
Sulphur dioxide	2.19E-10	8.64E-05	4.37E-04	3.66E-08
Water (evapotranspiration)	8.47E-07	0.045535794	0.045535794	0
Water vapour	1.95E-06	0.075240126	0.075240126	0
Organic emissions to air (group VOC)	**6.46E-10**	**6.18E-05**	**7.81E-05**	**2.17E-06**
Group NMVOC to air	***5.31E-11***	***3.38E-06***	***1.91E-05***	***2.11E-06***
Methane	5.83E-10	5.84E-05	5.89E-05	5.11E-08
Other emissions to air	***1.93E-06***	***0.038345729***	***0.038345729***	***0***

Clean gas	5.38E-10	9.21E-06	9.21257E-06	0
Exhaust	1.61E-06	0.036697377	0.036697377	0
Unused primary energy from solar energy	9.09E-08	0.000929779	0.000929779	0
Used air	***2.23E-07***	***0.00070936***	***0.00070936***	***0***
Particles to air	***6.36E-11***	***1.24E-05***	***2.54E-05***	***1.12E-06***
Emissions to fresh water	**0.000181552**	**10.7985837**	**10.7985837**	**0**
Analytical measures to fresh water	**4.18E-10**	**2.92E-06**	**2.91772E-06**	**0**
Biological oxygen demand (BOD)	1.15E-10	1.19E-07	1.19183E-07	0
Chemical oxygen demand (COD)	2.98E-10	5.78E-06	5.77934E-06	0
Heavy metals to fresh water	**3.93E-11**	**3.34E-06**	**3.33805E-06**	**0**
Inorganic emissions to fresh water	**5.89E-09**	**0.000182143**	**0.000182143**	**0**
Calcium	1.28E-10	1.46E-07	1.46126E-07	0
Carbonate	4.70E-11	1.07E-06	1.06758E-06	0
Chloride	4.99E-09	0.000169843	0.000169843	0
Chlorine (dissolved)	3.93E-13	1.87E-09	1.87053E-09	0
Fluoride	4.42E-11	5.94E-07	5.94092E-07	0
Hydrogen peroxide	8.68E-14	7.85E-10	7.84717E-10	0
Sodium	9.30E-11	3.84E-06	3.84449E-06	0
Sodium chloride (rock salt)	3.73E-14	1.82E-10	1.82439E-10	0
Sodium hypochlorite	1.51E-10	4.04E-08	4.03903E-08	0
Sodium sulphate	2.08E-12	3.42E-08	3.41932E-08	0
Sulfate	1.48E-10	5.68E-06	5.68367E-06	0
Sulphide	8.56E-12	2.39E-07	2.39135E-07	0
Organic emissions to fresh water	**1.24E-10**	**1.37E-06**	**1.36651E-06**	**0**
Other emissions to fresh water	**0.000175166**	**10.76473248**	**10.76473248**	**0**
Pesticides to fresh water	1.35E-15	1.37E-11	1.37225E-11	0
Collected rainwater to river	8.06E-08	0.002400908	0.002400908	0
Cooling water to river	3.34E-08	0.031276844	0.031276844	0
Processed water to groundwater	6.05E-10	1.46E-05	1.45677E-05	0
Processed water to river	1.30E-05	0.069948604	0.069948604	0
Turbined water to river	3.50E-06	2.052127399	2.052127399	0
Particles to fresh water	**4.90E-10**	**2.44E-05**	**2.44288E-05**	**0**
Soil loss by erosion into water	2.99E-10	1.10E-05	1.09689E-05	0
Solids (suspended)	1.91E-10	1.35E-05	1.346E-05	0

Radioactive emissions to fresh water	**6.38E-06**	**0.033637026**	**0.033637026**	**0**
Radium (Ra226)	6.38E-06	0.033637026	0.033637026	0
Emissions to sea water	**4.04E-07**	**0.407542513**	**0.407542513**	**0**
Analytical measures to sea water	**1.36E-12**	**4.38E-08**	**4.38106E-08**	**0**
Heavy metals to sea water	**9.92E-14**	**1.05E-09**	**1.04972E-09**	**0**
Inorganic emissions to sea water	**1.04E-09**	**2.62E-05**	**2.62269E-05**	**0**
Chloride	1.02E-09	2.56E-05	2.56437E-05	0
Organic emissions to sea water	**6.16E-13**	**1.89E-08**	**1.89269E-08**	**0**
Other emissions to sea water	**4.03E-07**	**0.407515806**	**0.407515806**	**0**
Particles to sea water	**2.48E-11**	**4.16E-07**	**4.15912E-07**	**0**
Emissions to industrial soil	**3.23E-11**	**7.39E-08**	**7.39353E-08**	**0**